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Integrated Freeway/Arterial Active Traffic Management

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UNITS CONVERSION

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
AREA				
in^2	Square inches	645.2	square millimeters	mm^2
ft^2	Square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
TEMPERATURE (exact degrees)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-Lamberts	fl
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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16. Abstract

This project aimd at developing a decision support system (DSS) for Integrated Active Traffic Management (IATM) for both freeways/expressways and arterials/collectors. In order to achieve the objectives, the following tasks were performed. The research team first reviewed different traffic detection technologies to understand the output data characteristics and operation mechanisms. After initially checking data availability and roadway network, the Greater Downtown Orlando Metropolitan Area was selected as the study area. In the study area, the research team devoted great effort to collect different data sources to ensure sufficient data coverage on both freeways/expressways and arterials/collectors. The data sources included HERE, NPMRDS (National Performance Management Research Data Set), MVDS (Microwave Vehicle Detection System), AVI (Automatic Vehicle Identification), BlueTOAD, BlueMAC, etc. All data were processed to reflect traffic for the same segment at the same time and evaluated with the consideration of accuracy and availability. Fusion algorithms were developed to improve the data accuracy as well. The appropriate data were used to identify the critical roadways and segments which experienced serious traffic congestion and travel time unreliability. Around 600 miles roadways, with around 1,200 segments in total, were evaluated based on measures reflecting traffic efficiency and reliability. Two critical corridors (i.e., I-4 corridor in Downtown Orlando and SR-417 corridor in East Orlando) were selected for developing the DSS for IATM. By using Aimsun Next, the research team has developed a dynamic traffic assignment (DTA) simulation platform, involving multi-resolution modeling (MRM) framework. The platform is the largest DTA-based simulation network attempted in the United States. The microscopic simulation models were developed to test IATM control strategies. Based on the developed simulation platform, different IATM control strategies, including Variable Speed Limit (VSL), Queue Warning (QW), Ramp Metering (RM), and their combinations were tested under three different congestion levels on both corridors. Two METANET models were developed to predict traffic conditions. The DSS was developed for the IATM controls by balancing the traffic on both freeways/expressways and arterials/collectors. A total of 420 simulation runs were conducted to evaluate the developed DSS of IATM, and the generic rules of IATM controls were summarized for implementation. The results suggested that the developed DSS could successfully reduce traffic congestion and improve travel time reliability. It is intended that the results of the project would provide a solution to help operators select efficient and effective control strategies to simultaneously improve traffic conditions of freeways/expressways and arterials/collectors.

17. Key Word

Integrated Active Traffic Management (IATM), Travel time and travel time reliability, Aimsun simulation, decision support system, METANET model

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EXECUTIVE SUMMARY

Active Traffic Management (ATM) is a well-defined concept in the Transportation Systems Management & Operations (TSM&O) realm, and includes freeways and expressways. The research team extended the concept of ATM by integrating traffic management for both freeways/expressways and arterials/collectors. To ensure the success of Integrated ATM (IATM), we developed a decision support system (DSS) to select appropriate control strategies with the objective of reducing travel time and improving travel time reliability.

First, the research team reviewed a variety of traffic data collection technologies and summarized the data characteristics and limitations. With the initial investigation of traffic detection data sources, the Greater Orlando Metropolitan Area was selected as the study area.

Subsequently, a variety of data in the study area was collected and processed, including different sources such as MVDS, HERE, NPMRDS, AVI, BlueTOAD, and BlueMAC. The accuracy of traffic detection data was evaluated based on extensive comparative analysis and data fusion algorithms were developed to improve data accuracy. Guidelines are provided to help select the appropriate data sources for different purposes such as real-time monitoring, roadway evaluation, and the simulation platform development. In the study area, around 600 miles of roadways, with around 1,200 segments in total, were evaluated. Three measures (i.e., TTI, PTI, and BTI) were used for the evaluation considering the traffic congestion and the travel time reliability. Based on the three measures, two critical corridors (I-4 Downtown Orlando and SR-417 East Orlando) were selected to develop the DSS of IATM.

By using Aimsun Next, the research team developed a data-intensive simulation platform to test control strategies. The microscopic simulation models covered networks of the selected

two corridors, including 412 miles of roadways, 307 TAZs, 2,436 links, 1,135 nodes, and 286 signalized intersections. Based on the developed microscopic simulation platform, different IATM control strategies, including Variable Speed Limit (VSL), Queue Warning (QW), and Ramp Metering (RM), were tested separately in the I-4 Downtown Orlando Area. Considering measures including travel time, travel time reliability, and safety, each strategy was implemented to investigate the potential benefits on I-4 and the impact on the adjacent arterials and network. To measure the travel time reliability from the simulation, the research team has developed two models to calculate travel time reliability (i.e., standard deviation of travel time rate) for both freeways/expressways and arterials/collectors.

Finally, METANET models of both freeway/expressways and arterials/collectors were developed to predict traffic status, and the models were coded in the simulation platform. Based on extensive simulation analysis for the two critical corridors, a decision support system for IATM controls was developed to improve traffic performance, with the consideration of balance between freeways/expressways and arterials/collectors. Based on simulation results, generic rules of IATM controls were provided under three different congestion conditions (i.e., moderate traffic congestion, heavy traffic congestion, and extreme traffic congestion). The simulation results suggested that the proposed DSS of IATM could improve the performance of freeways/expressways mainline and balance traffic between freeways/expressways and arterials/collectors.

In summary, this project conducted extensive analysis to evaluate different data sources. The critical corridors which experienced serious traffic congestion and unreliability problems were selected as the study corridors. The most appropriate data sources were adopted to calibrate the simulation model to test IATM control strategies. Based on all efforts, we successfully developed a decision support system for IATM, which could reduce traffic congestion and improve travel time reliability with the balance between freeways/expressways and arterials/collectors. It is expected that the results of this project could provide a comprehensive perspective on IATM and help operators implement the appropriate traffic management strategies considering both freeways/expressways and arterials/collectors.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

Active Traffic Management (ATM) is the ability to dynamically manage recurrent and non-recurrent congestions based on prevailing traffic conditions. Focusing on trip reliability, it maximizes the effectiveness and efficiency of the facility. Integrated Corridor Management (ICM) is a collection of operational strategies and advanced technologies that allow transportation subsystems, managed by one or more transportation agencies, to operate in a coordinated and integrated manner. Through ICM, transportation professionals manage the transportation corridor as a multimodal system rather than taking the more traditional approach of managing individual assets. A transportation corridor of ICM can have several types of networks such as a freeway roadway network, an arterial roadway network, and a bus transit network. The research team attempts to develop an Integrated Active Traffic Management (IATM), benefitting and building on the ATM and ICM programs. For the successful implementation of IATM controls, a decision support system (DSS) is necessarily required to find the best alternatives among various IATM strategies and changeable traffic conditions. The DSS should be able to identify traffic congestion based on prediction models using the real-time traffic and incident data, recommend proper response strategies, and adjust the response plan alternatives.

Managing traffic data plays a crucial role in the development of the freeway/arterial IATM System. In particular, historical traffic data, including speed or travel time, traffic volume, density, and other traffic-related measurements, could help practitioners and researchers to understand the performance of the existing traffic network, and it could be further utilized to determine the causes of recurrent and non-recurrent congestion. However, different detection technologies provide traffic data in different formats and with different accuracy. Hence, a comprehensive understanding of multiple data collection technologies is necessary, considering output data characteristics, operation mechanism, availability and implementability. The detection data should be evaluated first to ensure that reliable data are provided for the IATM.

The Integrated Freeway/Arterial Active Traffic Management (IATM) control is intended to implement strategies to increase corridor throughput and improve travel time reliability. To achieve IATM successfully and efficiently, it is essential to conduct the roadway evaluation analysis to select the critical corridors for IATM controls. The selected corridors should include both freeways/expressways and arterials, with the priority to those that experience traffic congestion and unreliable travel time. A simulation platform is required to evaluate the IATM under different traffic conditions. The simulation platform should include freeways/expressways and arterials/collectors, with the ability to integrate the traffic management on both types of road facilities. Meanwhile, the platform should be able to provide sufficient data to evaluate the IATM controls.

In summary, our vision is to develop a decision support system of IATM to reduce traffic congestion and improve travel time reliability with the balance between freeways/expressways and arterials/collectors. Based on the above discussion, the main objectives of this project are summarized as follows:

1. Review traffic data collection technologies
2. Identify the study area
3. Collect traffic data in the study area
4. Evaluate all existing traffic detection data and develop fusion algorithms
5. Evaluate roadways and select study corridors
6. Develop a simulation platform to test different control strategies
7. Evaluate benefits of IATM control strategies

8. Develop a Decision Support System (DSS) for IATM controls

Chapters by each task in this research project are as follows:

- Chapter 1: Introduction
- Chapter 2: Review of state-of-the-practice freeway, arterial, and integrated ATM and relevant master plans
- Chapter 3: Traffic data collection technologies
- Chapter 4: Identification of the study area
- Chapter 5: Data collection for the study area
- Chapter 6: Data evaluation and fusion
- Chapter 7: Roadway evaluation and selection for IATM control
- Chapter 8: Construction of traffic simulation
- Chapter 9: Evaluation of IATM benefits
- Chapter 10: Development of decision support system for IATM

CHAPTER 2. REVIEW OF STATE-OF-THE-PRACTICE FREEWAY, ARTERIAL, INTEGRATED ATM, AND RELEVANT MASTER PLANS

2.1 Overview

As of 2017, advanced traffic management system (ATMS) for freeways and arterials are evolving rapidly towards to Active Transportation and Demand Management (ATDM) including Active traffic management (ATM) and Integrated Corridor Management (ICM) to enhance travel time reliability, improve traffic safety, and contribute to eco-friendly society. These have shown that integrated, coordinated, automated, and intensive traffic management are more effective to solve traffic congestion. ATM was introduced after scanning international advanced intelligent transportation system (ITS) technologies about 10 years ago (Mirshahi et al., 2007b). Although ATM has been initiated for freeway traffic management, the concept of ATM has also been considered for arterials (Dowling and Elias, 2013). Many states have been deployed ATM strategies or are preparing to adopt these concepts. Recently, the Federal Highway Administration (FHWA) extended the concept of ATM to ATDM including Active Demand Management (ADM) and Active Parking Management (APM).

Freeways and arterials are not coordinated and integrated in terms of corridors under the ATM system. Thus, the concept of ICM has been studied to manage traffic congestion more effectively and efficiently by 1) integrating all corridor networks, including freeways, arterials, and transit and 2) coordinating with the related agencies.

Furthermore, new state-of-art traffic management system, which is Intelligent Network Flow Optimization (INFLO), has been suggested for future development. The INFLO is based on connected vehicle technology and utilizes three applications: Dynamic Speed harmonization, Queue Warning (Q-WARN), and Cooperative Adaptive Cruise Control (CACC).

2.2 Active Traffic Management

2.2.1 Initiative of Active Traffic Management

In the United States, the ATM was first introduced through an international technology scanning program in 2007 (Mirshahi et al., 2007b). The team of international technology scanning program examined best ATM practices of European countries including congestion management programs, policies, and experiences. From the scanning program, the team found out various ATM strategies and their potential benefits as shown in Table 1. The strategies for ATM were provided as methods to improve traffic congestion in the U.S.

Table 1. Potential benefits of Active Traffic Management (Mirshahi et al., 2007b)

Active Traffic Management Strategy	Potential Benefits												
	Increased throughput	Increased capacity	Decrease in primary incidents	Decrease in secondary incidents	Decrease in incident severity	More uniform speeds	Decreased headways	More uniform driver behavior	Increased trip reliability	Delay onset of freeway	Reduction in traffic noise	Reduction in emissions	Reduction in fuel consumption
Speed harmonization	●		●		●	●	●	●	●	●	●	●	●
Temporary shoulder use	●	●							●	●			
Queue warning			●	●	●	●	●	●	●		●	●	●
Dynamic merge control including ramp metering	●	●	●			●		●	●	●	●	●	●
Construction site management	●	●							●		●	●	●
Dynamic truck restrictions	●	●				●		●	●			●	●
Dynamic rerouting and traveler information	●		●	●				●	●			●	●
Dynamic lane markings	●	●							●				
Automated speed enforcement			●		●	●		●	●			●	●

According to the ATM description (Mirshahi et al., 2007b) of the technical report, FHWA also defines ATM as follows:

"ATM is the ability to dynamically manage recurrent and non-recurrent congestion based on prevailing and predicted traffic conditions. Focusing on trip reliability, it maximizes the effectiveness and efficiency of the facility. It increases throughput and safety through the use of integrated systems with new technology, including the automation of dynamic deployment to optimize performance quickly and without delay that occurs when operators must deploy operational strategies manually. ATM approaches focus on influencing travel behavior with respect to lane/facility choices and operations. ATM strategies can be deployed singularly to address a specific need such as the utilizing adaptive ramp metering to control traffic flow or can be combined to meet system-wide needs of congestion management, traveler information, and safety resulting in synergistic performance gains." (FHWA, 2017a)

2.2.2 Typical ATM Techniques

Based on ATM techniques of Europe, several states have developed and implemented various ATM strategies as below (Neudorff and McCabe, 2015):

- **Adaptive Ramp Metering (ARM)**: This aims to control the rate of vehicle entering a freeway facility by installing traffic signal(s) on ramps. Different from pre-timed or fixed time rates, adaptive ramp metering makes use of traffic responsive or adaptive algorithms to optimize either local or system-wide conditions. Adaptive ramp metering can also utilize advanced metering technologies such as dynamic bottleneck identification, automated incident detection, and integration with adjacent arterial traffic signal operations.

- **Adaptive Traffic Signal Control (ATSC)**: This strategy continuously monitors arterial traffic conditions and the queuing at intersections and dynamically adjusts the signal timing to smooth the flow of traffic along coordinated routes and to optimize one or more operational objectives (such as minimize overall stops and delays or maximize green bands). ATSC approaches typically monitor traffic flows and modifies specific timing parameters to achieve operational objectives.

- **Dynamic Junction Control (DJC)**: This strategy consists of dynamically allocating lane access on mainline and ramp lanes in interchange areas where high traffic volumes are present, and the relative demand on the mainline and ramps change throughout the day. For off-ramp locations, this may consist of assigning lanes dynamically either for through movements, shared through-exit movements, or exit-only. For on-ramp locations, this may involve a dynamic lane reduction on the mainline upstream of a high-volume entrance ramp.

- **Dynamic Lane Assignment (DLA)**: This strategy, also known as dynamic lane use control, involves dynamically closing or opening of individual traffic lanes as warranted and providing advance warning of the closure(s), typically through dynamic lane control signs, to safely merge traffic into adjoining lanes. DLA is often installed in conjunction with dynamic speed limits and also supports the ATM strategies of Dynamic Shoulder Lane (DShL) and DJC.

- **Dynamic Lane Reversal (DLR)**: This strategy, also known as or contraflow lane reversal, involves, consists of the reversal of lanes in order to dynamically allocate the capacity of congested roads, thereby allowing capacity to better match traffic demand throughout the day.

- **Dynamic Merge Control (DMC)**: This strategy, also known as dynamic late merge or dynamic early merge, consists of dynamically managing the entry of vehicles into merge areas with a series of advisory messages approaching the merge point that prepare motorists for an upcoming merge and encouraging or directing a consistent merging behavior. Applied conditionally during congested (or near congested) conditions, such as a work zone, DMC can help create or maintain safe merging gaps and reduce shockwaves upstream of merge points.

- **Dynamic Speed Limits (DSpL)**: This strategy adjusts speed limits based on real-time traffic, roadway, and/or weather conditions. Dynamic speed limits can either be enforceable (regulatory) speed limits or recommended speed advisories, and they can be applied to an entire roadway segment or individual lanes. In an ATDM approach, real-time and anticipated traffic conditions are used to adjust the speed limits dynamically to meet an agency's goals/objectives for safety, mobility, or environmental impacts. At UCF DSpL algorithms have been developed to adjust speed based also on real-time crash risk (Abdel-Aty et al., 2008; Abdel-Aty et al., 2006a; Abdel-Aty et al., 2006b).

- **Dynamic Shoulder Lane (DShL)**: This strategy, which has also been called hard shoulder running or temporary shoulder use, allows drivers to use the shoulder as a travel lane(s) based on congestion levels during peak periods and in response to incidents or other conditions as warranted during nonpeak periods. This strategy is frequently implemented in conjunction with DSpL and DLA. This strategy may also be used as a managed lane (e.g., opening the shoulder as temporary bus-only lane).

- **Queue Warning (QW)**: This strategy involves real-time displays of warning messages (typically on dynamic message signs and possibly coupled with flashing lights) along a roadway to alert motorists that queues or significant slowdowns are ahead, thus reducing rear-end crashes and improving safety. In an ATDM approach, as the traffic conditions are monitored continuously, the warning messages are dynamic based on the location and severity of the queues and slowdowns.

- **Transit Signal Priority (TSP)**: This strategy manages traffic signals by using sensors or probe vehicle technology to detect when a bus nears a signal controlled intersection, turning the traffic signals to green sooner or extending the green phase, thereby allowing the bus to pass through more quickly and help maintain scheduled transit vehicle headways and overall schedule adherence.

2.2.3 Representative ATM Practices

2.2.3.1 Washington Department of Transportation

After developing the concept of operation of ATM in 2008 (Brinckerhoff et al., 2008), Washington State Department of Transportation (WSDOT) started to build the ATM to reduce collisions associated with congestion and blocked lanes because about 25% of traffic congestion is due to events such as collisions or disabled vehicles. In the concept of operation of ATM, WSDOT had considered several ATM techniques such as variable speed limits, queue warning, hard shoulder running, travel time signs, and junction control. Currently, variable speed limits, queue warning, lane control measures, ramp metering, and junction control have been being operated. In particular, variable speed limits, queue warning, and lane control measures are integrated on a gantry (Figure 1).

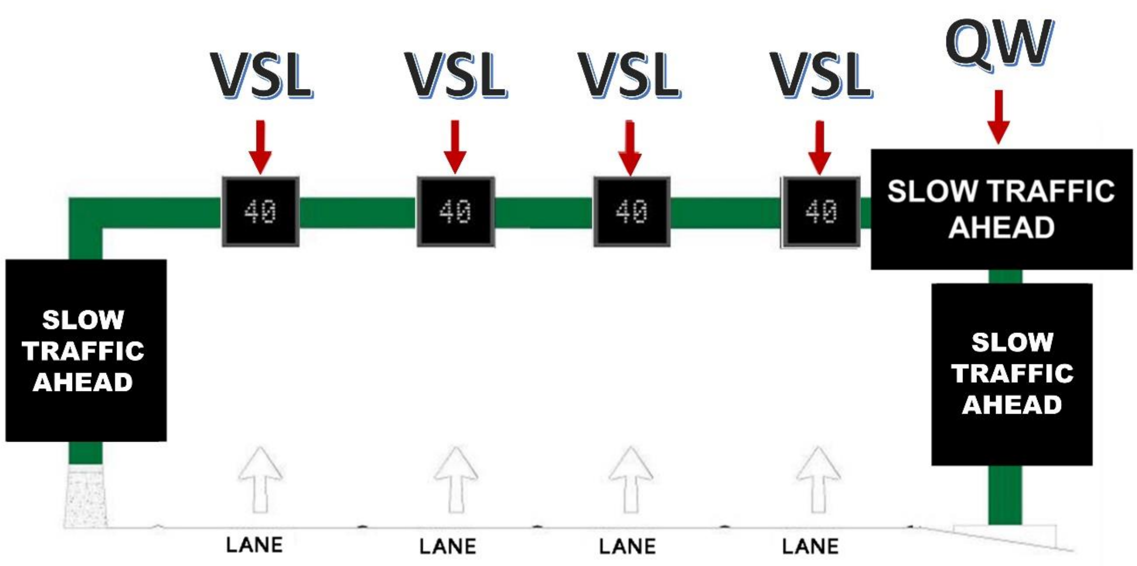


Figure 1. Gantry with speed displays, lane control, and supplemental signs

WSDOT currently is operating the ATM on I-5, I-90 and SR 520 in the Puget Sound region (Figure 2) (WSDOT). ATM on I-5 started to be operated on August 10, 2010. Fifteen signs are located on the northbound of I-5. And ATM on I-90 was activated in June 2011 and in May 2012 over two stages. Twenty-five signs are located in both directions of I-90 between I-5 and 130th Avenue. Finally, ATM on SR 520 was operated in November 2010. Nineteen signs are located on SR 520 between I-5 and 130th Avenue N.E.

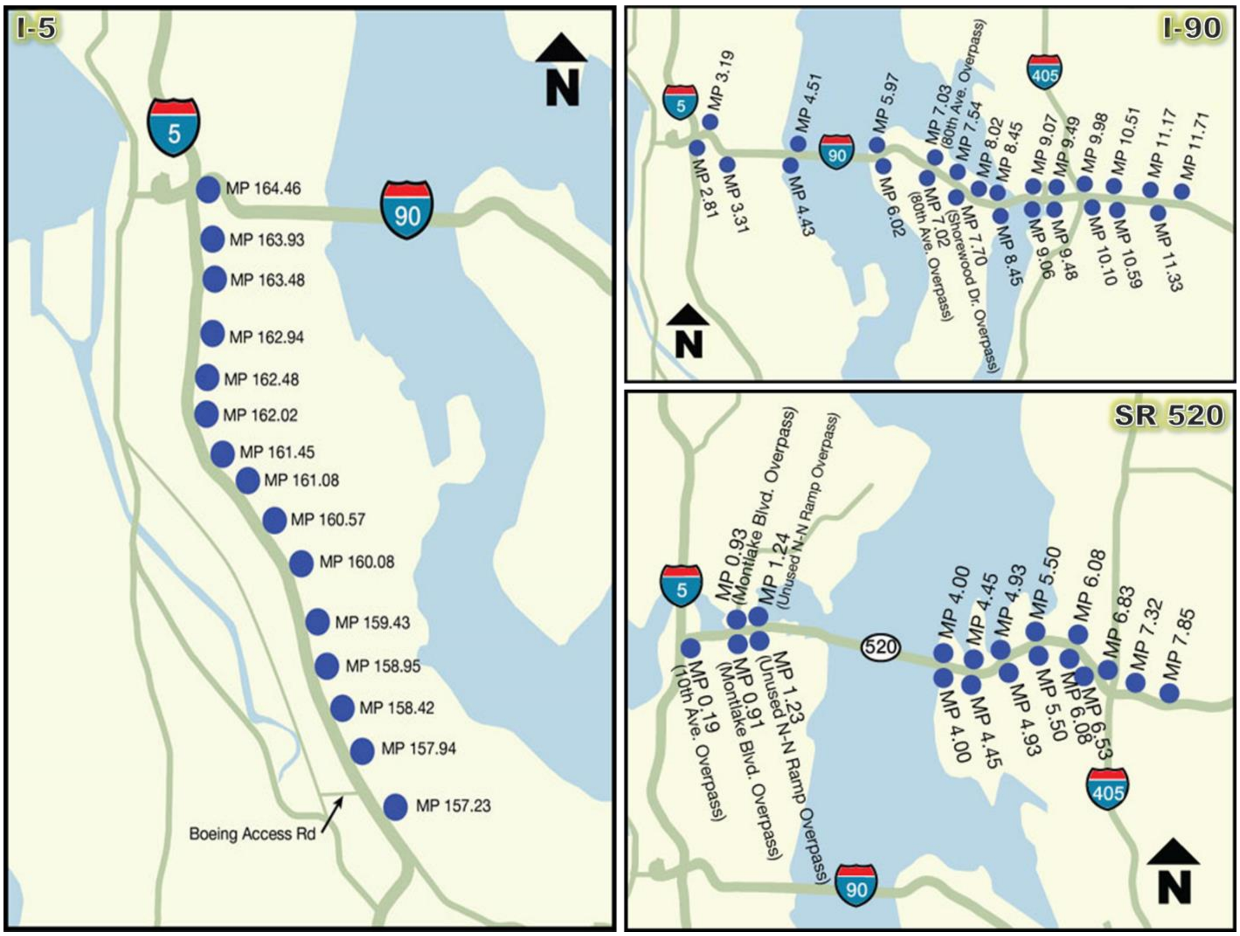


Figure 2. Sign locations for Active Traffic Management practice in Washington State

2.2.3.2 Virginia Department of Transportation

Virginia State Department of Transportation (VDOT) started to consider ATM from 2010 (Fontaine and Miller, 2012) and selected I-66 to deploy ATM in 2011. Because the I-66 corridor was one of the most congested Interstate highway corridors, and construction improvements of I-66 are restricted due to the constrained right-of-way and limited funding. The ATM project for I-

66 has started in August 2013 and completed in March 2016. Virginia's ATM mainly refers to an integrated set of operating strategies and technologies for managing traffic. The main objectives of Virginia's ATM are as follow:

- Reduce the number of primary and secondary crashes
- Rapidly respond to incidents
- Dynamically use shoulders and ramp meters
- Monitor and provide roadway condition information

ATM treatments for I-66 included lane control signal systems including advisory variable speed limits (VSL), hard shoulder running (HSR, or shoulder lane management systems), adaptive ramp metering, enhanced detection and camera systems, queue warning systems, and others. Several combinations of ATM treatments were deployed on about 34 miles from District of Columbia (Exit 74) to Haymarket (Exit 40/US-15) (See Figure 3). The corridor was divided into five segments including different combinations of ATM techniques planned for each segment (See Figure 4).

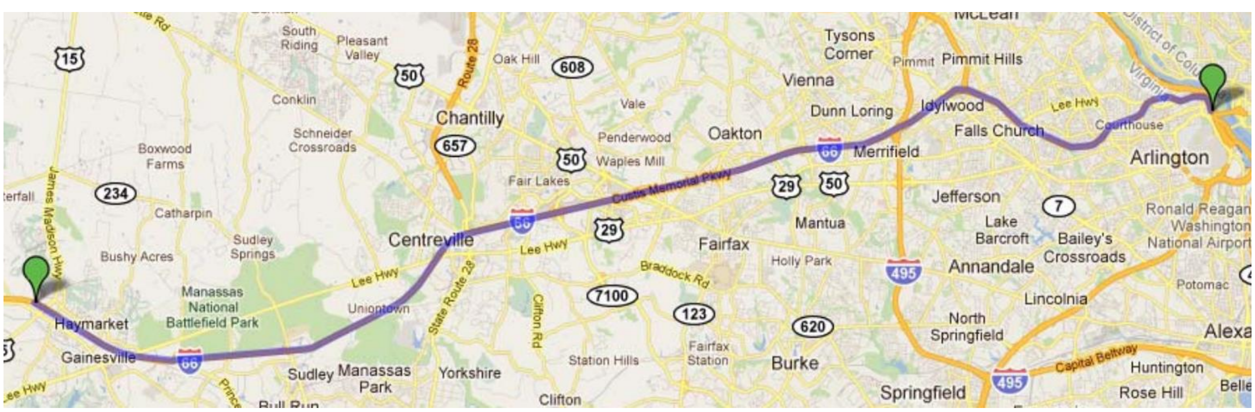


Figure 3. Spatial scope of ATM deployment project on I-66 (Map source: Google Maps)

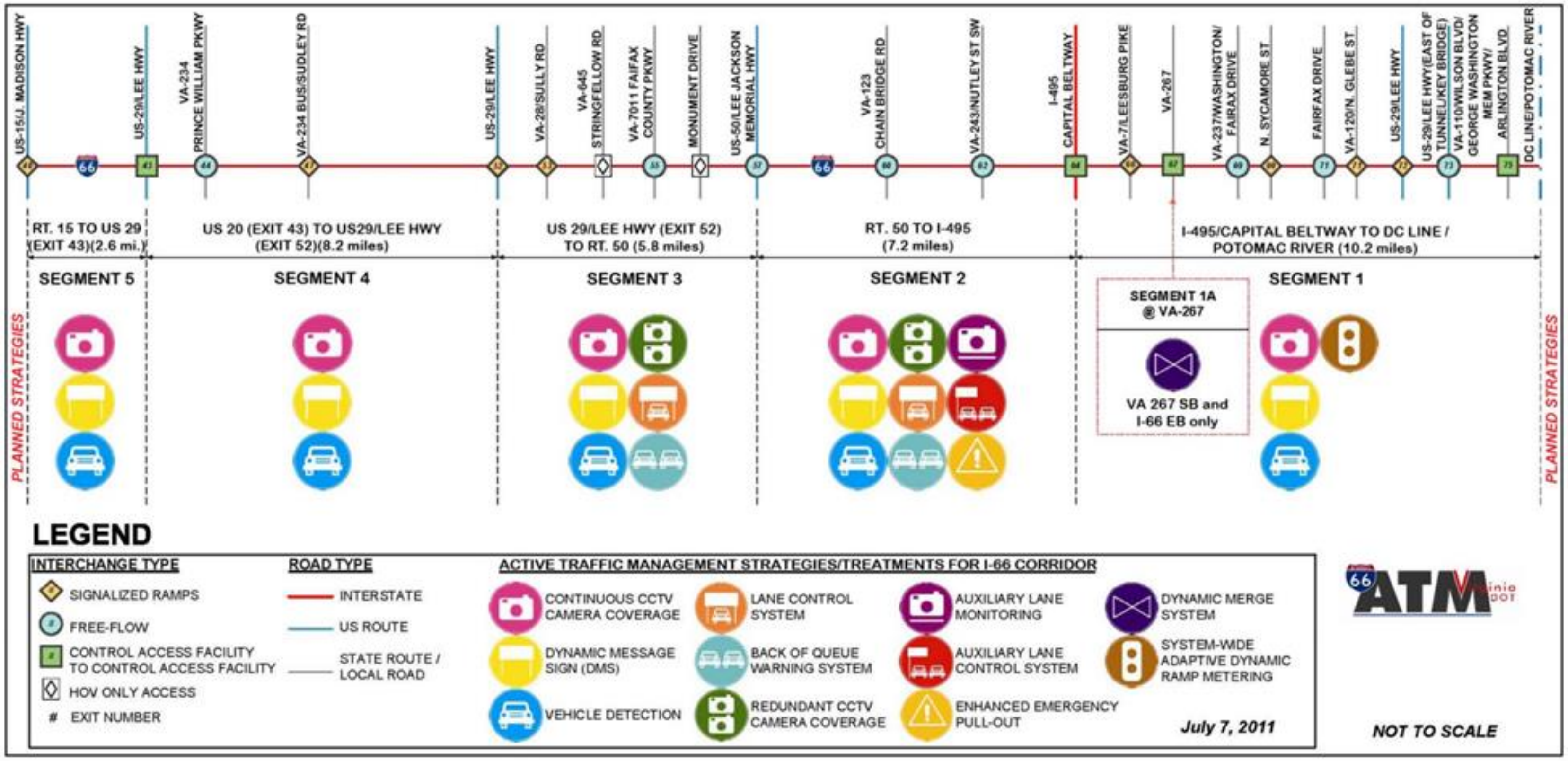


Figure 4. I-66 ATM project segments and treatments

Features of key ATM treatments are as follows (Kuhn et al., 2017):

- CCTV Camera monitoring all roadway lanes and shoulders, and several on- and off-ramps of ATM deployment area.

- DMS providing advisory messages including variable speed limits and queue warning as well as traffic information.

- Vehicle detection system collecting real-time traffic data every 20 seconds and is used to determine the appropriate ATM strategies. For example, vehicle detection systems were installed at strategic locations to detect the back of queues and bottlenecks.

- Hard shoulder running allowing the shoulder lane at segment 2 with 7.2 miles as a travel lane not only during specific times of day but also depending on traffic and roadways conditions.

- Lane control system, which uses overhead gantries, providing advisory speed limits, HOV lane restrictions as well as lane control indicators to manage traffic by lane.

- Queue warning system providing queue warnings, including back of queue warnings, on the freeway. This system uses vehicle detection system to detect a queue and LCS gantries to show a queue warning message.

- Dynamic merge system providing variable speed limit signs and lane control signs to guide drivers when approaching a merge area. This system is operating at only one interchange diverging to VA-267 roadway.

- Adaptive dynamic ramp metering to control the traffic flow at three on-ramps. The metering rates vary depending on traffic demand.

According to the preliminary evaluation of ATM benefits on I-66 corridor, improvement of travel time during the weekend showed significant evidence, but the weekday travel times and travel time reliability during peak periods were not improved because HSR was already being operated as a pre-ATM (Chun and Fontaine, 2016; Fontaine, 2016). In particular, the benefits of advisory VSLs were not confirmed due to the short operation time after the construction of ATM (Chun and Fontaine, 2016). Related to the compliance with advisory VSLs, the mean speed was recorded generally within about 5 mph of posted AVSL. LCS effects were not evaluated because of the quantification limitation of operational effects. Traffic safety also were not verified to have significant effects along the entire corridor due to the insufficient data, but the I-66 ATM had a positive impact on safety and operations during weekend peak and weekday off-peak periods (PM for Eastbound, AM for Westbound) (Chun and Fontaine, 2016; Fontaine, 2016).

2.2.3.3 Minnesota Department of Transportation

The ATM of MnDOT was introduced as part of their priced dynamic shoulder lane project and is called Minnesota's Smart Lanes (Fuhs, 2010). MnDOT is operating the ATM system within eighteen-mile section on Interstate 35 West (I-35W) in the Twin Cities Metro Area and within eight-mile section on Interstate 94 (I-94) between downtown Minneapolis and downtown St. Paul (FHWA, 2017b). The ATM is providing advisory variable speed limits and lane control information depending on traffic conditions through a series of overhead signs known as Intelligent Lane Control Signals (ILCS) (See Figure 5). The ILCS is controlled through a freeway traffic management system software known as Intelligent Roadway Information System (IRIS), which also controls loop detectors, DMS, and ramp meters.

Figure 5. Intelligent lane control signals on I-35W

The ATM on I-35W was deployed to provide dynamic speed limit, dynamic shoulder lane, and dynamic lane assignment for HOT. ILCS are used to inform drivers of closed lanes and/or recommended speed limits. The selection of dynamic speed limits is computed by an algorithm developed by the Regional Transportation Management Center (RTMC) and the University of Minnesota—Duluth. The dynamic speed limit purpose is to mitigate shock wave propagation from downstream bottlenecks by gradually reducing speed levels of incoming traffic flow.

The ATM system on I-35W includes the concept of a dynamic shoulder lane in the left-most lane along this stretch of road. This left-most dynamic shoulder lane operates as a priced dynamic shoulder lane at times when the adjacent stretch of I-35W is operated as a HOT lane, priced dynamic shoulder lane at times when the capacity is needed, and shoulder when needed. The dynamic shoulder lane is separated from the general purpose lanes by a single solid yellow stripe (See Figure 5). An additional yellow stripe was placed along the center median barrier to improve visibility and a static sign is placed at the beginning of the dynamic lane.

ATM on I-94 is located between I-35W and I-35E and is providing advisory variable speed limits, traffic control messages using lane control systems, and queue warnings (See Figure 6).

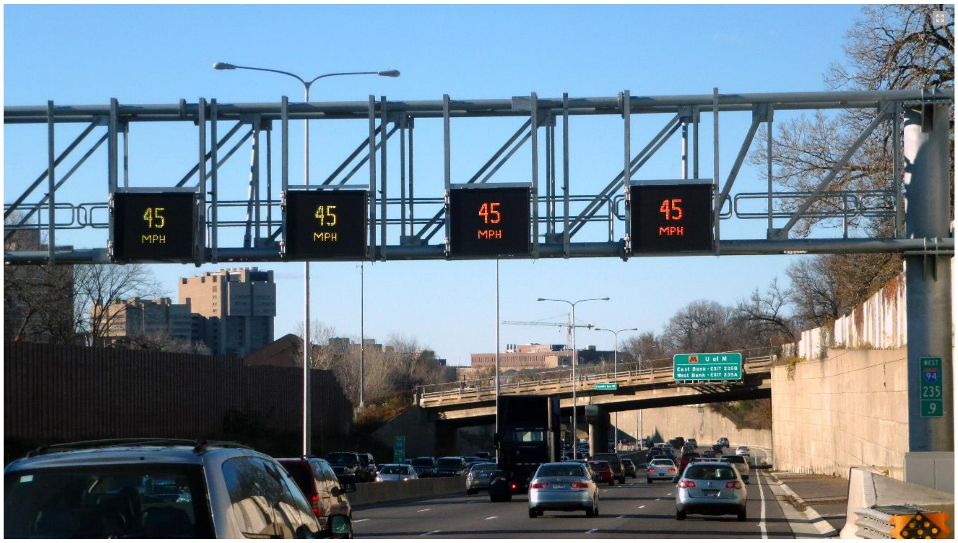


Figure 6. Active Traffic Management system on I-94
(Source: http://ungemah.com/sh_projects/i-94-managed-lanes-study-phase-1/)

In terms of the effectiveness of ATM strategies, variable advisory speed limit system was evaluated. According to the analysis results, there was a significant improvement (58%) in reducing the maximum deceleration in the I-35W northbound traffic flow during a peak hour. In particular, the travel time reliability, measured with the 95th percentile buffer index, showed substantial improvements (24-32%) after the VASL system was activated (Eil Kwon and Park, 2015). Whereas, according to investigation of the impact of the I-94 ATM System on the safety of the I-94 commons high crash area, there was no significant change in safety along the corridor due to the VSL system (Hourdos and Zitzow, 2014).

2.3 Integrated Corridor Management

Integrated Corridor Management (ICM) is a collection of operational strategies and advanced technologies that allow transportation subsystems, managed by one or more transportation agencies, to operate in a coordinated and integrated manner. Through ICM, transportation professionals manage the transportation corridor as a multimodal system rather than taking the more traditional approach of managing individual assets. A transportation corridor of ICM can have several types of networks: freeway roadway network, arterial roadway network, bus transit network, rail transit network (heavy rail and light rail), commuter rail network, freight rail network, and ferry network. According to the ICM implementation Guide, all corridors will have at least three networks: freeway, arterial, and bus transit (Christie et al., 2015).

The ICM has four primary goals to increase corridor throughput, improve travel time reliability, improve incident management, and enable intermodal travel decisions. The ICM provides the following capabilities:

- To deal with congestion and travel time reliability within specific travel corridor.
- To optimize the use of existing infrastructure assets and leverage unused capacity along our nation's urban corridors.
- To support transportation network managers and operators

In particular, the ICM concentrate on the following behaviors:

- Daily operations (no incident)
- Major freeway incident
- Major arterial incident

- Transit incident
- Special event
- Disaster response scenario

The ICM has two major modes: Normal mode and Event mode. Event mode considers planned event mode and unplanned event mode. Normal mode and Event mode can be switched during a single day. If an event continues for a long period, the Event mode can transition into a "Normal" mode of operation. Operating modes are not changed automatically when an event happens. According to the decision of the corridor manager considering the event severity, the operating modes would be switched (Christie et al., 2015). The ICM has four strategic areas: demand management, load balancing, event response, and capital improvement. Demand management deals with patterns of usage of transportation networks. Load balancing handles how travelers use the transportation networks in a corridor. Events can be classified either by their duration or by their effects: reduction of capacity, increase in demand, or change in demand pattern. Major improvement may be required to solve corridor-related traffic problems in the long-term perspective (Christie et al., 2015). Major stakeholders interacting with the ICM fall into five groups: travelers and other transportation network users, commercial and government entities, transportation network operators and their staff, public safety personnel, and other service providers. Several interfaces with the ICM are media feeds, Dynamic Message Signs (DMS), Highway Advisory Radio (HAR), 511 systems, and traffic and transit web sites (Christie et al., 2015).

Several key aspects for the successful ICM program were identified: institutional integration, including inter-agency cooperation and funding; technical integration, including traveler information and data fusion; and operational integration having performance measures and a decision support system. Thus, an institutional partnership is needed among the operating agencies. Basic ITS infrastructure and technology should be coordinated, and the agencies within the corridor need a cooperative operational mindset (Spiller et al., 2014). Multiagency information sharing can be accomplished through manual methods or through systems that are automated. ITS standards-based C2C (center to center) systems are used to share data automatically (Spiller et al., 2014). Traveler information is provided to the public through 511 services, Web sites, media feeds, mobile applications, and personalized information (Spiller et al., 2014).

A decision support system (DSS) for ICM identifies sudden or pending nonrecurring events or atypical recurring congestion beyond the norm via predictive modeling. The Dallas ICM system uses an expert rule system to select a pre-agreed response plan based on numerous variables, and then uses a real-time model to validate that the selected plan will provide a benefit. The San Diego system relies on its real-time model much more and allows the model to use engineering principles and algorithms to generate a response plan for an event within the corridor. The system has the capability to be fully automated or fully manual in responding to the event. (Spiller et al., 2014)

In the first stage, the eight Pioneer Sites developed their Concept of Operations and System Requirements Specification. In the second stage, three sites – Dallas, Minneapolis, and San Diego – were selected to model the potential impact of ICM on their corridors. In the third stage, two sites – Dallas and San Diego – were selected as ICM Pioneer Demonstration Sites to design, build, operate, and maintain their respective ICMSs (Integrated Corridor Management Systems) and evaluate the impact on the corridors.

2.3.1 Related Projects

2.3.1.1 San Diego

In 2010, the I-15 Corridor in the San Diego region was selected as one of two pilot sites in the nation to develop, implement, and operate an Integrated Corridor Management System (ICMS) (SANDAG). The I-15 corridor project includes freeway, surface street, and transit networks, covering a 20-mile section of I-15 from State Route 52 to State Route 78 (Dion; and Skabardonis, 2015). The I-15 corridor has HOT lanes of 8 miles, major arterial routes, and Bus Rapid Transit (BRT) using the HOT Lanes (FHWA, 2008). The HOT lanes are used as congestion pricing system and the major arterial routs are used as potential detours of I-15. As of April 2016, 40 alternate route signs were installed on surface streets along the I-15 corridor (SANDAG).

San Diego's ICMS aims to proactively and collaboratively manage the I-15 corridor to maximize transportation system performance and enable travelers the opportunity to make convenient shifts among modes and routes (USDOT). The goals and objectives developed by the I-15 ICMS are related to improve the following (Dion; and Skabardonis, 2015):

- Accessibility and mobility
- Transportation Safety
- Information dissemination to travelers
- Coordination among institutional partners
- Network Management

Based on the goals and objectives, the I-15 ICMS set up the following key strategies (Dion; and Skabardonis, 2015):

- Information sharing and distribution
  - Establish an information exchange network between networks and agencies
  - Provide automated, real-time information sharing capability
  - Establish a historical data archiving system
  - Provision of en-route traveler information to corridor travelers
  - Provision of pre-trip traveler information to corridor travelers
- Improve operational efficiency of network junctions and interfaces
  - Coordinate the operation of freeway ramp meters and nearby traffic signals
- Accommodate/promote cross-network routes and modal shifts
  - Modify ramp metering rates to accommodate traffic shifting from arterials
  - Modify arterial signal timing to accommodate traffic diverted from the freeway
  - Establish proactive corridor congestion management procedures for addressing both recurring congestion and incident situations
  - Bus Rapid Transit (BRT) operations
- Short-term capacity/demand management
  - Lane use control on I-15 Express Lanes
  - Modify HOV restrictions (minimum number of passengers, bus-only restrictions)

Among key strategies, the following ICM strategies were tested (Shah et al., 2013):

- Pre-Trip Traveler Information
- En-Route Traveler Information
- Freeway Ramp Metering
- Signal Coordination on Arterials with Freeway Ramp Metering
- Physical Bus Priority
- Congestion Pricing on Managed Lanes

To conduct the key strategies, the I-15 ICMS including DSS uses the new systems and various existing systems (See Figure 7) (Dion; and Skabardonis, 2015):

- Decision Support System (DSS): It was developed newly for I-15 ICMS as a tool to help operators identify incidents and implement response plans aimed at minimizing the impact of identified incidents on corridor operations.
- Regional Arterial Management System (RAMS): SANDAG developed RAMS in order to enhance inter-jurisdictional coordination of traffic signals along major arterial corridors throughout the San Diego region.
- Lane Closure System (LCS): It is Caltrans system collecting and managing information related to construction projects.
- Ramp Meter Information System (RMIS): System used by Caltrans to manage the operations of metering signals on freeway on-ramps.

- Advanced Traffic Management System 4.1 (ATMS 4.1): It is used by Caltrans to manage freeways. So ATMS provide connections to traffic detectors, CMSs, and CCTV Cameras and data processing capabilities to detect incidents automatically and generate automated response plan about incidents through an expert system.

- Congestion Pricing System (CPS): Caltrans system through which appropriate tolls are charged to single-occupancy vehicle users of the I-15 Express Lanes facility enrolled with FasTrak.

- Corridor Performance Measurement System (C-PeMS): Web-based application designed to retrieve, process, analyze, and store data collected by traffic detectors, as well as information from Caltrans' Lane Closure System, Caltrans-operated CMSs, incident reports logged on the CHP[1] Computer-Aided Dispatch (CAD) system, and accident records contained in the Traffic Accident Surveillance and Analysis System.

- Regional Event Management System (REMS) – XML-based, Web services interface to the CHP's CAD Media Server.

- Regional Transit Management System (RTMS) – System supporting all fixed-route transit operations for San Diego's MTS and NCTD.

- Smart Parking System (SPS) – Future system planned by SANDAG to collect real-time parking data, set dynamic parking rates, and provide real-time parking information to travelers.

[1] CHP: California Highway Patrol

- Real-Time Simulation System (RTSS) – System developed as part of the ICM demonstration to support DSS operations and used to manage and execute corridor simulations.

- Network Prediction System (NPS) – System developed as part of the ICM demonstration to support DSS operations and used to predict origin-destination flows within the I-15 corridor.

- Weather NWS – Interface with weather reporting systems, such as the National Weather Service and Weatherbug.

- Regional Traveler Information Management System (511) – System launched by SANDAG in 2007 allowing landline and cellular callers to receive tailored travel information via the Web, phone, and public access television.

- Arterial Travel Time System (ATTS) – System providing arterial travel time measurements from arterial sensors.

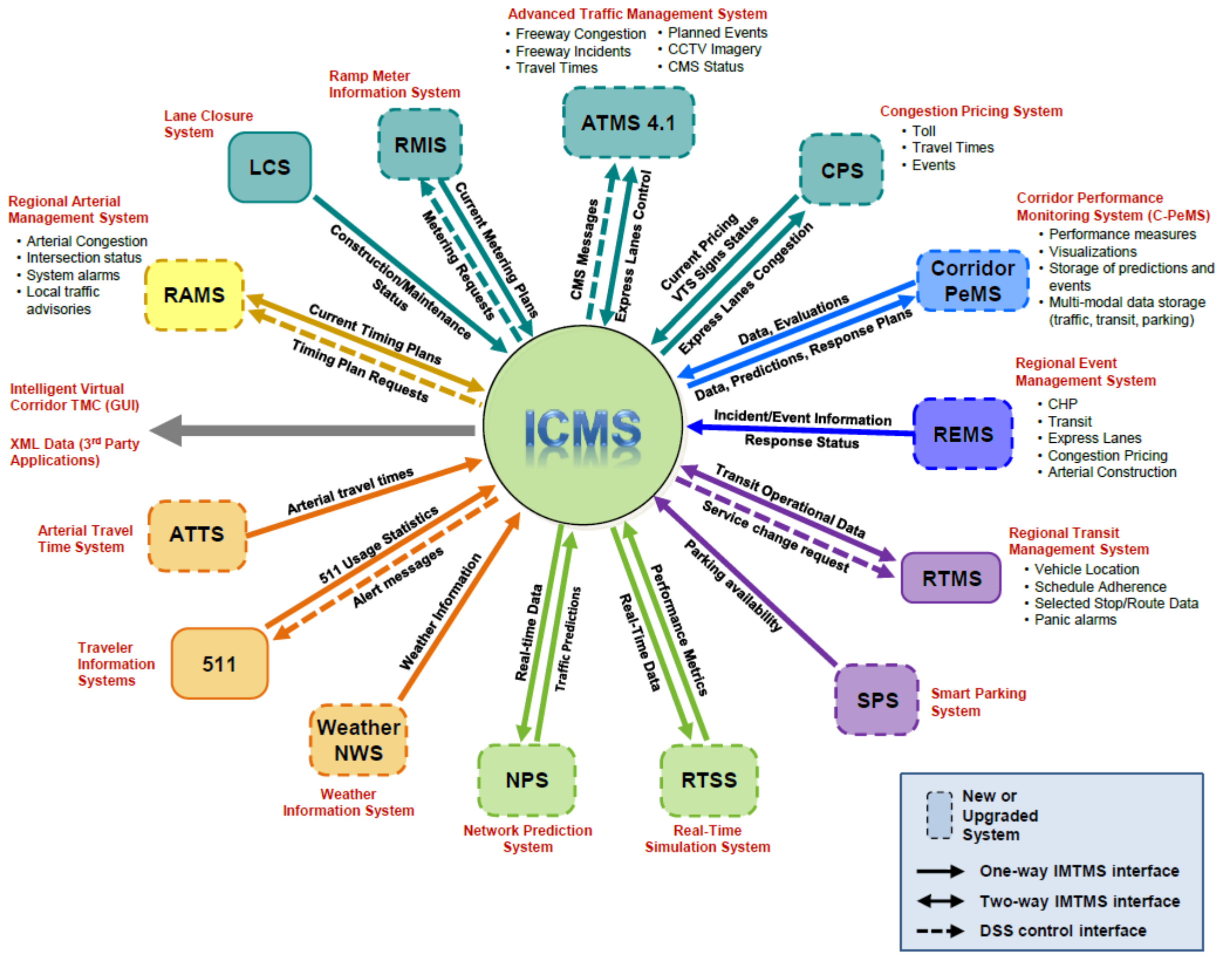


Figure 7. San Diego I-15 demonstration ICMS context diagram

The San Diego I-15 ICMS is operating through collaboration and cooperation with the following agencies:

- San Diego Association of Governments (SANDAG) – Agency responsible for transportation planning for the San Diego region and in charge of the development of the ICMS

- California Department of Transportation (Caltrans) District 11 – Agency responsible for the operations of the I-15 freeway, including the I-15 Express Lane system. This agency is specifically responsible for the operations of ramp meters, changeable message signs (CMSs) along the freeway, and traffic signals at arterial intersections at the end of freeway on-ramps and off-ramps.

- Cities of San Diego, Poway, and Escondido – Entities responsible, through their transportation departments, for the operations and maintenance of traffic control devices on major arterials within their jurisdiction that are part of the I-15 ICM corridor. Local police and fire departments were also expected to participate in corridor operations by reporting arterial incidents in their jurisdiction having a major impact on either local arterials or adjacent freeway operations.

- Metropolitan Transit System (MTS) – Operator of the San Diego metropolitan bus system, the San Diego Trolley light-rail system, the Bus Rapid Transit (BRT) system along the I-15 Express Lanes, and the regional Transit Call Center.

- North County Transit District (NCTD) – Operator of suburban transit service throughout North San Diego County, as well as the Coaster and Sprinter commuter rail services. Similar to MTS, the agency also owns and operates a fiber optic network that became part of the IMTMS.

- California Highway Patrol (CHP) – Agency responding to all reported incidents on freeways and state highways, as well as county roads in some areas. The CHP also operates and maintains the Freeway Service Patrol (FSP) that is provided by contracted towing companies.

Expected benefits of the I-15 ICMS were evaluated as the high-level results of proposed ICM strategies by Cambridge Systematics as part of the Analysis, Modeling, and Simulation (AMS) activities of the USDOT ICM initiative. According to operational conditions, the following strategies were evaluated (See Table 2). The analysis results showed that significant benefits could be obtained from the I-15 ICM strategies.

Table 2. ICM strategies and operational conditions analyzed for I-15 (Alexiadis and Armstrong, 2012)

Strategies \ Operational Conditions	Daily Operations – No Incident			Minor Incident			Major Incident		
	L	M	H	L	M	H	L	M	H
Comparative, multimodal travel time information (pre-trip and en-route)	●	●	●	●	●	●	●	●	●
Signal coordination on arterials with freeway ramp metering	●	●	●	●	●	●	●	●	●
Freeway ramp metering	●	●	●	●	●	●	●	●	●
Congestion pricing on managed lanes			●						●
Physical bus priority related to BRT		●	●		●				
Notes: L = Low Demand; M = Medium Demand; and H = High Demand.									

While full system evaluations were not yet available when this report was written, the deployed I-15 ICM system had already demonstrated its ability to identify incidents and unusual congestion events, to develop traffic management strategies integrating freeway, arterial, and transit operational elements, and to implement recommended strategies either automatically or following approval by relevant system operators. The system has also demonstrated the feasibility of using a microscopic traffic simulation model in a real-time operational environment to forecast corridor operations under alternative scenarios. Simulation evaluations have further consistently shown operational benefits exceeding deployment costs.

2.3.1.2 Dallas Texas

The US 75 Corridor of 28 miles in the Dallas-Fort Worth region was chosen as the demonstration site in Dallas because it has good transportation network for Integrated Corridor Management

(ICM) to divert traffic demand. The US 75 Corridor has been defined at two levels: the primary corridor and travel shed (See Figure 8). The primary corridor is composed of the freeway with continuous frontage roads and the managed HOV lanes, a light-rail line, transit bus service, park-and-ride lots, and major regional arterial streets within about two-mile buffer of the freeway. In addition, a full "travel shed" influence area covers other alternate modes and routes which may be influenced by a major incident or event (TxDOT, 2010; Alexiadis and Chu, 2016).

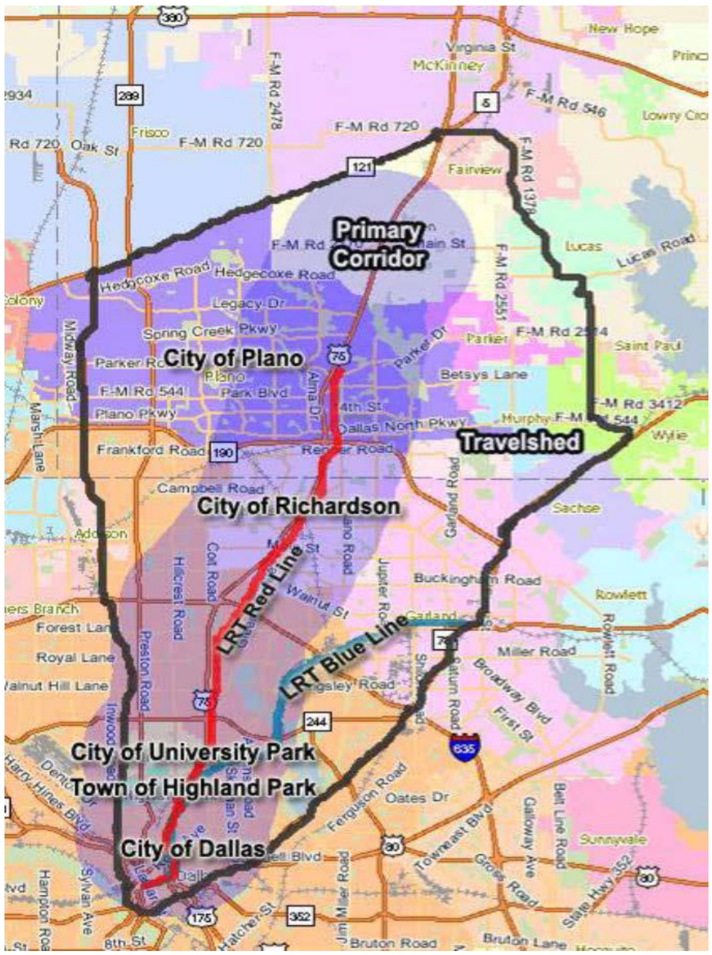


Figure 8. US-75 corridor in Dallas, Texas

The US 75 ICM purposes to implement a system and organizational structure that will provide for the operation of the Corridor in a multimodal, integrated, efficient, and safe fashion. The Integrated Corridor Management System (ICMS) is a component-based system that supports corridor management by sharing internal and external incidents, construction, special events, transit, and traffic flow data, and using this data to provide operational planning and evaluation through a decision support system (DSS) (Miller et al., 2015). The ICM of US 75 Corridor focuses on four goals (Roberts et al., 2014):

- To improve incident management
- To enable intermodal travel decisions
- To increase corridor throughput
- To improve travel time reliability

To achieve the ICM goals based on route diversion and mode shift (See Figure 9), the US 75 ICM in Dallas has deployed the following strategies:

- Providing improved multimodal traveler information (pre-trip, en-route), such as:
  - New 511 system (real-time information, including traffic incident information, construction information, traffic speeds, light rail transit (LRT) passenger loads, LRT vehicle locations, Red Line park-and-ride utilization).
  - My511 e-mail alerts.
  - ICM dynamic message signs (DMS) messages.
  - Social media.
  - Dallas Area Rapid Transit (DART) data feeds for third-party application development.

- Congestion Pricing
- Signal timing modification: Diverting traffic to key frontage roads and arterials (Greenville Ave.) with coordinated and responsive traffic signal control.
- Transit service modification: Increasing utilization of Red Line capacity with the potential of additional train cars or decreased headways.
- Transit Signal Priority
- Parking management and pricing: Implementing a parking management at Red Line park-and-ride facilities.
- Encouraging travelers to use transit during major incidents on the freeway.

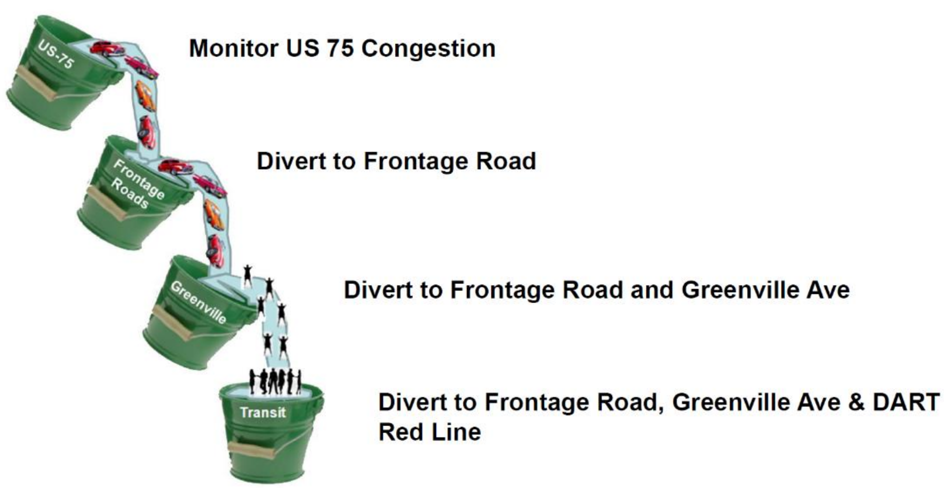


Figure 9. Diversion strategy of the decision support system (DSS)

For the above strategies, the US-75 ICM developed preapproved ICMS response plans and a Decision Support System to support ICM strategy identification and selection. Furthermore, the as-planned ICM system will deploy a shuttle service to LRT private overflow parking and a valet service at the park-and-ride parking expansion lot.

To conduct the strategies for US-75 corridor, the Dallas ICM implemented two kinds of systems: ICM system and agency operations systems. The ICM system as major system components includes a decision support system (DSS), a SmartNET subsystem, and a SmartFusion Subsystem (See Figure 10). The DSS recommends strategies and response plan according to events' location and severity, and furthermore analyze and predicts response plan benefits. The SmartNET is the means for communicating and monitoring response plans through a graphical user interface. The SmartFusion provides data collection, processing, fusion and dissemination functions for the system. The agency operations systems provide or supports field operations in order to implement ICMS strategies and response plan, collect systems data and so on. (Miller et al., 2013)

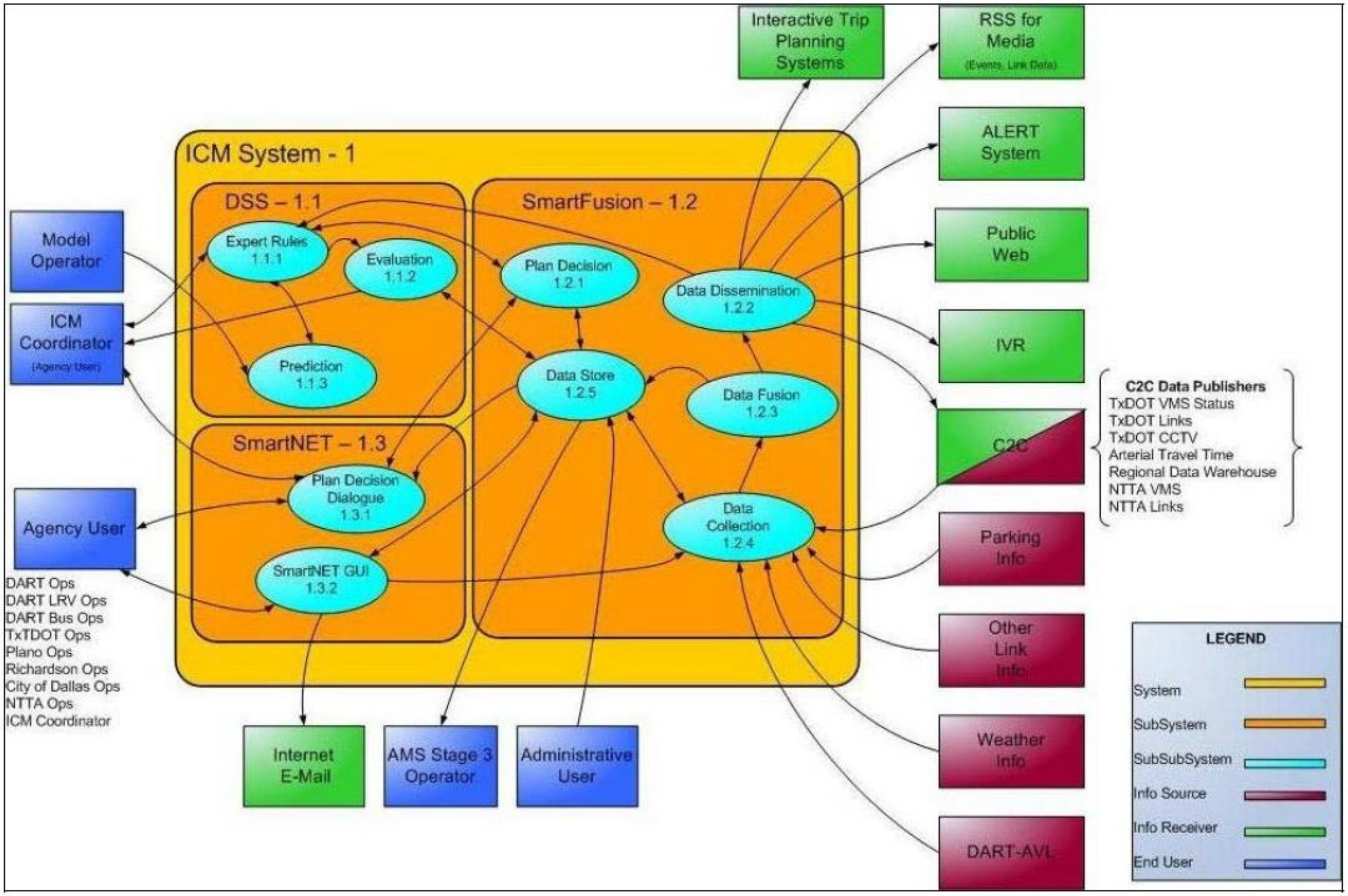


Figure 10. High-level ICMS conceptual diagram (FHWA, 2012)

Based on the ICM system and the agency operations systems, the existing systems are integrated and coordinated. The various data are collected from the following:

- ATMS data about freeway management and HOV lane monitoring from TxDOT for Dallas ATMS, Fort Worth ATMS, etc.
- ATMS data from North Texas Tollway Authority
- Travel time and speeds from Arterial Street Monitoring using Bluetooth Technology
- Regional Data Warehouse
- Availability at 5 Park & Ride lots along LRT Red Line from Parking Management System
- Real-time transit vehicle information such as Automatic Passenger Counter (APC) and Automatic Vehicle Location (AVL) from DART
- General Transit Feed Specification (GTFS) and events from DART
- NAVTEQ data as an external data source and weather information

And based on the collected various data, the incident response strategies used the following systems:

- Responsive Traffic Signal
- Transit Signal Priority

- Regional Trip Planner[2]

In addition, multimodal traffic and transit information disseminated to the public via 511 DFW[3]:

- A public web site
- Interactive Voice Response (IVR)
- A mobile web site and mobile application
- My511 (WEB, IVR, Alerts)
- Social Media

In the US-75 ICM, four types of user (i.e., ICM coordinator, model operator, agency user, and administrative user) are related. The ICM coordinator and agency users will conduct the recommended responses about the incidents when there is an incident. The ICM coordinator plays a role to provide the recommended response plans to the agency users. The agency users can select or decline the recommended plans based on their traffic or system situations. The Dallas US-75 Corridor is operated through the collaboration and cooperation with the following agencies:

- Dallas Area Rapid Transit
- City of Dallas
- City of Richardson

[2] So far, It is not confirmed.
[3] DFW: Dallas-Forth Worth

- City of Plano
- Town of Highland Park
- City of University Park
- North Central Texas Council of Governments
- North Texas Tollway Authority
- Texas Department of Transportation – Dallas District

The expected benefits on US-75 ICM had been analyzed by using a macroscopic trip table manipulation for determining trip patterns and a mesoscopic analysis (DIRECT) for assessing the influence on driver behavior in reaction to ICM strategies and for reflecting the effects of signal timing. Morning peak periods of 2007 as the model base year was used for the benefit analysis (Cambridge Systematics, 2010). The evaluation measures were selected in terms of mobility, reliability and variability, and emissions and fuel consumption. Travel time, delay, and throughput correspond to mobility measures. Reliability and variability were estimated from multiple simulated runs about all scenarios. Emissions and fuel consumption were determined by calculating and matching emission rates to reference values in EMFAC, the California Air Resources Board's emission factors model. According to operational conditions, the following strategies were evaluated (See Table 3). The analyzed benefits showed that the travel time, fuel consumption, and emissions were reduced and the travel time reliability was increased.

Table 3. ICM strategies and operational conditions analyzed for US-75 corridor (Alexiadis and Armstrong, 2012)

Strategies \ Operational Conditions	Daily Operations – No Incident			Minor Incident			Major Incident		
	L	M	H	L	M	H	L	M	H
Comparative, multimodal travel time information (pre-trip and en-route)	●	●	●	●	●	●	●	●	●
Incident signal retiming plans for frontage roads[4]					●	●	●	●	●
Incident signal retiming plans for arterials[5]					●	●	●	●	●
HOV lane[6]	-	-	-	-	-	-	-	-	-
LRT Smart parking system								●	●
LRT Red line capacity increase								●	●
LRT Station parking expansion (private parking)								●	●
Notes: L = Low Demand; M = Medium Demand; and H = High Demand.									

2.3.1.3 I-394 ICM in Minneapolis, Minnesota

The I-394 ICM corridor connects the Minneapolis central business district (CBD) and the area's western suburbs. The western end of the I-394 crosses with I-494 and the eastern end of the I-394 meets with the border of the Minneapolis CBD. And there are highway 55 and highway 7 as parallel routes of the I-394. The two parallel routes and the I-394 are linked by the north-south connection roads (see Figure 11) (Minnesota, 2008).

[4] The frontage road retiming plan was run as an individual traffic management strategy for minor incidents.
[5] The traffic management strategies (frontage road timing and arterial timing) are combined and were not run as separate strategies for a major incident.
[6] HOV lane 2+ currently is in operation, thus is not considered an ICM strategy, but was part of all scenarios.

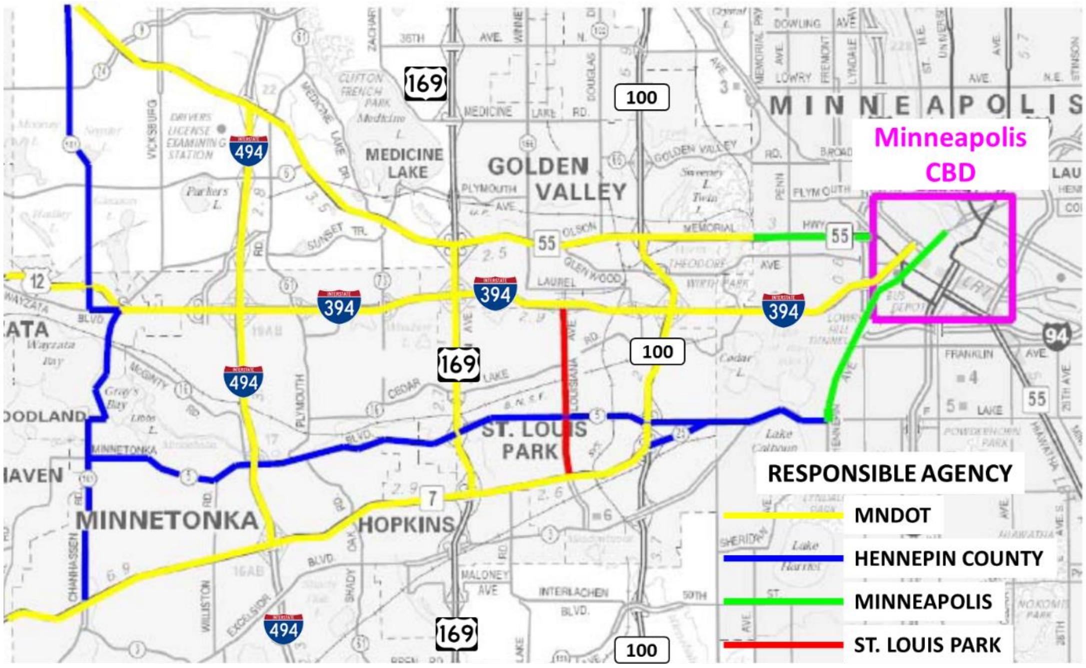


Figure 11. Operational scope and responsibility of I-394

The I-394 ICM involves various stakeholders (Minnesota, 2008):

- Minnesota Department of Transportation
- Mn/DOT Office of Transit
- Mn/DOT Office of Transit Bicycle and Pedestrians
- Mn/DOT Office of Freight
- MnPASS Phase 2 Initiative Team
- Metropolitan Council
- Hennepin County Emergency (police & fire) Dispatch and responders
- Hennepin County traffic management

- City of Minneapolis Emergency (police & fire) Dispatch and responders
- City of Minneapolis Traffic Management
- Metro Transit
- Plymouth Metrolink (transit)
- SouthWest Transit
- Minnesota State Patrol
- Hennepin County Dispatch
- Additional local Police/Fire Departments
- FHWA

The I-394 ICM aims to provide travelers for the rich options and real-time conditions of the various routes and modes of travel throughout the corridor. So, the goals and objectives of the I-394 ICM were established as (Minnesota, 2008):

- Mobility and Reliability
  - To reduce the variation in travel times experienced by travelers throughout the corridor.
  - To maintain options for travelers to effectively travel throughout the corridor using personal vehicles, transit or bicycles.
- Corridor-wide Capacity Utilization

    - To monitor and understand the ever changing available capacity of roadways, transit, parking, park-n-ride, and alternative transportation options throughout the corridor.
    - To encourage pattern changes (either through information sharing or incentives) to better utilize spare capacity.
- Corridor Event and Incident Management
    - To inform travelers of incidents, the resulting impacts, and available options in order to encourage route and mode changes.
    - To manage traffic around events through early notification, communication and coordination among responders, and informed reactions.
- Holistic Traveler Information Delivery
    - Travelers are aware of their modal and route options, and understand the current conditions facing each option.
    - Travelers do not experience delays without also being informed of options for avoiding or minimizing the impacts of such delays.

To accomplish the above goals and objectives, the I-394 ICM set up plenty of strategies in terms of 4 approaches (Minnesota, 2008):

- Approach A. Information Sharing and Distribution
    - Manual information sharing

- Automated information sharing (real-time data)
- Automated information sharing (real-time video)
- Information clearing-house / Information Exchange Network between corridor networks / agencies
- A corridor-based advanced traveler information system (ATIS) database that provides information to travelers pre-trip
- En-route traveler information devices owned / operated by network agencies (e.g., DMS, 511, transit public announcement systems) being used to describe current operational conditions on another network(s) within the corridor
- A common incident reporting system and asset management (GIS) system
- Access to corridor information (e.g., ATIS Database) by Information Service Providers (ISPs) and other value-added entities.

- Approach B: Improved Operational Efficiency of Network Junctions and Interfaces
    - Signal priority for transit (e.g. extended green times to buses that are operating behind schedule)
    - Signal pre-emption / "best route" for emergency vehicles
    - Multi-modal electronic payment
    - Transit hub connection protection

- Multi-agency / multi-network incident response teams / service patrols and training exercises
- Coordinated operation between ramp meters and arterial traffic signals in close proximity
- Promote Equipment Reliability

- Approach C. Accommodate / Promote Cross-Network Route & Modal Shifts - Passive Network Shifts ("Inform")
  - Modify arterial signal timing to accommodate traffic shifting from freeway.
  - Modify ramp metering rates to accommodate traffic, including buses, shifting from arterial
  - Modify transit priority parameters to accommodate more timely bus / light rail service on arterial

- Approach C. Accommodate / Promote Cross-Network Route & Modal Shifts - Promote Network Shifts ("Instruct")
  - Promote route shifts between roadways via en-route traveler information devices (e.g. DMS, HAR, "511") advising motorists of congestion ahead, directing them to adjacent freeways / arterials
  - Promote modal shifts from roadways to transit via en-route traveler information devices (e.g. DMS, HAR, "511") advising motorists of congestion ahead, directing them to high-capacity transit networks and providing real-time

information on the number of parking spaces available in the park and ride facility

  - Promote shifts between transit facilities via en-route traveler information devices (e.g. station message signs and public announcements) advising riders of outages and directing them to adjacent rail or bus services
  - Re-route buses around major incidents.

- Approach D: Manage Capacity – Demand Relationship Within Corridor – Capacity Oriented
  - Lane use control (reversible lanes / contra-flow)
  - Convert regular lanes to "transit-only" or "emergency-only"
  - Add transit capacity by adjusting headways and number of vehicles
  - Add transit capacity by adding temporary new service (e.g., express bus service, "bus bridge" around rail outage / incident)
  - Add capacity at parking lots (temporary lots)
  - Increase roadway capacity by opening HOV / HOT lanes / shoulders
  - Coordinate scheduled maintenance and construction activities among corridor networks
  - Restrict ramp access (metering rates, closures).

- Approach D: Manage Capacity – Demand Relationship Within Corridor – Demand Oriented
    - Variable speed limits (based on Time of Day, construction, weather conditions)
    - Modify toll / HOT pricing
    - Modify transit fares to encourage ridership
    - Modify parking fees

To illustrate operational concepts, several operational scenarios were defined (Minnesota, 2008):

- Scenario #1: Major Traffic Incident
- Scenario #2: Minor Traffic Incident
- Scenario #3: Major Arterial Highway Incident
- Scenario #4: Infrastructure Reliability Incident
- Scenario #5: Minor Transit Incident
- Scenario #6: Major Planned Event Scenario – Afternoon Baseball Game
- Scenario #7: Major Planned Event Scenario Evening Baseball Game
- Scenario #8: Evacuation Scenario
- Scenario #9: Weather Incident Scenario
- Scenario #10: Major Event on a Secondary Arterial Impacting a Freeway

- Scenario #11: Daily Operational Scenario (Recurring Congestion)

For the evaluation of the I-394 ICM, ICM strategies modeled in Minneapolis include:

- Earlier dissemination of traveler information
- Comparative travel times
- Parking availability at park-and-ride
- Incident signal retiming plans
- Predefined freeway closure points
- HOT lanes
- Dynamic rerouting
- Transit signal priority

The selected operational scenarios are scenario #1 and #2 (see Table 4). It was assumed that the minor incident occurred on freeway and the major incident occurred on freeway and arterial. In the freeway case, the incident severity is designated as full segment closed and 1-lane blocked. Major incident scenarios examined both full closures of freeway segments and blocking of one freeway general purpose and auxiliary lane for 80 minutes. Minor incident scenarios examined blocking of one freeway general purpose and auxiliary lane for 30 and 45 minutes. The major arterial incident scenario assumed closure of an arterial segment for 65 minutes (Alexiadis and Armstrong, 2012).

Table 4. ICM strategies and operational conditions analyzed for I-394 corridor

Strategies \ Operational Conditions	Minor Incident			Major Incident				
	Freeway			Freeway: Full Segment Closed			Freeway: 1-lane blocked	Arterial
	L	M	H	L	M	H	M	H
Earlier dissemination of information	●	●	●	●	●	●	●	●
Comparative, multimodal travel time information (pre-trip and en-route)	●	●	●	●	●	●	●	●
Parking availability at park and ride lots	●	●	●	●	●	●	●	●
Signal timing optimization				●	●	●	●	●
Freeway ramp metering[7]	-	-	-	-	-	-	-	-
Predefined Freeway Closure Points				●	●	●		●
HOT Lanes (open to all traffic during an incident)[8]				●	●	●		
Transit signal priority	●	●	●	●	●	●		●
Notes: L = Low Demand; M = Medium Demand; and H = High Demand.								

I-394 ICM was planned to use four primary components (see Figure 12) (MnDOT, 2008):

- Existing field devices and control systems already in place in the corridor
- A set of field devices and control systems planned to be developed and deployed by funding sources outside the ICM Project;
- The ICM System (ICMS) itself; and
- Partnerships, agreements, and actions to complement the systems being deployed.

[7] Ramp metering was in place before ICM, was not funded by ICM, and will continue to be there after ICM deployment. Ramp metering, therefore, was analyzed but only as part of baseline – not as part of ICM improvements.
[8] The HOT Lane (congestion pricing) is currently in operation and thus is not considered an ICM strategy; however, opening the HOT lane to all traffic during an incident was included in the analysis as an ICM strategy.

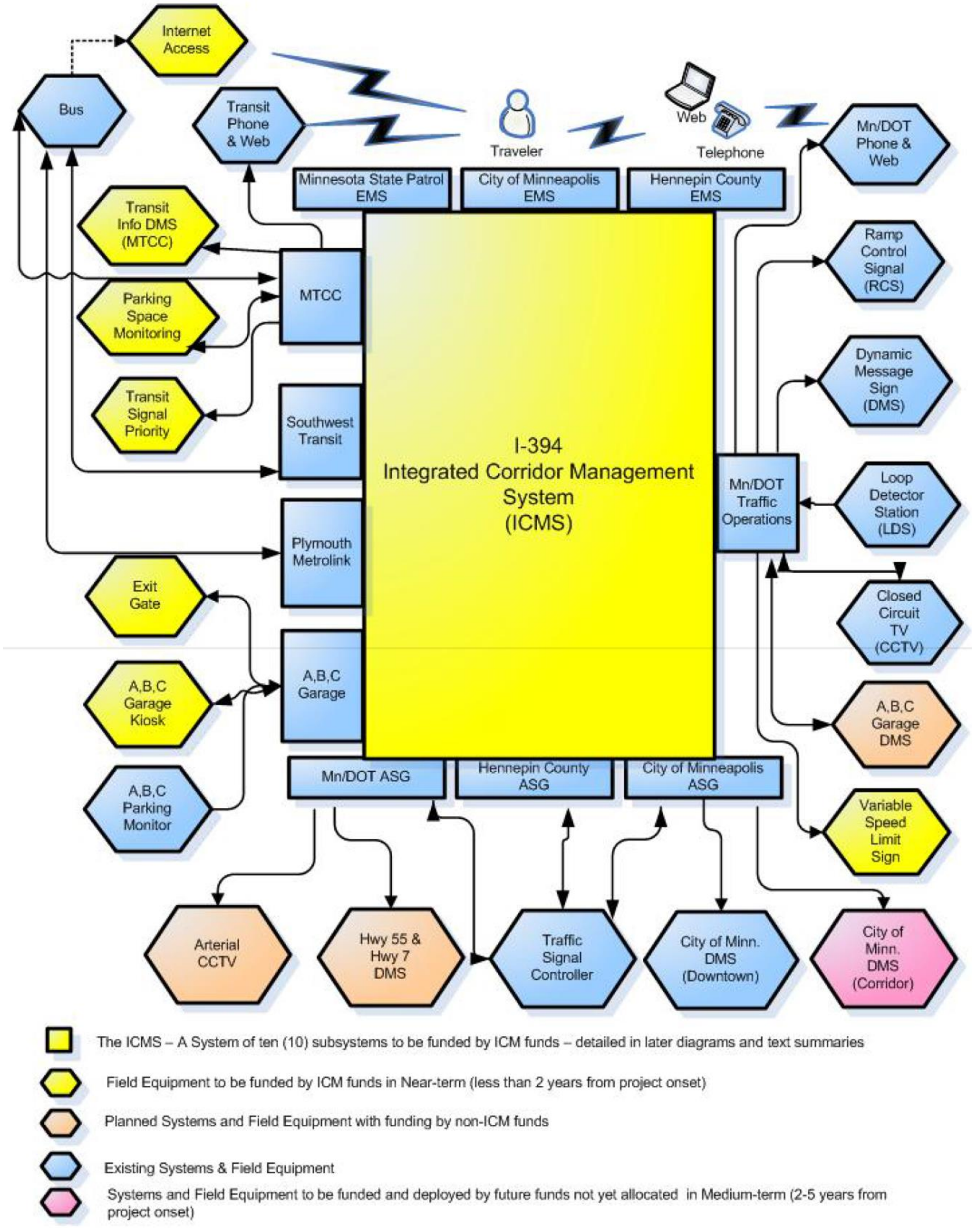


Figure 12. Block diagram of ICM components (MnDOT, 2008)

2.3.1.4 I-95 ICM in Broward County, Florida

I-95 corridor has freeway network, toll road network, arterial network, transit network, and bicycle and pedestrian network (See Figure 13). The freeway network includes I-95 with the 95 Express lanes, I-75 and I-595. The toll road network consists of the Sawgrass Expressway in Broward County; and five toll roads within Miami-Dade County, that is SR 836, SR 112, SR 874, SR 924). The arterial network encompasses Miami-Dade, Broward and Palm Beach Counties, which are operating the arterial traffic management signal systems. The transit network is composed of Tri-Rail commuter rail services and bus operations provided by Miami-Dade Transit, Broward County Transit, and Palm Tran. Bus Rapid Transit operates along the 95 Express (AECOM, 2013). I-95 is transforming toward the regional managed lanes network.

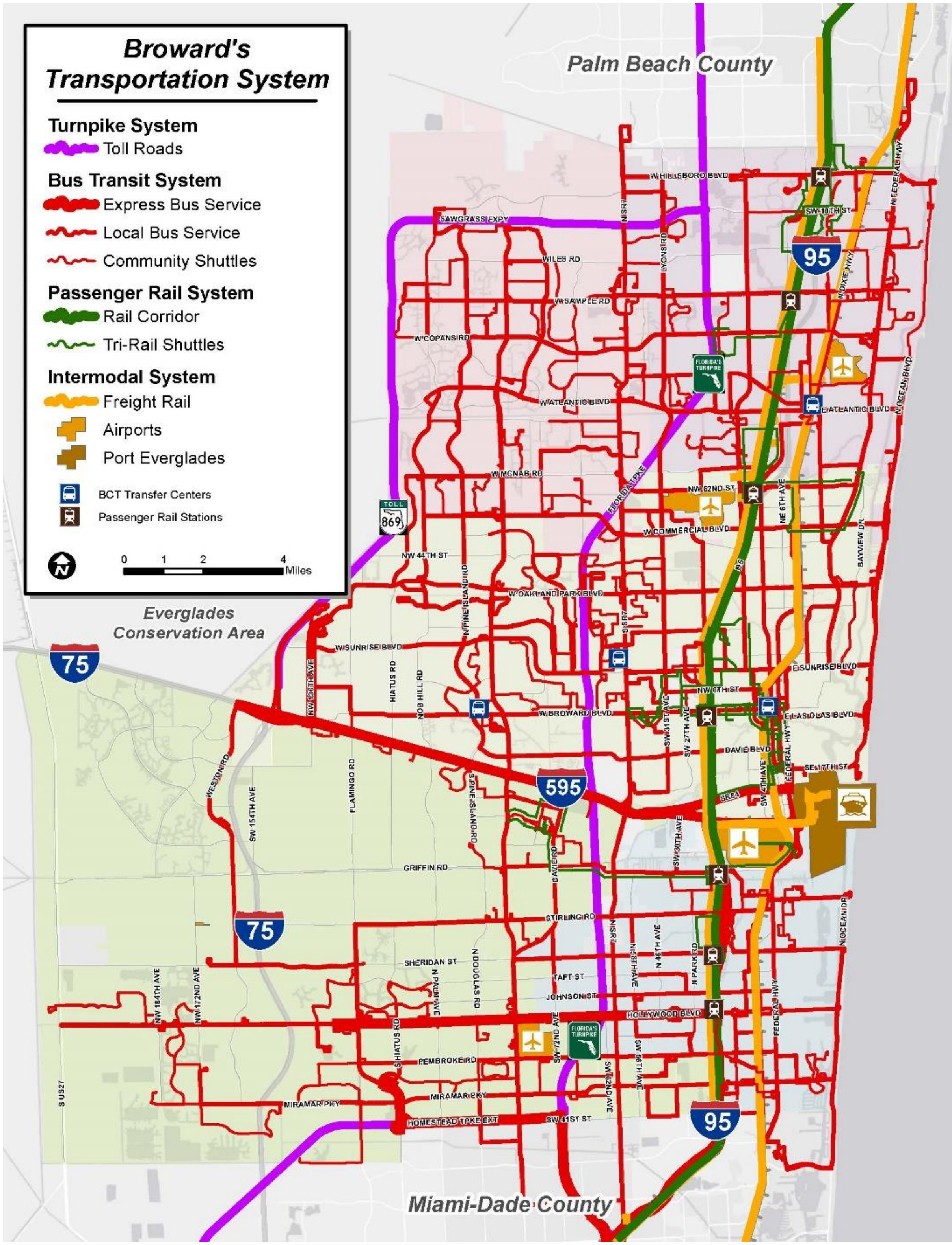


Figure 13. Broward's transportation system (BrowardMPO, 2018)

The I-95 ICM established the vision: "Operate the I-95 Corridor in a true multimodal, integrated, efficient, and safe fashion where the focus is on the transportation customer." Based on the vision, goals and objectives that were defined under the following categories (AECOM, 2013) (Florez and Fleming, 2016):

- Increase Corridor Throughput (People/Goods and Vehicle)
- Improve Travel Time Reliability (and predictive abilities)
- Improve Incident Management
- Enable Intermodal Travel Decisions
- Improve accessibility to travel options and attain an enhanced level of mobility for corridor travels - make it convenient
- Employ an integrated approach through a corridor-wide perspective to resolve problems

Considering the goals and objectives, the I-95 ICM includes the following strategies:

- Information Sharing/ Distribution
    - Manual information sharing (e.g., voice telecommunications, emailing)
    - Automated information sharing: real-time data and video
    - Information clearinghouse / Information Exchange Network (corridor networks / agencies)
    - Corridor-based ATIS integrated database and distribution
    - Access to corridor ATIS database by 3rd party traveler information providers

    - En-route traveler information devices (e.g., DMS, HAR, 511, transit Public Address systems) being used to describe current operational conditions on another network within the corridor
    - A common incident reporting system and asset management (GIS) system
    - Decision support tools to model responses – pre-planned, real-time, predictive
    - Signal priority for transit (e.g., extended green times to buses that are operating behind schedule)
    - Transit hub connection protection
    - Multi-agency / multi - network incident response teams and training exercises
    - Use of dynamic lanes assignment to increase available capacity in case of accidents on the freeway and increase amount of green in the direction of the accident.
- Accommodate / Promote Cross-Network Route & Modal Shifts
    - Modeling of mode shift
    - Modify arterial transit signal priority timing to accommodate traffic shifting from freeways
    - Facilitating mode shift from roadways to transit (or vice-versa) via en-route traveler information devices (e.g., DMS, HAR, 511) to advise motorists of, e.g.: congestion ahead, directions to Tri-Rail stations, and real-time information on the number of parking spaces available.

- Manage Capacity–Demand Relationship – Real-time / Short-Term
    - Add transit capacity by adjusting headways and number of vehicles
    - Add capacity at parking lots
    - Coordinate scheduled maintenance and construction activities
    - Consider modifying Express Lane restrictions
    - Restrict / re-route commercial traffic
- Manage Capacity – Demand Relationship - Long-Term Capacity Oriented
    - Low-cost infrastructure improvements to cross-network linkages and junctions
    - Possible Express Lanes along arterial connections between I-95 and other limited access expressways
    - Increase/maximize supply
- Demand-Oriented
    - Ride-sharing programs
    - Marketing/ advertising

The above strategies should be cooperated with I-95 corridor stakeholders:

- Broward County Metropolitan Planning Organization (MPO)
- Miami-Dade Metropolitan Planning Organization (MPO)
- Palm Beach Metropolitan Planning Organization (MPO)

- Florida Department of Transportation (FDOT) District 4
- Florida Department of Transportation (FDOT) District 6
- Florida Turnpike Enterprise
- Miami-Dade Expressway Authority
- Florida Highway Patrol
- Broward County Traffic Engineering Division (BCTED)
- Miami-Dade Public Works Department
- Palm Beach County Traffic Engineering Division (PBCTED)
- City of Boca Raton Traffic Division
- City of West Palm Beach Traffic Division
- Broward County Transit (BCT)
- Miami-Dade Transit (MDT)
- Palm Beach County Transit (Palm Tran)
- South Florida Regional Transit Authority (SFRTA)
- South Florida Commuter Services

In terms of evaluation of the I-95 corridor, preliminary performance measures are identified below (Florez and Fleming, 2016):

- Increased Corridor Throughput
    - Person Throughput (Freeway/Arterial/Transit)
    - Vehicle Throughput (Freeway/Arterial)
    - Volume/Capacity Ratio
    - Travel Time Index
    - Average Vehicle Occupancy
    - Transit Ridership
- Improve Travel Time Reliability
    - Variance to Baseline Expectations (% change) for time of day and for optimal conditions
    - Planning Index – 95th percentile travel time
    - Buffer Index – change between mean and 95th percentile travel time
    - Transit Arrival Time vs. Scheduled Arrival Time
- Improved Incident Management
    - Clearance time for an incident
    - Response time
    - Delay to the user
    - Impact to capacity as a result of the incident

- Enable Intermodal Travel Decisions
    - Mode Shift
    - Park & Ride Lot Occupancy
    - Revenue / Ticket Sales for Transit
- Improve Freight Movement Efficiency
    - Reduction in Bob Tails (i.e., truck empties)
    - Reduction in Travel Times
    - Reduction in Wait Times
    - Reduction in Freight Involved Incidents

According to the high-level concept of the I-95 ICM System (See Figure 14), the system is coordinated with freeway management systems, arterial management systems, transit management systems, ports and emergency responders. The future ICM system may incorporate use of a Decision Support System (DSS) to produce pre-developed response plans.

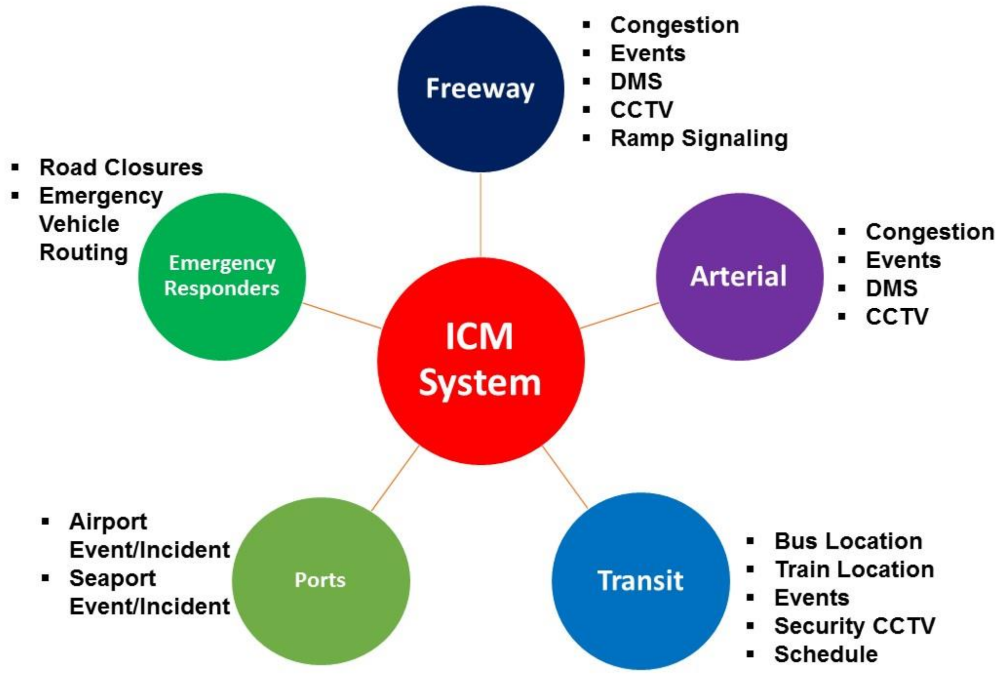


Figure 14. High-level ICM concept (Florez and Fleming, 2016)

The I-95 ICM considered six operational scenarios as of 2016: 1. Daily Operations, 2. Freeway Incidents, 3. Arterial Incidents, 4. Transit Incidents, 5. Special/Planned Events, and 6. Disaster Response.

2.3.2 Analysis, Modeling, and Simulation (AMS) of ICM Strategies

According to the ICM AMS guide (Alexiadis et al., 2012), the ICM AMS methodology blends up to three classes of modeling tools for comprehensive corridor-level modeling and analysis (See Figure 15). Because ICM would require both a planning-based modeling approach and an operations-modeling approach. The planning models are used to evaluate scenarios to ensure that the ICM program will provide benefits to the corridor before implementation. The operations model is used for validating and potentially developing response plans to events in the corridor. Three sites were selected to evaluate their ICM scenarios, and they used the different simulation tools (See Table 5).

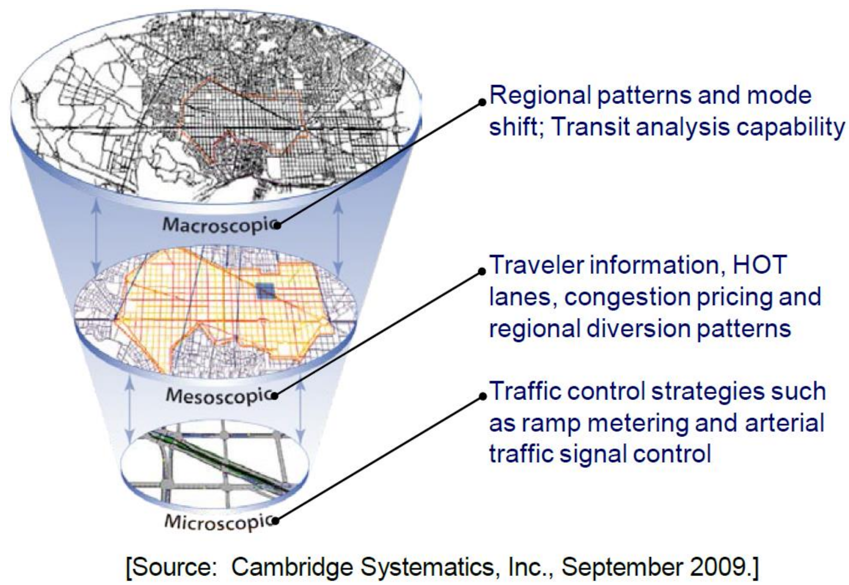


Figure 15. Three classes of modeling tools for comprehensive corridor-level modeling and analysis (Alexiadis et al., 2012)

Table 5. ICM AMS pioneer site modeling tools used (Alexiadis et al., 2012)

Analysis Level	Minneapolis Minnesota	Dallas Texas	San Diego California
Macroscopic	Metro Model in TP+	North Central Texas Council of Governments Model (TransCAD)	TransCAD
Mesoscopic	Dynus T – supported by University of Arizona	DIRECT – supported by Southern Methodist University (SMU)	-
Microscopic	-	-	Trans-Modeler Micro

Through the above three sites, new key integrated corridor performance measures were developed and used (Alexiadis et al., 2012):

- Travel time based on each trip by modes starting at a particular time
- Delay calculated the difference with the zero-delay thresholds of each trip
- Travel time reliability, measuring outlier travel times experienced by a traveler making the same trip over many days and operational conditions.

- Variance in travel time
- Corridor throughput including reliable passenger-miles delivered (PMD) and reliable passenger-trips delivered (PTD)
- Estimation of travel times and travel distance for incomplete trips
- Comparing pre-ICM and post-ICM cases to evaluate response plans or scenarios
- Comparing observed and simulated performance measures to validate modeling accuracy

2.3.3 Decision Support System (DSS) for ICM

A DSS is necessarily required to find the best alternatives among various ICM strategies and changeable traffic conditions. The DSS has the following basic functionalities:

- Identification of nonrecurring events or abnormal recurring congestion based on prediction model using the real-time traffic and incidents data
- Recommendation of response strategies
- Assessment and adjustment of the response plan alternatives

Depending on user requirements, data availability, and corridor network composition, the various DSSs can be made.

Representatively, the Dallas ICM system uses an expert rules system to select a pre-agreed response plan based on numerous variables such as location, time of day, and lanes affected and then uses a real-time model to validate that the selected plan will provide a benefit. The San Diego system relies on its real-time model much more and allows the model to use engineering principles and algorithms to generate a response plan for an event within corridor.

For ICM operation, the Dallas ICM team uses a mesoscopic model to evaluate the proposed response plans. This mesoscopic model is a subset of the one used during the AMS phase, which has been optimized to be used as a real-time model. Examples of these strategies include pre-trip and en-route traveler information, dynamic signal timing, HOV and managed lanes, and congestion pricing.

Different from the evaluation stage, the San Diego ICM system uses the Aimsun product to provide a multilevel, microscopic, mesoscopic, and macroscopic, model analysis tool to provide a comprehensive network prediction and analysis tool for day-to-day operations. The Aimsun on-line subsystem uses live data feeds to understand existing conditions and predict traffic conditions 15, 30, 45, and 60 minutes ahead every 5 minutes. The system is the basis for monitoring and anticipating congestion hot spots and launching evaluations of the available strategies to select the best response, minimizing congestion and guaranteeing more accurate travel times for drivers and users of the transportation network. The micro-simulation on-line tool plays a key role in the response-plan evaluation process. Each prediction of recommended response plans is given a score using the following formula (Spiller et al., 2014):

$$\text{Corridor Score} = \frac{D_0 - D_z}{D_0} \times 100$$

Where,

D_0= Person-delay under “do nothing” case;

D_z= corresponds to the response plan evaluation;

D_1= Person-delay under Response Plan A;

D_2= Person-delay under Response Plan B;

D_3= Person-delay under Response Plan C.

2.4 Relevant Master Plans

2.4.1 FDOT District 5 ITS Master Plan

District 5 has recognized the importance of integration and coordination between arterial and freeway applications. Local agencies, Metropolitan Planning Organizations (MPO) or Transportation Planning Organizations (TPO) were involved in the District 5 ITS Master Plan. Information about the existing infrastructure includes ITS End Devices, Miles of Fiber Optic Cable, Number of Signals, and so on (see Figures 16, 17, and 18).

LEGEND CCTV = Closed-Circuit Television Camera, DMS = Dynamic Message Sign, MVDS = Microwave Vehicle Detectors, and AVI = Automated Vehicle Identification						
STAKEHOLDER	Miles of Fiber Optic Cable	Total ITS Devices	CCTV	DMS	MVDS / AVI	Bluetooth
FDOT Districts						
FDOT District 5	239	763	271	80	322	90
FTE	168	684	202	31	451	0
Lake-Sumter MPO						
Lake County	43	14	14	0	0	0
Sumter County	0	0	0	0	0	0
MetroPlan Orlando						
CFX	200	833	178	93	562	0
Orange County	218	306	107	13	158	28
Osceola County	75	75	64	6	0	5
Seminole County	400	291	180	29	0	82
City of Kissimmee	0	6	6	0	0	0
City of Maitland	0	0	0	0	0	0
City of Orlando	55	192	101	11	0	80
City of Winter Park	0	0	0	0	0	0
I-4 Mobility Partners	100	465	130	150	185	0
Ocala-Marion MPO						
Marion County	2*	110	58	0	0	52
City of Ocala	0**	44	37	7	0	0
River to Sea TPO						
Flagler County	0	0	0	0	0	0
Volusia County	27	35	35	0	0	0
City of Daytona Beach	8	60	60	0	0	0
City of Palm Coast	40	0	7	0	0	0
Space Coast TPO						
Brevard County	71	179	80	49	0	50
City of Melbourne	3.2	9	9	0	0	0
City of Palm Bay	0	1	1	0	0	0
City of Titusville	0	0	0	0	0	0

Figure 16. Summary of ITS end devices maintained (King, 2016)

LEGEND CAD = Computer Aided Dispatch, MDT = Mobile Data Terminal, CCTV = Closed Circuit Television Camera, APC = Automated Passenger Counter, AVL = Automated Vehicle Locator, and TSP = Transit Signal Priority						
STAKEHOLDER	Total Transit ITS Devices	CAD/MDT	CCTV	APC	AVL	TSP
LYNX	1391	486	174	111	486	134
SCAT	NA	NA	NA	NA	0	0
SUNTRAN	84	12	50	10	12	0
VOTRAN	948	124	638	62	124	0

Figure 17. Summary of transit ITS end devices maintained (King, 2016)

Summary of Signalized Intersections				
Stakeholder	Number of Signals	Number of Interconnected Signals	Number of Adaptive Signals	Number of Coordinated Signals
Brevard County	332	149	110	Unavailable
Flagler County	3	0	1	2
Lake County	198	74	0	102
Marion County	115	46	Unavailable	Unavailable
Orange County	591	457	88	369
Osceola County	150*	86	0	42
Seminole County	383	382	57	282
Sumter County	49	0	0	0
Volusia County	326	187	5	171
City of Daytona Beach	125	93	22	46
City of Kissimmee	37	22*	0	31
City of Maitland	29	0	0	17
City of Melbourne	67	67	0	45
City of Ocala	126	126	14	75
City of Orlando	537	460	0	368
City of Palm Bay	43	0	0	11
City of Palm Coast	50	0	0	23
City of Titusville	42	4	4	0
City of Winter Park	47	25	0	30

* City of Kissimmee maintains all Osceola County and the City of St. Cloud signals. All interconnected signals in the City of Kissimmee are operated from the Osceola County TMC. The seven signals owned by the City of St. Cloud are shown with the City of Kissimmee, since they are maintained through contract with the City of Kissimmee.

Figure 18. Summary of signalized intersections (King, 2016)

About 70 ITS strategies into twenty-two major categories were reviewed. The available ITS strategies are identified in three aspects: FDOT District 5 districtwide strategies (see Table 6), regional strategies on the MPO/TPO level (see Table 7), and local strategies within the District 5 region (see Table 8).

Table 6. FDOT District 5 strategies

• Active Traffic Management / Traffic Control
  o Active Arterial Management (AAM)
  o Dynamically HOV & Managed Lanes
  o Dynamic Routing
  o Adaptive Ramp Metering
  o Transit Signal Priority
• Integrated Corridor Management (ICM)
• Traveler Information
  o Predictive Traveler Information
  o Pre-trip Traveler Information
  o En-route Driver Information
  o Route Guidance
  o Traveler Services Information
• Travel Demand Management
• Public Transportation Management
  o Dynamic Transit Capacity Assignment
  o Dynamic Fare Reduction
  o Transfer Connection Protection
  o Transit Traveler Information
  o Personalized Public Transit
	• Incident Management
	• Dynamic Wayfinding
	• Dynamic Ridesharing
	• Electronic Payment Services
	  o Regional Payment System
	  o Electronic Toll Collection
	• Emergency Management
	• Emergency Notification & Personal Security
	  o Emergency Vehicle Management
	  o Disaster Response and Evacuation
	• Information and Data Management
	  o Archived Data
	  o Big Data/Analytics
	  o Performance Management/Measurement
	• Wrong Way Driving Countermeasures
	• Asset Management
	• Public Travel Security

Table 7. ITS strategies for MPO/TPO

• Advanced Parking Management
  o Dynamic Parking Guidance and Reservation
  o Dynamic Overflow Transit Parking
	• Commercial Vehicle Operations
	  o Automated Roadside Safety Inspection
	  o Hazardous Materials Security & Incident Response
	  o On-Board Safety and Security Monitoring
	  o Freight Parking

Table 8. Local strategies within District 5 region

• Active Traffic Management
  o Dynamic Merge Control
  o Queue Warning
• Advanced Parking Management
  o Dynamic Priced Parking
  o Freight Parking
• Traffic Control
  o Adaptive Signal Control
• Highway Rail Intersection
• Electronic Payment Systems
  o Electronic Transit Ticketing
	• Advanced Vehicle Safety Systems
	  o Longitudinal Collision Avoidance
	  o Lateral Collision Avoidance
	  o Intersection Collision Avoidance
	  o Vision Enhancement for Crash Avoidance
	  o Automated Vehicle Operations
	• Bike & Pedestrian Innovative ITS Solutions
	  o Pedestrian Safety Systems
	  o Bicycle Warning Systems
	• Innovative Intersection Designs

Current project efforts using ITS strategies were reviewed in terms of active traffic management/traveler information, incident management, dynamic wayfinding, electronic payment services, emergency management/event management, information management, wrong way driving countermeasures, asset management, integrated corridor management (ICM). Related to active traffic management/traveler information, there are Active Arterial Management (AAM) providing consulting services for full ATMS operations, I-4 Ultimate including new Express Lanes with dynamic toll pricing, and Regional ATMS/DSS developing the concept of operations. District efforts for incident management include the RTMS Operation contract, which is to provide full traffic management, ITS operations, and monitoring for the Department and CFX at the RTMC. Emergency management/Event management include the District 5 Event Management project to design the necessary ITS components and their locations to facilitate traffic flow following an event or during an evacuation in and around east Volusia County. Big data study has been conducted for information management. ICM includes all kinds of strategies and considers data collection, data cleaning/fusion, data analytics/operations, ICM operations, and Regionally Coordinated Responses using a DSS tool.

2.4.2 Space Coast TPO ITS Master Plan

The Space Coast Transportation Planning Organization (SCTPO) was established to provide and coordinate transportation plans for the following local jurisdictions and transportation authorities (Hills and Caetano, 2015; SCTPO, 2017):

- One county: Brevard County Board of County Commissioners
- Sixteen cities and towns: Cape Canaveral, Cocoa, Cocoa Beach, Grant-Valkaria, Indialantic, Indian Harbour Beach, Malabar, Melbourne, Melbourne Beach, Melbourne Village, Palm Bay, Palm Shores, Rockledge, Satellite Beach, Titusville, and West Melbourne
- Two airports: Melbourne International and Titusville-Cocoa (TICO)
- One seaport: Port Canaveral
- One spaceport: Cape Canaveral Spaceport (Kennedy Space Center and Cape Canaveral Air Force Station)

The Space Coast TPO identified the lack of **consistency in the level of service** and also **uniform performance measurement** as the main cause of congestion. To deal with traffic congestions, the SCTPO recognized that "Active Arterial Management" (AAM) is required in the Space Coast region. A main issue to implement Space Coast TPO ITS was indicated the funding deficiencies. For an integrated operations center, the regional consortium structure was recommended (Figure 19).

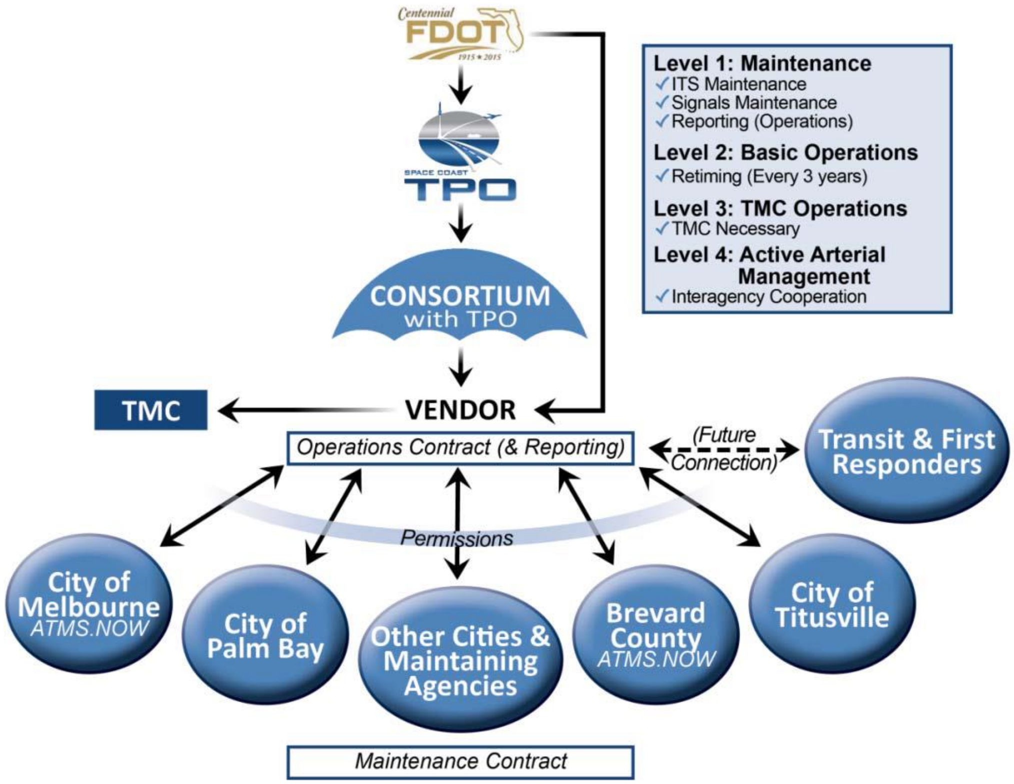


Figure 19. Proposed regional consortium structure (Hills and Caetano, 2015)

Vision of SCTPO ITS Master Plan was established to maximize the use of the existing Space Coast transportation system by providing increased accessibility, reliability, and safety as a part of a fully integrated multi-model experience. Considering the vision and the 2035 Long Range Transportation Plan (LRTP) (SCTPO, 2011), goals, objectives, and performance measures were established (Figure 20).

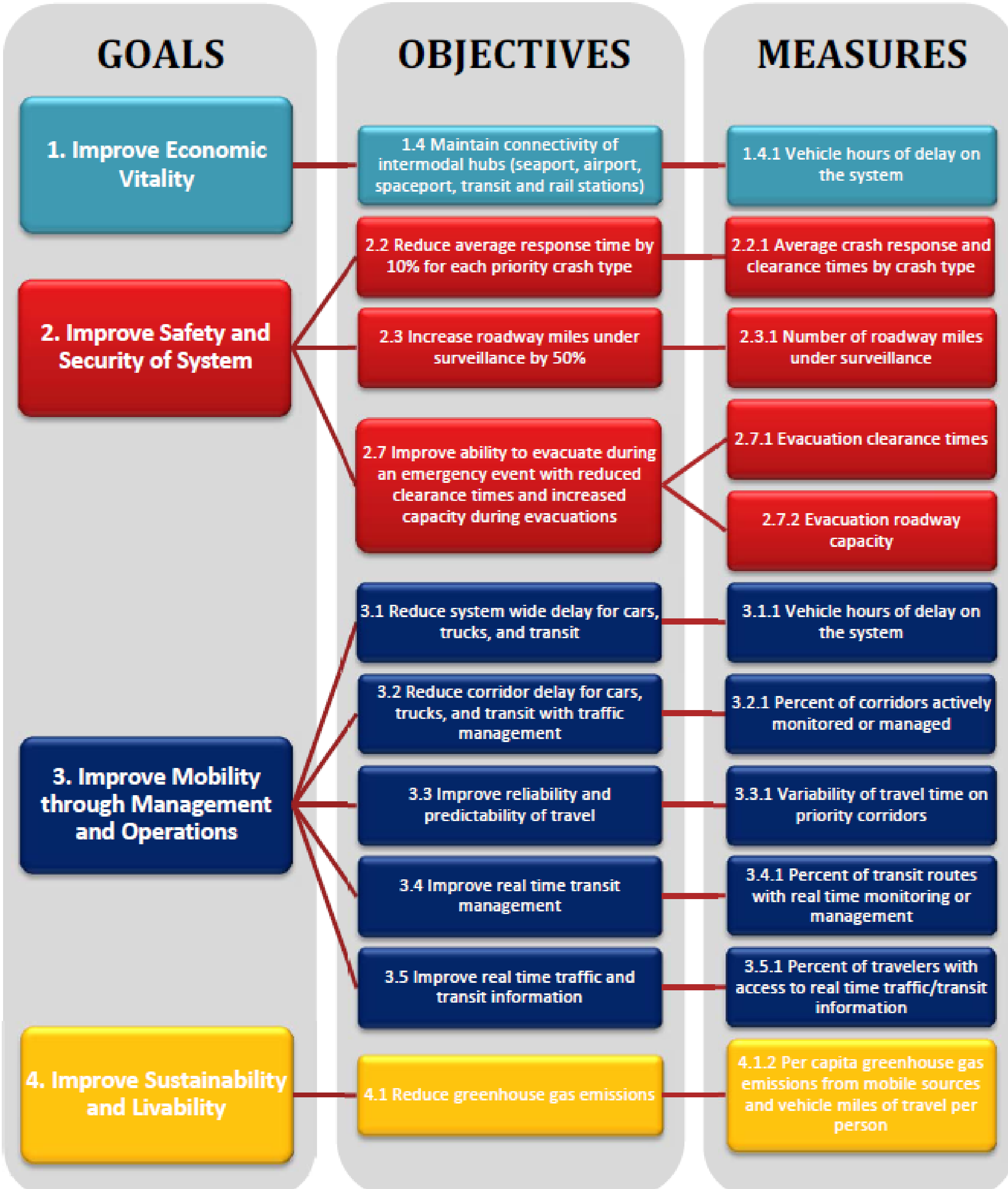


Figure 20. ITS master plan goals, objectives, and performance measures

SCTPO identified that Bluetooth readers as part of the Advanced Traffic Management System (ATMS) Expansion project, AAM operations, and implementation of the existing ITS enhancement can be used to achieve goals, objectives, and measures of SCTPO ITS Master. In particular, the Bluetooth data can be used to determine variability of travel time through the following measures:

- $Travel\ Time\ Index\ (TTI) = \frac{Average\ Travel\ Time}{Free\ Flow\ Travel\ Time}$

- $Buffer\ Time\ Index\ (BTI)\ = \frac{(95\%\ Travel\ Time - Avergae\ Travel\ Time)}{Average\ Travel\ Time}$

- $Planning\ Time\ Index\ = \frac{95\%\ Travel\ Time}{Free\ Flow\ Travel\ Time}$

- $Travel\ Time\ Reliability = \frac{90\%\ Anticipated\ Travel\ Time}{Time\ by\ Time\ of\ \ Day}$

- $Response\ Time\ of\ Traffic\ Incident\ = \frac{90\%\ of\ Incidents}{Clearing\ within\ 30\ minute\ or\ less}$

The measures can be enhanced ITS strategies such as improved signal retiming efforts and AAM (including retiming in real time). Crashes cause the steepest fluctuations in travel time variability due to lane blockages and "rubber-neckers". AAM operations enable to facilitate proper and swift response of incidents and to expedite the arrival of specialized responders. The implementation of ITS enhancement can optimize significantly evacuation clearance times.

In terms of TSM&O program's goal, the integration and coordination between the arterials and freeways, SCTPO ITS Master Plan reviewed options of the available ITS techniques and technologies:

- Closed-Circuit Television (CCTV) to monitor traffic conditions

- Microwave Vehicle Detection System (MVDS) to collect vehicle speeds and volume

- Traveler Information Dissemination using DMS, radio (Highway Advisory Radio (HAR) system), phone applications such as 511, and third parties such as television, Google Mapss and radio stations

- Traffic Incident Management Program (TIM) focusing on the arterials as well as the existing freeways

- Active Incident Management including Integrated Corridor Management (ICM) principles

- Road Ranger Service Patrols extending service areas to the critical arterial corridors from freeways

- Rapid Incident Scene Clearance within 90 minutes to reduce the impact of major traffic incidents, which is based on an incentive-based program.

- Emergency Preparation, Security, Response, and Recovery using multiple ITS strategies and technologies

- Regional Signal Coordination through a common communications network

- Traffic Signal Detection for on-demand based operation

- Adaptive Traffic Control Systems (ATCS)

- Traffic Signal Preemption for an approaching emergency vehicle

- Automatic Vehicle Location (AVL) and Automatic Passenger Count (APC) for transit monitoring

- Transit Signal Priority to ensure improved schedule and Queue Jumping to allow only the bus to proceed through the intersection
- Managed Lanes to provide enhanced travel time reliability and provide incentives to HOV
- Ramp Metering to prevent traffic flow from exceeding the freeway's capacity
- Traffic and Weather Information Systems using RWIS and DMS
- Work Zone Management
- Variable Speed Limits
- Parking Guidance and Information Systems
- Connected Vehicle Initiative
- Freight Advanced Traveler Information Systems (FRATIS)

The existing systems and communications are under consideration to expand to the arterials:

- Wide ITS network of FDOT District 5 Regional Traffic Management Center (RTMC)
- FL 511 Traveler Information System/Program (FLATIS)
- Waze for the state's arterial network
- Traffic Incident Management (TIM) program

Finally, regional ITS needs have been identified (see Figure 21) and the most important needs are as follows:

- Active Arterial Management
- Insufficient Maintenance and Operations Resources
- Regional Signal Coordination/Re-timing
- Work Zone Management
- Road Ranger Service Patrols
- Transit Based ITS

TRAVEL AND TRAFFIC MANAGEMENT	PUBLIC TRANSIT MANAGEMENT
Communications	TSP support/Queue jumps
Utilize County's existing communications infrastructure	AVL and APC
Expand existing traffic operations communications	Passenger Advisory System
Traffic Operations and Management	
Regional signal coordination	**Emergency Management**
AAM system	Remote monitoring/information sharing
Expanded video surveillance	Coordination with EOC and Police
Regular signal re-timing	Automatic incident detection
Enhanced traffic control capabilities	Road Ranger service patrols
Common TMC (Physical or Virtual)	
Adaptive Signal System	**Information Management**
Travel time, speed and volume vehicle data information	Expanded interagency data sharing
Signal pre-empt for emergency vehicles	GIS based equipment management/fiber network as-built
Red light and speed photo enforcement	
Automatic detection of traffic equipment malfunctions	**Maintenance and Construction**
Traveler Information	Work zone management
DMS installation	Performance Measurement of equipment
Dynamic detour route development and management	Regular preventive maintenance
Expand 511 to Arterial System	
Parking management system	**Airports, Ports and Freight**
Incident management	FRATIS
Interagency incident management (TIM/RISC)	Traveler information sharing

Figure 21. ITS needs of Space Coast TPO (Hills and Caetano, 2015)

2.4.3 River to Sea TPO ITS Master Plan (Phase I)

River to Sea TPO (Freeman, 2016) ITS Master Plan (Phase I) contains vision, goals, and objectives established by considering the R2CTPO's 2040 Long Range Transportation Plan (LRTP) (Moore, 2016). In addition, inventory of existing ITS elements and the top transportation related issues by agency were summarized. According to the top transportation related issues by agency, all agencies recognize that it is necessary to communicate between them and share their own ITS elements to respond to recurring and non-recurring traffic congestion. Necessity of ITS asset management was also identified.

The vision of the R2CTPO ITS master plan is to improve safety, facilitate the movement of goods and people, and to enhance the transportation system's efficiency, sustainability, and reliability through deployment of advanced technology and interagency coordination to maximize the transportation system's utilization. The specified goals and objectives are as follows:

- Goal 1 - Improve safety and security for all modes
    - Objective 1.1 - Reduce crashes.
    - Objective 1.2 - Improve ability to detect, verify, respond to, and clear incidents through effective communications and coordination between local governments, public safety officials, and transportation system operators.
    - Objective 1.3 - Provide traffic management during evacuation conditions.
    - Objective 1.4 - Share ITS data between transportation and law enforcement agencies.
- Goal 2 - Provide real-time and accurate user information to make informed travel decisions

- Objective 2.1 - Provide pre-trip planning information and accurate and timely traveler information.
- Objective 2.2 - Provide route guidance information and information on traffic/travel conditions during adverse weather or evacuation conditions.
- Objective 2.3 - Use mobile applications to actively inform the public and invite feedback.
- Objective 2.4 - Integrate mobile systems to support multi-modal trip planning.
- Objective 2.5 - Promote the use of private-funded technologies and applications.

- Goal 3 - Facilitate the efficient movement of goods and people
    - Objective 3.1 - Support efficient intermodal transfer of people and goods.
    - Objective 3.2 - Improve multimodal travel time reliability and predictability.
    - Objective 3.3 - Efficiently accommodate special event traffic.
    - Objective 3.4 - Reduce delays caused by predictable non-recurring congestion.
- Goal 4 - Preserve and enhance access to multimodal choices and facilitate connections
    - Objective 4.1 - Provide traveler information services with local and regional route and mode choice information.
    - Objective 4.2 - Improve transit travel time reliability.

    - Objective 4.3 - Leverage multi-modal approaches in Transportation Systems Management & Operations projects.

- Goal 5 - Integrate ITS projects with local and regional partner agencies and build on existing efforts
    - Objective 5.1 - Maximize use of regional partnering opportunities.
    - Objective 5.2 - Promote transparent regional agency interoperability.
    - Objective 5.3 - Expand regional adoption and support of Transportation Systems Management & Operations.

- Goal 6 - Protect the environment by improving efficiency and reducing congestion and emissions with technology
    - Objective 6.1 - Reduce the need for roadway widening by maximizing the use of technology.

- Goal 7 - Collect, monitor, and report transportation data to support informed transportation policy decisions
    - Objective 7.1 - Deploy technology for travel-time and reliability data collection
    - Objective 7.2 - Collect multimodal traffic counts.
    - Objective 7.3 - Report system performance in a dashboard accessible to the public.
    - Objective 7.4 - Develop data warehouse.

2.4.4 Sumter County ATMS Master Plan

Sumter County established ATMS Master Plan (VIBE, 2017) to deploy a countywide new ATMS including traffic signal controllers, detection/travel time systems, traffic control options, traffic monitoring system, information dissemination, central control software, traffic management center, communications and other features. The new ATMS aims to provide effective traffic management and improve public safety and security through the use of appropriate devices that provide the ability to monitor and control traffic flows, detect incidents, and inform drivers and the general public of roadway conditions. It is recommended that Sumter County should participate with the I-75 Florida's Regional Advanced Mobility Elements (FRAME) project, as well as other regional ATMS and ITS projects to have opportunities to expand the abilities of an ATMS.

According to the Sumter County ATMS Master Plan, the traffic signal controllers were recommended as the standard NEMA TS2, Type 1 controller, in terms of standardization of the traffic controller. For intersection detection, video image detectors (VID) and a microwave vehicle detection system (MVDS) were selected because the VID is cost-effective and the MVDS is more reliable under adverse weather conditions. Traffic control functions should have several abilities: multiple timing plans based on certain scenarios, traffic responsive systems, and adaptive traffic control systems (ATCSs), and coordinate between control sections.

To collect travel time, Bluetooth readers were considered as the most cost-effective and reliable solution, which should be installed on corridors at or near locations where saturated conditions occur during peak hours. As a traffic monitoring system to surveil traffic flows, incident management, and signal maintenance, dome HD CCTV cameras were recommended. For traffic information dissemination, the additional installation sites of ADMSs were provided to effectively manage traffic and divert drivers around incidents and areas of severe congestion.

To integrate and operate ITS elements efficiently, a Commercial Off-the –Shelf (COTS) central control software, a traffic management center (TMC), and several types of communications were recommended.

2.4.5 FDOT District 5 ICM Plan

FDOT District 5 has an ICM plan on I-4 Corridor, which is located in the center of Orlando Regional Integrated Operations Network (ORION) (See Figure 22). The ORION include a freeway network, toll road networks, arterial networks, public transportation routes via bus and commuter rail, air passenger travel, and freight services.

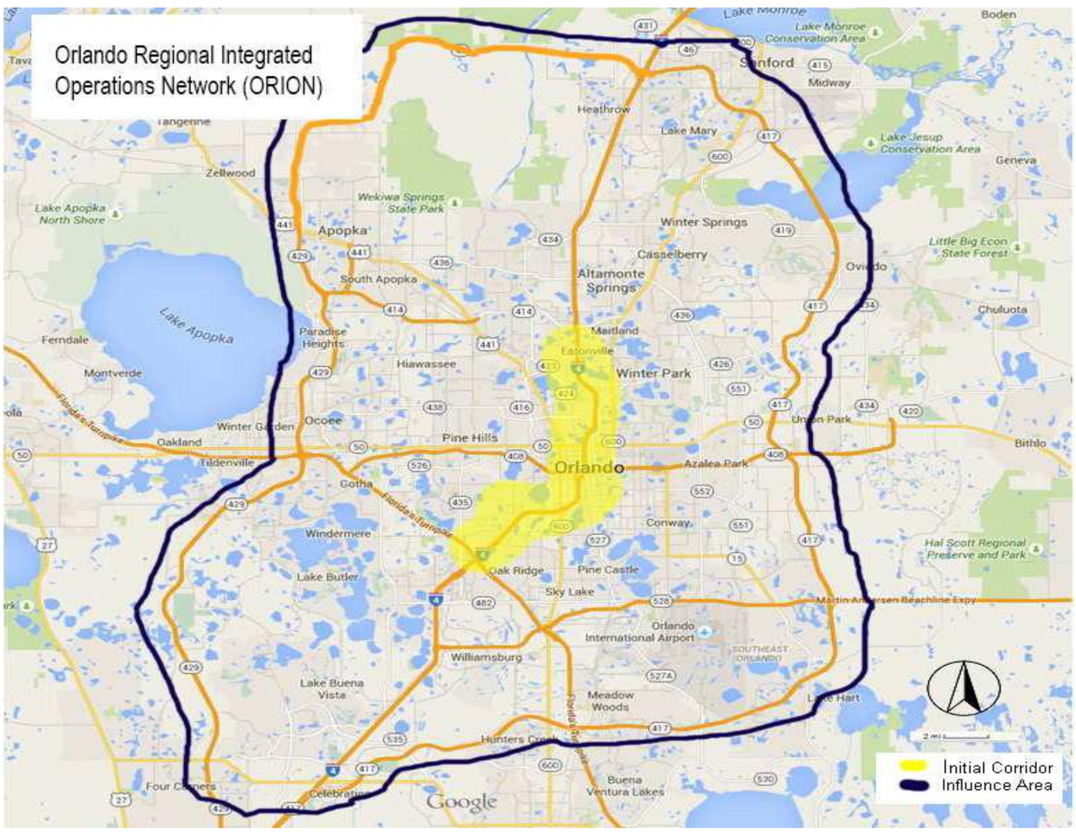


Figure 22. Orlando regional integration management system (Kapsch TrafficCom, 2016)

I-4 corridor with seventy-three miles as a freeway network is considered a designated Strategic Intermodal System (SIS) Highway Corridor link of the state's intermodal transportation network. Toll road networks are operated and maintained by the Central Florida Expressway Authority (CFX) and Florida's Turnpike Enterprise (FTE) (See Figure 23).

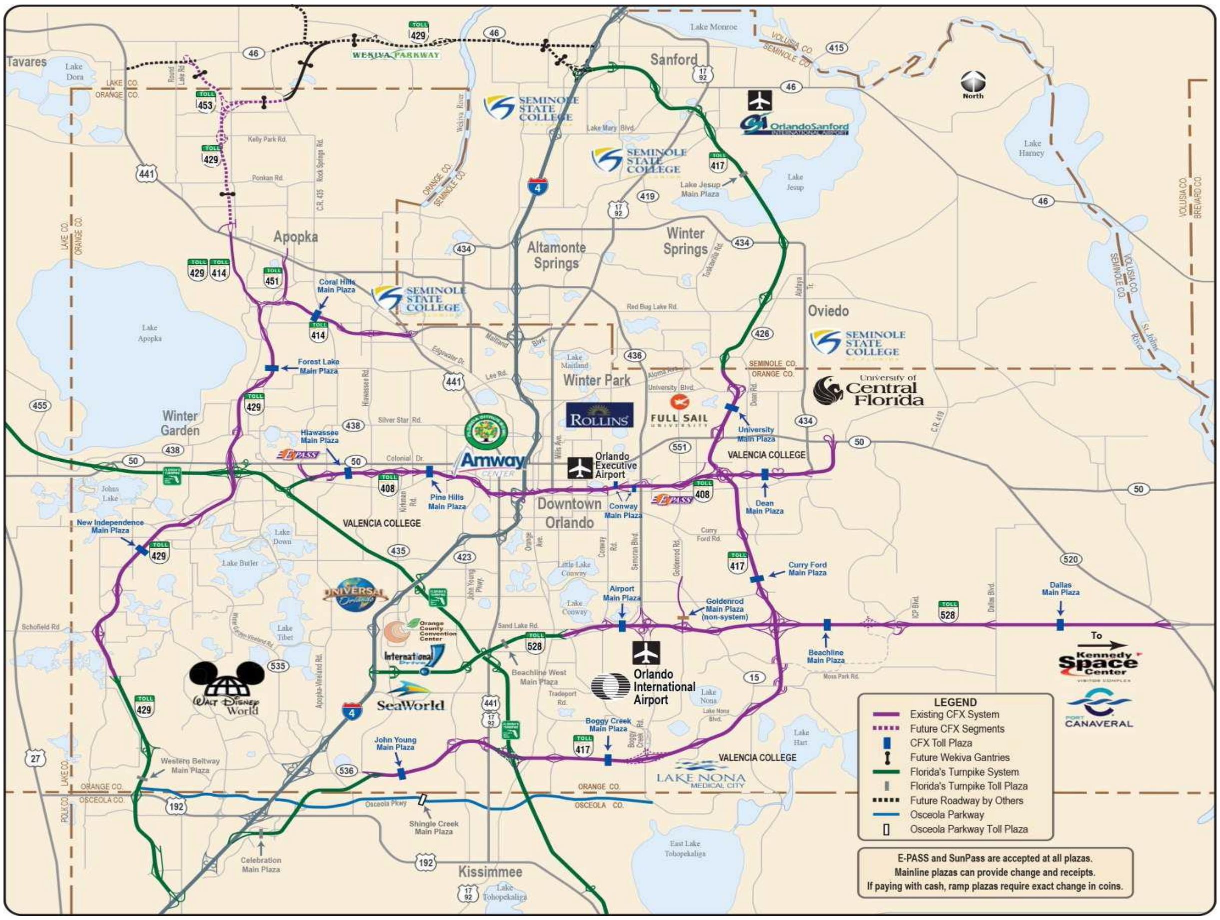


Figure 23. Orlando interstate and toll roads (Kapsch TrafficCom, 2016)

Arterial networks consist of east-west and north-south arterials. Primary east-west arterials are Colonial Drive (SR 50), SR 536, Lee Road (SR 423), Aloma Av (SR 426), Lake Mary Blvd, SR 434, Maitland Blvd (SR 414), and Sand Lake Road (SR 482). Primary north-south arterials include Orange Blossom Trail (US 441), John Young Parkway (SR 423), International Drive, Orange Avenue (SR 527), US 17/92, Kirkman Road (SR 435), Semoran Boulevard (SR 436), Apopka Vineland Road (SR 535), Goldenrod Road (SR 551), and Alafaya Trail (SR 434).

The Active Arterial Management (AAM) project is in progress (see Figure 24), using the traffic signals and other key ITS devices such as Bluetooth to actively manage arterials. Arterials under the AAM related to the I-4 ICM are as follows:

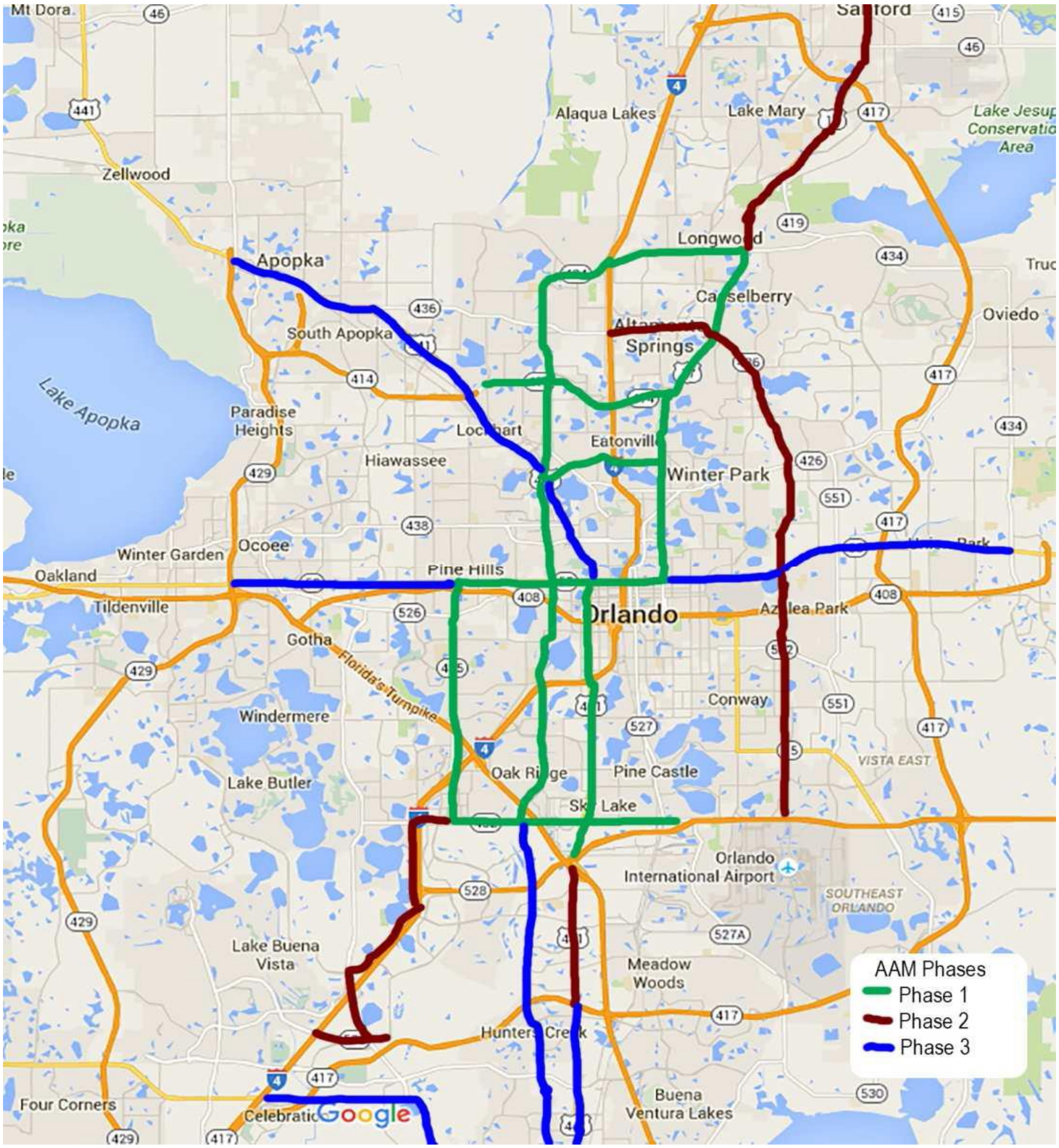


Figure 24. AAM project phases within the corridor

Related to the I-4 Ultimate project, east-west and north-south detour roads near I-4 were developed. Public transit networks are provided by buses of LYNX including FASTLINK, LYMMO, and ACCESS LYNX. As the other transit network, a new commuter rail line, which is called SunRail, is developing in Central Florida to provide a reliable mobility alternative to I-4 (see Figure 25).

Figure 25. SunRail routes

Orlando transportation facilities within the Orlando region are operated and maintained under 8 Transportation Management Centers (TMC): FDOT/CFX, City of Orlando, Orange County, Seminole County, Osceola County, LYNX, SunRail, and FTE. FDOT is managing I-4 of 72 miles including 21 miles of express lanes. FTE and CFX are managing Florida Turnpike of 55 miles and toll roads of 109 miles respectively. City of Orlando (500 signalized intersections), Orange County (600 signalized intersections), Seminole County (380 signalized intersections), and Osceola County (177 signalized intersections) are using centrally-managed computerized traffic signal control systems which have capabilities to select traffic responsive plan and to manually override existing plans in response to special events and circumstances (weather, major crashes, or spillages, etc.). SunRail provides commuter rail transit system of 61.5 miles based on GPS technology and LYNX operates 63 local routes of bus transit system with AVL technology and some SPC equipment.

For coordination and cooperation with agencies related to the I-4 ICM, stakeholders and their roles are defined as follows (Figure 26):

Traffic Related Roles	Florida Central Office	Florida DOT District 5	Florida Turnpike Enterprise	MetroPlan	Central Florida Expressway	SunRail	Orange County	Osceola County	Seminole County	City of Kissimmee	City of Maitland	City of Orlando	City of Winter Park	Florida Highway Patrol	LYNX	Universities
Police											X	X		X		
Fire							X	X	X	X	X	X	X			
Emergency Services							X	X	X	X	X	X	X	X		
Road Ranger/ Courtesy Patrol		X	X		X											
Traffic Signal System		X					X	X	X	X	X	X	X			
Detectors		X	X		X		X	X	X	X	X	X	X			
DMS		X	X		X		X	X	X	X	X	X	X			
Public Works							X	X	X	X	X	X	X			
CCTV		X	X		X		X	X	X	X	X	X	X			
Electronic Toll /Fare /Parking equipment			X		X	X						X			X	
Transit – Bus/ Commuter Rail						X									X	
Parking Management												X				
Maintenance/ Construction		X	X		X	X	X	X	X	X	X	X	X		X	
Data Warehouse/ Analytics	X	X		X												X
Modeling		X	X	X	X											
Internet Traveler Information	X	X	X		X	X									X	
Congestion Pricing		X	X													

Figure 26. Traffic-related roles of the Orlando region

Corridor management tactics applying the I-4 ICM were considered as regional Center-to-Center (C2C) functionality, cross-jurisdictional traffic signal retiming, Florida 511, FDOT District 5 regional traffic management center, FTE Traffic Management Centers, and City and

County Transportation Management Centers. The existing city and county traffic signal systems are as follows:

- City of Orlando – ATMS.Now software, Naztec Controllers
- City of Winter Park, City of Maitland –Eagle controllers
- Orange County – Siemens Tactics Central System Guide, Version 2.2.8, Eagle model M03, M04,
- M10, M40, M42 and M52 controllers
- Seminole County – ATMS.Now Software, Naztec Controllers
- Osceola County – Econolite Centracs software, ASC3 Controllers
- City of Kissimmee - Econolite Centracs software, ASC3 Controllers

Based on prioritized typical goals, which are to increase corridor throughput, improve travel time reliability, improve incident management, enable intermodal travel decisions, improve information sharing, and improve infrastructure coverage, the more specific goals and objectives were established:

- Improve information sharing
    - Share results of incident detection through the data fusion project for the entire region
- Improve travel time reliability

    - Through the use of historical crash data, identify key corridors that experience higher than normal incidents and place a focus on these corridors for DSS/ATMS.
    - Use historical travel time data collected by Bluetooth devices to determine normal travel times in order to assess reliability over time.
    - Individuals transferring between modes or within a mode should be able to routinely make connections without delaying the connecting mode.
    - Travel time through the corridor should remain consistent with no more than a 10% deviation in time.
- Enable intermodal travel decisions
    - Use of mobile phone apps that predict travel times from origin to destination based on different mode choices.
    - Facilitate intermodal transfers and route and mode shifts.
    - Increase transit ridership.
    - Expand existing ATIS systems to include mode shifts as part of preplanning.
    - Expand coverage and availability of ATIS devices.
    - Obtain accurate real-time status of the corridor network and cross network connections.

- Provide information that is easy to locate and easy to understand by casual users including those not familiar with the area.
- Facilitate intermodal connections that are easy to access and that allow quick intermodal vehicle access into the corridor (not 5 or 10 minutes diversion out of the corridor or delay to reenter the flow of travel).
- Provide dynamic decision support information that changes the recommended options based upon the information provided to the system.

- Improved incident management
  - Use of travel time data by FDOT's RTMC to more quickly identify need for incident response.
  - Coordinate with local agency TMCs on activation of special signal timing plans as needed.
  - Provide/expand means for communicating consistent and accurate information regarding incidents and events between corridor networks and public safety agencies.
  - · Provide an integrated and coordinated response during major incidents and emergencies, including joint-use and sharing of response assets and resources among stakeholders, and development of common policies and processes.

    - · Continue comprehensive and ongoing training program – involving all corridor networks and public safety entities – for corridor event and incident management.

- Increase corridor throughput
    - Increase transit ridership, with minimal increase in transit operating costs.
    - Maximize the efficient use of any spare corridor capacity, such that delays on other saturated networks may be reduced.
    - Facilitate intermodal transfers and route and mode shifts
    - Improve pre-planning (e.g., developing response plans) for incidents, events, and emergencies that have corridor and regional implications.
- Improve infrastructure coverage
    - Provide redundant communication systems
    - Improve arterial data collection for travel times
    - Deploy arterial DMSs
    - Deploy CCTV on arterials used for diversion routes

FDOT District 5 recognizes that core success factors of the I-4 ICM are Big Data Platform, Decision Support System, ATMS Traffic Signal Platform, Active Arterial Management, and Data Fusion.

2.4.5.1 Decision Support System (DSS) and ATMS

Under six representative operational scenarios: daily operations, freeway incident, commuter rail incident, arterial incident, non-recurrent congestion, and special event, various ICM strategies for I-4 were considered. The ICM strategies will be based on I-4 Corridor Baseline operations. Basically, a DSS and ATMS System will be used for the operations and coordination of the corridor (See Figure 27). The DSS will utilize an ATMS Software platform and the C2C interface to communicate to the various agency systems. The ATMS software will provide a single interface for all vendor traffic signals within the region.

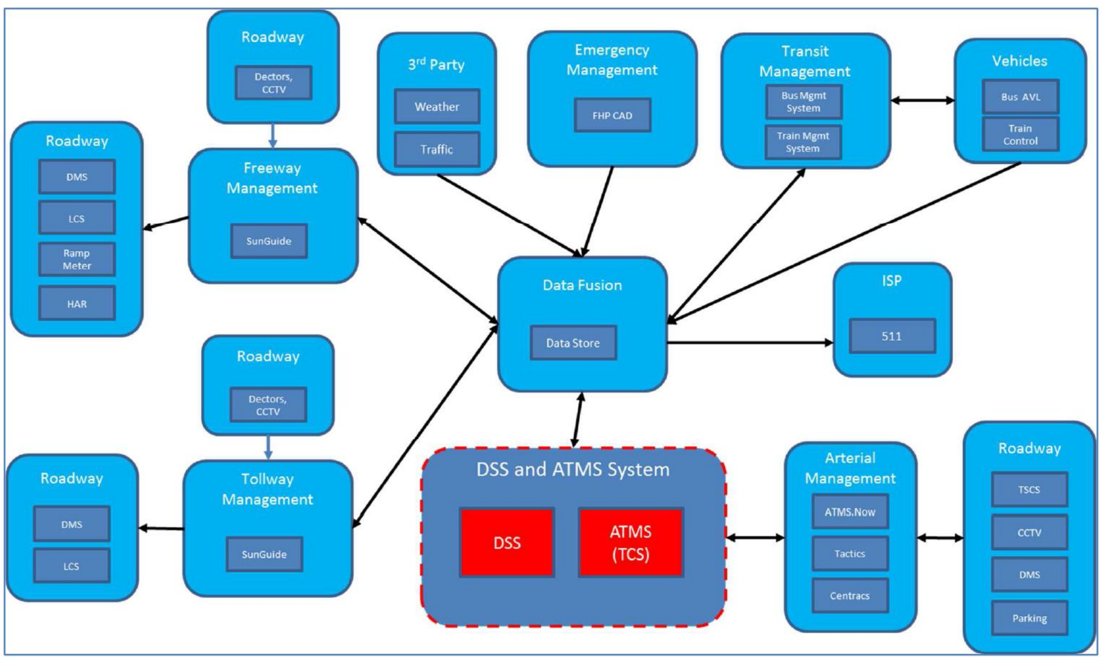


Figure 27. I-4 Corridor baseline operations

Through the Decision Support System and the ATMS Traffic Signal Platform, several strategies about six scenarios of the I-4 ICM were identified.

- Daily operations
  - Automated information sharing

- Advanced traveler information (511)
- En-route traveler information (3rd party, 511 and field devices)
- Access to corridor information by information service providers (ISPs)
- Value pricing for managed lanes
- Smart parking
- Coordinated operation of arterial traffic signals
- Signal priority for transit
- Accommodate cross network shifts for unusually heavy congestion

* Freeway incident
    - Information sharing and distribution (as in baseline scenario)
    - Operational efficiency at network junctions (as in baseline scenario)
    - Common incident reporting system and asset management system
    - Promote route/ network/mode shifts via traveler information, (e.g., providing travel times on different networks)
    - Opening freeway shoulders to traffic at certain locations
    - Restrict/ reroute/ delay commercial traffic
    - Modify arterial signal timing to accommodate traffic shifting from freeway
* Commuter rail incident

- Information sharing and distribution (as in baseline scenario)
- Common incident reporting system and asset management system
- Emergency vehicle signal preemption
- Transit Vehicles connection protection
- Emergency road closure

- Arterial incident
  - Information sharing and distribution (as in baseline scenario)
  - Operational efficiency at network junctions (as in baseline scenario)
  - Common incident reporting system and asset management system
  - Emergency road closure (including freeway off ramps)
  - Modify arterial signal timing to accommodate traffic shifting from the incident location
  - Reroute Transit Vehicles
- Non-recurring congestion
  - Information sharing and distribution (as in baseline scenario)
  - Pre-agreed response plans
  - Real-time Model of the Corridor
  - Predicted performance of the corridor

- Special event
    - Information sharing and distribution (as in baseline scenario)
    - Distribution of event management plan to the public in advance
    - Operational efficiency at network junctions (as in baseline scenario)
    - Coordinated scheduled maintenance activities on corridor networks to ensure available capacity at event
    - Joint Transportation Operations Center
    - Desktop sessions for enacting event plans
    - Add transit capacity
    - Reroute transit vehicles
    - Provide transit priority (exclusive lanes, transit priority at traffic signals)
    - Planned road closure and restrictions
    - Modify ramp metering rates to accommodate traffic
    - Implement special traffic signal timing plans
    - Parking management
    - Police assistance in directing traffic

DSS will have an expert rules engine, predictive model, and evaluation model. The expert rules engine has criteria-based logic to select a response plan set. The predictive model has an ability to select best options within each response plan set and recommend a response plan or do nothing. Finally, the evaluation model will be used offline how response was done, and recommend improvements to plans (TrafficCom).

2.4.5.2 Big Data

FDOT expects that Big data will synergize various input data streams and sources, provide real-time information to TSM&O Operations, and provide TSM&O information and valuable analytics to users. These capabilities will achieve TSM&O goals to operate the arterial and freeway system more effectively, efficiently, and autonomously, and to identify and predict transportation issues earlier for prevention and resolution (TrafficCom). Big Data Store includes Waze data and historic HERE data from HERE.com cloud.

2.4.6 Active Arterial Management (AAM)

The statewide TSM&O Program for arterial and freeway operations (Birriel, 2012) initiated Active Arterial Management (AAM) to search for how to optimize the arterial network through performance-based operations and maintenance initiatives (Ackert, 2018; Hills and Caetano, 2015). In particular, AAM addresses recurring or daily congestion and/or non-recurring congestion from incidents, taking into consideration the spill-over effect congestion can have on arterial roadways. The project also manages congestion relating to special events and work zones. Active Arterial Management includes active signal retiming, coordination with local responders, facilitation of emergency maintenance needs, and the dissemination of travel-related information through dynamic message signs. The program capitalizes on investments already made on the roadways, ports, signal systems, etc., by providing real-time traffic management. The goal is to reduce delays for all travelers, while improving congestion-related environmental factors such as air pollutants. (FDOT)

In addition, in FDOT District 4, Active Arterial Management (AAM) focuses on recurring congestion, non-recurring congestion from incidents, special events, and work zones by using ATM dealing with active signal retiming. Different with the passive management such as TOD signal plans and unconditional Transit Signal Priority, AAM uses real time congestion management for all modes and conditional transit signal priority (Ackert, 2018). AAM is required to coordinate with local responders and facilitate emergency maintenance needs. Traffic information will be disseminated on arterials through Arterial Dynamic Message Signs (ADMS) and FLATIS (SCTPO, 2014). The AAM is being applied in Palm Beach County and Broward County. They concentrate on reducing delay, for all users by expanding AAM coverage.

AAM wants to interface with the following data sources (FDOT, 2016a):

- Priority 1:
  - BlueToad, BlueMac, Signal 4, SunGuide
- Priority 2:
  - WAZE, HERE, ATMS, MVDS, INRIX, BlinkLink, MOMS, NMS, Vanguard, CCTV, Other FDOT databases as determined by FDOT staff, Traffic Counts, MIMS

AAM will concentrate on the following data (FDOT, 2016a):

- Priority 1:
  - Travel Time
  - Travel Speed

- Safety
- Citizen Complaints/Compliments
- AAM Program Summary
- AAM Program Benefits
- Scheduled Events
- Emergency Contact Information

- Priority 2:
  - Traffic Volumes
  - Traffic Congestion
  - Travel Time Reliability
  - Signal Assets
  - Incidents
  - Device Uptime
  - Asset Growth Trends
  - Preemption Logs
  - Signal Timing Changes
  - Wrong Way Driving Alerts

- Dynamic Message Sign Message Verification
- Emergency Contact Information
- Lane Occupancy
- Vehicle Classification
- CV/AV Lane Usage
- Scheduled Events
- CV/AV V2I Reporting
- CCTV Feeds

2.4.7 FDOT District 4 ITS Strategic Business Plan

FDOT District 4 established a plan to deploy Express Lanes, Ramp Metering, Transportation System Management & Operations (TSM&O), Integrated Corridor Management (ICM), Active Transportation & Demand Management (ATDM), and Connected and Automated Vehicles until 2020. Based on interagency agreements, FDOT District 4 is beginning to operate freeways and the major arterials as an integrated system share hardware, software, and communications equipment as one system. The detail description about the expected deployment items is as follows (FDOT):

- Express Lanes – Operating express lanes as part of a regional network along I-95, I-595 and I-75 that will be integrated with other express lane facilities operated by FDOT District Six and Florida's Turnpike.

- Ramp Meters – Ramp meters are installed along I-95 at each ramp. The ramp meters are integrated with the Broward County Signal System as well as the FDOT District Six ramp metering system.

- Active Arterial Management (AAM) – AAM systems along arterials within Broward and Palm Beach County, including Boca Raton, are well advanced towards buildout. These systems include ADMSs, CCTV cameras and detectors along arterials and are connected to the RTMC using fiber optic and wireless communications.

- Traffic Adaptive Signal Control – Traffic Adaptive Signal Control is being implemented along selected corridors; Okeechobee Boulevard, PGA Boulevard, SR 7, SR 80, Commercial Boulevard and US 1 in the vicinity of Southeast 17th Street, as part of the signal system programs within Broward and Palm Beach Counties.

- Transportation System Management & Operations (TSM&O) – Providing a higher level of operational integration among freeway, arterial and transit systems aligned with achieving selected performance measures.

- Integrated Corridor Management (ICM) – Advancing the concept of an ICM program along I-95 within Broward County to apply dynamic decision support tools to improve the efficiency of moving people and goods within the corridor using the full range of transportation assets.

- Active Transportation and Demand Management (ATDM) – ATDM projects are being implemented as pilot programs along selected segments of I-95 and I-75. These ATDM pilot projects are initially focused on hard shoulder running and use of lane control signs to support speed harmonization and incident management functions.

- Connected and Automated Vehicles – Preparing for future Connected and Automated Vehicles programs by providing the systems and operational tools to facilitate applicable functions at the SMART SunGuide RTMC.

Beyond the year 2020, it is recommended that the next generation transportation should prepare the following:

- Operational Integration: This will require a higher level of technical, operational and institutional integration in managing the regional multi-modal transportation system more efficiently

- Multimodal Applications: Legacy ITS systems should be integrated with multimodal partners such as transit, airports, seaports and multimodal centers; parking information systems should be implemented for downtown cities; and monitoring information systems should be deployed for movable bridges

- Connected and Automated Vehicles: As the national program of Connected and Automated Vehicles evolve, FDOT District Four should be prepared to provide the needed ITS infrastructure and systems to utilize and leverage these programs.

2.4.8 Hillsborough County ITS Master Plan

Hillsborough County set up their own ITS vision (URS, 2013): to operate our transportation system the highest-level of cost effective performance resulting in 1) reduced excess delay on arterials AND freeways, 2) increased safety for all operating, managing and using our transportation network, 3) increased mobility options for all Tampa-Bay residents, 4) real-time traveler information for all travel modes and 5) seamless coordination with ALL operating agencies. Considering the vision, objectives and strategies of Hillsborough ITS were established into four areas: traffic management, incident/emergency management and safety, traveler information dissemination, and inter-agency coordination and communications. According to the Hillsborough County ITS Master Plan, they have identified the importance of the integration and coordination between freeways and arterials and between agencies. In terms of four goals, it is possible for the following defined objectives and strategies to be used in ICM and ATM:

- Traffic management in terms of transportation efficiency and quality
    - Provide and/or enhance special event management capabilities
        - Provide and/or expand arterial traffic management/traffic surveillance systems
        - Enhance and/or expand real-time traveler information
        - Continued a proactive traffic signal timing optimization program
        - Provide active traffic management (ATM)
    - Provide and/or enhance special event management capabilities
        - Expand and provide ATMS capabilities along major event routes
        - Provide portable Intelligent Traffic Management System
    - Provide and enhance (optimize) traffic signal coordination and corridor system performance

        - Systematically re-time traffic signals on priority network
        - Upgrade and interconnect signals on priority network
        - Provide active monitoring of traffic signal systems
        - Provide upgrades to signal hardware equipment
    - Provide integrated corridor management (ICM) strategies and support systems
        - Provide a regional ICM deployment plan
        - Develop an inter-agency traffic control/ITS concept
    - Develop and implement traffic control measures to enhance the efficiency, mobility, safety, and/or reliability of the transportation system
        - Evaluate a ramp metering program for interstate on-ramps
        - Implement congestion pricing programs, including high occupancy toll (HOT)/managed lanes
        - Evaluate the feasibility of implementing ATM systems along the interstates including the following techniques: speed harmonization measures, queue warning systems, and hard shoulder running measures along the interstates
        - Develop and implement advance parking management systems at major parking facilities
        - Develop and expand TSP (Traffic Signal Priority) program

        - Provide and/or expand emergency vehicle preemption (EVP) systems
    - Support measures to mitigate and track regional environmental impacts and Environmental Protection Agency (EPA) compliance
    - Preserve ITS/Traffic signal equipment and infrastructure investments
- Incident/emergency management and safety in terms of transportation safety and security
    - Improve Incident Detection and Verification Times
        - Develop, implement and/or upgrade TMCs.
        - Expand and Upgrade ATMS/traffic surveillance systems
        - Provide the capability to share 911 and highway patrol computer aided dispatch (CAD) information with City/County TMCs
    - Improve Incident Response Times
        - Provide and/or expand enhanced reference location signs
        - Provide AVL and identification for emergency vehicles/responders
        - Provide the capability to share traffic information with emergency responders
        - Evaluate and provide additional interstate median crossover points
    - Improve Incident Clearance (Duration) Times

    - Provide freeway service patrol (Road Ranger) expansion and upgrades
    - Develop policy and procedures to modify signal timings on detour routes and upgrade traffic controllers/field-to-center communication systems
    - Identify and implement dynamic routing application for route diversions and evacuations
  - Reduce crash rates and improve safety at signalized intersections (including vehicles, pedestrians, bicycles)
    - Provide and expand red light running programs at intersections with high crash rates
    - Provide, coordinate, and/or improve pedestrian/bicycle safety solutions
  - Improve mobility and reduce vehicle crash rates related to weather and other low visibility events
    - Develop and deploy a RWIS
  - Improve safety and coordination of intermodal conflicts (highway-rail interface /crossings):
    - Provide crossing gate video enforcement
    - Upgrade signal interconnect with traffic signals
    - Provide an active advanced warning system (AAWS)

        - Evaluate and implement in-vehicle warning systems

    - Identify and develop diversion routes and system strategies

    - Identify and provide ITS strategies to support regional emergency evacuation plans and response

        - Review regional evacuation plan and disaster response and recovery plan

        - Expand and/or enhance the capability to provide regional emergency/traffic text alerts

- Traveler information dissemination in terms of accessibility and mobility

    - Provide and/or enhance multi-modal information dissemination and trip planning tools that may affect roadway users and travel choices across all modes

        - Provide real-time parking garage/lot space availability with map of Downtown Tampa as part of the 511 mobile app

        - Provide commercial truck parking lot space availability as part of the 511 mobile app

        - Provide and/or expand real-time travel-time data along arterials

    - Expand and/or enhance en-route traveler information systems

- Inter-agency coordination and communications in terms of reliable and coordinated operations
  - Develop regional interagency operational and communications plan(s)
    - Identify and enhance regional concept of operations, policies, and procedures involving transportation, emergency, and law enforcement stakeholders.

2.4.9 Decision Support System (DSS)

FDOT District 4 developed a Decision Support System (DSS) to support the objectives and activities of Transportation System Management and Operations (TSM&O), which combines the ITS Data Capture and Performance Management (ITSDCAP) and the Integrated Regional Information Sharing and Decision Support System (IRISDS) (Hadi et al., 2015). The ITSDCAP captures data from multiple sources, estimates various performance measures (mobility, reliability, safety and environmental), performs data mining techniques, support benefit-cost analysis, and allows the visualization of data. The multiple data sources include SunGuide data, central data warehouses (STEWARD and RITIS), incident databases, FDOT planning statistics office data, weather data, pricing rates, construction database, crash data such as Crash Analysis Reporting (CAR) System, 511 traveler information systems, Automatic Vehicle Identification (AVI) data, and private sector data. The IRISDS is a proof-of-concept Web-based system that displays regionally shared information in real-time and provides a decision support environment for transportation system management agencies in a region.

The DSS of FDOT District 4 provides the following functions:

- Estimation and analysis of system performance in terms of segments and intersections

- Benefit-cost analysis including freeways and arterials
- Impacts analysis of construction and maintenance activities
- Method for real-time prediction of breakdown conditions on arterial streets
- Signal timing diagnostic system
- Prediction of travel time under rainfall intensity

ITSDCAP used the segment-based and intersection-based performance measurements for freeway and arterial segments. As the segment performance measurements, mobility measures, travel time reliability measures, safety performance measures, and energy and emission measures were applied. The mobility measures include average speed, volume, occupancy, travel time, delay, free-flow speed-based congestion index, desired speed-based congestion index, Vehicle-Miles Traveled (VMT), and Vehicle-Hours Traveled (VHT). The travel time reliability measures contain CDF (Cumulative density function) of travel time rate, PDF (Probability density function) of travel time rate, unreliability contributions, percentage of occurrence by regime, percentage of severity by regime, standard deviation, buffer index, travel time index (including 95th percentile, 80th percentile, median, and mean travel time index), policy index, failure/on-time, misery index, and skew statistics (Table 9). The safety performance measures consist of crash frequency by crash type, crash frequency by severity, total crash frequency, crash rate by type, crash rate by severity, and total crash rate. The energy and emission measures are based on fuel consumption rates of gas and diesel, which are estimated using vehicle-miles traveled, speed, and vehicle type. As the intersection performance measurements, the following measures were proposed:

- Averages[9] and standard deviation of occupancy, volume, and speed: These can be obtained from the point detectors, AVI technologies such as Bluetooth or Wi-Fi.

- Volume/capacity (v/c) ratio, percentage of volume/capacity ratio greater than one, and approach delay[10]: These can be measured by using stop line detector data, which are not available at present. So, the Highway Capacity Manual (HCM) procedure was used to estimate the saturation flow rate and the delay.

- Green utilization[11]: This is a ratio of the time interval used to the total green time and requires high-resolution signal phase data and volume counts at the stop bars.

- Split failure percentage[12]: A phase failure occurs when the traffic demand in a phase cannot be served by the phase green time. This can be calculated through the high resolution detector and signal data, or a surrogate measure.

- Oversaturation severity index[13]: This is the ratio of unusable green time due to the discharge of residue queue or spillback from the downtown intersection to the total available green time in a cycle. This requires high resolution vehicle actuation data and signal event data.

- Phase occupancy/green ratio[14]: This is the ratio of the detector occupancy during the green phase to the green time. This can be used as a surrogate measure for the v/c ratio.

[9] Currently it is not available.
[10] Currently it is not available.
[11] Currently it is not available.
[12] Currently it is not available.
[13] Currently it is not available.
[14] Currently it is not available.

- Platoon ratio and percentage of arrival on green[15] (R_p): $R_p = P \times \frac{C}{g}$, where P is the percentage of arrivals on green, C is cycle length, and g is green time. It can be estimated through platoon progression equations and/or AVI data.

- Green time percentage: This is the percentage of time that the signal is green during a given time interval.

Table 9. Definitions of travel time reliability measures

Reliability Performance Metric	Definition
Standard Deviation	The standard deviation of travel time distribution.
Buffer Index (BI)	The difference between the 95th percentile travel time and the average travel time, normalized by the average travel time.
Mean Travel Time Index	Mean travel time divided by free-flow travel time.
Median Travel Time Index	Median travel time divided by free-flow travel time.
80th Percentile Travel Time Index	The 80th percentile travel time divided by the free-flow travel time.
95th Percentile Travel Time Index	The 95th percentile travel time divided by the free-flow travel time.
Policy Index	Mean travel time divided by travel time at target speed.
Failure/On-Time Performance	Percent of trips with travel times less than: • 1.1* median travel time • 1.25* median travel time
Skew Statistics	The ratio of 90th percentile travel time minus the median travel time, divided by the median travel time minus the 10th travel time percentile.
Misery Index	The average of the highest five percent of travel times divided by the free-flow travel time.

Furthermore, ITSDCAP contains the probability of breakdown to describe the point of transition to congestion. ITSDCAP dealt with both freeway traffic breakdown and arterial traffic breakdown. The derived probability of breakdown for freeways using volume, speed, occupancy in RITIS is for recurrent congested conditions. So the RITIS data were filtered using incident data and weather data. It was defined that the breakdown on arterials occur when the speed is less than

[15] Currently it is not available.

30% of the base free-flow speed in the Highway Capacity Manual. Based on the definition of breakdown on arterials, the breakdown probability model was developed through the decision tree approach with the binary logistic regression, which utilizes data of point detectors and AVI technologies using Bluetooth readers.

Related to construction impacts, ITSDCAP suggested multi-level work zone impact analysis framework (Table 10). The analysis for Stage 1 to Stage 3 of the framework must be conducted using the several modeling tools. ITSDCAP supports to make the necessary inputs for the several modeling tools. For Stage 4, ITSDCAP can estimate the impacts of the work zone based on the collected data if there are real data before, during and after construction.

Table 10. Multi-level work zone impact analysis stage and tools

Stage	Tools
Early Planning	Q-DAT, Realcost, SHRP 2 C11
Preliminary Design	SHRP 2 L07, QuickZone, FHWA Procedures
Design and Implementation	Simulation-Based DTA Methods and Tools, HCM-Facility Procedures and Tools
During construction and post-construction	Data Analytics

Different with the existing signal timing optimization software using turning movement counts and tube counts, ITSDCAP developed an initial signal timing diagnostic system that uses AVI technologies such as Wi-Fi or Bluetooth readers. The signal timing diagnostic system can assess the travel time performance of turning movements by making the Cumulative Density Function (CDF) plots (Figure 28). Or, instead of travel time, the Travel Time Index (TTI) is also used to the CDF plots. TTI is the ratio of the actual travel time to the travel time at free flow condition. Furthermore, the combination of the 50^{th}, 80^{th}, and 95^{th} percentiles of the TTIs was used to investigate the patterns or relationships in the travel time data.

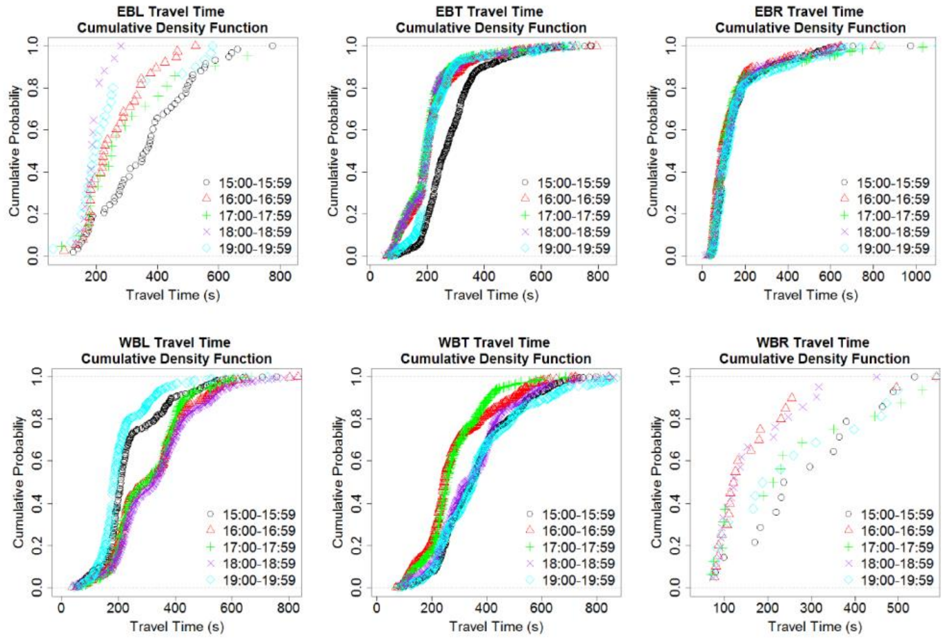


Figure 28. Cumulative density functions by time period for the eastbound and westbound approaches

Using signal timing history, a decision support signal operation diagnosis scheme (Figure 29) was proposed to evaluate the relationship between signal timings and vehicle travel time performances. The developed intersection-level signal inspection module under the diagnosis scheme calculates the average TTI of all critical movement (aTTI), the range of TTI for the critical movement (rTTI), and the maxed-out ratio (mRatio) for a phase on the basis of a critical movement (Figure 30). The following inspection results are recommended:

1. Recommend to increase cycle length (or improve geometry/capacity) and the diagnosis will continue to individual phase split.
2. Recommend to increase cycle length (or improve geometry/capacity)
3. Diagnosis will continue to individual phase split
4. Recommend to keep the current signal plan
5. Recommend to increase the maximum green time for this individual phase split.

6. High TTI due to uncertain reason (to be explored).

7. Recommend to increase the maximum green time for this individual phase split. However, excessive delays at the downstream link are suspected and need to be further explored.

8. Recommend to keep the current phase split parameters.

9. Recommend to flag this individual phase split as a candidate to have its maximum green time decreased.

10. Recommend to change the offsets.

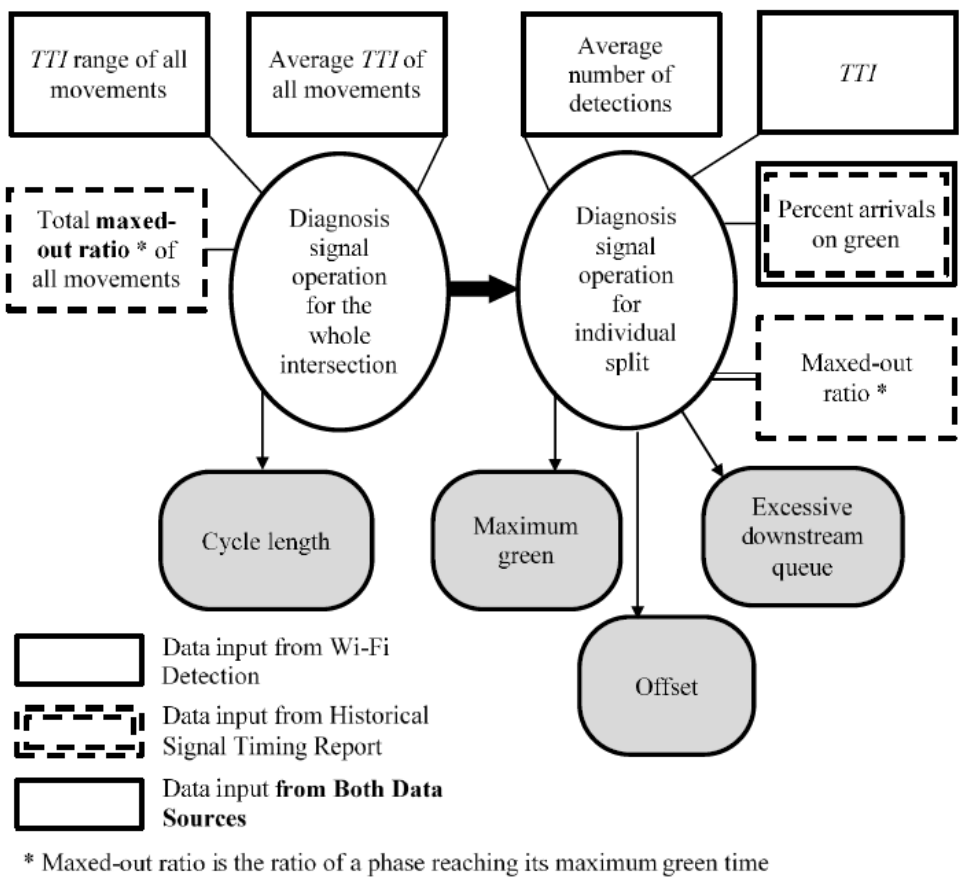
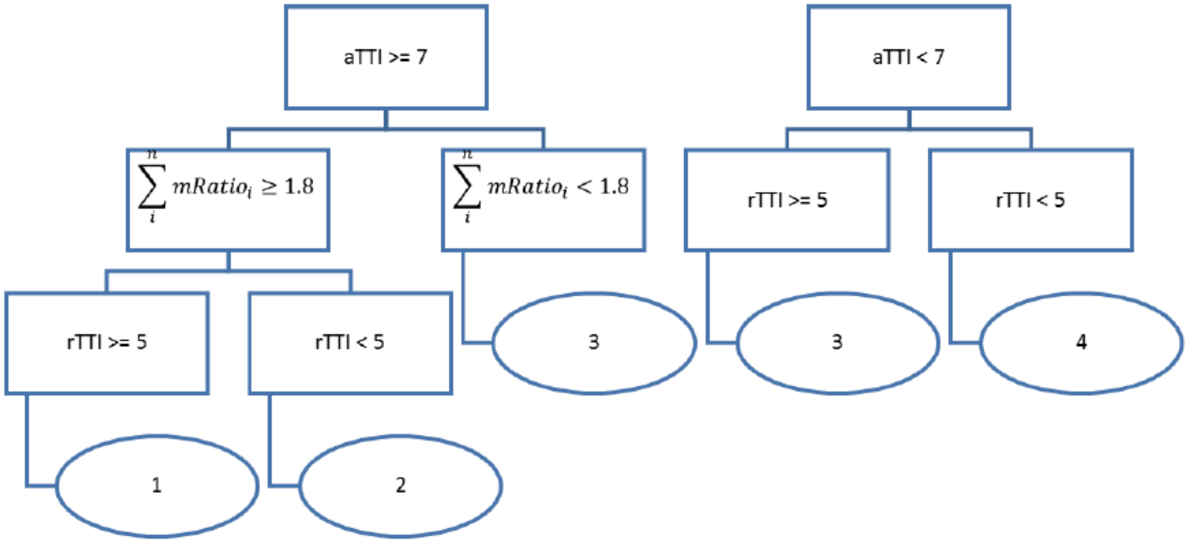


Figure 29. Proposed decision signal operation scheme



where,

i **indicates the i^{th} critical phase split.**

n **is total number of the phase splits corresponded to the critical movements.**

Figure 30. Flowchart of the intersection-level signal inspection module in the decision support signal operation diagnosis system

ITSDCAP can predict travel time under rainfall using the urban street computational engine of the HCM 2010 (STREETVAL). As input values of STREETVAL, the saturation flow rates (SF) and the free flow speed (FFS) according to rainfall intensity were adjusted.

2.5 Practices and Lessons from Other Countries

2.5.1 Europe

Active Traffic Management (ATM) is a combination of dynamic traffic management, ITS technologies, infrastructures, and roadway designs. The concept uses a range of traffic management measures to actively monitor the motorway and dynamically control speeds, add capacity, and inform road users of conditions on the network with the objective to optimize traffic and safety performance.

In Europe, a term named "Managed Motorways" is used and it combines actively or dynamically managed operational regimes, specific infrastructure designs, and technology solutions. Since most of European countries face constraints of land space and anticipates constructing few new roadway infrastructures, they have used a range of traffic management measures to actively monitor the motorway and, based on the monitoring, dynamically control speeds, add capacity, and inform road users of conditions on the network to optimize traffic and safety performance (Jones et al., 2011). Below are more specified objectives to implement "Managed Motorways" strategy (Brown, 2010).

- Optimize safety and operation performance, in accordance with the volume and makeup of the traffic.
- Provide more consistent journey times.
- Minimize harmful emissions and fuel consumption.
- Reduce delays and disruption from crashes and incidents.
- Provide improved warnings and traffic management in association with routine maintenance operations.

It is important to conduct extensive research and studies to determine the most appropriate ATM technique or strategy to the current highway problem. The key performance measures used in European countries are travel time reliability, safety, travel speed and traffic flow (e.g., congestion). In order to manage roadways actively and effectively, coordination across different disciplines (e.g., design, ITS, etc.) is required. In particular, collaboration among planning, operations, and design is imperative. Managed motorway strategies are synergistic and are most effective when applied in an integrated and dynamic system (Jones et al., 2011).

Several Managed Motorways practices have been implemented in European countries (i.e. England, Germany, Netherlands, Belgium, Denmark, Sweden, and Spain) in order to enhance highway services based on innovative technologies and treatments as below (Berman et al., 2006; Fontaine and Miller, 2012; Fuhs and Brinckerhoff, 2010; Jones et al., 2011; Mirshahi et al., 2007a; Pesti et al., 2008; Wiles et al., 2003; Wiles et al., 2005):

- Hard shoulder running
- Speed harmonization
- Variable speed limits
- Through junction running
- Queue protection and warning
- Lane control
- Ramp metering (i.e. Access control)
- Driver information
- Incident detection and automatic signaling
- Incident management
- Emergency refuge areas

- Variable message signs
- Signals
- Speed limit
- Enforcement
- Automated enforcement
- Lighting with shoulder running
- Ramp junctions
- Gantry and detector spacing
- Some treatments were found to be more effective when they installed and are operating simultaneously. They can result in complementary and synergistic operations and benefits.
    - Shoulder running + VSL
    - Shoulder running + Emergency area
- England, Germany, and the Netherlands cases found that it is important to test new sign messages with users before implementation.

While the above techniques are known as mainly improving traffic congestion and travel time reliability, several methodologies are also being used to ensure traffic safety under ATM conditions. Below hazard conditions have been identified for typical risks under ATM.

- Vehicle stops in running lane.
- Vehicle enters main carriageway unsafely.
- Tailgating occurs.
- Driver loses control of vehicle.
- Pedestrian runs in lane (live traffic).

- Vehicle rejoins running lane.
- Motorcycle filters through traffic.
- Vehicle reverses to exit slip.
- Individual vehicle drives too fast.
- Vehicle stops on the hard shoulder when it is closed.
- Debris is in the running lane.
- Vehicles collide on hard shoulder while opening:
  - Switching between three- and four-lane running is excessive.
  - Vehicle is stopped on hard shoulder as hard shoulder opens.
  - Motorcycle is stopped on hard shoulder as hard shoulder opens.

Overall, most of these countries were striving to create more livable, sustainable cities by creating and implementing integrated packages of ATM measures. In general, broad significant benefits of implementing the ATM strategies can be summarized as below (Mirshahi et al., 2007a):

- Increases in throughput of 3% to 7% during congested periods
- Decreases in primary incidents of 3% to 30% and decreases in secondary incidents of 40% to 50%
- Increased trip reliability
- Improved ability to delay the onset of breakdown conditions

Several studies have attempted to develop general guidance for the selection of different ATM techniques based on their potential benefits and characteristics (Fontaine and Miller, 2012; Mirshahi et al., 2007a). A summary of characteristics of the four ATM techniques is presented in Figure 31 (Mirshahi et al., 2007a).

Characteristic[a]	Variable Speed Limits	Queue Warning Systems	Hard Shoulder Running	Dynamic Ramp Metering
Installation characteristics	• Signs posted on overhead gantries at spacings of 0.5 to 1 km (0.31 to 0.62 mi) • Inductive loops used for detection at spacings of 0.5 to 1 km • Lane control signs commonly implemented on gantries	• Signs posted on overhead gantries or roadside installations at varying spacings; may be implemented with VSLs	• Emergency refuge areas with detection may be used; refuge areas spaced every 0.5-1 km • CCTV and/or shoulder detection needed to determine if shoulder can be used for travel • Overhead lane control signs used to indicate appropriate travel lanes; supplemental barriers sometimes present • Need mainline detection to determine whether shoulder should be opened to travel	• Detection needs on ramps and mainline vary depending on specific algorithm used • Good sensor data quality and strong communications needed to ensure effectiveness
Operational characteristics	• Changing speed thresholds based on speed-occupancy relationships commonly used • Incidents and weather can also trigger reductions • Reduced speeds typically posted 1 to 2 miles upstream of reduced speeds • Automated enforcement key aspect of European deployments	• Speed and occupancy thresholds generally used to trigger queue warnings	• Shoulders often opened only when speed limits reduced	• Local and coordinated options available • Operations vary depending on specific algorithms used
Effects on safety	• Property damage only crashes declined by up to 30% • Injury crashes declined by 10%-30% • Secondary crashes declined by 2/3	• 29% reduction in single-vehicle crashes • 20% reduction in multi-vehicle crashes • 15%- 25% reduction in primary crashes; 40%-50% reduction in secondary crashes	• Crashes fell 5%-70%	• Crash reductions possible if congestion is reduced on mainline, with 1 study reporting 39% reduction in crash rate
Effects on operations	• More even headways • Higher critical flow rates • 1.5%-10% increase in capacity • Inconsistent impacts on travel times and speed compliance	• Speed reductions 0-3.4 mph • Decline in speed variance	• Travel times declined 9%-26% • Capacity increased 7%-22% • Speeds increased 9%	• Speed improvements on mainline between 5% and 8% typical • Delays reduced by up to 18.1% • Can produce limited or negative effects depending on site
Areas of application	• Most appropriate in areas with significant recurring congestion because of economic cost of system	• Most appropriate at areas with recurring queuing and many secondary crashes so that signs can be located appropriately; especially useful when sight distance limited	• Best used in areas with recurring congestion where shoulder construction and detection can support system	• Improves flow on freeway, but must have storage on ramps to avoid harming arterial operations • Freeway must be regularly congested to realize benefit on mainline

CCTV = Closed Circuit Television

[a]Dynamic junction control was not included because of limited data on its effectiveness.

Figure 31. Summary of characteristics of four ATM techniques

Another example shows some high-level considerations for screening potential locations for various ATM measures. It was suggested that the following factors be reviewed (Fuhs and Brinckerhoff, 2010):

- Travel patterns
- Freeway geometrics
- Observed locations with recurring congestion or persistent queuing
- Locations with higher than expected crash rates

It is suggested that existing equipment, detection, and systems should be reviewed to ensure that they can be used for their original intent and also for the ATM application. Since many ATM approaches require a high level of detection, the ability to maintain this detection is critical for many applications (Fuhs and Brinckerhoff, 2010).

Moreover, it is important to check whether multiple ATM techniques can be used together in a complementary manner (Fuhs and Brinckerhoff, 2010). Figure 32 presents a matrix that shows the compatibility of different ATM strategies (Fuhs and Brinckerhoff, 2010). Checkmark indicates the compatibility of approaches. It is worth noting that research at UCF has shown the compatibility of Variable Speed Limits with Ramp Metering also.

	Technique				
Technique	**Variable Speed Limits**	**Queue Warning System**	**Hard Shoulder Running**	**Dynamic Junction Control**	**Dynamic Ramp Metering**
Variable Speed Limits	N/A	✓			
Queue Warning System	✓	N/A			
Hard Shoulder Running	✓	✓	N/A	✓	✓
Dynamic Junction Control	✓		✓	N/A	✓
Dynamic Ramp Metering		✓			N/A

Figure 32. Compatibility of ATM techniques

2.5.2 Asia

2.5.2.1 Taiwan

Several regions and cities in China have utilized several Active Traffic Management strategies since the last decade. Taiwan's ATMS on freeways and expressways includes Incident Management System, Advanced Traveler Information System and Adaptive Ramp Metering. Incorporated with the manually input information, Incident Management System collects incident information from traffic detectors and cameras automatically and generate response plan automatically, semi-automatically or manually. Advanced Traveler Information System disseminate the congestion Information, pre-trip traveler information, en-route travel time information and route guidance by dynamic message signs and Internet (Figure 33).

Figure 33. Route guidance provided by DMS in response to an accident

Ramp metering was firstly introduced in 1996. By 2012, Taiwan Area National Freeway Bureau has developed an adaptive ramp metering algorithm using vehicle detectors on upstream main lane and on-ramps. After the deployment of adaptive ramp metering, travel time was reduced significantly and recurring congestion was eliminated. In addition to the ATMS of the whole road network, Wugu-Yangmei Elevated Road, a part of Freeway 1, is using hard shoulder running and HOV lane to mitigate congestion.

2.5.2.2 China

Another example is Beijing. By the end of 2009, Beijing had developed a traffic management system including traffic detection on the ring roads, adaptive signal control, VMS and other information dissemination approaches. Traffic detection and monitoring systems include thousands of loop detectors and hundreds of high definition cameras installed on urban expressways and the ring roads. Adaptive signal control systems have been installed in 1,535 intersections in Beijing. The incident management system in Beijing automatically sends incident information to the nearest traffic police station which significantly reduces the response time. Additionally, a decision support system was developed in 2010. Subsequently, traffic conditions were improved through the application of effective incident management and route guidance techniques.

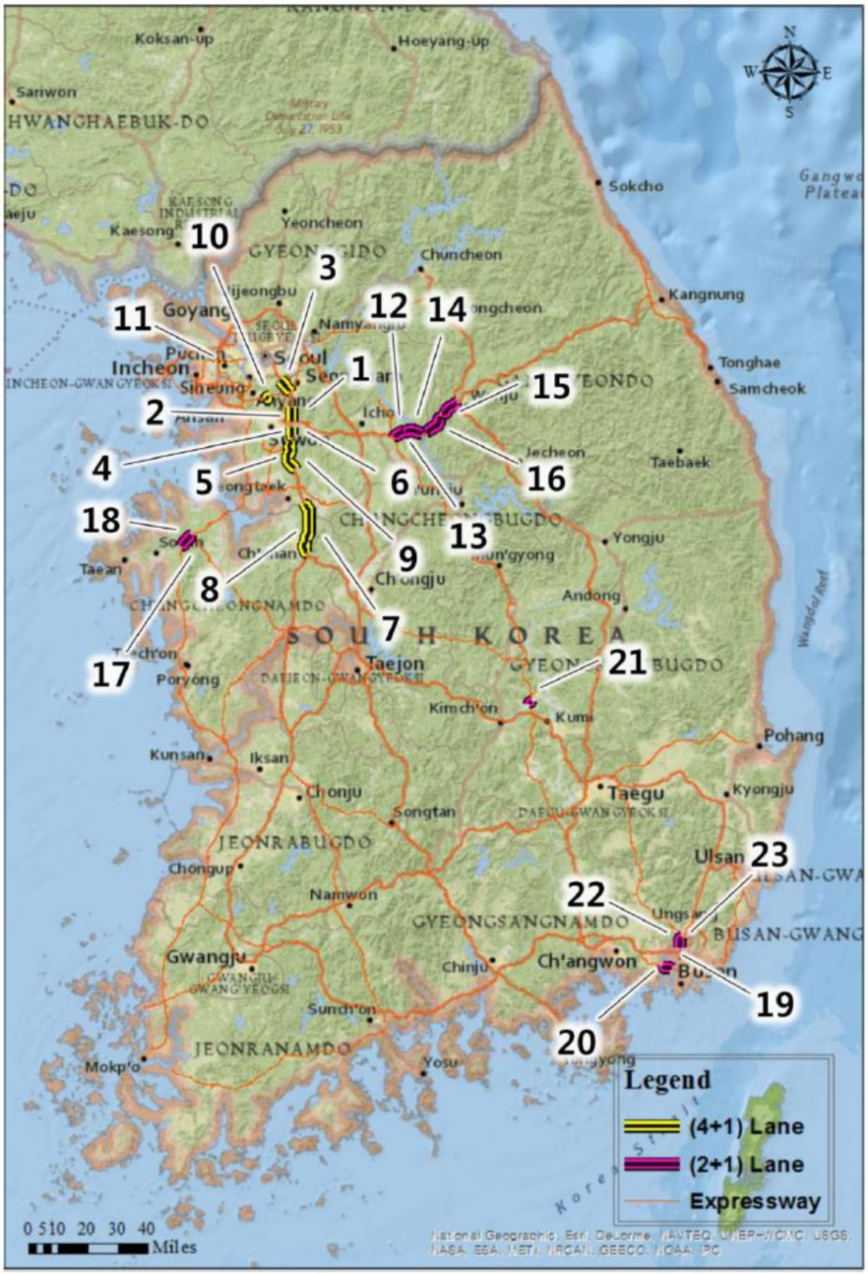
2.5.2.3 South Korea

Two kinds of managed lanes have been implemented on Korean expressways, i.e., bus lanes and allowing vehicles to operate on the hard shoulders of roads during peak periods. The former is a type of high-occupancy vehicle lane that is allocated for the exclusive use of buses. The second type of managed lanes is a supply-side strategy that allows vehicles to travel on the hard shoulder when traffic is congested, thereby temporarily increasing capacity (Jang et al., 2014).

The bus lane was implemented on a five-lane, 37.9-km expressway running in both directions between Osan and Seoul (see Figure 34 (a)). The bus lanes were installed as a demand management strategy on the most heavily used roadway in Korea. The active development of the areas along this route over the last decades has severely aggravated the congestion problem on the roadway. At the present time, the traffic volume on the Gyeongbu expressway is almost 19% greater than it was in 2000, and, consequently, the route is more congested on weekdays and weekends. In July 2008, a median lane was converted to a concurrent-flow, contiguous bus lane. The lane is operated every day, but only between the hours of 7:00 A.M. until 9:00 P.M., and it is demarcated by double, solid-blue lines, and buses are allowed continuous access over the entire length of the lane. (See Figure 34 (b).) The minimum occupancy requirement for this lane is either i) vans with a capacity of nine or more passengers with more than six occupants onboard or ii) buses. The requirement was determined due partly to more effective automatic enforcement. The automatic enforcement system uses video surveillance (Figure 34 (b)), which detects only the size of vehicles; the number of occupants cannot be enforced automatically by the current system. Although enforcement is done mostly by the automatic enforcement system, the occupancy requirement is also enforced by police officers.

Figure 34. (a) Map of bus lane on the Gyeongbu expressway; (b) Picture of bus lane and occupancy enforcement cameras

Expansion of expressway capacity via construction often requires high costs over a prolonged duration of time, but users want immediate solutions at low costs for the congestion problem. In this regard, hard-shoulder running (HSR) provides an ad-hoc but effective option for mitigating congestion. HSR provides extra capacity on the congested expressways by temporarily converting the shoulder areas into lanes that vehicles can use. Since November 2007, HSR projects have been deployed on 23 sections of Korean expressways, covering a total of 145 km as of January 2013 (See Figure 35)



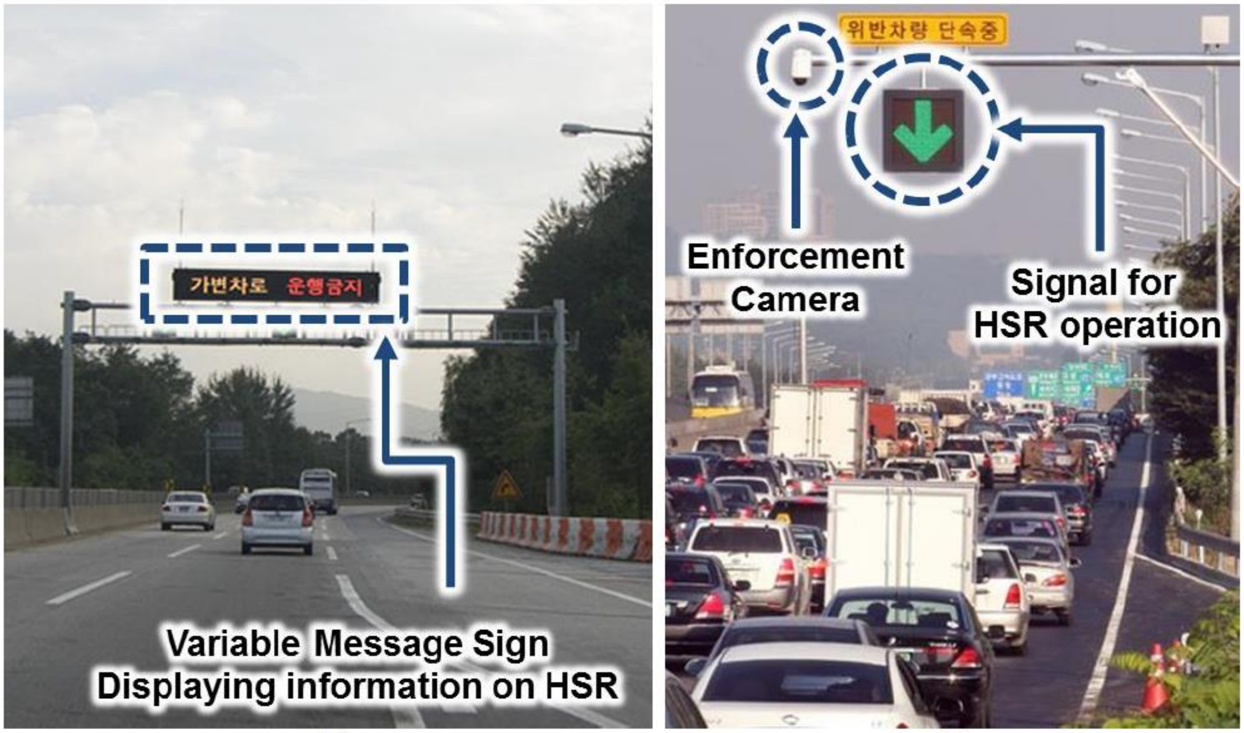
No.	Length (km)	Open
1	7.0	Nov 2007
2	7.0	Jun 2008
3	7.6	Oct 2008
4	3.1	Dec 2008
5	8.3	Dec 2011
6	3.7	Jun 2009
7	5.5	Sep 2010
8	20.0	Jul 2012
9	9.4	Sep 2012
10	1.5	Nov 2010
11	0.7	Sep 2012
12	6.2	Sep 2007
13	6.2	Jul 2008
14	7.0	Jul 2008
15	9.2	Jul 2008
16	12.4	Jul 2011
17	6.6	Sep 2008
18	6.9	Jan 2010
19	1.4	Jul 2012
20	3.6	Dec 2008
21	1.7	Sep 2012
22	5.0	Dec 2008
23	5.0	Dec 2008

Figure 35. Sites where HSR is in effect on Korean Expressways

For feasible and effective implementation of HSR projects, the sections were required to satisfy the following criteria:

- The section contains a merge bottleneck that occurs due to localized, high traffic volume.
- The traffic condition of the section is categorized as level of service of E or worse.
- The number of lanes must increase along the direction of traffic (to avoid creating another lane-drop bottleneck downstream).
- The shoulder is sufficiently wide to accommodate traffic. A width of at least 3.5 m is recommended for HSR. Otherwise, only vehicles with capacities of 15 or fewer passengers are allowed.
- Emergency bay areas are available in addition to HSR. There must be an emergency bay in every 750 m, and the bays must be at least 4 m wide and 30-50 m long.

HSRs are implemented by using variable message signs (VMSs) that display the status of the system and monitor the speed of vehicles on the expressways. Two types of VMSs have been installed, i.e., one that displays text messages that are positioned upstream of the section to notify incoming traffic of the status of the system (Figure 36 (a)) and one that displays only on and off signs (green arrow, ↓, and red cross, ×), which are placed every 400 m along the section (Figure 36 (b)). These VMSs turn on the signs (↓ and "Hard Shoulder Running is in Effect") when the average travel speed within the section of the expressway diminishes to less than 60 km/h, which is monitored by closed circuit TV, loop detectors, and tag readers of electronic toll collection.



(a) (b)

Figure 36. (a) Variable message signs (VMSs) displaying HSR information; (b) Signal for HSR operation

The bus lane could encourage a modal shift and thereby reduce passenger vehicle demand. As a result, travel times that are collectively spent by travelers on traversing freeway sections could be reduced. In all five cases examined, average travel time was reduced. Spatial-temporal plots of speed showed that the activation of HSR can relieve congestion and allow speeds to increase.

2.5.2.4 Japan

The National Police Agency, Japan (NPA), which governs the Japanese traffic management, has been promoting to introduce an advanced traffic management system called Universal Traffic Management System (UTMS) (Aoyama, 1994; UTMS, 2013). The UTMS is a new and comprehensive project that includes an integrated traffic control system, advanced mobile information system, mobile operation control system, dynamic route guidance system, public transportation priority system and environment protection management system.

The UTMS being an important part of the Intelligent Transport System (ITS) are deployed under the budget for the Earmarked Traffic Safety Facility Improvement Programs, since the systems need to be deployed under uniformed functions covering wide-area throughout Japan and with supply of real time information. In 1997, approximately 75% of the whole expenses of the Earmarked Traffic Safety Facility Improvement Programs are appropriated for deployment of the UTMS (JTMTA, 2013).

In general, the UTMS includes following functions and services (UTMS, 2013).

- ITCS (Integrated Traffic Control Systems)
- AMIS (Advanced Mobile Information Systems)
- PTPS (Public Transportation Priority Systems)
- MOCS (Mobile Operation Control Systems)
- EPMS (Environment Protection Management Systems)
- DSSS (Driving Safety Supports Systems)
- HELP (Help System for Emergency Life Saving and Public Safety)
- PICS (Pedestrian Information and Communication Systems)
- FAST (Fast Emergency Vehicle Preemption Systems)

Currently, ITCS, AMIS, and HELP approaches have already been implemented in all prefectures in Japan. Figure 37 presents the implementation status of different UTMS approaches in Japan.

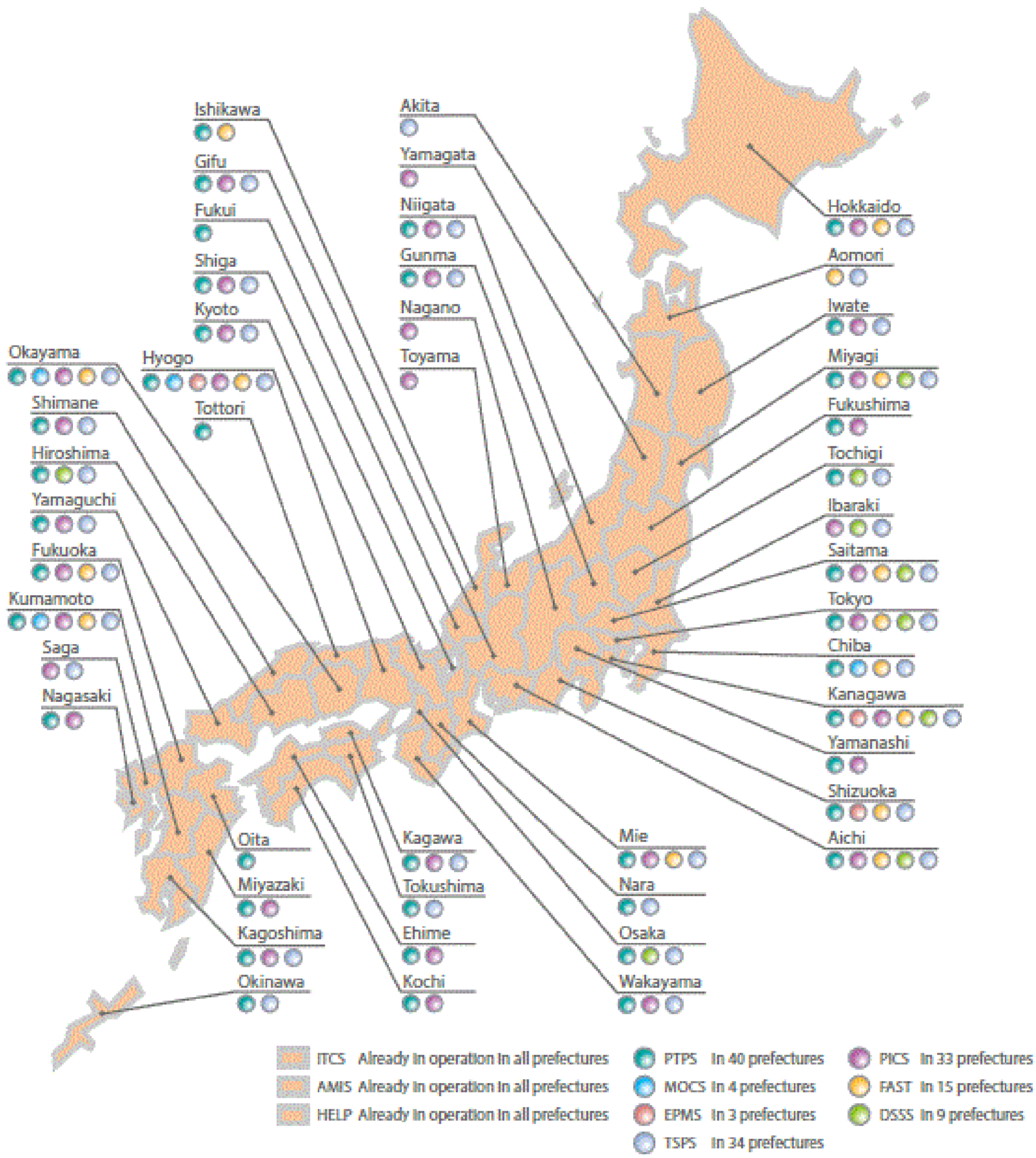


Figure 37. Prefectures implementing UTMS (As of March 2018)

The Integrated Traffic Control Systems (ITCS) are the key components of the Universal Traffic Management Systems (UTMS) and provide advanced traffic management. The ITCS achieve optimum signal control to effectively deal with ever-changing traffic flow patterns, provide real-time traffic information, and implement each subsystem of the UTMS. Figure 38 presents a diagram that explains the main functions of ITCS.

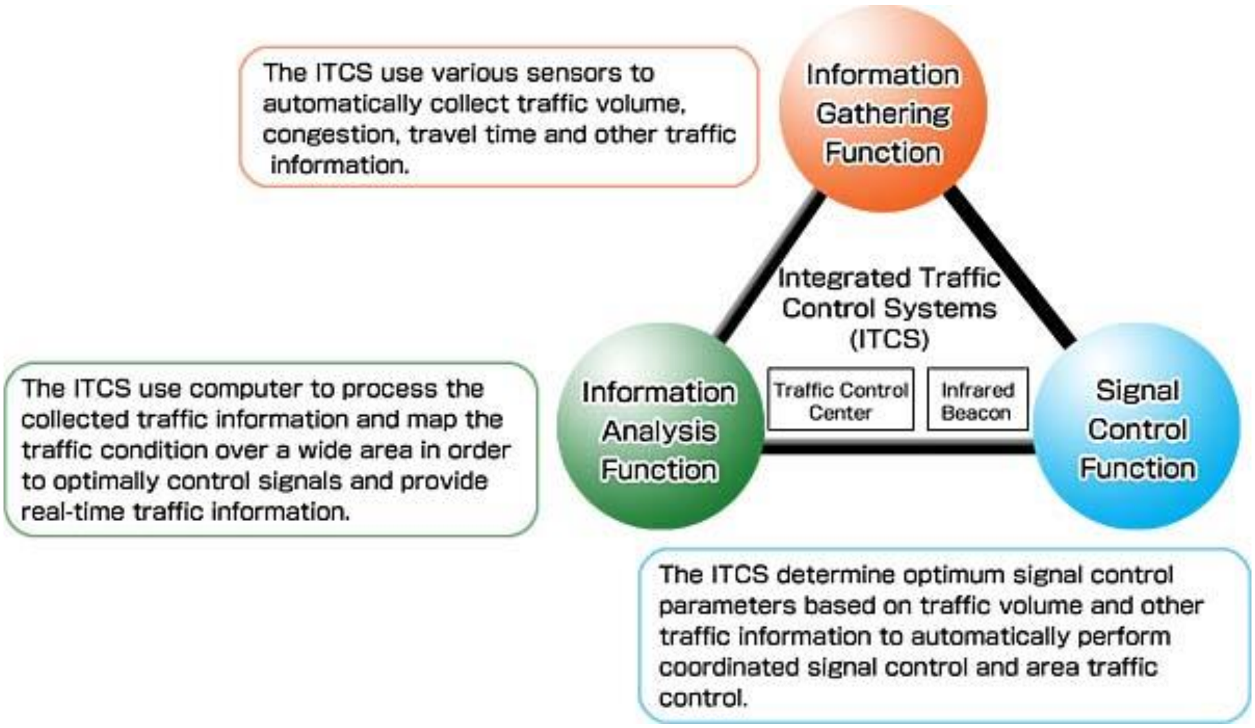


Figure 38. Main functions of ITCS

The main benefits of ITCS can be summarized as below (UTMS, 2013):

- Ensure traffic safety and smooth traffic flow
- Alleviate traffic congestion
- Reduce travel time
- Minimize traffic pollution

The Advanced Mobile Information Systems (AMIS) provide real-time traffic information required by drivers. Traffic information gathered at the Traffic Control Center is fed to in-vehicle car navigation systems or provided via traffic information display boards, car radios, and other-media.

Followings are the main benefits of AMIS (UTMS, 2013):

- Disperse traffic flow
- Alleviate traffic congestion
- Reduce travel time
- Ease drivers' stress
- Great economic effect

The Public Transportation Priority Systems (PTPS) give priority to public transportation such as buses by means of bus lanes, warnings to vehicles which are illegally running in the bus lane, and traffic signal preemption.

The main benefits of PTPS are presented as below (UTMS, 2013):

- Improve convenience for users
- Encourage the use of public transportation
- Ensure on-time bus operation
- Reduce bus waiting time at intersections
- Reduce the number of traffic violators driving in a bus lane
- Ensure bus safety (When making a right turn or merging into traffic out of the bus bay)

The Mobile Operation Control Systems (MOCS) help transportation administrators of bus, freight, sanitation and other services to properly manage their operations. The MOCS provide the administrators with accurate time and locations of their vehicles.

The main benefits of MOCS can be summarized as below (UTMS, 2013):

- Improve efficiency of vehicle management
- Improve efficiency of movement of people and goods
- Advance the road transportation industry and improve its service
- Increase the number of public transportation users

The Environment Protection Management Systems (EPMS) reduce traffic pollution such as exhaust gas pollutants and noise, and protect the regional environment. The EPMS collect environmental and traffic information to control traffic signals, provide alternative route guidance, and limit traffic flow. The main benefits of implementing the EPMS are to reduce air pollution and to resolve noise problem (UTMS, 2013).

The Driving Safety Support Systems (DSSS) assist drivers to drive safely. Various sensors are used to detect cars, motorcycles, and pedestrians that are not in the driver's sight. Based on this information, the DSSS alert drivers via message display boards or in-vehicle units.

The DSSS includes different prevention and enhancement systems such as stop sign recognition enhancement system, rear-end collision prevention system, crossing collision prevention system, signal recognition enhancement system, etc.

Followings are the main benefits of DSSS (UTMS, 2013):

- Reduce traffic accidents at intersections
- Lessen driver's burden of making decisions
- Increase driver's awareness about safe driving

The Help system for Emergency Life saving and Public safety (HELP) assist emergency vehicles including police cars, fire engines, and road service vehicles to conduct prompt rescue activities. The HELP immediately reports location information to rescue organizations in the case of an emergency such as traffic accidents, vehicle breakdowns, and sudden illness. Figure 39 shows a chart for the HELP system configuration.

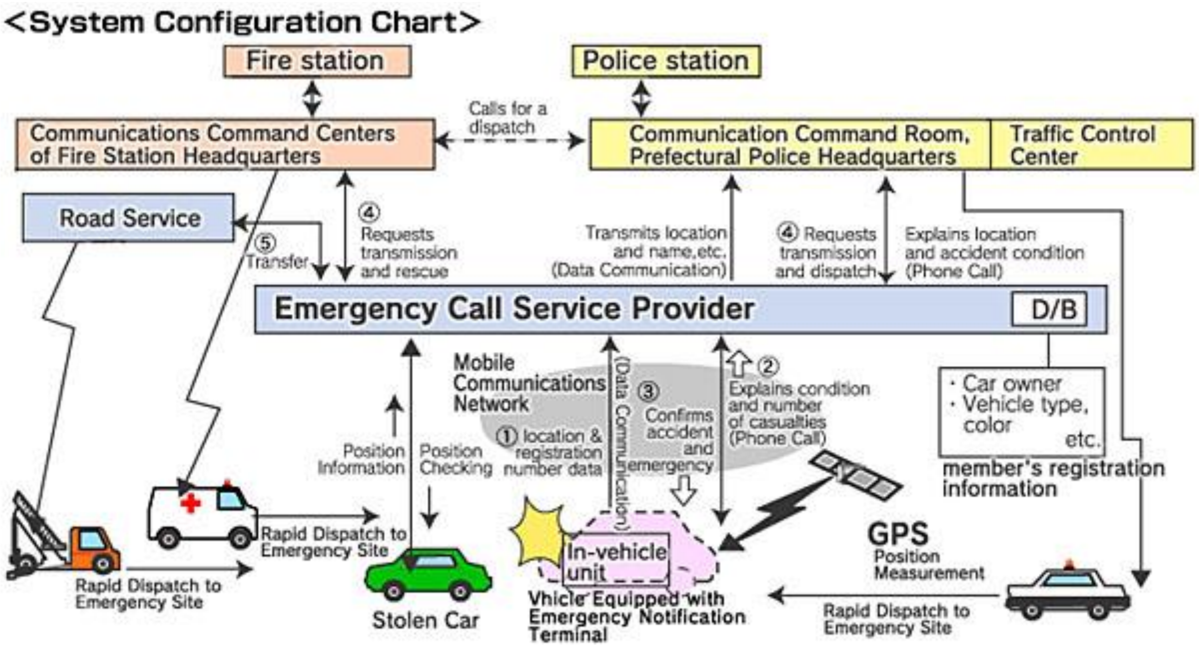


Figure 39. Flowchart of HELP system

The main benefits of HELP are as follow (UTMS, 2013):

- Reduce time to call initiation
- Reduce the number of fatalities in traffic accidents
- Minimize serious injuries
- Prevent secondary accidents
- Alleviate traffic congestion

The Pedestrian information and Communication Systems (PICS) support the elderly and the disabled to move around safely. The PICS provides accurate information about the safety of the intersection by voice. The main benefit of PICS is to support to cross an intersection safely.

The Fast Emergency Vehicle Preemption Systems (FAST) assist emergency vehicles to reach an accident site as quickly as possible. The FAST controls traffic signals to prioritize driving of emergency vehicles.

Below are the main benefits of implementation of FAST (UTMS, 2013):

- Improve life-saving rate
- Improve criminal arrest rate
- Prevent traffic accidents at intersections involving emergency vehicles

2.6 Summary

In this task, the research team reviewed recent freeway, arterial, and integrated active traffic management (ATM) and integrated corridor management (ICM) practices in the United States and other countries. Moreover, the literature for state-of-the-art in TSM&O and ATM including the two ICM demonstration sites (i.e., I-15 corridor in San Diego, CA and US-75 corridor in Dallas, TX) have been reviewed.

Traffic management systems have been advanced and enhanced through active transportation and demand system (ATDM) approaches which includes ATM, active demand management (ADM), active parking management (APM), etc. In particular, the ATM strategies have been deployed for freeways implementing various techniques such as Adaptive Ramp Metering, Dynamic Junction Control, Dynamic Lane Assignment, Dynamic Lane Reversal, Dynamic Merge Control, Dynamic Speed Limits, Dynamic Shoulder Lane, and Queue Warning. Moreover, the ICM system has recently been suggested and studied based on an integration of traffic management systems for multiple corridors.

In the United States, three states (i.e., Washington, Virginia, and Minnesota) deployed the ATM techniques at specific sections on freeways. In general, they introduced adaptive ramp metering and installed overhead sign gantries at freeway mainlines to provide dynamic lane assignment, dynamic speed limits, dynamic shoulder lane, and queue warning information. From the ATM practices and research results of the three states, it was found that ATM has benefits on enhancing traffic operation (i.e., flow, travel time reliability, congestion, etc.). Due to the lack of data, the safety effectiveness of ATM techniques implemented in the three states was not evaluated. On the other hand, the ATM systems deployed in European countries (i.e., Denmark, Netherlands, Germany, and England) presented both operational and safety benefits.

The ICM has been deployed to exert synergy among networks and modes by maximizing the utilization of the existing infrastructure assets. The ICM aims to integrate institutions, technologies such as traveler information and data fusion, and operation with performance measures and decision support system (DSS). Major strategic areas of the ICM are demand management, load balancing, event response, and capital improvement. In order to examine technical standards and provide supporting analysis approaches of implementing ICM, the current ongoing ICM projects including San Diego I-15, Dallas US-75, Minneapolis I-394, and I-95 ICM in Broward County have been reviewed. All sites planned to implement the DSS-oriented system. According to the effect analysis results, which is followed by the guideline of analysis, modeling, and simulation (AMS) of ICM strategies, for the condition of before ICM deployment, it was found that the ICM has benefits under the representative traffic conditions: daily operation, major freeway incident, major arterial incident, transit incident, special event, and disaster response scenario. As for the after deployment of ICM condition, a capability to monitor, control and report, DSS evaluation, traveler response, corridor performance mobility, corridor performance safety, air quality, benefit-cost Analysis are planned to be considered.

All master plans related to Intelligent Transportation System (ITS) in Florida are also considering the integration of freeway, arterial and further transit network, which is the basic direction of TSM&O. In particular, active arterial management (AAM) including adaptive traffic signal operation and Bluetooth data is one of the key strategies in Florida.

The DSS which is an essential part of the integrated operation was considered in District 4 and District 5. District 4 developed DSS system in terms of performance measures. District 5 has been designing DSS including the big data system and this effort is still ongoing.

Based on the findings and lessons from the reviewed practices and materials, the followings can be recommended and considered for this project:

- It is required to follow the concept and operational scenarios of ICM except for multimodal operation.
- To maximize benefits of IATM, appropriate ITS technologies (e.g., provision of advanced information, adaptive signal control, etc.) and ATM techniques (e.g., managed lane, hard shoulder running, etc.) should be considered.
- Post-deployment evaluation as well as pre-deployment evaluation need to be considered. The post-deployment evaluation requires considerable time.

- Pre-deployment evaluation should refer to the guideline for analysis, modeling, and simulation of ICM strategies

- The best practices of well-developed ATM and ICM implementation guideline should be referred to.

- The existing active arterial management (AAM) needs to be considered for the IATM.

- Performance measures including travel time and travel time reliability should be developed for the DSS of IATM strategies.

- IATM's goals should include the followings: 1) increase of traffic throughput, 2) improvement of travel time reliability, and 3) safety enhancement by incident management.

CHAPTER 3. TRAFFIC DATA COLLECTION TECHNOLOGIES

3.1. Overview

Managing traffic data plays a crucial role in the development of the freeways/arterial IATM system. In particular, historical traffic data including speed or travel time, traffic volume, density and other traffic related measurement could help practitioners and researchers to understand the performance of the existing traffic network, and it could be further utilized to determine the causes of recurrent and non-recurrent congestion. Besides, historical traffic data is also a resource in the development of the IATM algorithms and traffic simulation scenarios. Apart from that, real-time streaming of the traffic data will support the operation of future developed IATM system as a fundamental data input. Furthermore, the spatial-temporal data availability is also the bottom line for the selection of study area of the current IATM project or even future development locations. Hence, a comprehensive understanding of multiple data collection technologies is necessary.

This chapter reviews the data collection technologies such as infrastructure-based traffic data collection technologies including Microwave Vehicle Detection System (MVDS), Automatic Vehicle Identification (AVI) by Toll Tag Reader and Bluetooth, and other infrastructure-based traffic data such as inductive loop detectors and video image processing; vehicle based third party data from HERE® and INRIX®; and crowd source data platform.

3.2. Data Collection Technologies

According to the standard specifications for vehicle detection systems (VDS) in Florida, VDS is categorized by functional types and technological types (FDOT, 2017b). The functional types are vehicle presence detection systems, traffic data detection systems, and probe data detection systems. Usually, the vehicle presence detection systems are used for signal operation systems to detect vehicles presence of approaches at intersections. The traffic data detection systems are installed to collect traffic data about volume, occupancy, and speed data. The probe data detection systems are deployed to collect speed data and travel times for a road segment. In this project, different types of traffic data were collected through different data collection technologies.

3.2.1 Infrastructure-Based Traffic Data

3.2.1.1 Microwave Vehicle Detection System (MVDS) Data

Microwave Vehicle Detection System (MVDS) is a point-based roadside vehicle detection system utilizing microwaves. MVDS system is able to detect the traffic states at their installed locations (points), including volume, speed, density derived by lane occupancy and even vehicle length grouped into several length bins lane by lane. MVDS generates representative point measurements such as volume, speed, and occupancy by detecting vehicle presence through a FCC-certified, low-power microwave radar signal (FDOT, 2017b). According to the microwave radar operation concept (see Figure 40), the MVDS can determine presence, passage, volume, lane occupancy, speed, and vehicle length grouped into several length bins lane by lane (Lawrence et al., 2006). As shown in Figure 41, the MVDS is installed above ground on the side of the roadway has a minimum 200-foot range and the capability to detect 8 lanes of traffic.

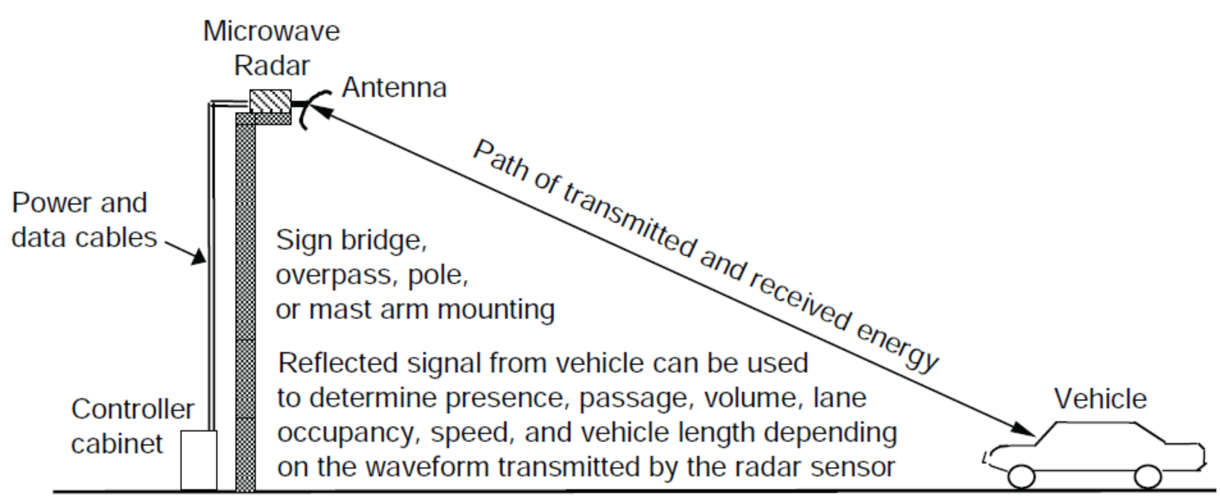
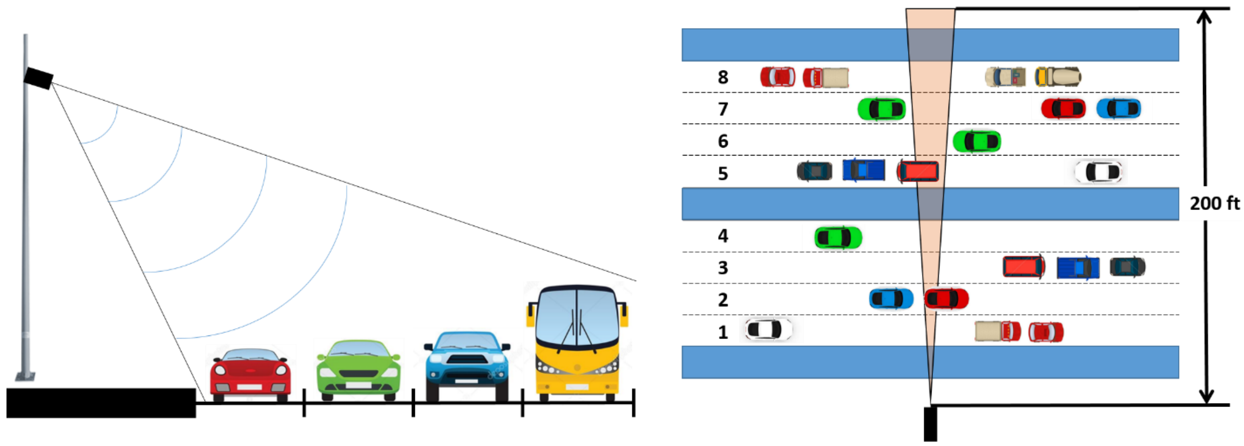


Figure 40. Microwave radar operation



(a) The front view of MVDS detection coverage

(b) The top view of MVDS detection coverage

Figure 41. Detection coverage of side-fire MVDS

MVDS measuring all vehicles will satisfy at least minimum performance requirements: a presence detection accuracy of 98%, a volume accuracy of 95%, an occupancy accuracy of 90%, and a speed accuracy of 90% for all eight lanes, although the MVDS can get some errors such as double count, miss count, occlusion, and phantom detection (see Figure 42) (FDOT, 2017b).

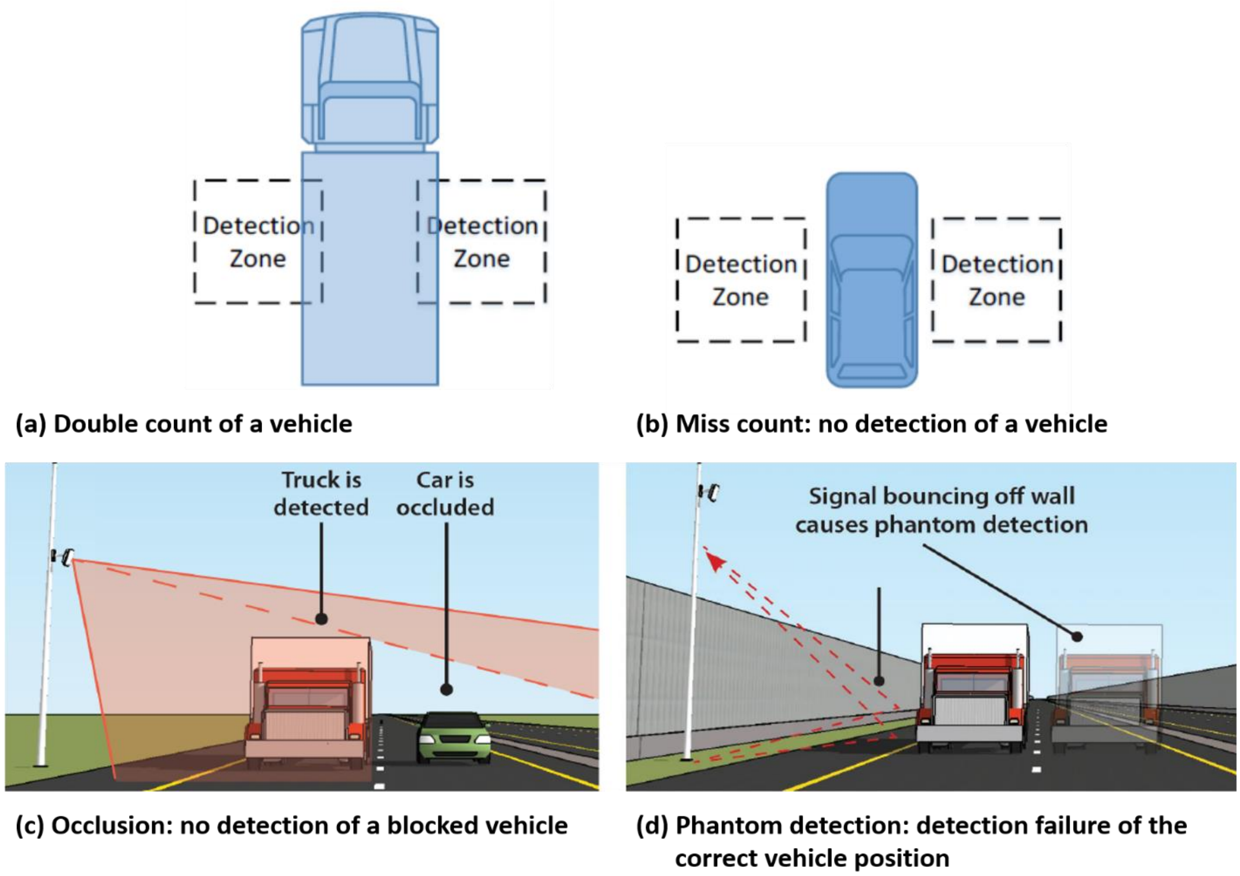


Figure 42. Common detector data collection errors (Scholler and Wu, 2017)

Microwave Vehicle Detection System (MVDS) in Florida District 5 is collecting traffic data for traffic network surveillance on freeways, expressways, and turnpikes. Since last decade, MVDS are widely deployed as a part of Intelligent Transportation System (ITS) for monitoring traffic flows of limited-access freeways and expressways in Florida, including I-4, SR 91 (Florida's Turnpike), SR 408, SR 414, SR4- 417, SR 429 and SR 528.

3.2.1.2 Automatic Vehicle Identification (AVI) Data by Toll Tag Reader

As a probe data detector, Automatic Vehicle Identification (AVI) systems collect the time and location of vehicles passing the specific points where AVI readers are installed. Based on the time and location of vehicles, travel times of links and corridors can be calculated and estimated directly. The AVI systems can use several technologies such as radio-frequency identification (RFID), optical character recognition, and Bluetooth® (FDOT, 2017b). In the study area, it was investigated that RFID readers are deployed on freeways, expressways, and turnpikes. The Bluetooth® readers are applied to collect travel times for major arterials.

In Florida District 5, AVI technology using RFID was deployed for both electronic toll collection (ETC) and travel time collection. The AVI technology to monitor traffic conditions were first introduced through iFlorida Model Deployment Project for Orlando area (Haas et al., 2009). An AVI system consists of four primary components: electronic transponders, roadside antenna, roadside readers, and a central computer (see Figure 43). Transponder readers of the AVI system is compatible with UHF (Ultra High Frequency) RFID standards and frequencies within 902-928 MHz bandwidth (FDOT, 2017b). According to the design specification of vehicle detection systems in Florida, the AVI system will satisfy minimum performance requirements: penetration rate of 75%, a match rate of 5% between upstream and downstream detection, and a total roadway segment speed and travel time accuracy level of 90%.

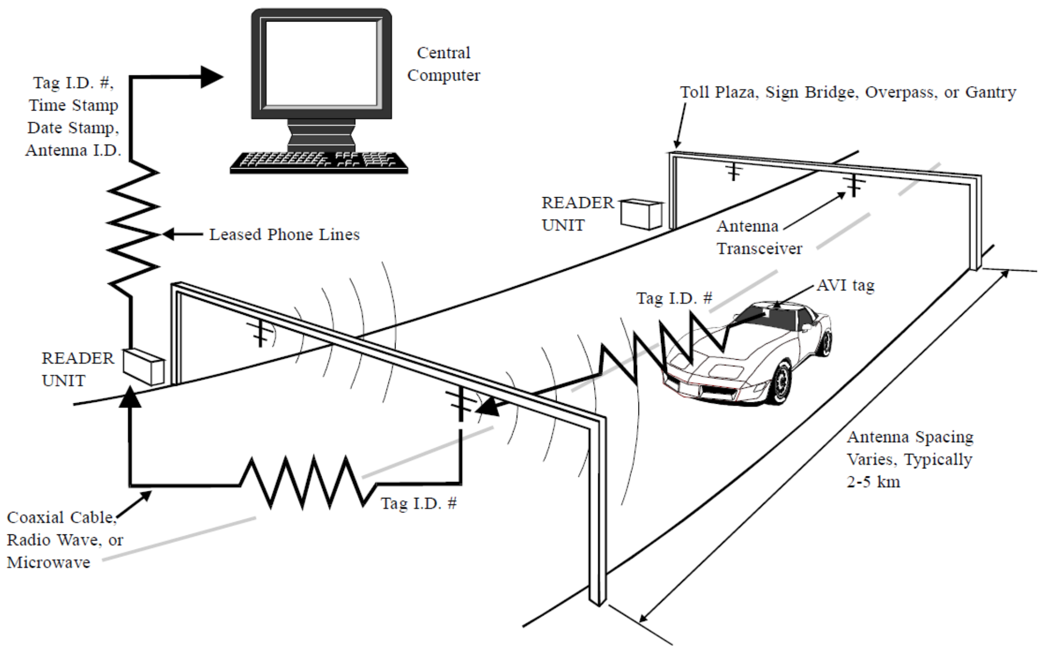
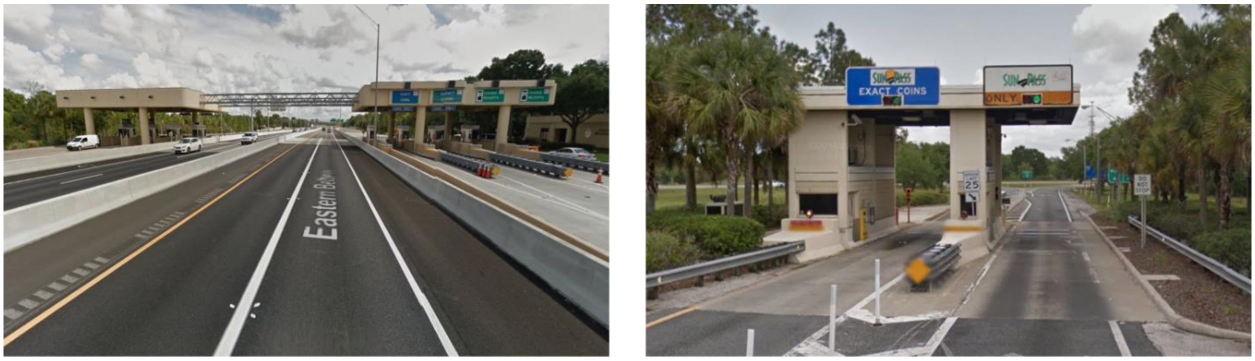


Figure 43. AVI vehicle-to-roadside communication process (Turner et al., 1998)

There are two types of electronic toll collection systems (ETC), E-PASS and SUNPASS, in Central Florida. Except for I-4, all highways for uninterrupted traffic flows belong to toll roads. Transponders for the ETC are compatible with both systems because they adopted standardized ETC protocol and wireless frequency bands. Toll transaction data collected by toll collection systems can be used to make O/D matrix with AVI using RFID. The O/D matrix will include toll collection locations of expressways and major intersections of arterials. The O/D matrix can be applied to logic to select the optimal traffic information provision to drivers according to the real-time traffic demands. Furthermore, the toll transaction data can be used to validate travel time and traffic volumes collected by MVDS. As shown in Figure 44, local toll collection devices are located in mainline plazas and on/off ramps. Detail toll transaction data with the encrypted transponder ID were obtained through the cooperation of CFX.



(a) Mainline toll plaza (b) Toll gate on on/off ramp

Figure 44. Two types of local toll collection

Electronic toll tag identifier matching can be used to find the ground truth travel time for the evaluation of travel time and speed data from other data sources (Turner et al., 2011a). Furthermore, the qualified travel time can be utilized for various real-time travel time prediction, reliability analysis, and effectiveness assessment for various active traffic management strategies. To use the travel time as a real-time performance measurement, the existing AVI tag matching algorithm and travel time estimation algorithm should be enhanced in terms of more advanced statistical techniques and big data analysis methods.

Usually, travel time is estimated every one minute with one-minute time window size by electronic toll tag identifier matching algorithm. For instance, the estimated travel time can be used for travel time index, which was developed by the research team in an earlier project to identify congestion situations (Abdel-Aty et al., 2014a). The travel time index (TTI) is calculated by dividing the actual travel time by the free flow travel time. Based on TTI, three types of traffic conditions, no congestion ($TTI < 1.25$), moderate congestion ($1.25 \leq TTI < 2$) and high congestion ($TTI \leq 2$), can be monitored.

3.2.1.3 Automatic Vehicle Identification (AVI) Data by Bluetooth

In recent years, a lot of traffic agencies begin to employ Bluetooth Detection System to collect travel time data on both freeways and arterials. Bluetooth Detection Systems is one of Automatic Vehicle Identification (AVI) systems which utilize Bluetooth wireless technology. In Bluetooth Detection Systems, the Media Access Control (MAC) address of a discoverable Bluetooth enables device carried by a vehicle serves as a unique identifier to identify and re-identify the vehicle. The travel time of the vehicle is calculated by matching two detections with the same MAC address. And the space mean speed of the vehicle is further derived from the location information of two detectors.

The mechanism for deriving traffic information of Bluetooth vehicle detection system is similar to the AVI system utilizing toll tag reader. A Bluetooth vehicle detector (BT detector) attaches the timestamp, location identifier, and maybe a signal strength indicator (typically Received Signal Strength Indicator, RSSI) to the detected MAC address. By matching the spatial-temporal information with same MAC address from two BT detectors, the travel time of an individual vehicle is calculated by two detection timestamps. And the space mean speed of the vehicle is further derived from the location information of two detectors. Figure 45 illustrates the fundamental mechanism of Bluetooth vehicle detection system (Díaz et al., 2015).

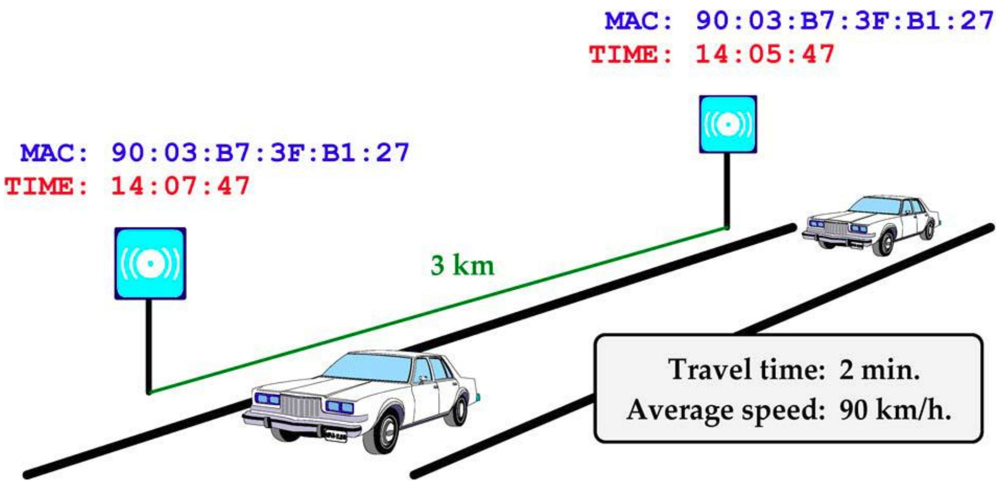


Figure 45. Fundamental mechanism of bluetooth vehicle detection system

Currently, Bluetooth detection systems from three different vendors are deployed in our study area. They are BlueMAC, Iteris® Vantage Velocity®, BlueTOAD® (Bluetooth Travel-time Origination and Destination). Table 11 shows the information regarding these three Bluetooth detection systems.

Table 11. Information of bluetooth detection system

Name	Vendor	County	Collection Agency	Roadway	Data Type
BlueMAC	Digiwest	Orange	Orange County	4 arterial corridors	Raw detection logs
			District 5	Major arterials	First detections and 30-second aggregated travel time
Vantage Velocity®	Iteris	Orange	Orange County	2 arterial corridors	Filtered travel time of individual vehicles
BlueTOAD	TrafficCast	Seminole	Seminole County	All arterials	Filtered travel time of individual vehicles
		Orange Seminole	FTE	SR-417	5-min aggregated travel time

BlueMAC is a Bluetooth traffic monitoring system developed by Digiwest, LLC. Since Dec. 2016, BlueMAC BT detectors are deployed near the signalized intersections of four arterial corridors in Orange County, which are SR 434 (Alafaya Trail) from McCulloch Road to Curry Ford Road, University Boulevard, Lake Underhill Road from Legacy Place to Woodbury Road and SR 426 (Aloma Avenue) from Balfour Drive to SR 436. Until May 2017, only the detector planned to be installed near the intersection of University Boulevard and Alafaya Trail is still under deployment.

Iteris® Vantage Velocity® is a Bluetooth travel time calculation and performance measurement system developed by Iteris® Inc. Iteris® Vantage Velocity® were deployed along 4 arterials in Orange County since 2015, which are US 17/92/441 (Orange Blossom Trail) from Wakulla Way to Taft Vineland Road, SR 482 (Sand Lake Road and McCoy Road) from Presidents Drive to Jetport Drive, SR 535 from Lake Street to LBV Factory Stores Drive and SR 536 from World Gateway Drive to World Center Drive.

BlueTOAD® is a Bluetooth traffic-monitoring system. BlueTOAD® travel time data are available for all limited-access freeways and expressways and major arterials in Seminole County. AVI systems are able to measure travel time of individual vehicle directly, thus, a number of practitioners and researchers employed travel time from Bluetooth detectors as a "ground truth".

Different Bluetooth systems are providing different types of data including raw detection logs, filtered detection logs, travel time of individual vehicles and aggregated travel times. Vantage Velocity® and BlueTOAD are providing travel times of the individual vehicle. However, those data were filtered and processed by their proprietary algorithms. Meanwhile, BlueMAC system in Orange County could provide raw detection data and the travel time of the individual vehicle could be obtained by "Max-Max Matching" method. However, the BlueMAC data from District 5 only includes the first detection of a specific vehicle instead of all detections. Thus, the

"Max-Max Matching" method could be utilized and another "First-First Matching" method will be applied.

Max-Max Matching method refers to matching the detection with maximum signal strength of a vehicle by the upstream detector and the detection with maximum signal strength of the same vehicle by downstream detector. Received Signal Strength Indicator (RSSI) is the signal strength indicator. The detection with maximum signal strength might reflect the closest location of vehicle to the detector. Figure 46 illustrates the logic of max-max matching.

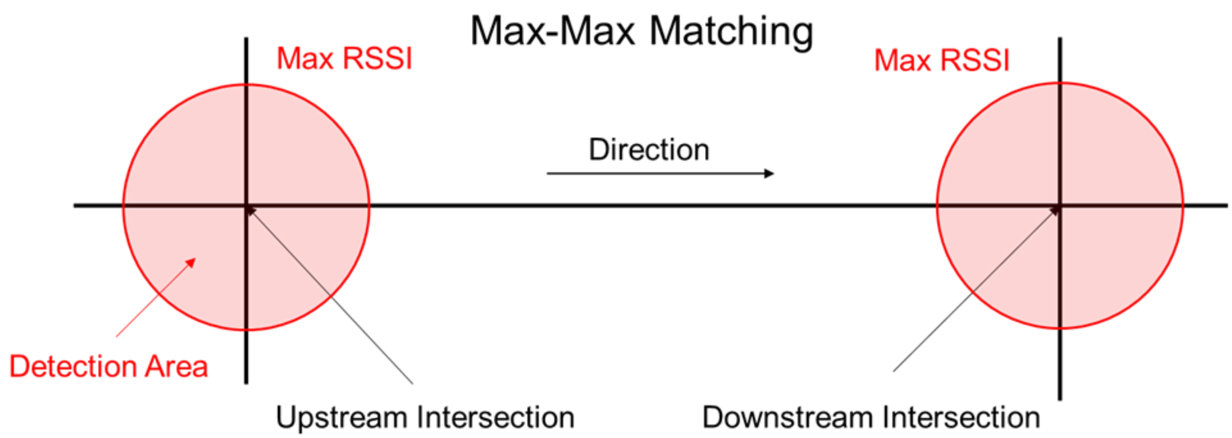


Figure 46. Max-Max matching method

First-First Matching method refers to matching the first detection of a vehicle by the upstream detector and the first detection the same vehicle by downstream detector. The method might lead to some error since it takes randomly 0.01 to 10.24 seconds for to detector to catch a vehicle. Figure 47 illustrates the logic of first-first matching.

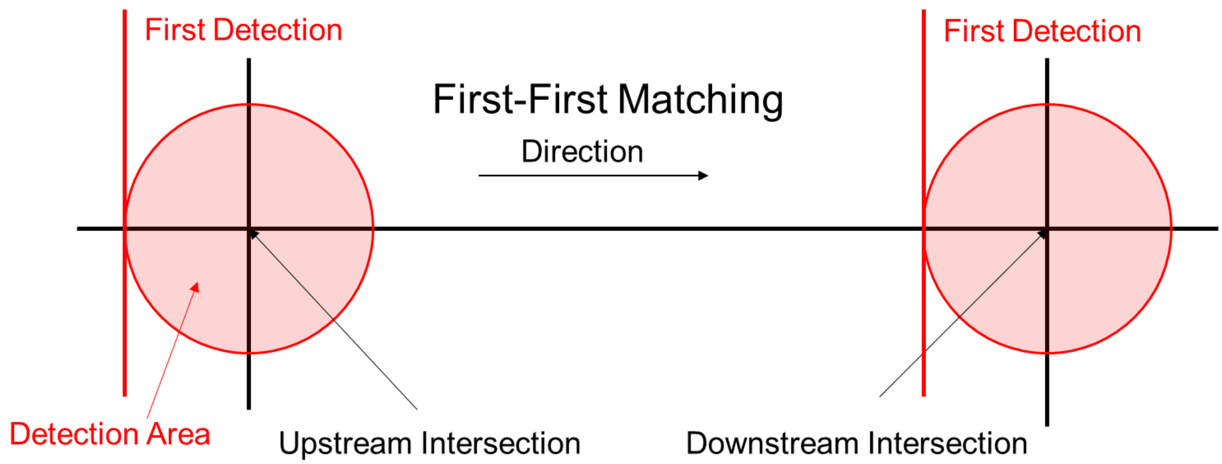


Figure 47. First-First matching method

AVI systems are able to measure travel time of individual vehicle directly. Thus, a number of practitioners and researchers utilized the travel time from Bluetooth detections systems as the "ground truth".

3.2.2 Vehicle-Based Traffic Data System

Recently, public traffic agencies started to provide speed and travel time data as supplementary data sources. The data are collected from private sector traffic service companies such as INRIX, HERE, and TomTom. These data vendors could take advantages of probe vehicle tracking technologies to provide extensive coverage of the road network including all freeways and most of the arterials.

Florida Department of Transportation (FDOT) has purchased traffic data from HERE® Technologies, a leading company which provides mapping data and relevant services including navigation and traffic data. HERE data are available for all limited-access freeways and expressways, all other principle arterials and most of minor arterials in the study area since October, 2013. HERE provides the one-minute space mean speed of the specific roadway segments. The associated confidence level, which is a quality indicator pre-defined by HERE®

company, is also provided for each speed reading. All HERE® data are retrieved from Regional Integrated Transportation Information System (RITIS).

INRIX® is a global traffic software and data service provider. From October, 2008 to September, 2013, INRIX® provided space mean speed collected from probe vehicles for several Interstate Freeways (e.g. I-10, I-75, I-95) and several principle arterials in Miami/Ft. Lauderdale metropolitan area and Jacksonville metropolitan area. However, currently, INRIX® data is only available on 2.5-mile segment of I-95 near Palm Beach Airport, which is not in the study area.

In addition, NPMRDS (National Performance Management Research Data Set) was approved by MAP-21 for calculating national performance management measures to assess the performance of the National Highway System. The NPMRDS includes speed and travel time data. The NPMRDS data is available at a 5-minute interval. If necessary, the data can be aggregated at 15-minute or hourly interval. The NPMRDS data have the following types of data:

- Passenger vehicles only
- Trucks only
- Trucks and Passenger vehicles

Since NPMRDS data is based on only raw observed probe-based traffic, it seems that NPMRDS data is close to ground truth. However, it cannot be used to estimate travel times in real time. Instead, the data could be used to evaluate travel time estimation systems or estimate roadway performance measures such as travel time reliability. Therefore, NPMRDS can be used to evaluate the quality of traffic data collected from private sector providers. As shown in Figure 48, the NPMRDS covers the majority of roadways related to this project.

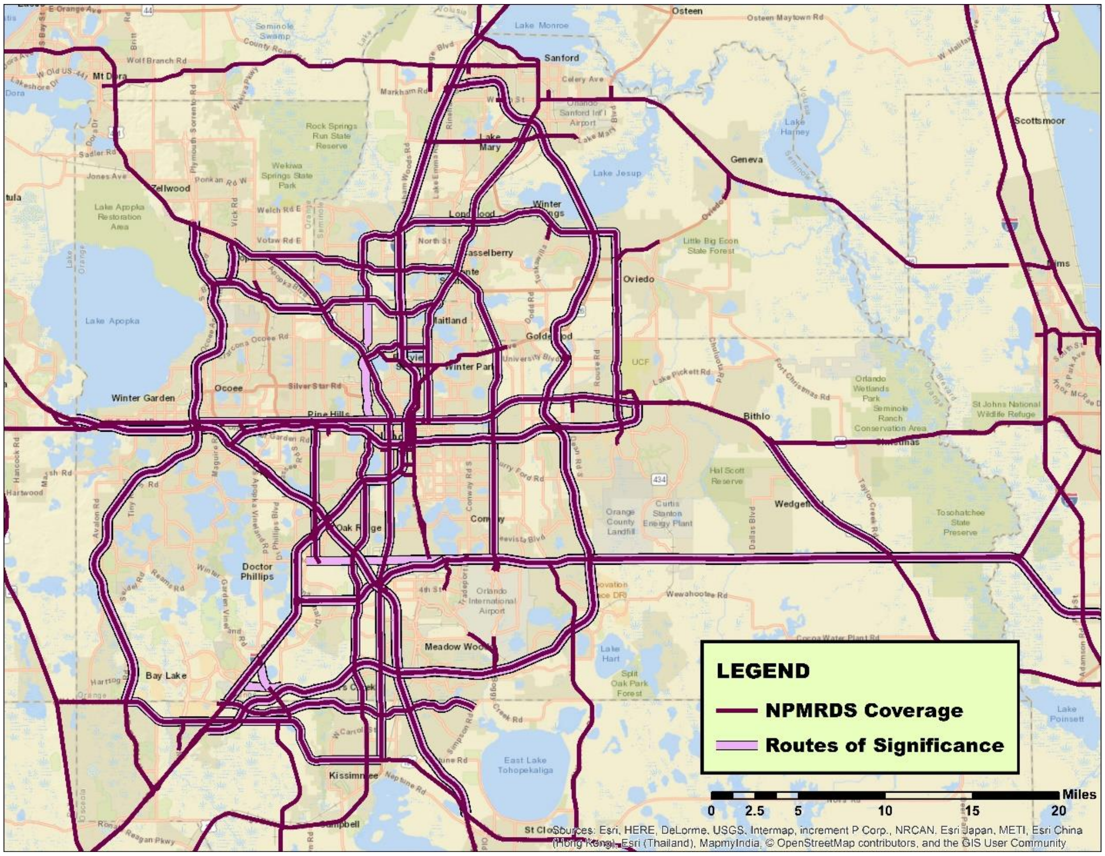


Figure 48. Roadways in NPMRDS coverage

3.2.3 Signal Control System Data

In this project, the algorithms for IATM strategies will be developed and evaluated by traffic simulation based on the traffic flow of both freeways and arterials. In order to understand the traffic flow of arterials comprehensively, the data from the signal control system at the intersections are necessary.

There are two types of signal control systems in the study area, including traditional pre-programmed actuated signal controller and advanced adaptive traffic signal control system.

Orange County has provided the scanned signal timing sheets of 606 intersections (Figure 49) to the research team, and they are upgrading their traffic signal system to the InSync® adaptive traffic control system. Until August 2017, the InSync® adaptive traffic control system is deployed for 7 corridors: Orange Blossom Trail (US-441), Apopka Vineland Road (SR-535), World Center Drive (SR-536), Alafaya Trail (SR-434), Lake Underhill Road, University Boulevard and Aloma Avenue (SR-426).

Phase	1	2	3	4	5	6	7	8
Direction	NBL	SB		WB	SBL	NB		EB
Min Green (sec)	5	15		5	5	15		5
Vehicle Gap (sec)	1.8	3.0		3.0	1.8	3.0		3.0
Max Green 1 (sec)	20	50		30	20	50		30
Max Green 2 (sec)	20	50		30	20	50		30
Yellow (sec)	4.8	4.8		3.4	4.8	4.8		3.4
All-Red (sec)	2.0	2.0		3.1	2.0	2.0		3.1
Walk (sec)		7		7		7		7
Flash Don't Walk (sec)		29		38		26		41
Recall/Memory	NL	SF/LK		NL	NL	SF/LK		NL
Delay (sec)				CD 10				DRT 10
Detector Switching	1>6				5>2			
Dual Entry		Y		Y		Y		Y
Overlap								
Flash		Y		R		Y		R
Speed (mph)	45	45		25	45	45		25
Veh Distance (ft)	100	100		129	100	100		129
Ped Distance (ft)		103.0		133.0		92.0		143.0
Ped Clearence (sec)		29		38		26		41

COORDINATION PLANS

Coordination Pattern	1/1/1	2/1/1	3/1/1			Day	Time	Pattern
Cycle	150	170	170			1	0:01	FREE
Split 1	21	21	14			1	10:00	2/1/1
Split 2	73	90	100			1	22:00	FREE
Split 3						2	0:01	FREE
Split 4	56	59	56			2	6:00	1/1/1
Split 5	13	14	28			2	9:00	2/1/1
Split 6	82	97	86			2	16:00	3/1/1
Split 7						2	19:00	2/1/1
Split 8	55	59	56			2	22:00	FREE
Offset	69	150	160					
Lagging Phases								
Source Day	Equate 1	Equate 2	Equate 3	Equate 4	Equate 5			
1	7							
2	3	4	5	6				

Figure 49. Signal timing sheet of Orange county

Since InSync® system is one of the adaptive traffic control systems, there is no pro-programmed signal operation plan. Instead, the system chooses the phase combinations to best serve the real-time traffic condition. Thus, the historical traffic signal timing information was extracted from the system operation logs, which includes phase combination and phase duration. And several important signal performance measures such as the maximum waiting time and queue length of each phase are provided by the system operation logs. Table 12 shows the data structure of InSync® logs.

Table 12. Data structure of InSync® Signal operation logs

Attribute	Data Type	Description
Date	Date	Date
Time	Time	The beginning timestamp of a phase combination
Movement	Text	The allowed movement direction of the vehicle in the phase combination or a pedestrian call
Duration	Number	Phase duration
Phase 1-m Queue	Number	Queue length of the phase
Phase 1-m Wait	Number	Maximum waiting time of the vehicles during the phase
Errors	Text	Controller errors or detector errors

Additionally, since adaptive traffic control systems utilize loop detectors and/or image processing to detect the real-time traffic condition, the traffic volume data are also collected by those detectors. InSync® is providing a 15-minutes aggregated volume for each signal operation phase and each approaching direction. Detectors of InSync® is able to distinguish vehicles from protected left turn lanes with those from through lanes. However, it is not able to distinguish vehicles from permissive left turn lanes and right turn lanes.

Seminole County has employed advanced traffic signal controllers for 327 intersections on the arterials (Figure 50), and the Automated Traffic Signal Performance Measures (ATSPM) is utilized to measure the actual performance of the traffic signal control systems. The ATSPM is initially used to provide information for retiming process. ATSPM data consist of high-resolution monitoring logs of traffic signals. The logs have a simple data structure with only three attributes: timestamp, event type and event parameter (for signifying detector numbers and phases). The events recorded in the log include active phase event (phase on, phase green etc.), active pedestrian event, detector event (detector on/off), barrier/ring events, phase control events, overlap events, preemption events, coordination events, and cabinet/system events.

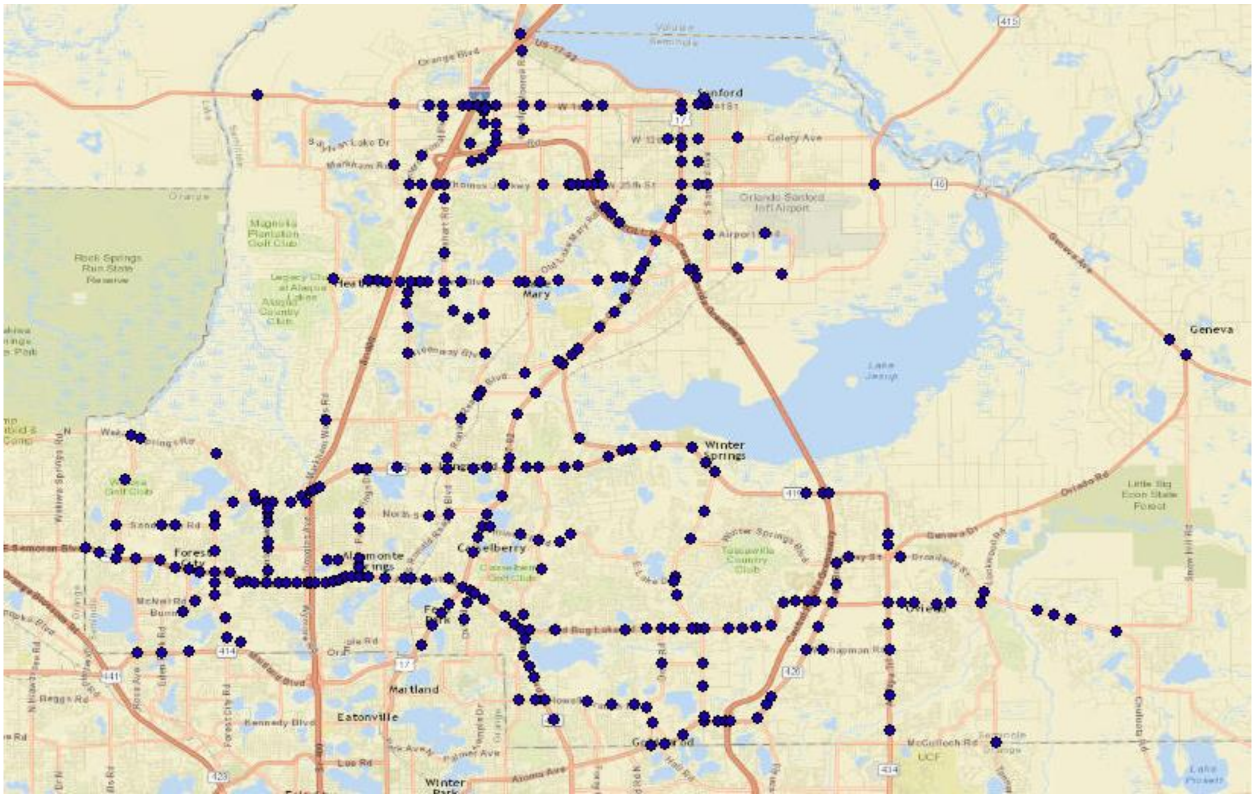


Figure 50. Intersections with ATSPM in Seminole county

ATSPM event log data provide different information about the traffic condition and traffic signal performance on arterials. For example, the actual signal phase sequence and phase timing are able to be estimated from the active phase events, and the volume per lane per phase is able to be estimated from the detector events. Other signal performance measures such as queue length and v/c ratio can also be estimated from the event log data. It should be noted that the ATSPM detectors are only installed on arterials, which means that the traffic information of the lower-level roadways would not be available.

3.2.4 Dynamic Message Signs (DMS)

Dynamic Message Signs (DMS) are operated to provide drivers with real-time traffic information such as traffic conditions, travel times, and traffic crashes. DMS displays various message types: emergency, incident management, traffic management, construction or maintenance activities, weather condition, special events, safety campaigns, travel time, AMBER alerts, LEO (Law Enforcement Officer) alerts, test messages, and blank sign (Montes et al., 2008). According to MUTCD's recommendation, messages are displayed with two phases (FHWA, 2009). As a default display, DMS should provide travel time except for the case that travel time information would not be useful. FDOT specified three types of DMS, which are embedded DMS, front access DMS, and walk-in DMS, to ensure interoperability and compatibility between various DMSs (see Figure 51) (FDOT, 2017b). The embedded DMS was not identified in the study area.

(a) Embedded DMS **(b) Front Access DMS** **(c) Walk-in DMS**

Figure 51. Three types of DMS

DMSs on arterials were started to be installed to provide traffic information of freeways and expressways (see Figure 52). Figure 53 shows locations of DMS for traffic information by authorities.

Figure 52. Arterial DMS

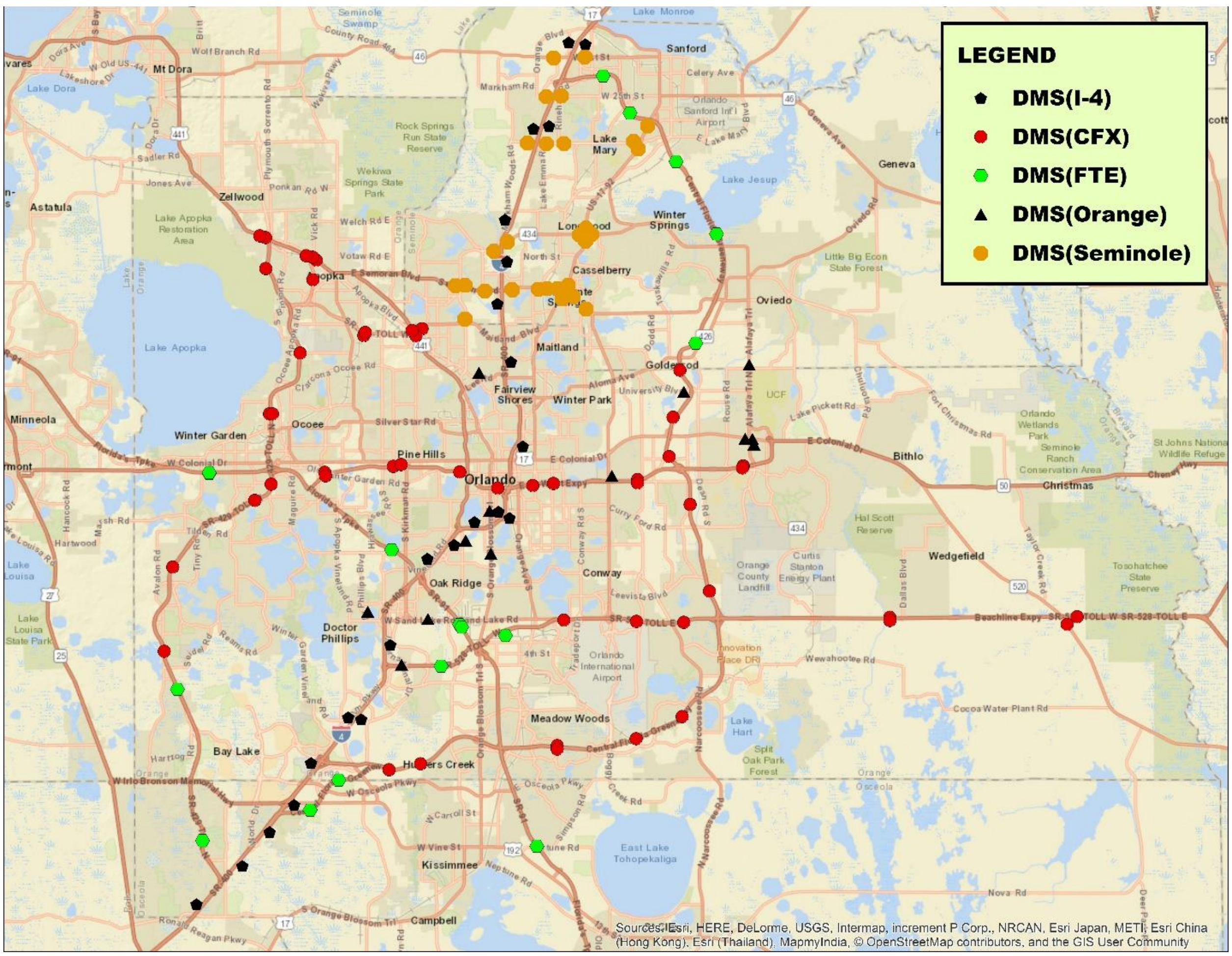


Figure 53. Locations of DMS

Except for DMS, FDOT implemented VSL (Variable Speed Limits) of 28 on I-4 under iFlorida Model Deployment project in 2008 (Haas et al., 2009). Currently, the VSLs are replaced by speed limit signs (See Figure 54).

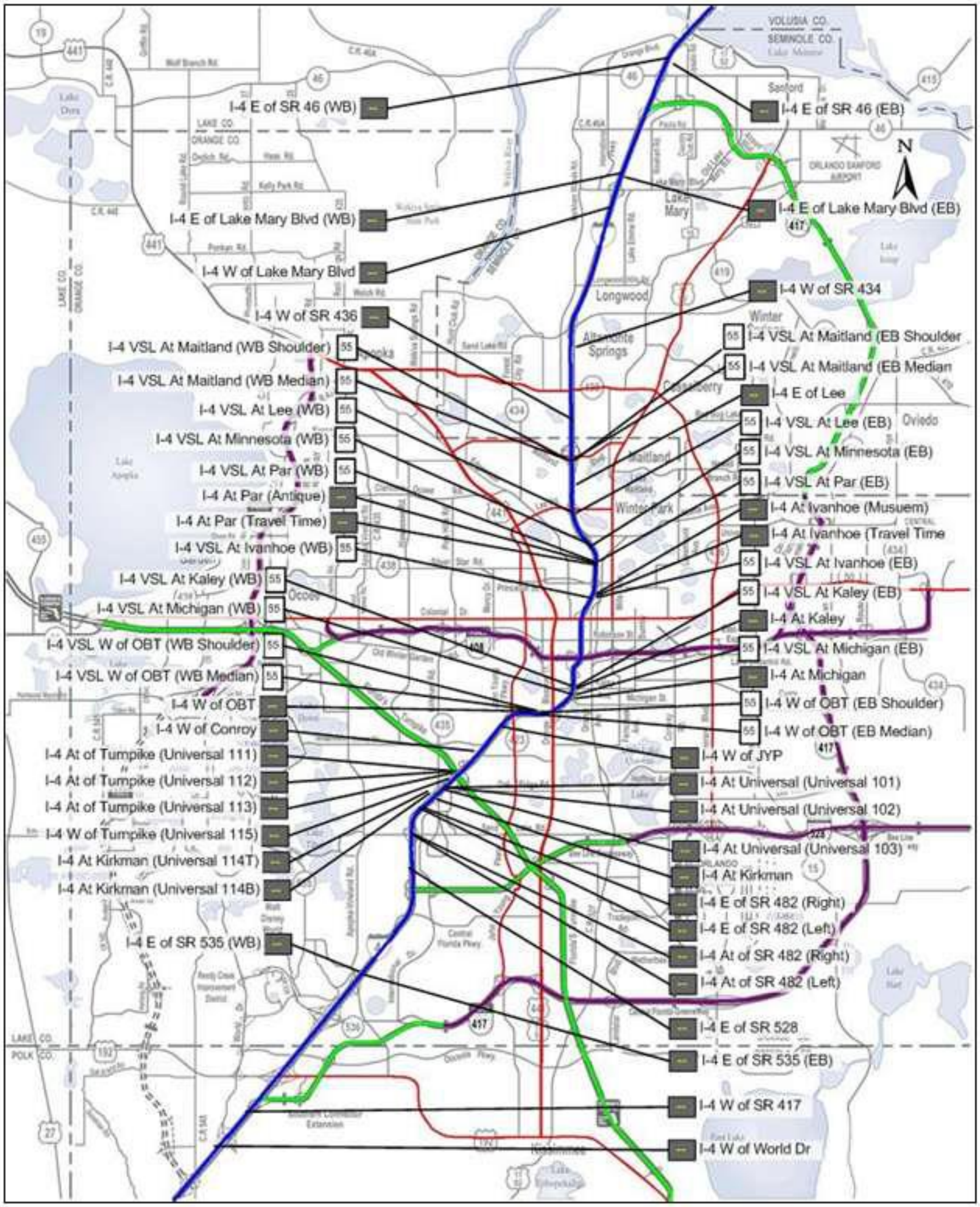


Figure 54. Dynamic message and variable speed limit signs on I-4 for Florida (Haas et al., 2009)

3.2.5 Crowdsourced Data

Crowd sourcing platforms can be useful information sources for developing integrated active traffic management strategies. These platforms include social media systems such as Twitter, mapping application such as Google Mapss, incident reporting application such as Waze. We have investigated how Twitter can be used to collect traffic information and incident data.

Twitter is the most widely used social media platform in USA with 67 million active users (Omnicore, 2017). It is a micro blogging service used to share views, activities, and thoughts through a 140 character long short message called 'tweet'. Apart from the text portion of a tweet there are a number of features which carry important clues to latent attributes of social media users. With twitter, one can extract spatial (geo-tagged) and temporal (time-stamped) information for a longer period of time and for large number of sample size without accessing personal details or the content of the tweets (Frias-Martinez et al., 2012; Hasan and Ukkusuri, 2015). In recent social media based transportation studies, innovative ways have been adopted to extract useful information from Twitter to apply in activity recognition (Lian and Xie, 2011), discovering mobility and activity choice behavior (Cheng et al., 2011; Noulas et al., 2011; Phithakkitnukoon, 2011; Ukkusuri et al., 2013), enhance traffic incident detection and awareness (D'Andrea et al., 2015; Fu et al., 2015; Zhang, 2015), transportation safety studies (Chen and Krishnan, 2013), classifying activity choice patterns (Cheng et al., 2011; Noulas et al., 2011), and estimating urban travel demand and traffic flow (Chang and Sun, 2011; Liu et al., 2014; Wu et al., 2014).

3.3. Summary

In this chapter, the research team has comprehensively reviewed the output data characteristics, operation mechanism, availability, and implementability of the infrastructure-based traffic data collection technologies, vehicle based third party from vendors and crowd source platforms.

Based on the review, the research team could understand the corresponding traffic data provided by the collection technologies, which could help select the study area and collect the appropriate data for the study.

CHAPTER 4. IDENTIFICATION OF THE STUDY AREA

4.1. Overview

In this chapter, the research team has identified a study area for development of the Integrated Freeway/Arterial Active Traffic Management (IATM) strategies considering the availability of traffic data and roadway network for future simulation analyses.

According to the comprehensive reviews of state-of-the-practice freeway, arterial, and Active Traffic Management (ATM) systems, relevant master plans, and the traffic data collection technologies, Orlando Metropolitan Area in Central Florida is identified as the appropriate study area for this project. With a population of 2,134,411 (US Census, 2013), Orlando Metropolitan Area is the third populous and one of the representative metropolitan areas in the State of Florida. It can be expected that the IATM strategies developed in this area could be also transferred to other metropolitan areas in the State of Florida such as Miami/Ft. Lauderdale, Tampa, and Jacksonville (Florida Department of Transportation (FDOT), 2016a).

4.2. Study Area Selection

Figure 55 provides the map of the selected study area with the following information: 1) information of county boundaries and 2) roadway networks by functional classification (FDOT, 2016b) in the selected study area.

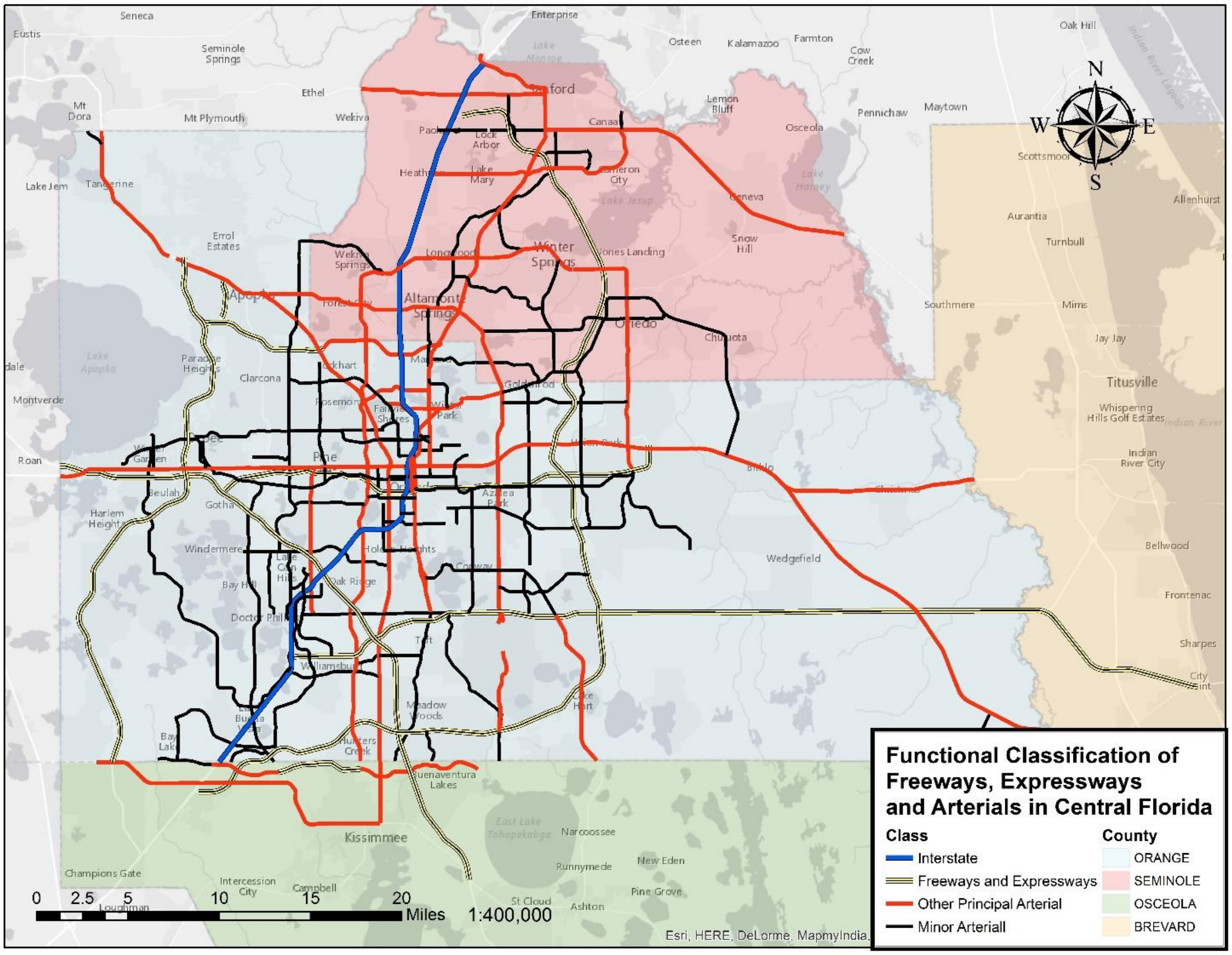


Figure 55. Selected study area

As seen from Figure 55, Seminole and Orange counties are the major regions for the Orlando Metropolitan Area in Central Florida. Meanwhile, the research team also reviewed and tried to include all roadway networks listed as the Routes of Significance (RoS) (FDOT, 2016a) for the selected study area. For this reason, the other two counties (Osceola and Brevard) were also listed as the study area. According to the Federal Highway Administration (FHWA), the RoS are non-Interstate roadways in metropolitan areas that are designated by States as meriting the collection and provision of information related to traffic and travel conditions. Factors to be considered in designating RoS include roadway safety (e.g., crash rate, routes affected by environmental events), public safety (e.g., routes used for evacuations), economic productivity, severity and frequency of congestion, and utility of the highway to serve as a diversion route for congestion locations (FDOT, 2016a).

The FHWA Rule (i.e., Title 23, Code of Federal Regulations (CFR), Part 511, hereinafter referred to as "the Federal Highway Administration Regulation (FHWA Rule)") requires state Department of Transportations (DOTs) to establish a Real-Time System Management Information Program (RTSMIP) to make available construction, incident, weather, and other traveler information in real-time to both the motoring public and other entities that respond to these events (FDOT, 2016a). The FDOT State Traffic Engineering and Operations Office, working with the FDOT Districts, has compiled a list of RoS that meet the criteria set forth in the FHWA Rule as shown in Figure 56.

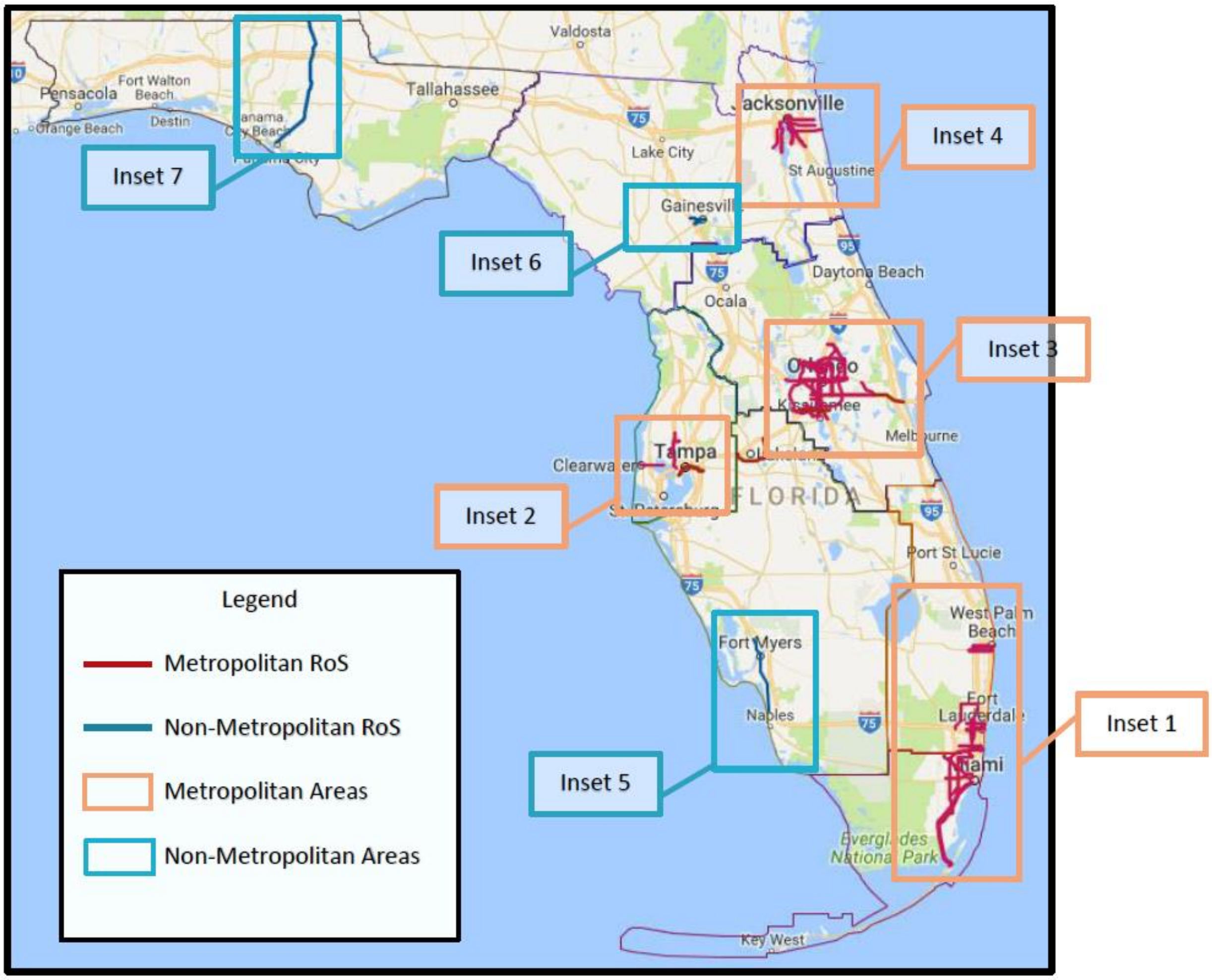


Figure 56. Florida's RoS map (FDOT, 2016a)

In particular, the FDOT worked closely in coordination with the Metroplan Orlando (MPO) to determine the list of RoS in the Orlando Metropolitan Area. Figure 57 presents the RoS within the Orlando Metropolitan Area and all of the roadways in the list of RoS are presented in Table 13.

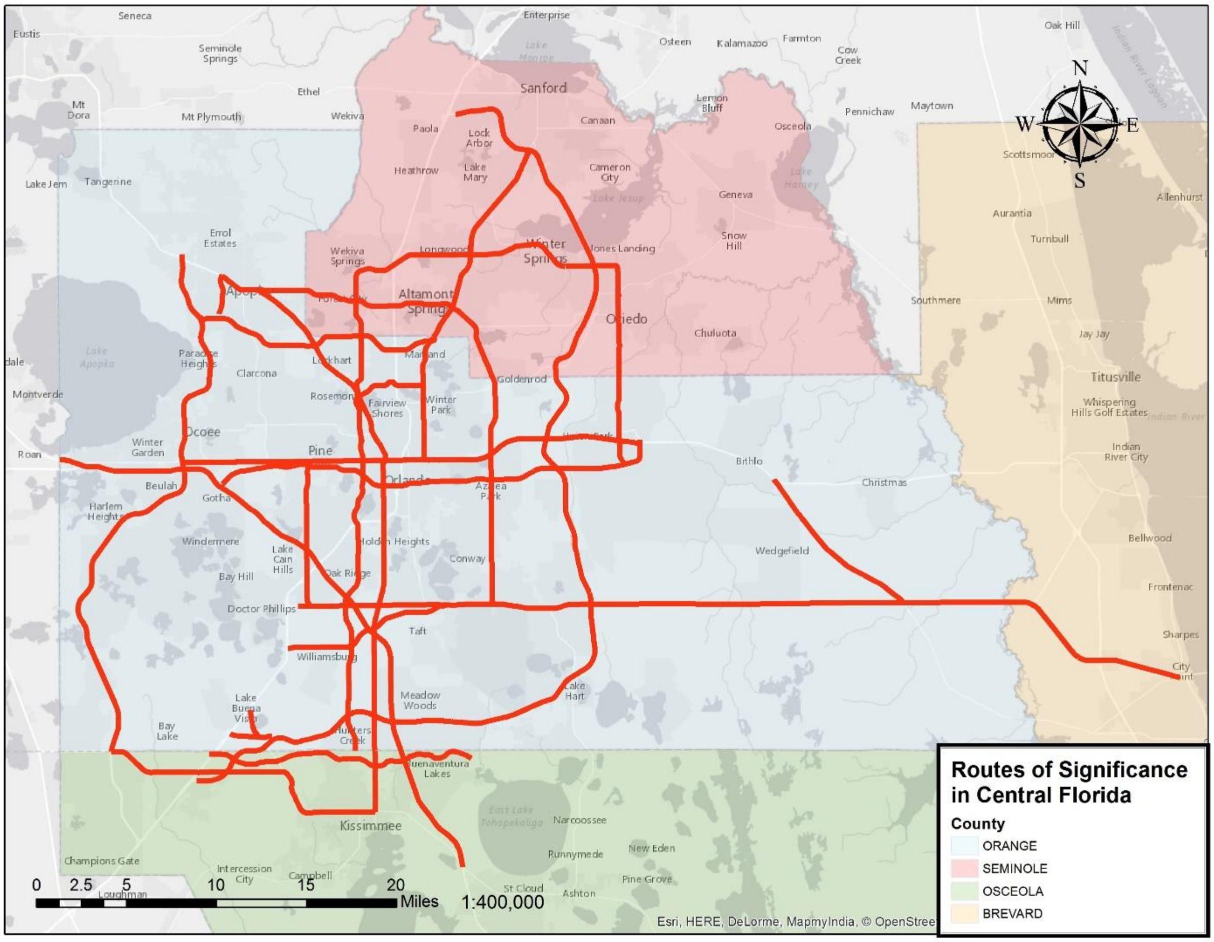


Figure 57. RoS in Orlando metropolitan area

Table 13. List of ROS in Orlando metropolitan area

Route	Limit From	Limit To	Functional Designation	MPO/TPO
SR50	SR 429	Hiawassee Road	Urban Principal Arterial	Metropolitan Orlando
SR50	Semoran Boulevard	Hastings Street	Urban Principal Arterial	Metropolitan Orlando
SR50	West of US 17	Between Kirkman Road and SR 423	Urban Principal Arterial	Metropolitan Orlando
SR50	North Semoran Boulevard	Woodbury Road	Urban Principal Arterial	Metropolitan Orlando
US 441	County Club Drive	Americana Boulevard	Urban Principal Arterial	Metropolitan Orlando
US 441	Landstreet Road	SR 408	Urban Principal Arterial	Metropolitan Orlando
US 441	Doss Avenue	US 192	Urban Principal Arterial	Metropolitan Orlando
US 441	Princeton Street	Jones Avenue	Urban Principal Arterial	Metropolitan Orlando
US 17/92	1st Street	North of Colonial Drive	Urban Principal Arterial	Metropolitan Orlando
US 17/92	Mayo Avenue/ Greenwood Drive	SR4- 417	Urban Principal Arterial	Metropolitan Orlando
SR91	Lake/Orange County Line	Orange/Osceola County Line	Urban Other Freeway/Expressway	Florida's Turnpike Enterprise
SR408	Lake/Orange County Line	Orange County Line	Urban Principal Arterial Expressway	Central Florida Expressway Authority
Osceola Parkway	World Drive	SR 530	-	Osceola County
SR429	Seidel Road	US 441	Urban Principal Arterial Expressway	Central Florida Expressway Authority
SR429	I-4	Seidel Road	Urban Principal Arterial Expressway	Florida's Turnpike Enterprise
SR423	President Drive	US 192	Urban Principal Arterial	Metropolitan Orlando
SR423	Aldrich Avenue	John Young Parkway at 33rd	Urban Principal Arterial	Metropolitan Orlando
SR423	US 17/92	North of Colonial Drive	Urban Principal Arterial	Metropolitan Orlando
SR414	Rose Avenue	Maitland Avenue	Urban Principal Arterial Expressway	Metropolitan Orlando
SR414	US 17/92	SR 434	Urban Principal Arterial	Metropolitan Orlando
SR414	SR 429	US 441	Urban Principal Arterial Expressway	Central Florida Expressway
SR435	Carrier Drive	Colonial Drive	Urban Principal Arterial	Metropolitan Orlando
SR435	SR 408	Florida's Turnpike	Urban Minor Arterial	Metropolitan Orlando
SR434	Edgewater Drive	SR 50	Urban Principal Arterial	Metropolitan Orlando
US 192	Orange Blossom Trial	SR 429	Urban Principal Arterial	Metropolitan Orlando
SR536	I-4 (SR 400) EB on Ramp	Greenway (SR4- 417)	Urban Minor Arterial	Metropolitan Orlando
SR482	I-4 (SR 400)	Beachline (SR 528)	Urban Major Collector	Metropolitan Orlando
SR436	US 441	SR 528	Urban Principal Arterial	Metropolitan Orlando
SR528	I-4	South Conway Road	Rural Other Principal Arterial	Florida's Turnpike Enterprise
SR528	SR 520	Indian River Drive	Urban Principal Arterial Expressway	Florida's Turnpike Enterprise
SR528	South Conway Road	SR 520	Urban Principal Arterial Expressway	Central Florida Expressway Authority
SR4-417	Milepost 6	Milepost 37.5	Urban Principal Arterial Expressway	Central Florida Expressway Authority
SR4-417	I-4 (Milepost 1)	Milepost 6	Urban Principal Arterial Expressway	Florida's Turnpike Enterprise
SR4-417	Seminole County Line	I-4	Urban Principal Arterial Expressway	Florida's Turnpike Enterprise
SR535	Winter Garden Vineland	SR 536	Urban Minor Arterial	Metropolitan Orlando
SR451	SR 414	US 441	Urban Principal Arterial Expressway	Central Florida Expressway Authority
SR520	SR 50	SR 528	Rural Principal Arterial Expressway	Metropolitan Orlando

The geographical coverage of real-time and historical traffic data is extensive in Orlando Metropolitan Area in Central Florida. As shown in Figure 58, there are at least two data sources available for all limited-access freeways and expressways in the selected area. Moreover, the HERE data is available for all principle arterials and almost all minor arterials. The Bluetooth travel time data is collectable for all limited-access freeways and expressways, and the most of arterials in Seminole county.

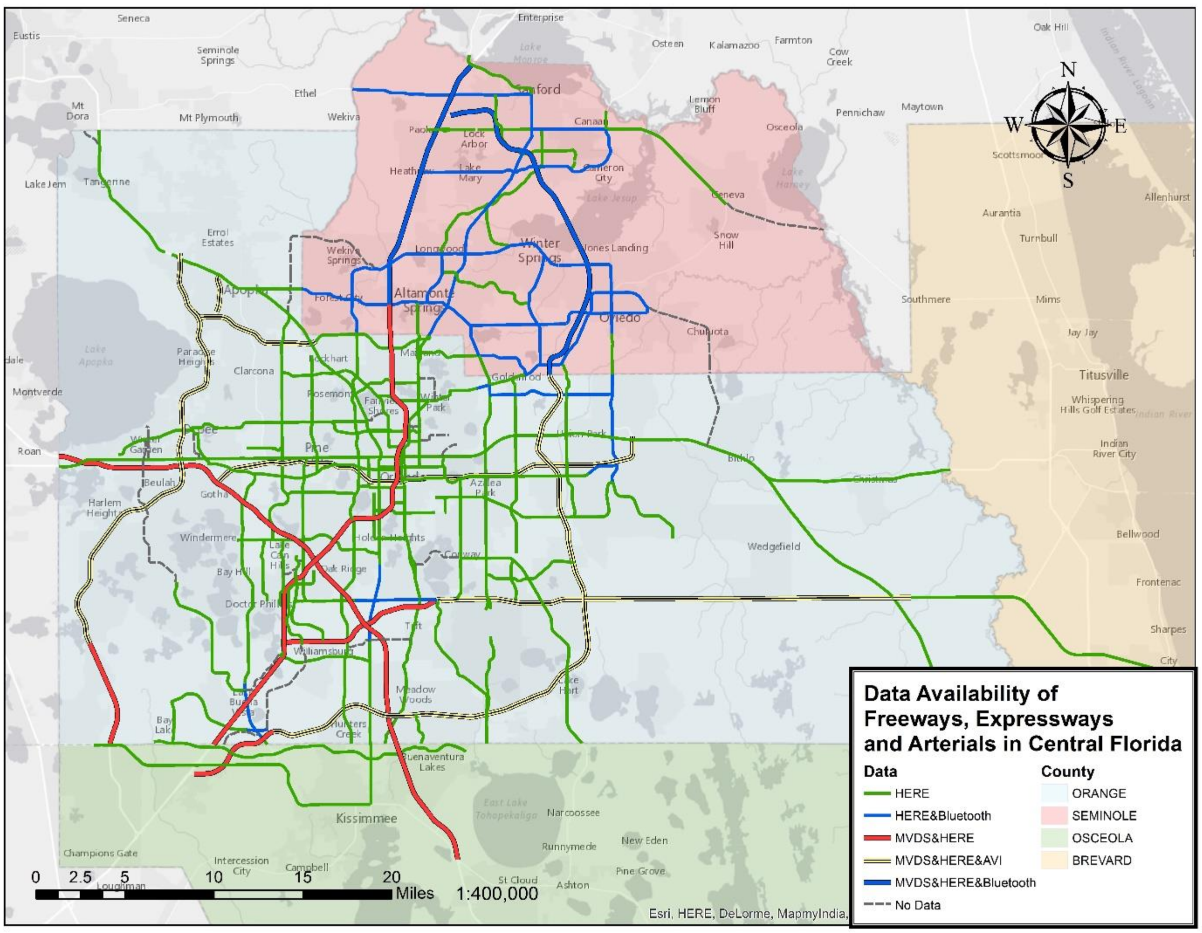


Figure 58. Data availability

The IATM concepts, strategies, and technologies can involve significant capital costs such as installation, maintenance, operations, etc (Neudorff and McCabe, 2015). As such, it is important to conduct the feasibility screening process: 1) identify the major roadway segments for potential IATM strategies, 2) define the network to be analyzed using simulation, and 3) investigate the feasibility of deployment. In order to perform this screening process, the research team will consider not only the current data availability of real-time traffic data but also the historical traffic flow and roadway geometric parameters such as annual average daily traffic (Figure 59), number of lanes (Figure 60), etc. This screening process will be further performed in future tasks to conduct the micro/meso/macro-scopic simulation analyses.

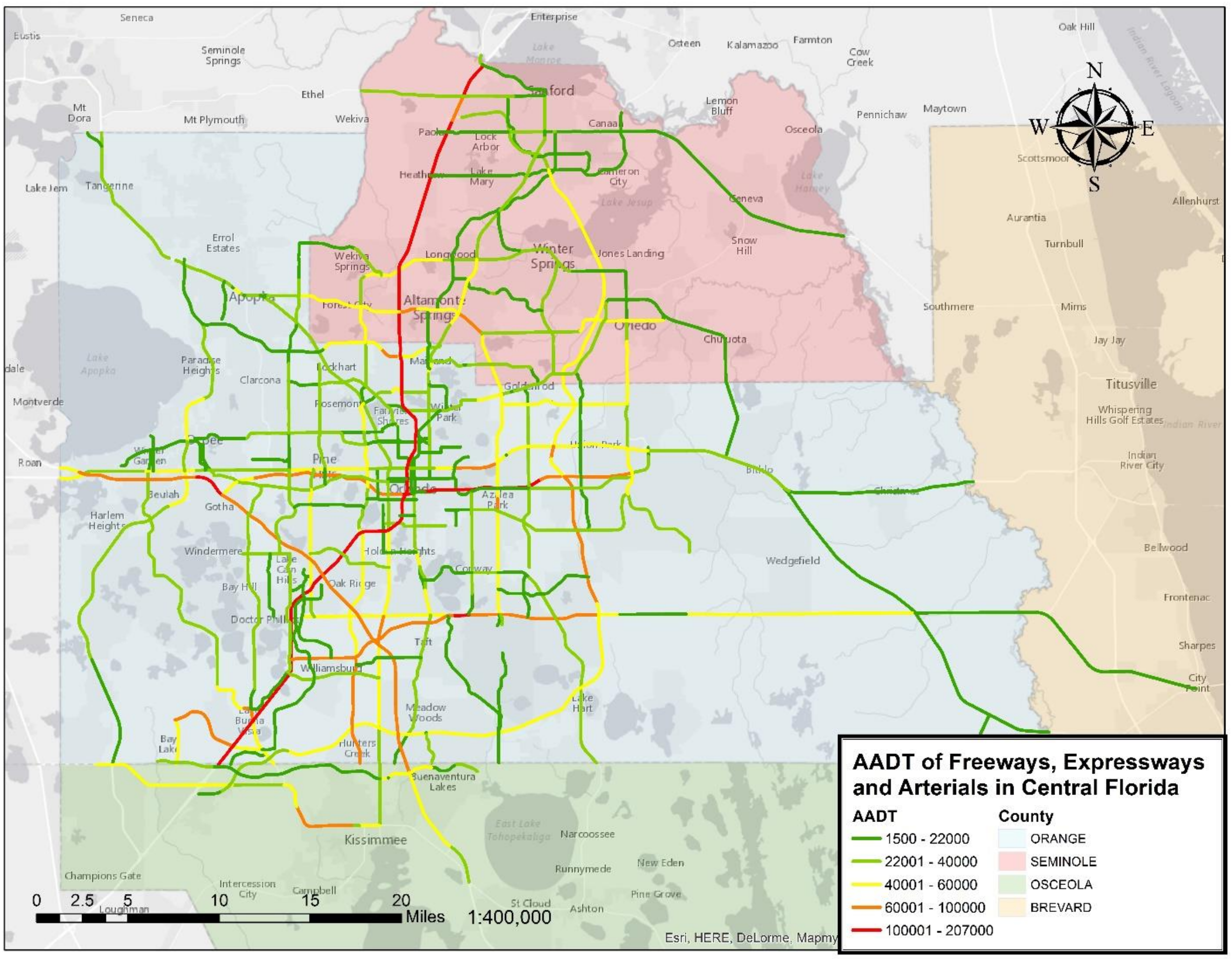


Figure 59. AADT information

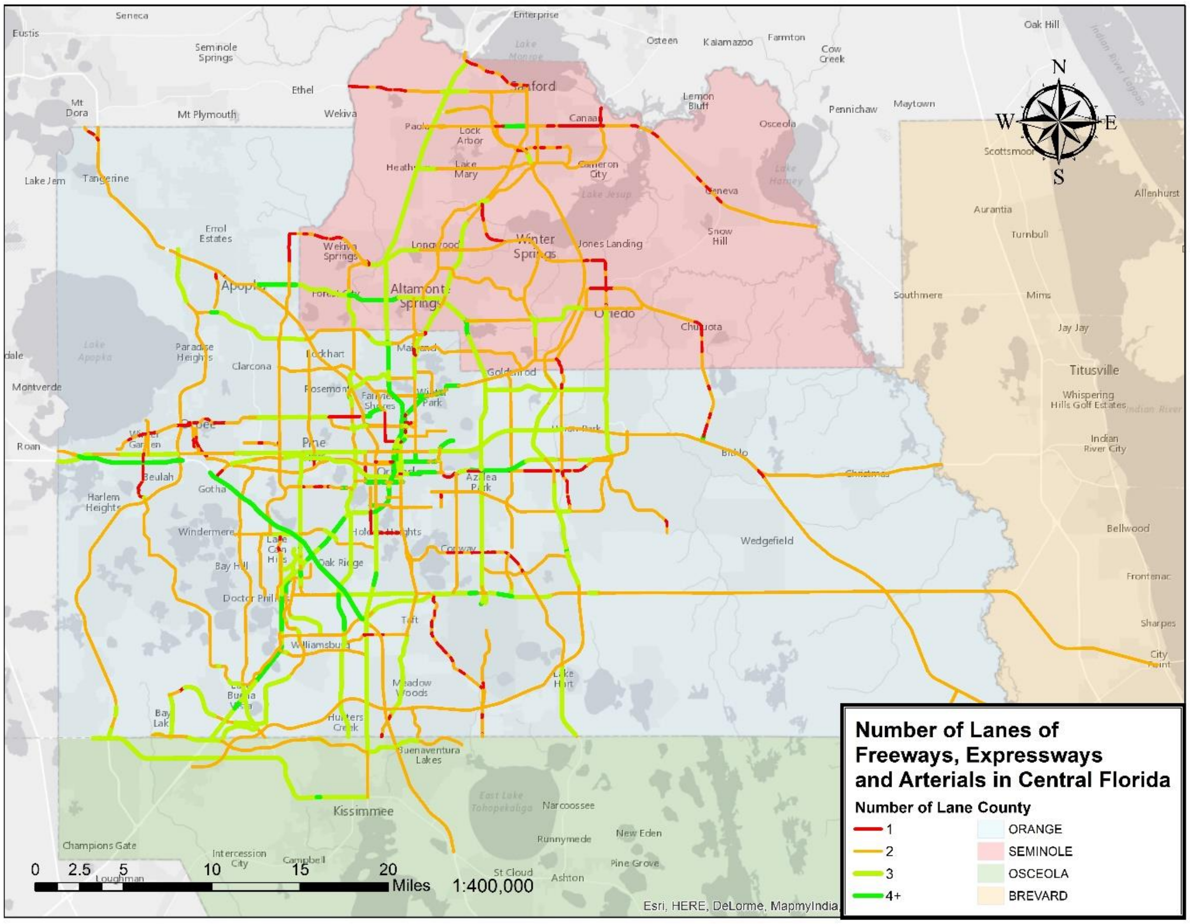


Figure 60. Number of lanes information

4.3. Summary

In summary, the Orlando Metropolitan Area is a favorable location to develop IATM strategies, since extensive data is available and we have the cooperation of the different local agencies and FDOT district 5. The research team will focus on the roadway networks including all limited-access freeways and expressways, the RoS, and most of the arterials in the Orlando Metropolitan Area.

CHAPTER 5. DATA COLLECTION FOR THE STUDY AREA

5.1. Overview

Traffic data plays an essential role in the development of the freeway/arterial IATM System. The research team has comprehensively reviewed the output data characteristics, operation mechanism, availability, and implementability of the infrastructure-based traffic data collection technologies, vehicle-based third party from vendors and crowd source platforms. The Orlando Metropolitan Area was selected as the study area to develop IATM strategies in this project, and the corresponding roadway networks have been determined.

In this chapter, the research team has devoted much effort and time to coordinate with all data collection agencies to collect all possible data in the study area. After combining all available data on our two high performance data server computers, the data availability was checked and summarized.

Section 5.2 comprehensively reviews the data collection technologies, including infrastructure-based traffic data collection technologies such as Microwave Vehicle Detection System (MVDS), the automatic vehicle identification (AVI) by toll tag reader and Bluetooth; vehicle-based data collection technologies such as HERE® and INRIX®; and crowd source data platform, etc. Section 3.3 introduces all the data collection agencies, such as Regional Integrated Transportation Information System (RITIS), Florida Turnpike Enterprise (FTE), and Orange and Seminole County's traffic engineering authorities.

Section 5.3 discusses the data availability in the study area. In particular, the availability of travel time and volume data on roadway network has been presented.

Although the opportunities that big data (e.g., large data size and multiple data sources) offer to improve traffic flow and safety are promising, there are still many difficulties to collect, handle, formulate and analyze big data. For instance, in order to collect the multiple datasets from a wide range of different sources, the research team has coordinated with various authorities and put much effort and time to contact and set the data collection arrangement up with each agency. In the following section, the detailed description of data collection authorities and the dataset provided by each authority are presented. Table 14 shows a summary of the information of different datasets from their collection agencies.

Table 14. Data collection source agencies

Agency	Type	Data Source
CFX	AVI(Toll Tag)	AVI
	MVDS	MVDS
RITIS	MVDS	MVDS
	Third Party	HERE
	Third Party	INRIX
Orange County	AVI(Bluetooth)	BlueMAC
	AVI(Bluetooth)	Iteris
	Traffic Count	InSync
	Signal Operation Log	InSync
Seminole County	AVI(Bluetooth)	BlueTOAD
Twitter	Crowd Sourced	

5.2. Data Collection Agencies

5.2.1. Regional Integrated Transportation Information System (RITIS)

Regional Integrated Transportation Information System (RITIS) is a traffic data sharing, dissemination, and archiving system maintained by the Center for Advanced Transportation Technology Laboratory (CATT Lab) at the University of Maryland. RITIS includes performance measure, dashboard, and visual analytics tools which could help agencies to gain situational awareness, measure performance, communicate information between agencies, and disseminate information to the public. There are three main RITIS component, i.e., real-time data feeds, real-time situational awareness tools, and archived data analysis tools (*22*).

RITIS has an online graphic user interface (GUI) for agencies to fully utilize the whole system. Data archived in RITIS includes both infrastructure based traffic data and data from third parties. The RITIS system is collaborated with many State DOTs (Department of Transportation), including FDOT, to collect real-time traffic data from detectors maintained by public agencies. Besides, the RITIS system is also collecting data from third party traffic data vendors: HERE®, INRIX® and TomTom® through the I-95 Corridor Coalition's Vehicle Probe Project (VPP). With the authorization from FDOT, RITIS staffs helped the research team to create several accounts to use the system.

The research team are currently retrieving two types of traffic data from RITIS: one is MVDS data collected by infrastructure based detectors, and the other is vehicle based traffic data from private sector, HERE®. Table 15 shows the characteristics of the traffic data retrieved from RITIS.

Table 15. Characteristics of the data retrieved from RITIS

Data Name	Data Type	Temporal Coverage	Spatial Coverage	Aggregation Level	Data Size Estimation
MVDS	Time Mean Speed	Varies for different roadways	All freeways and expressways	From 30 second to 1 minute	600 MB per 24 hours
	Volume				
	Occupancy				
HERE®	Space Mean Speed	October 2013 till now	All freeways and principal arterials and most of minor arterials	1 minute	280 MB per 24 hours

5.2.1.1. MVDS of RITIS

The MVDS data retrieved from the RITIS includes point-based aggregated traffic parameters such as time mean speed, volume and lane occupancy at one-minute interval (FTE) or 30-second interval (I-4). Traffic parameters are provided in two aggregation levels: lane-based (traffic parameters of one specific lane) and zone-based (traffic parameters of all lanes). A data quality indicator (coded as "0 (valid)" or "1 (invalid)") is also provided.

Table 16 provides the format of lane-based aggregated MVDS data and Table 17 shows the description of attributes. The only difference between lane-based aggregated and zone-based aggregated data is that zone-level data does not specify the lane_id and lane_nunber.

Table 16. An example of MVDS data collected from RITIS on I-4

zone_id	lane_number	lane_id	measurement_start	speed	volume	occupancy	quality
6096	1	24278	6/8/2017 0:00:10	51	4	2	0
6096	1	24278	6/8/2017 0:00:40	53	6	5	0
6096	1	24278	6/8/2017 0:01:10	56	2	1	0
6096	1	24278	6/8/2017 0:01:40	54	8	4	0

Table 17. Description of attributes

Variable	Description
zone_id	ID of MVDS Detector
lane_number	Lane Location ID. Largest is the shoulder lane.
lane_id	ID of Lane Detector
measurement_start	The start timestamp of measurement
speed	Time mean speed
volume	Volume
occupancy	Lane Occupancy
quality	Data quality indicator

The MVDS data reflects the traffic conditions at their installed locations (point-based). Thus, it cannot directly measure travel time information. To overcome this limitation, researchers had developed algorithms to estimate travel time based on point based such as speed-based estimation model (Li et al., 2006), cumulative plot based method (Bhaskar et al., 2010), regression model (Kwon et al., 2000) and artificial intelligence (van Lint and van Zuylen, 2006).

5.2.1.2. MVDS of HERE

HERE Data retrieved using "Probe Data Analytics Suite" tool includes a location information file and a data file with following attributes (RITIS, 2017):

- TMC (Traffic Message Channel) Code: 9-character codes that uniquely identify a specific directional segment of roadway. The definition of TMC is based on logical breaks in facilities where one would expect the potential for different traffic conditions, such as an interchange or major at grade intersection (Meese and Pu, 2011).
- Speed: One-minute aggregated space mean speed for the roadway segment in miles per hour
- Travel Time: Time it will take to drive along the roadway segment in minutes (Distance Traveled / Speed).
- Reference Speed: The calculated "free flow" mean speed for the roadway segment in miles per hour. This attribute is calculated based upon the 85th-percentile point of the observed speeds on the roadway segment for all time periods, which establishes a reliable proxy for the speed of traffic at free-flow for that segment.
- Confidence: A data quality indicator. A range between 0.7 and 1.0 (including 1.0) indicates real time speed data for that specific segment. A range between 0.5 and 0.7 (including 0.7) indicates historical speeds. A range between 0.0 and 0.5 (including 0.5) indicates speed limit.

Table 18 presents an example of the collected HERE data.

Table 18. An example of HERE data collected from RITIS

tmc_code	measurement_tstamp	speed	reference_speed	travel_time_minutes	confidence
102N10968	6/19/2017 0:00	21	24	0.05	0.7
102N21101	6/19/2017 0:00	20	20	0.04	0.7
102N50931	6/19/2017 0:00	25	25	0.05	0.7
102N50948	6/19/2017 0:00	29	22	0.07	0.7

5.2.1.3. MVDS of INRIX

INRIX® data can also be retrieved from "Probe Data Analytics Suite" tool. The data structure is similar to the HERE® except its data quality indicator. Table 19 shows the format of INRIX data.

Table 19. An example of INRIX data collected from RITIS

tmc_code	measurement_tstamp	speed	average_speed	reference_speed	travel_time_minutes	confidence_score	cvalue
102P04156	6/7/2017 0:00	67	67	67	0.93	30	67
102+04157	6/7/2017 0:00	65	65	65	0.28	30	72
102P04157	6/7/2017 0:00	66	66	66	0.47	30	65
102+04158	6/7/2017 0:00	66	65	65	0.33	30	80

The INRIX® data employed confidence score and c-value to indicate the data quality (RITIS, 2017):

- Confidence Score: There are three levels of confidence score:
  - 30: high confidence. Data are based on real-time data for that specific segment.
  - 20: medium confidence. Data are based on real-time data across multiple segments and/or based on a combination of expected and real-time data.
  - 10: lower confidence. Data are based primarily on historical data or road reference speeds.

- C-Value: The value indicates the probability that the current probe reading represents the actual roadway conditions based on recent and historic trends (0= low probability, 100 = high probability). This value is only used when the confidence score is 30.

5.2.2. Central Florida Expressway Authority (CFX)

Central Florida Expressway Authority (CFX) operates and maintains toll roadways, SR 408, SR 414, SR4- 417, SR 429, and SR 529, which connect Brevard, Lake, Orange, Osceola and Seminole counties. Until 2017, the CFX system includes 392 Microwave Vehicle Detectors, 163 AVI readers using RFID, and 49 DMSs in the study area (see Figure 61). The MVDS and AVI data for expressways managed by CFX have been obtained since 2013, and the DMS logs from 2013 to 2017 were collected to review traffic information provision strategies. Furthermore, toll transaction data were obtained to build daily origin and destination matrix on expressways.

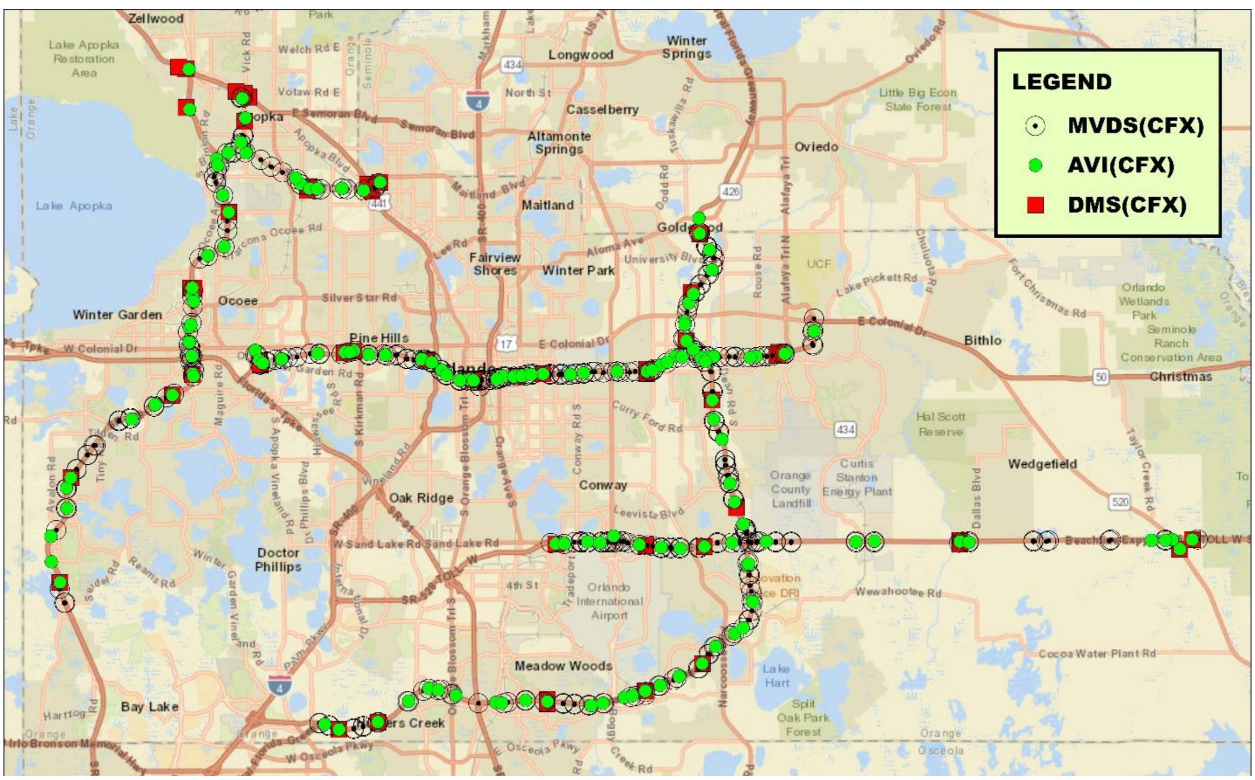


Figure 61. Local ITS devices on CFX expressway

5.2.2.1. MVDS of CFX

The MVDS of CFX is collecting traffic data of each lane (see Figure 62). The traffic data aggregated at one-minute interval were obtained from the CFX. The CFX is operating MVDS at 392 locations, which places on SR 408, SR 414, SR4- 417, SR 429, and SR 528 (See Table 20). The traffic data include lane type, volume, speed, occupancy, volume per vehicle types. The lane type is defined by four categories:

- Type 1: Mainline
- Type 2: Ramp
- Type 3: Mainline TP Express (Mainline toll plaza for vehicles equipped with tags)
- Type 4: Mainline TP Cash (Mainline toll plaza for vehicles without tags)

The vehicle types are classified according to vehicle length:

- Type 1: vehicle 0 to 10 feet in length
- Type 2: vehicles 10 to 24 feet in length
- Type 3: vehicles 24 to 54 feet in length
- Type 4: vehicles over 54 feet in length

Figure 62. Example of MVDS installation and lane type distinction

Table 20. MVDS on CFX expressway

Route	Length (Miles)	Direction	No. of MVDS detectors	Average distance between adjacent detectors		
				Mean	Min.	Max.
SR 408	22	EB	62	0.38	0.1	1
		NB	1	n/a	n/a	n/a
		WB	61	0.39	0.1	1
SR 414	9	EB	14	0.44	0.2	0.7
		WB	14	0.46	0.1	0.9
SR4-417	55	NB	57	0.58	0.2	1.3
		SB	56	0.58	0.2	1.2
SR 429	23	NB	30	0.66	0.2	2.8
		SB	29	0.70	0.1	3.1
SR 451	1.9	NB	3	0.85	0.3	1.4
		SB	4	0.85	0.3	1.4
SR 528	41	EB	29	0.84	0.1	3
		WB	32	0.84	0.1	3.1

The collected MVDS data have been processed according to the following procedures:

- Removal of abnormal data
- Calculation of 5-minutes average speed
- Calculation of congestion index (CI)

$$CI = \frac{\text{free flow speed} - \text{actual speed}}{\text{free flow speed}} \; when\; CI > 0; = 0 \; when\; CI \leq 0$$

- Calculation of 5-minutes average occupancy
- Calculation of 5-minutes, hourly, and daily volume

With the processed MVDS data, it is able to understand overall and detailed traffic conditions on expressways. For example, the spatial and temporal visualizations based on the calculated congestion index (CI) (using data of March 2017) indicate that SR 408 is the most congested roadway among expressways under CFX whereas SR 429 does not have any congestion. The examples of CI spatial and temporal visualization for five major expressways in Central Florida are presented in Figures 63 to 67.

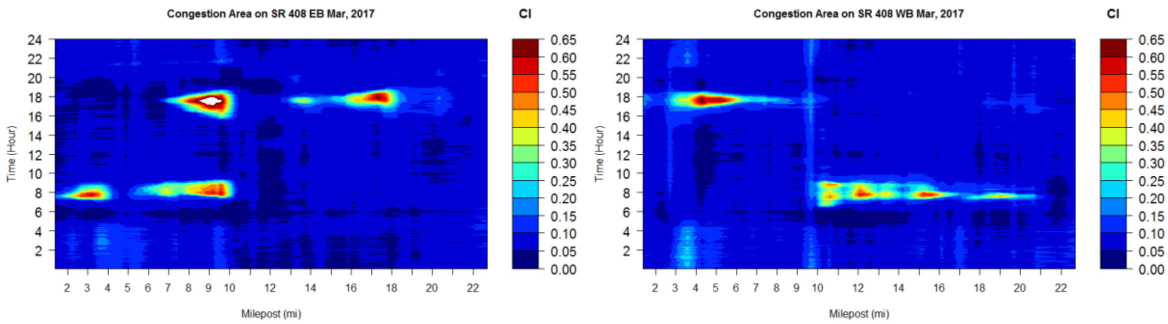


Figure 63. CI in space-time on SR-408 in March 2017

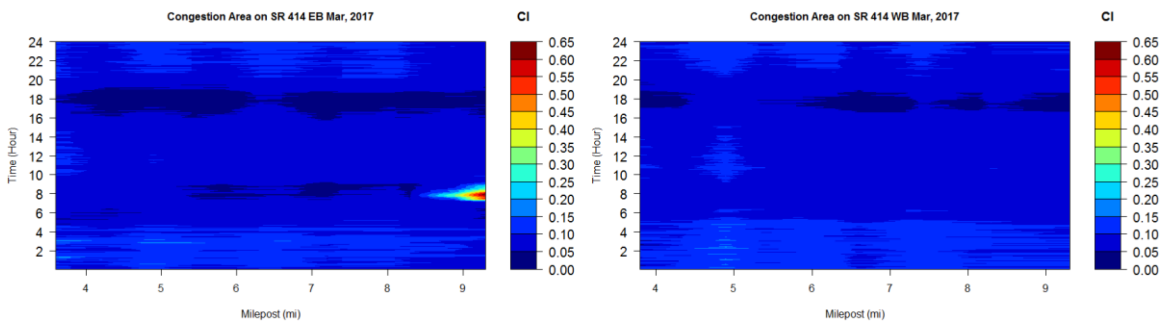


Figure 64. CI in space-time on SR-414 in March 2017

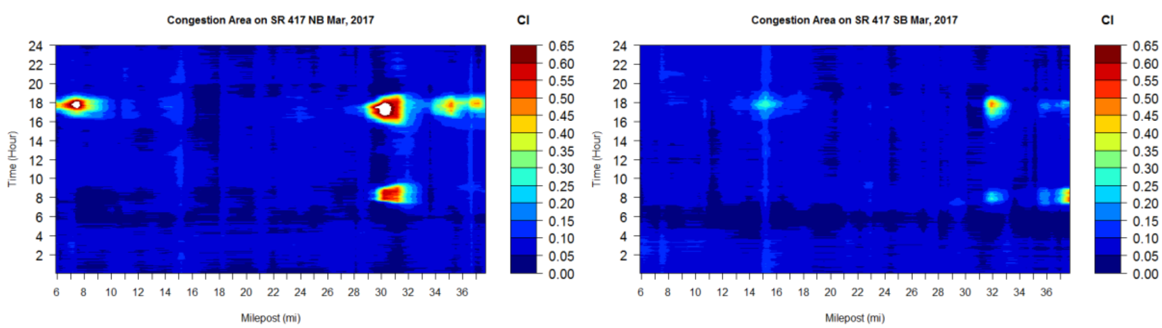


Figure 65. CI in space-time on SR-417 in March 2017

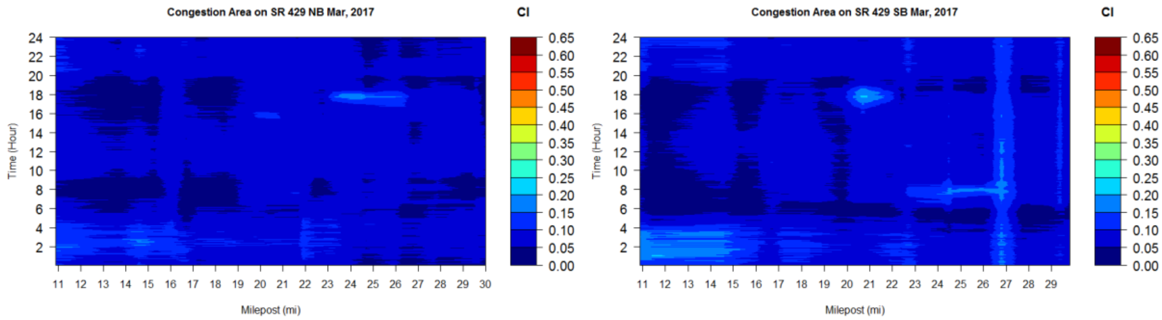


Figure 66. CI in space-time on SR-429 in March 2017

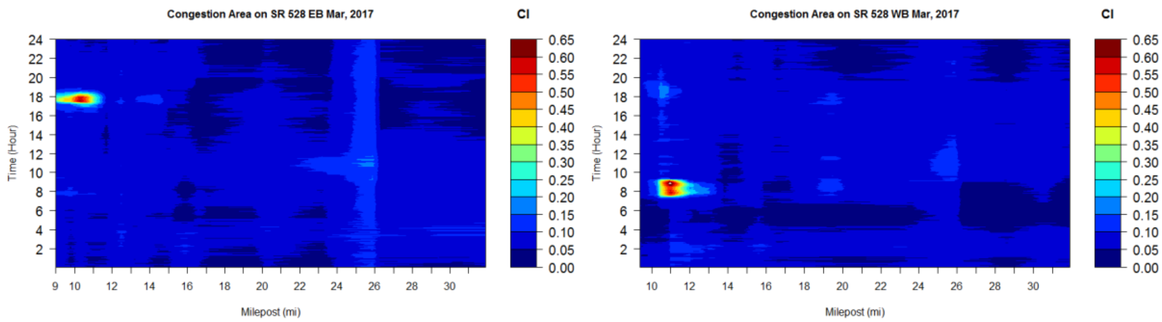


Figure 67. CI in space-time on SR-528 in March 2017

5.2.2.2. AVI of CFX

Since the MVDS has drawbacks to underestimate travel time due to its characteristic using time mean speed instead of space mean speed (Martí, 2016), it is important to use AVI data to analyze and validate travel time reliability on expressways. While the capped AVI data could have an underestimate issue on travel time estimation, the raw AVI data is not capped to the speed limit and it can be used to estimate buffer index (BI), travel time index (TTI), and Planning Time Index (PTI) (Abdel-Aty et al., 2014b). For this reason, we have collected and processed raw AVI data (i.e., individual vehicle level data) from the CFX.

The AVI readers of CFX are installed at interchanges, system boundaries, and DMS (see Figure 68). Tag data collected by AVI readers are processed to estimate reliable travel time based on the predefined 180 AVI segments (see Table 21). The estimated real-time travel time information is provided for drivers through DMS (41 locations in total) and FDOT's 511 traveler information service.

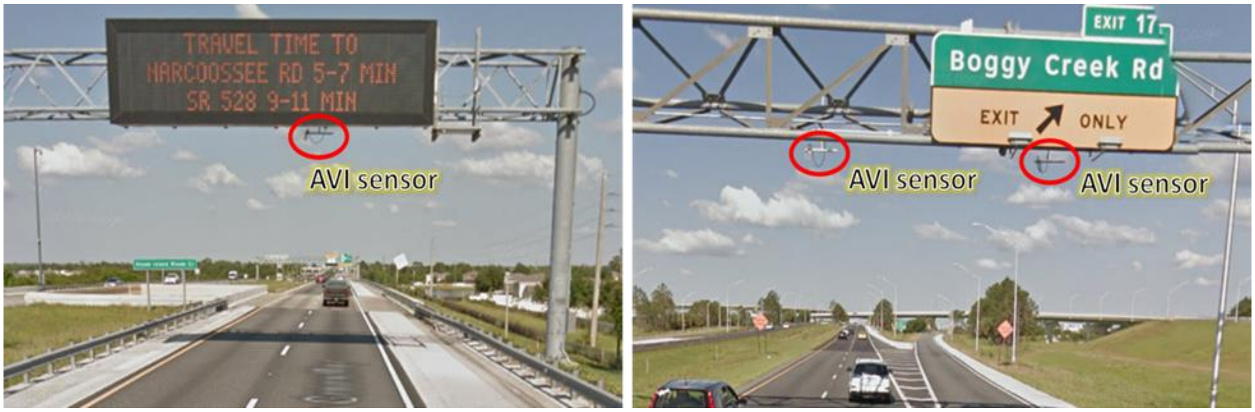


Figure 68. AVI installation locations

Table 21. CFX's expressways covered by AVI readers

Route ID	Direction	No. of AVI sensors	No. of Segments	Segment Length		
				Mean	Min.	Max.
SR 408	EB	27	28	0.947	0.199	2.475
	WB	24	27	1.249	0.393	3.981
SR 414	EB	6	7	2.212	0.350	4.500
	WB	5	6	1.150	0.293	2.022
SR4- 417	NB	20	23	1.787	0.313	4.619
	SB	25	28	1.492	0.304	5.219
SR 429	NB	15	16	1.675	0.573	4.271
	SB	15	16	1.727	0.198	4.143
SR 451	NB	2	1	0.9	0.9	0.9
	SB	3	4	1.029	0.647	1.903
SR 528	EB	10	10	2.553	0.329	7.058
	WB	10	13	3.192	0.859	13.833
SR 520	WB	1	1	8.024	8.024	8.024
Total		163	180	n/a	n/a	n/a

As shown in Table 20, AVI readers on CFX are installed closely (about 1 or 2 miles). Hence, compared with FDOT's AVI system, the CFX's AVI could provide (Haas et al., 2009):

- More accurate estimates of the average travel time

- More timely travel time estimates
- Resilience in case of a detector failure
- Potential for incident detection

In order to handle the raw AVI data, application of filtering methods is required. Figure 69 presents the travel time estimation algorithm developed by the CFX. The collected raw AVI data without duplicated tags have been matched to estimate travel time on the basis of segments made by AVI readers. The abnormal estimated travel times can be filtered based on the following logics:

(1) 1.5 * IQR (Interquartile Range)

(2) M ± 3 * MAD (Median Absolute Deviation)

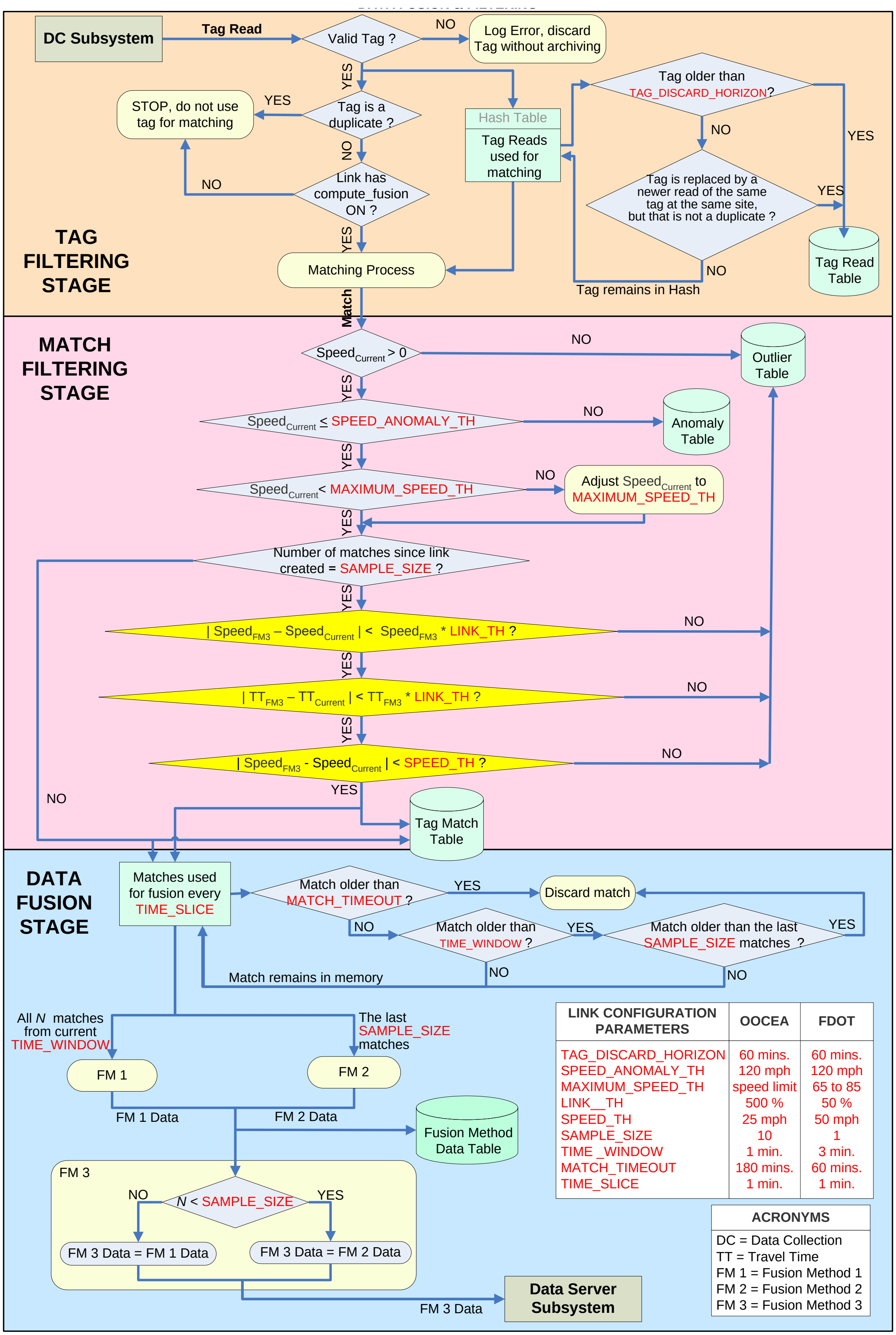


Figure 69. Example of filtering approaches for AVI data

The filtering algorithms based on IQR and MAD values are well-accepted methods to derive reliable travel time from the archived time-series datasets (Dion and Rakha, 2001; Pirc et al., 2014; Tam and Lam, 2008). Figure 70 shows an example of applying two filtering approaches based on IQR and MAD values.

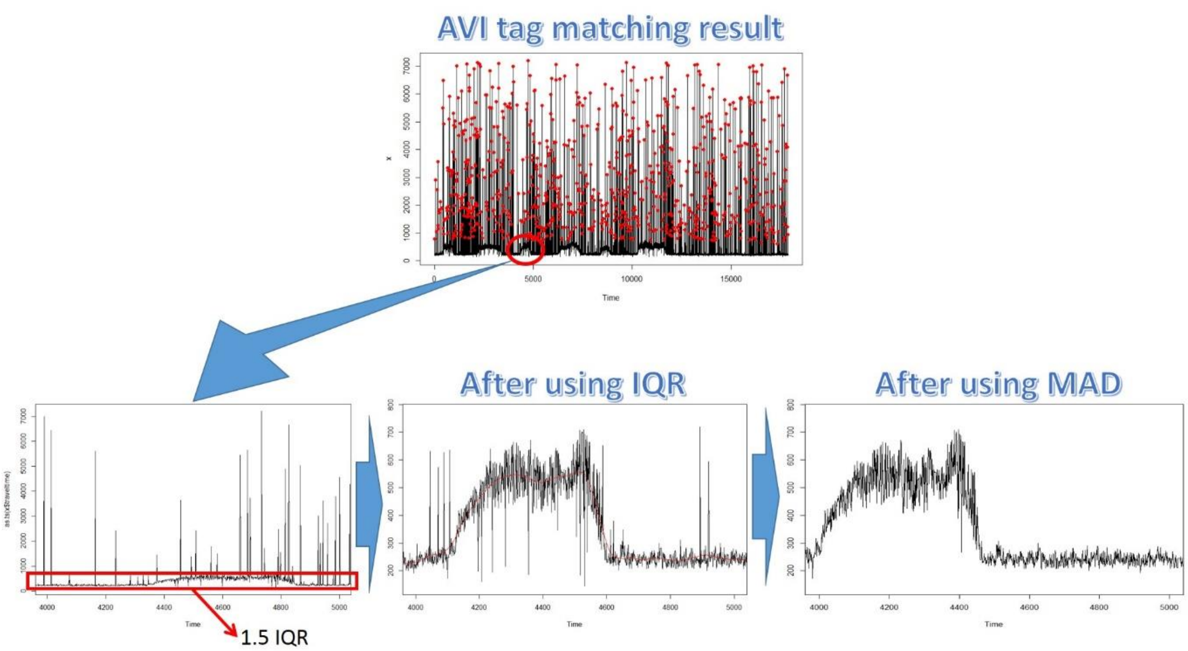


Figure 70. An example of filtering AVI data

5.2.2.3. DMS of CFX

CFX installed DMSs on the mainline of expressways and on arterials at the entrance of two expressways, i.e., SR 429 and SR 451 (see Figure 71). The CFX is logging DMS message every one second and the most of information are related to travel time, incident management, construction or maintenance activities, weather condition, etc. (see Table 22). Based on the DMS message logs, it is possible to analyze the traffic management strategies and the coordination status among agencies conducting the traffic management strategies.

(a) DMS on the mainline **(b) DMS on arterials at the entrance of an expressway**

Figure 71. DMS types of CFX

Table 22. Message types and ratio of DMS messages

Message type	Display frequency (one-second interval)	Ratio (%)	Relevant Keywords
Travel time	844,628	70.5%	Travel time
LEO Alerts	234,857	19.6%	Vehicle tracking
Incident management	76,485	6.4%	Crash, incident, debris, closed, blocked, alternate, detour
Construction or maintenance activities	35,151	2.9%	Road work
Weather condition	7,134	0.6%	Smoke, fog
Total	1,198,255	100%	
※ This aggregation is based on DMS message logs of SR4- 417 from January to April 2017			

Toll transaction data during August and September 2017 were obtained from CFX. The transaction data can be used to validate volume, speed, and travel time. Furthermore, it is possible to develop algorithms to estimate daily, hourly, and real-time origin-destination matrix. Currently, CFX is operating 87 toll plazas on mainline and on/off ramps (see Figure 72). On average, more than 27 million vehicles in a week were using the CFX expressway. As shown in Figure 73, CFX's daily toll transaction has an obvious weekly pattern. Notably, there was no detection during the period of hurricane Matthew in October 2016 since all CFX expressways were free.

According to daily toll transaction statistics on mainline plazas (see Table 23), mainline plazas on SR 408 and SR4- 417 have many toll transactions.

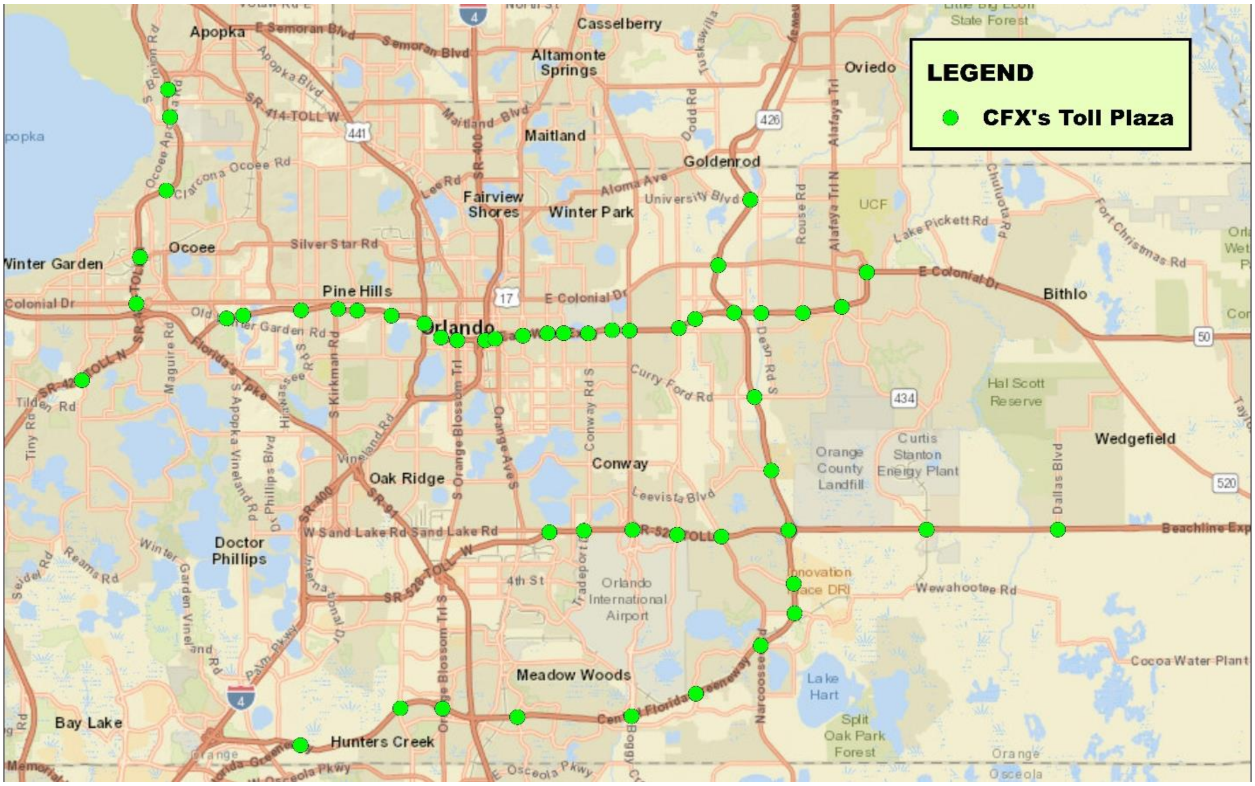


Figure 72. CFX's toll transaction locations

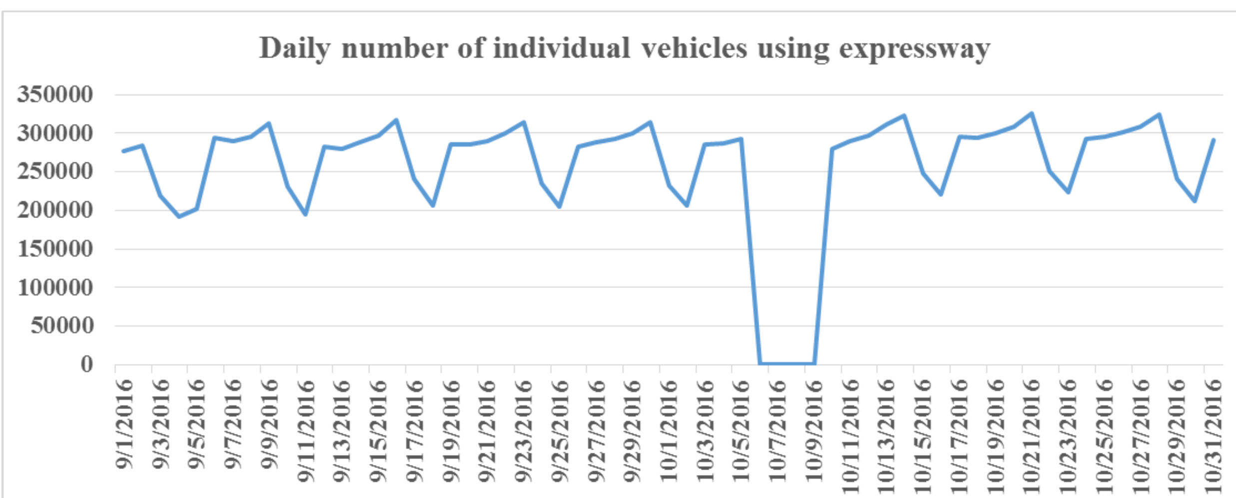


Figure 73. Daily number of individual vehicles using expressway

Table 23. Daily toll transaction statistics on mainline plazas of CFX

Mainline plaza name	Daily total transaction				Count
	Mean	Standard deviation	Minimum	Maximum	
Conway	115,224	8,807	65,840	123,004	41
Curry Ford	82,784	6,431	48,964	90,481	41
University	80,652	6,923	46,586	89,389	41
Pine Hills	73,342	6,155	39,028	78,744	41
Dean	66,095	5,142	37,265	71,304	41
Hiawassee	62,161	5,182	34,150	67,578	41
Boggy Creek	52,873	4,427	39,677	62,647	41
John Young	49,358	4,869	41,887	62,344	41
Beachline	46,846	5,021	27,182	54,871	41
Forest Lake	44,416	3,863	24,370	48,908	41
Dallas	35,164	3,731	20,850	41,891	41
Coral Hills	27,580	2,690	12,610	30,082	41
Independence	26,820	2,625	18,796	33,002	41
Goldenrod	9,177	690	5,357	10,061	41

5.2.3. Florida Turnpike Enterprise (FTE)

Florida Turnpike Enterprise (FTE) operates and maintains toll roadways including Florida's Turnpike, Part C of Daniel Webster Western Beltway on SR 429, Beachline West Expressway on SR 528, Seminole Expressway on SR4- 417, and Southern Connector Extension on SR4- 417 in the project scope (see Figure 74). In 2017, 276 MVDS, 51 AVI readers using RFID, 12 AVI readers using Bluetooth®, and 17 DMSs have been installed on Florida's Turnpike system in the study area (see Figure 74). Locations of MVDS, and AVI were identified through RITIS system. Latest information about Bluetooth® system of FTE was obtained directly from FTE.

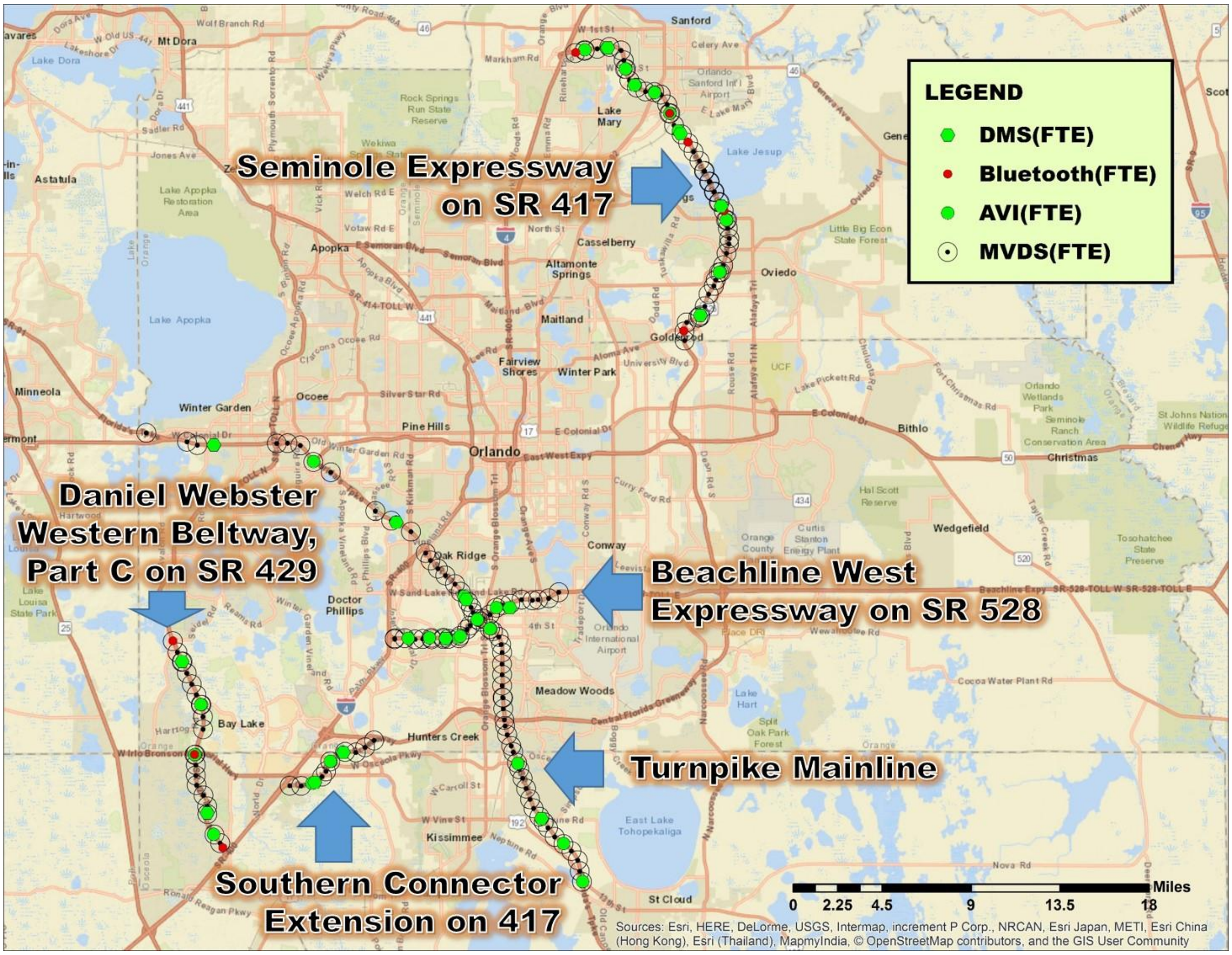


Figure 74. Local ITS devices on the turnpike mainline and expressways of FTE

5.2.4. Orange County

Orange County Traffic Engineering is a division of Public Works Department of Orange County Government. It is responsible for the planning, design, construction, and maintenance of traffic control systems and ITS devices of Orange County of Florida. Currently, it provides the research team with traffic signal operation plans, operation logs of adaptive signal control system InSync® and traffic data from Bluetooth detection system including BlueMAC and Iteris® Vantage Velocity®. Table 24 shows the characteristics of the traffic data collected from Orange County Traffic Engineering.

Table 24. Characteristics of the data collected from Orange county traffic engineering

Data Name	Data Type	Temporal Coverage	Spatial Coverage	Aggregation Level	Data Size Estimation
InSync®	Signal Logs (Phase combination, phase duration, the maximum waiting time, queue length)	March 2017 till now	6 corridors (SR 434, Lake Underhill Rd, US 17/92/441, SR 535, SR 536 and University Blvd)	Phase	2.2 GB per month
	Volume			15 minute	
Iteris® Vantage Velocity®	Space Mean Speed and Travel Time	2015 till now	4 corridors (US 17/92/441, SR 535 and SR 536)	Individual Vehicle (Filtered)	185 MB per month
BlueMAC	Space Mean Speed and Travel Time	March 2017 till now	4 corridors (SR 434, Lake Underhill Rd, SR 426 and University Blvd)	Raw detection (Lower than Individual Vehicle)	4.1 GB

Due to the information security concern, Orange County Traffic Engineering could not provide direct access to their data archiving systems through Internet. Instead, the research team drive to Orange County Traffic Engineering offices monthly to get hard copies of the latest data with the help from Orange County traffic engineers.

5.2.4.1. BlueMAC data of Orange County

The BlueMAC data collected from Orange County Traffic includes three types of information:

- Raw detection log (truncated MAC Address, timestamp, location identifier and RSSI).
- One-hour detection statistics (Number of detections and number of unique devices).

- Travel time of individual vehicles by matching any two BlueMAC detectors and aggregated travel time etc. The BlueMAC system provides both segment level travel time and route level travel time.

The travel time of an individual vehicle can be calculated by matching spatial-temporal information with same MAC address from two Bluetooth detectors. However, there is a multiple detection issue (i.e., same MAC address is detected multiple times) from the individual vehicle BlueMAC data.

5.2.4.2. Iteris® Vantage Velocity® of Orange County

The Iteris® Vantage Velocity® data collected from Orange County Traffic Engineering includes travel time of individual vehicles by matching closest two detectors (segment travel time), aggregated travel time information, and other statistics. The Iteris® Vantage Velocity® system is not able to provide raw detection log. Table 25 provides the format of Iteris® Vantage Velocity individual vehicle data.

- Probe ID: Encrypted MAC Address
- Origin/Destination ID: Intersection (Detector IDs)

Table 25. An example of Iteris® vantage velocity

Probe ID	Origin ID	Destination ID	Start Time	End Time	Travel Time	Speed	Validity Check	Filter ID
efd9255aae00386857cad83635554ac6	OBT/Sand_Lake	OBT/Oakridge	2/25/2017 23:56	2/25/2017 23:59	167	34	valid	45
6a9dccaa18040f6ebc5a8f4d16be7e4f	535/Hotel_Plaza	535/I_4	2/25/2017 23:57	2/25/2017 23:59	150	13	valid	45
0c687659a067393e89c84f9b8ce51467	535/Hotel_Plaza	535/I_4	2/25/2017 23:57	2/25/2017 23:59	118	17	valid	45
595ef1d6fe52c684a6ddfd3e2bf3c2b5	OBT/Southland	OBT/Lancaster	2/25/2017 23:58	2/25/2017 23:59	62	39	valid	45

5.2.4.3. InSync® Vantage Velocity® of Orange County

InSync® is an adaptive traffic control signal system deployed at 6 corridors (SR 434, Lake Underhill Road, US 17/92/441, SR 535, SR 536 and University Boulevard) in Orange County. The research team is currently collecting traffic volume and signal operation logs information from this system. Traffic count data from the InSync® is 15-minute aggregated volume for each signal operation phase and each direction. The InSync® is able to distinguish the volume of protected left turn traffic and through traffic but not for the volume of permissive left turn traffic and right turn traffic.

5.2.5. Seminole County

Traffic Engineering Division of Seminole County Public Works Department (Refers as "Seminole County Traffic Engineering" in this report) is a division of Seminole County Government which provides similar public service as Orange County Traffic Engineering. Similarly, Seminole County Traffic Engineering provides the research team with Automated Traffic Signal Performance Metrics (ATSPM) data and travel time from BlueTOAD, one of Bluetooth detection systems. Table 26 shows the characteristics of the traffic data collected from Seminole County Traffic Engineering.

Table 26. Characteristics of the data collected from Seminole county traffic engineering

Data Name	Data Type	Temporal Coverage	Spatial Coverage	Aggregation Level	Data Size Estimation
ATSPM	Signal Operation Logs	April-June, 2017	Almost all signalized intersections of Seminole County	Phase	Around 125 GB per month
	Volume			Individual Vehicle Count	
	Pedestrian Events			Individual Pedestrian	
BlueTOAD	Space Mean Speed and Travel Time	Since 2014	I-4, principal arterials and most of minor arterials	Individual Vehicle (Filtered)	350 MB per month

5.2.5.1. BlueTOAD of Seminole County

The travel time data from BlueTOAD system are retrieved from BlueARGUSTM system, the online platform of BlueTOAD system for data reporting and roadway system performance measuring. With the authorization from FDOT, traffic engineers from Seminole County helped the research team to create a standard user account exclusively for querying and downloading travel time data. The research team are routinely downloading data from BlueARGUSTM system. However, the system is not stable and sometimes travel time data are unavailable for several roadways. Data retrieved from the BlueARGUS™ includes filtered segment travel time of individual vehicles and aggregated segment travel time, and other statistics. The BlueARGUS™ does not provide able to the raw detection log.

Most of BlueTOAD® detectors in Seminole County are installed close to intersections. However, there are some detectors installed in the middle of segments (i.e., between two intersections). Figure 75 shows the interaction "pairs" map in the BlueARGUS™. The travel time information from the BlueARGUS™ system can be retrieved only for these "pairs" and the intersection "pairs" defined by Seminole County Traffic Engineering are fixed. In the BlueARGUS™ system, the travel time information is filtered before being provided to users. The BlueARGUS™ employed the filtering algorithm based on the minimum and maximum speed to remove any abnormal data.

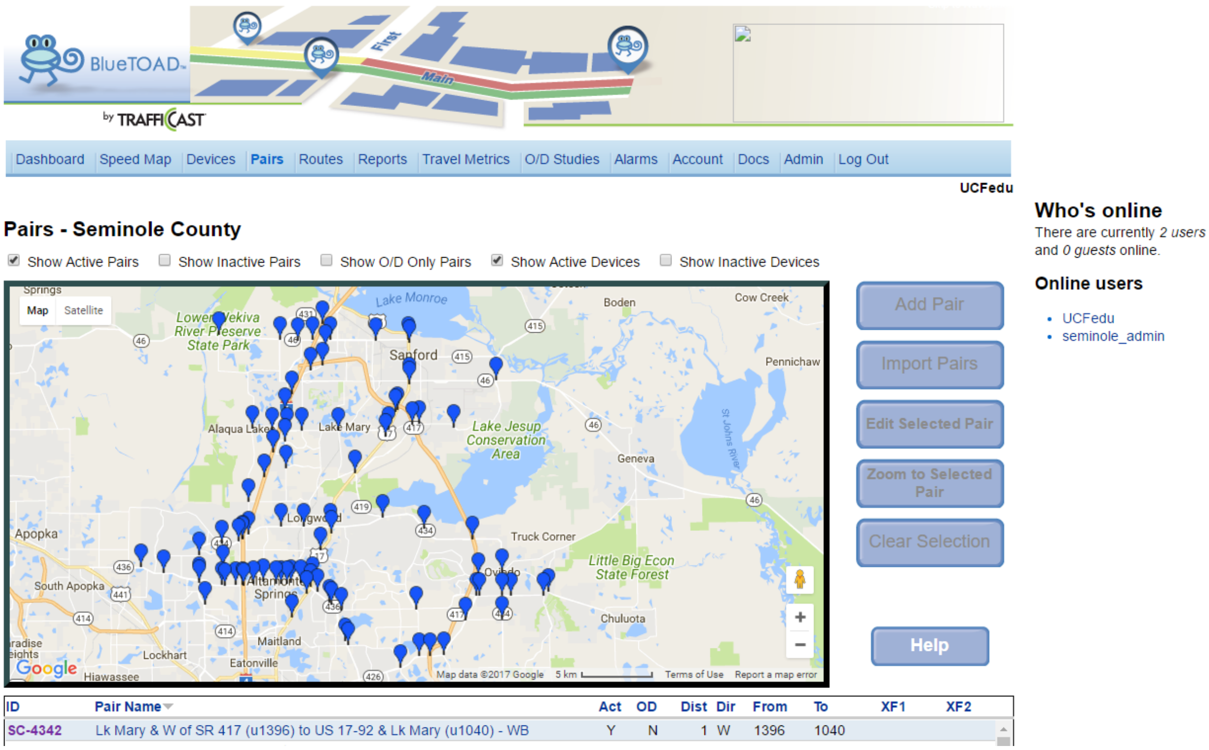


Figure 75. Pairs map in BlueARGUS™

5.2.5.2. ATSPM of Seminole County

From April, 2017 to June, 2017, traffic engineers from Seminole County routinely backed up the ATSPM database and MOE database, and uploaded to the County's ftp service for downing. The schema of MOE database is showed in Figure 76.

The research team are keeping downloading the backup files and restoring the database. Due to the extremely large size of the database, the database is deleted and the backup file will be saved for future study after we check the data integrity. After July, 2017, the MOE database is provided by District 5 Office of FDOT instead of Seminole County.

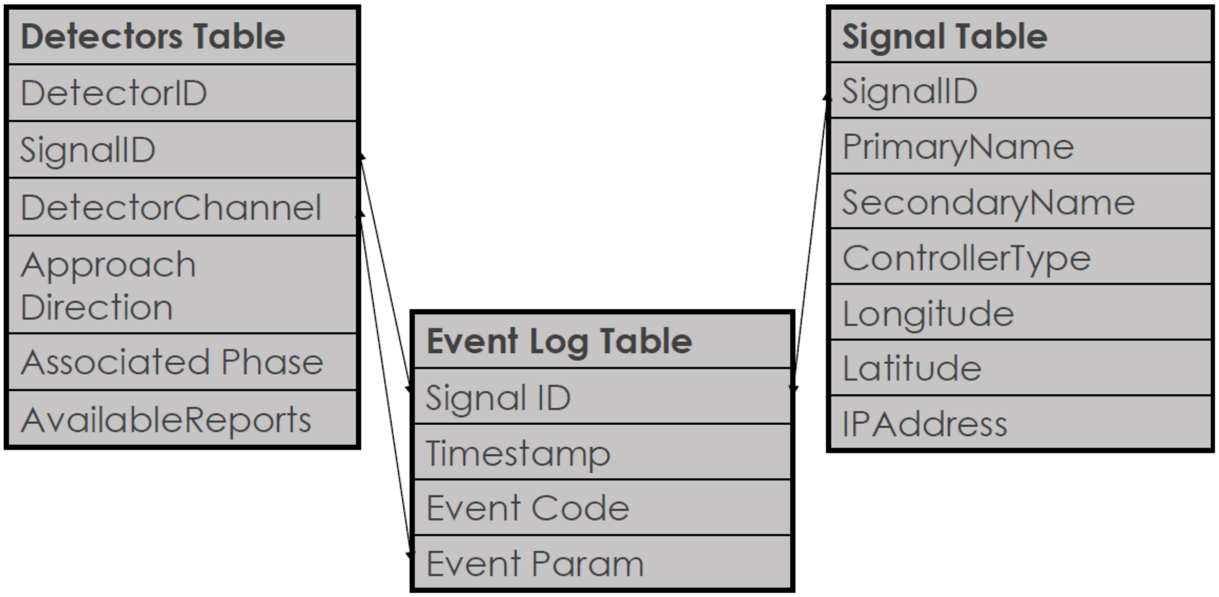


Figure 76. Data schema of MOE database

5.2.6. District 5

District 5 Office of FDOT is currently providing the research team with the backup files of the database of their SunGuide software and the backup files of the MOE database of Seminole County.

SunGuide software is an advanced traffic management system (ATMS) software that is used at all regional traffic management centers (RTMCs) in Florida. SunGuide software offers a comprehensive set of tools to the traffic management centers (TMCs) including managing Intelligent Transportation Systems (ITS) devices, automated incident detection and assisting with event management (*23*). Staffs from District 5 Office of FDOT helped the research team to set up a workstation computer which could connect to District 5's network. Every Sunday, the database of SunGuide software is backed up and restored to the workstation computer. In addition, the MOE database of Seminole County is provided since July, 2017.

SunGuide database is a large database with 330 tables whose size is 450 GB per update (per week). In the current stage of this project, only data from the transportation sensor (TSS) subsystem and the dynamic message sign (DMS) subsystem of SunGuide are utilized. The TSS subsystem is archiving data from all transportation sensors maintained and operated by FDOT district 5, including MVDS data and BlueMAC data. The DMS subsystem is providing the log of the messages showed in the DMSs on I-4 and arterials. Table 27 shows the characteristics of the traffic data collected from the subsystems.

Table 27. Characteristics of the data collected from SunGuide database

Data Name	Data Type	Temporal Coverage	Spatial Coverage	Aggregation Level	Data Size Estimation
TSS-MVDS	Time mean speed	Since July, 2017	Interstate 4, SR 528 in Brevard County,	Lane-poll data: 30 second Roll-up data: 15 minute	450 GB per update (per week)
	Volume				
	Occupancy				
TSS-BlueMAC	Space mean speed and travel time	Since July, 2017	Principal arterials in Orange County	Lane-poll data: 30 second Roll-up data: 15 minute Tag Reads: First detection of individual vehicle	
DMS	Messages from DMSs	Since January, 2015	I-4 and principal arterials	Individual Message	

The research team downloads the backup files and restore the database every week. Due to the extremely large size of the database, the database is deleted and the backup file is kept for future study after checking the data integrity.

5.2.7. Twitter

Among the other social media based information sharing platforms (e.g., Facebook, Flickr, Instagram etc.) Twitter is a potential data source as it is collectable through simple web scripts and has a wide range of information within each post (tweets). It is one of the attribute of twitter data set which made it alluring for researchers in multiple fields including social science, computer science, transportation science and so on (Hasan and Ukkusuri, 2015). Twitter provides a set of authentication keys which provides an OAuth (Open Authorization) which is an open standard for token-based authentication and authorization to collect tweets data. Through a set of unique OAuth keys one can use the Twitter REST API and Stream API to web scrap from twitter web pages. The REST API provides programmatic access to read and write Twitter data, i.e. create a new Tweet, read user profile and follower data etc. and Streaming API continuously delivers new responses to REST API queries over a long-lived HTTP connection receiving updates on the latest Tweets matching a search query, stay in sync with user profile updates etc. (Twitter, 2017). These developer keys are free provided a certain query limits for specific types of search requests (Twitter, 2017). In brief, with valid OAuth keys one can search for tweets containing certain key words and/or a group of key words, can search for tweets from certain user accounts, search specific tweets within a selected geographical boundary box etc.

Using Twitter search API, tweets data have been collected for specific user accounts. For collecting user specific tweets there is a limitation which imparts that an API request can collect only the latest 3200 tweets of any user account. Hence, if a user account has more than 3200 tweets only the last 3200 can be collected. Although for a more active account if we search the tweets in every two to three weeks we can get most of the latest tweets posted by that account. A sample code written in Python language is attached in the Appendix.

We have been collecting data at regular interval starting from 24 February to June 12 of 2017 for 13 FDOT maintained Twitter accounts and one traffic incident related account (WazeTrafficOrl) These users are carefully selected which include some of the most active FDOT accounts and traffic information provider of Central Florida region. Table 28 shows collected number of tweets using different user accounts.

Table 28. Tweet data collected until June 12, 2017

No.	User Name	Total Unique Tweets	Created at
1	@FL_511_I4	6,862	1/12/2012 14:48
2	@FL511_95EXPRESS	4,742	1/24/2017 19:51
3	@FL511_CENTRAL	11,069	10/6/2010 16:54
4	@FL511_I10	4,640	10/6/2010 17:30
5	@FL511_I75	4,206	10/6/2010 17:33
6	@FL511_I95	4,690	10/6/2010 17:37
7	@FL511_NORTHEAST	4,952	10/7/2010 12:38
8	@FL511_PANHANDL	4,121	1/12/2012 14:20
9	@FL511_SOUTHEAST	6,454	5/10/2017 1:42
10	@FL511_SOUTHWEST	3,572	10/6/2010 17:15
11	@FL511_STATE	6,444	10/7/2010 12:57
12	@FL511_TAMPABAY	4,441	10/6/2010 17:01
13	@FL511_TURNPIKE	3,726	10/6/2010 17:23
14	@WazeTrafficOrl	3,245	4/3/2017 16:07
		73,164	

As seen from Table 27, the total tweets collected from all the user accounts mentioned is 73164. Each tweet contains a series of useful information about that account and its activity. For instance, each tweet has a unique tweet id, the date and time it was posted, the text (the main body of a tweet), whether that tweet has been re-tweeted or not, the number of times that tweet has been re-tweeted, and user description etc. A sample tweet from @FL511_I75 account contains:

tweet id: ‘874500692173623000’

tweet date: ‘6/13/2017 5:36:27 AM’

text: ‘b'Updated: Planned construction in Columbia on I-75 south at US-90, 2 left lanes blocked’

user created at: ‘10/6/2010 5:33:57 PM’, etc.

Within the user description, we can find the user’s total follower count, total friends count etc. Table 29 contains the description of the 14 user accounts of Table 27 extracted from twitter using the search API.

Table 29. User description

User Name	User Description
@FL_511_I4	traffic info for I-4 provided by @MyFDOT #Florida #Tampa #Lakeland #LakeBuenaVista #Orlando #LakeMary #Daytona
@FL511_95EXPRESS	traffic info for I-95 express lanes provided by @MyFDOT. #Florida #FortLauderdale #Miami
@FL511_CENTRAL	traffic info for Central Florida provided by @MyFDOT. #Orlando #Daytona #SpaceCoast #Kissimmee #Ocala #Brevard
@FL511_I10	traffic info for I-10 provided by @MyFDOT. #Florida #Jacksonville #Tallahassee #Pensacola #LakeCity #Crestview
@FL511_I75	traffic info for I-75 provided by @MyFDOT. #Florida #Gainesville #Ocala #Tampa #Sarasota #FortMyers #LakeCity
@FL511_I95	traffic info for I-95 provided by @MyFDOT. #Florida #Jacksonville #DaytonaBeach #FortLauderdale #Miami
@FL511_NORTHEAST	traffic info for Northeast Florida provided by @MyFDOT.#Jax #StAugustine #Gainesville #StJohns #LakeCity
@FL511_PANHANDL	traffic info for the Panhandle provided by @MyFDOT. #Tallahassee #Pensacola #PanamaCity #Destin #Crestview
@FL511_SOUTHEAST	traffic info for Southeast Florida provided by @MyFDOT. #SEFL #Miami #FtLauderdale #Broward #PalmBeach
@FL511_SOUTHWEST	traffic info for Southwest Florida provided by @MyFDOT.#Naples #FtMyers #CapeCoral #Sarasota #SWFL
@FL511_STATE	traffic reports from @myfdot. #Tampa #Orlando #Miami For information in Spanish check @FL511_Estatal
@FL511_TAMPABAY	traffic info provided by @MyFDOT. #Tampa #Hillsborough #Pinellas #Pasco #Lakeland #Polk #SRQ
@FL511_TURNPIKE	traffic info for Florida's Turnpike Mainline provided by @MyFDOT. #Miami #FortLauderdale #Orlando #PortStLucie
@WazeTrafficOrl	Official @Waze account. First to report unusual traffic in #Orlando. Broadcast w/credit to Waze. Partnership requests: Broadcasters@waze.com

During data collection, it is standard to collect all the available information or extract the tweet data in raw format. Twitter data is provided in json format where each piece of information can be called by its 'key'. The data set can also be stored in other formats i.e. '.text', '.csv' etc. A single tweet contains a series of valuable information. Figure 77 shows a glimpse of all the possible information that can be collected from Twitter data. However, in analysis all the information is not required at a time and therefore working with a big data file is unnecessary and sometimes impossible. Before diving into a specific study, one has to extract the useful information from the raw tweets and store them in different files. A sample python script is attached in Appendix C and D which reads the tweet text, user name, date of the tweet posted, date on which the account was created and the tweet coordinates (if provided) from a csv file and writes them in a separate csv file.

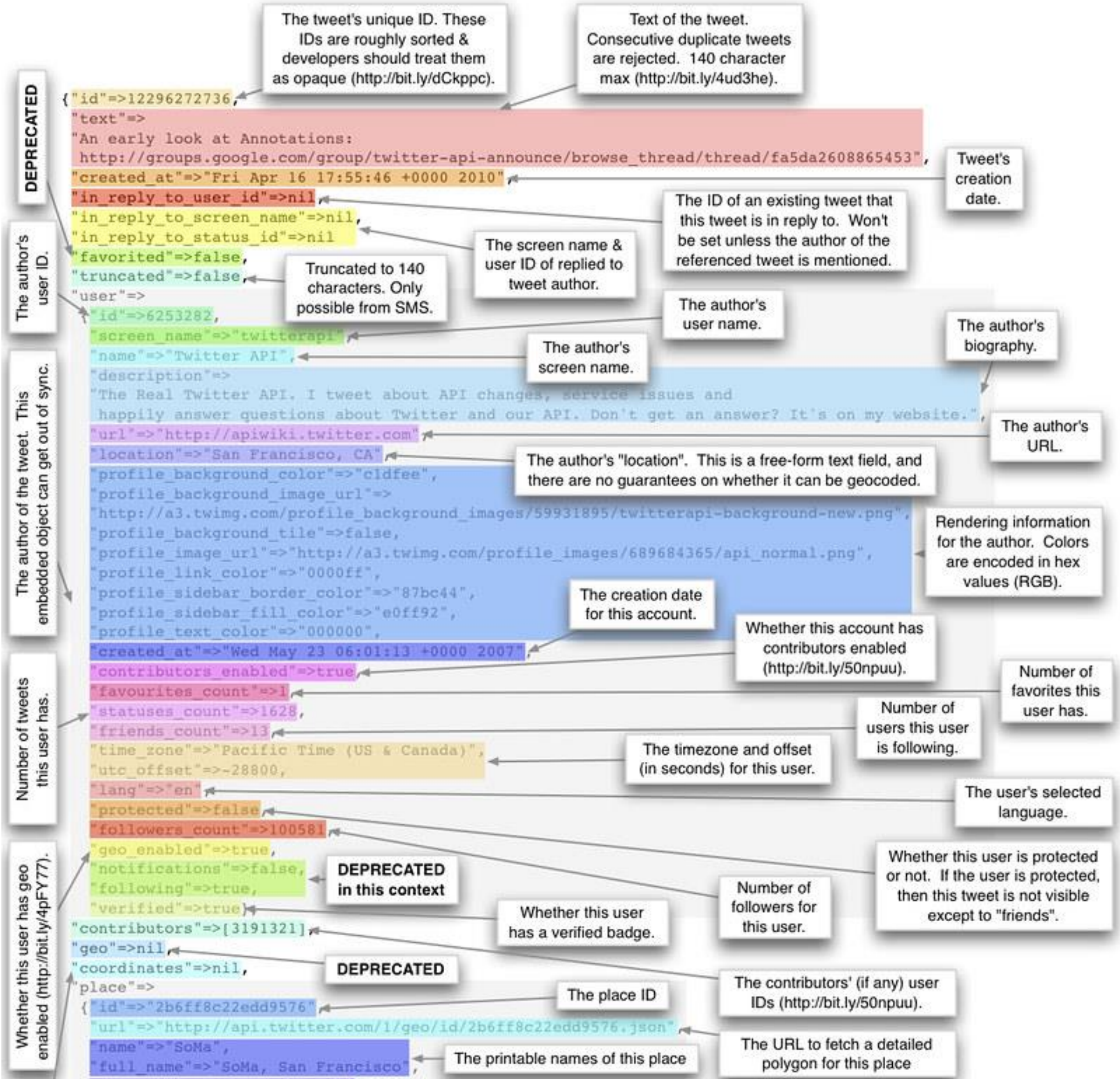


Figure 77. Information in a single tweet message. (Krikorian, 2017)

5.3. Data Availability for the Study Area

In Chapter 4, the research team has identified the Orlando Metropolitan Area as the study area for development of the Integrated Freeway/Arterial Active Traffic Management (IATM) strategies. After combining all the collected data in the study area, the data availability and implementability of the study area was checked. The data availability of the freeways and arterials are discussed separately.

5.2.1. Freeway

District 5 system, CFX system, and Florida Turnpike System are related to freeways and expressways (see Figure 78). It is shown that I-4, SR-408, SR-417, SR-414, SR-429, SR-451, SR-528, and Turnpike belong to the freeways and expressways. HERE data could cover all freeways and expressways in the study area. District 5, CFX, and FTE are using different traffic data collection systems including MVDS, AVI, and Bluetooth® systems (see Table 30). MVDS system could cover most of freeways and expressways. It should be noted that the data for I-4 would not be applicable since the road is now under construction. Hence, the project traffic data will be used for the future study.

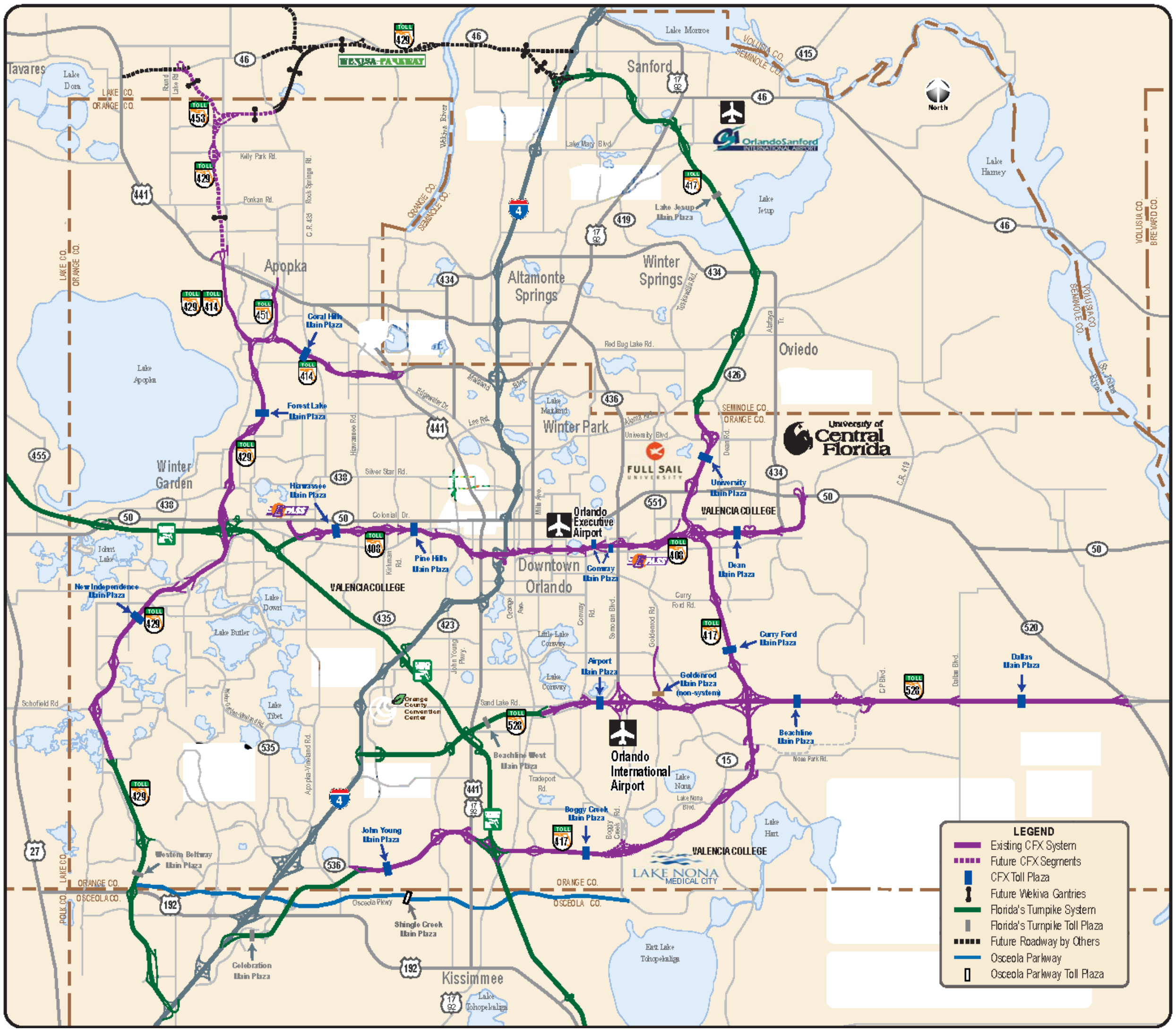


Figure 78. Freeways and expressways in the spatial scope

Table 30. Summary of MVDS, AVI, and Bluetooth®

Route	Authorities	MVDS	AVI	Bluetooth®
I-4	FDOT	167	-	8
SR 408	CFX	124	51	0
SR4- 417	CFX	103	45	0
	FTE	98	22	7
SR 414	CFX	28	11	0
SR 429	FDOT	5	0	0
	CFX	59	30	0
	FTE	35	7	5
SR 451	CFX	7	5	0
SR 528	FDOT	4	-	0
	CFX	61	21	0
	FTE	42	10	0
Turnpike	FTE	99	12	0
Total		832	214	20

Locations of AVI sensors were identified through RITIS, FDOT, CFX, and FTE. Figure 79 shows the availability of HERE data, the locations of RFID readers, and Bluetooth® readers. HERE data could cover all freeways and expressways in the study area. It is shown that the RFID readers of CFX were installed very densely, whereas the Bluetooth readers of FDOT and FTE were deployed sparsely. Currently, CFX has been operating AVI system using RFID to collect travel times. Meanwhile, FTE installed Bluetooth® readers instead of RFID readers on SR-429, SR-417 North, and I-4 North and the travel time could be also collected through the Bluetooth® readers. However, several freeways/expressways such as I-4 South, Turnpike, and SR-528 West don't have either RFID or Bluetooth® readers. In that case, only HERE data are available on these roads.

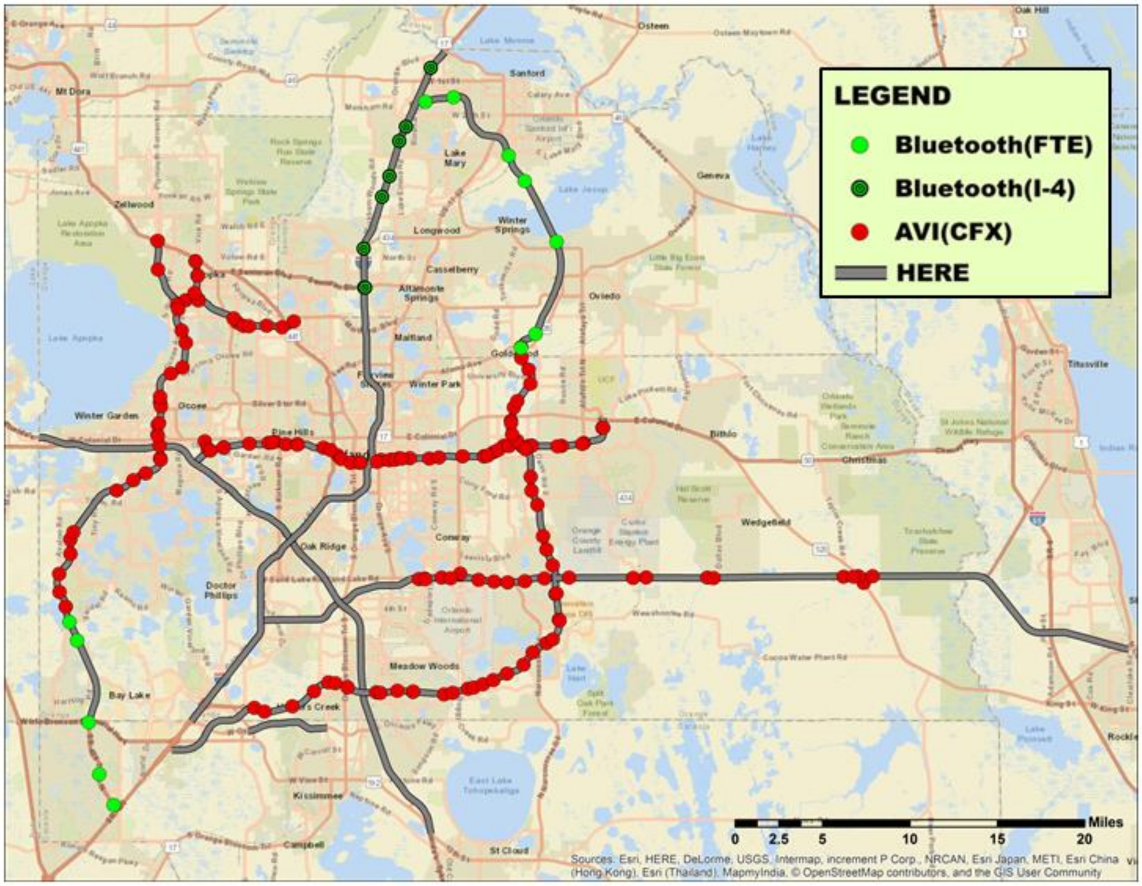


Figure 79. AVI and HERE availability on freeways and expressways

Figure 80 presents the data availability of HERE and locations of MVDS detectors. MVDS is collecting traffic data and monitoring traffic conditions on most freeways and expressways. The traffic data include volume, time mean speed, and occupancy, which are provided by FDOT, CFX, and FTE. All MVDS data can be collected from RITIS. MVDS detectors were not available on an overlapping section of SR 429 and SR 414, and Osceola parkway. Although MVDS could not provide travel time directly, the travel time could be still obtained by transforming the time mean speed.

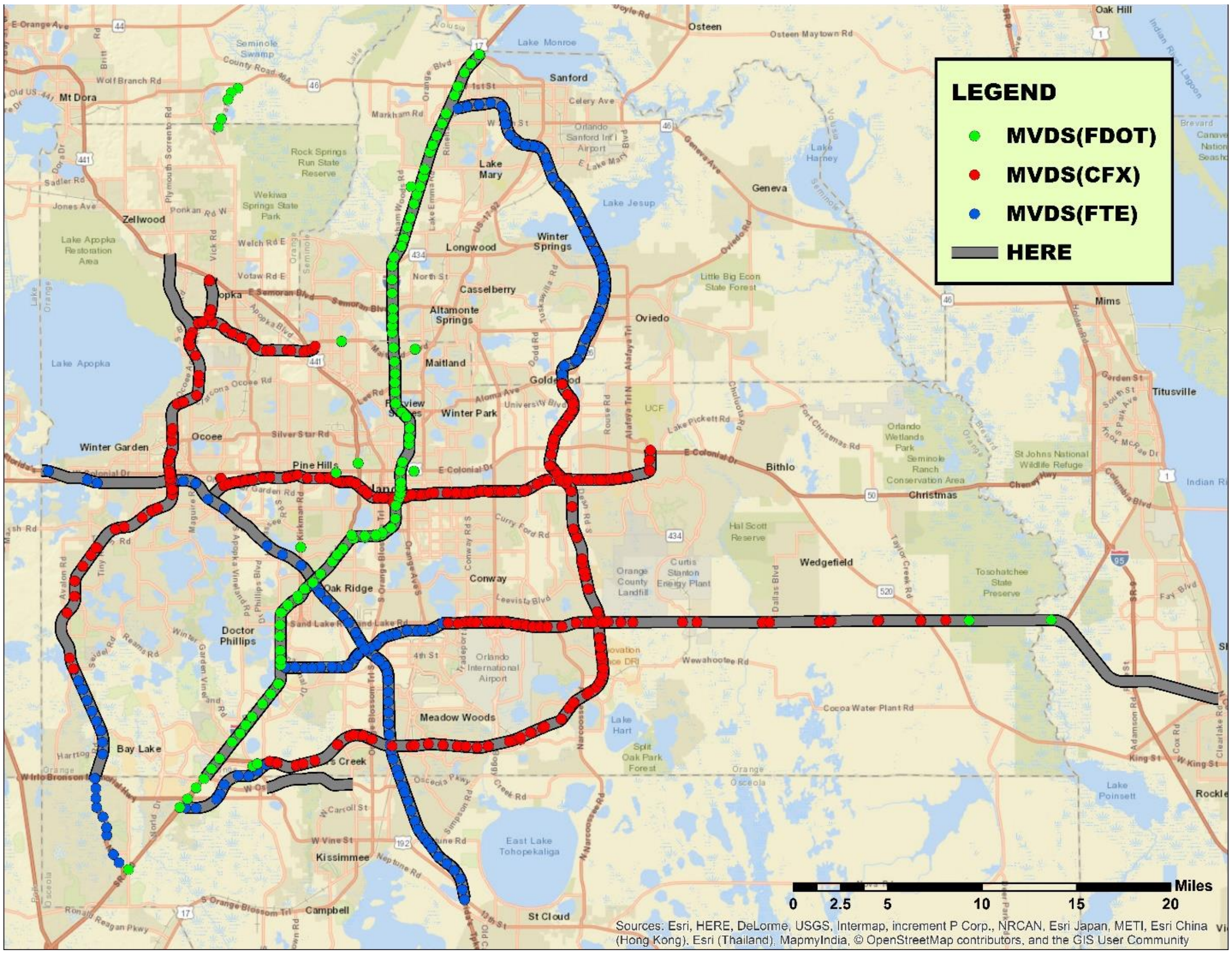


Figure 80. MVDS and HERE availability on freeways and expressways

5.2.2. Arterial

Travel time data and volume data will be collected for arterials in the study area from several agencies. Table 31 summarized the data collection systems available for arterials and their collection agencies.

Table 31. Summary of data collection systems and agencies

Data Type	System	Vendor	Agency	Highest Granularity
Travel time	Bluetooth	BlueTOAD	Seminole County	Filtered travel time of individual vehicle
		Iteris® Vantage Velocity®	Orange County	Filtered travel time of individual vehicle
		BlueMAC	Orange County	All detection timestamps of the vehicle
			District 5	First detection timestamp of the vehicle
	Prove Vehicle	HERE	RITIS	1-minute aggregated travel time
Volume	Loop detector and image processing	InSync®	Orange County	15-minute aggregated volume per lane
	Loop detector	ATSPM	Seminole County (previous) District 5(now)	Individual vehicle count

Figure 81 shows the availability of Bluetooth data and the location of the detectors for arterials in the study area. As shown in the figure, Bluetooth data could not cover all arterials. BlueTOAD covers most of the arterials in the Seminole County while the BlueMAC and Iteris® Vantage Velocity® data is only available for several major arterials in Orange County. In downtown Orlando area, the BlueMAC data are not only available on arterials but also on major collectors.

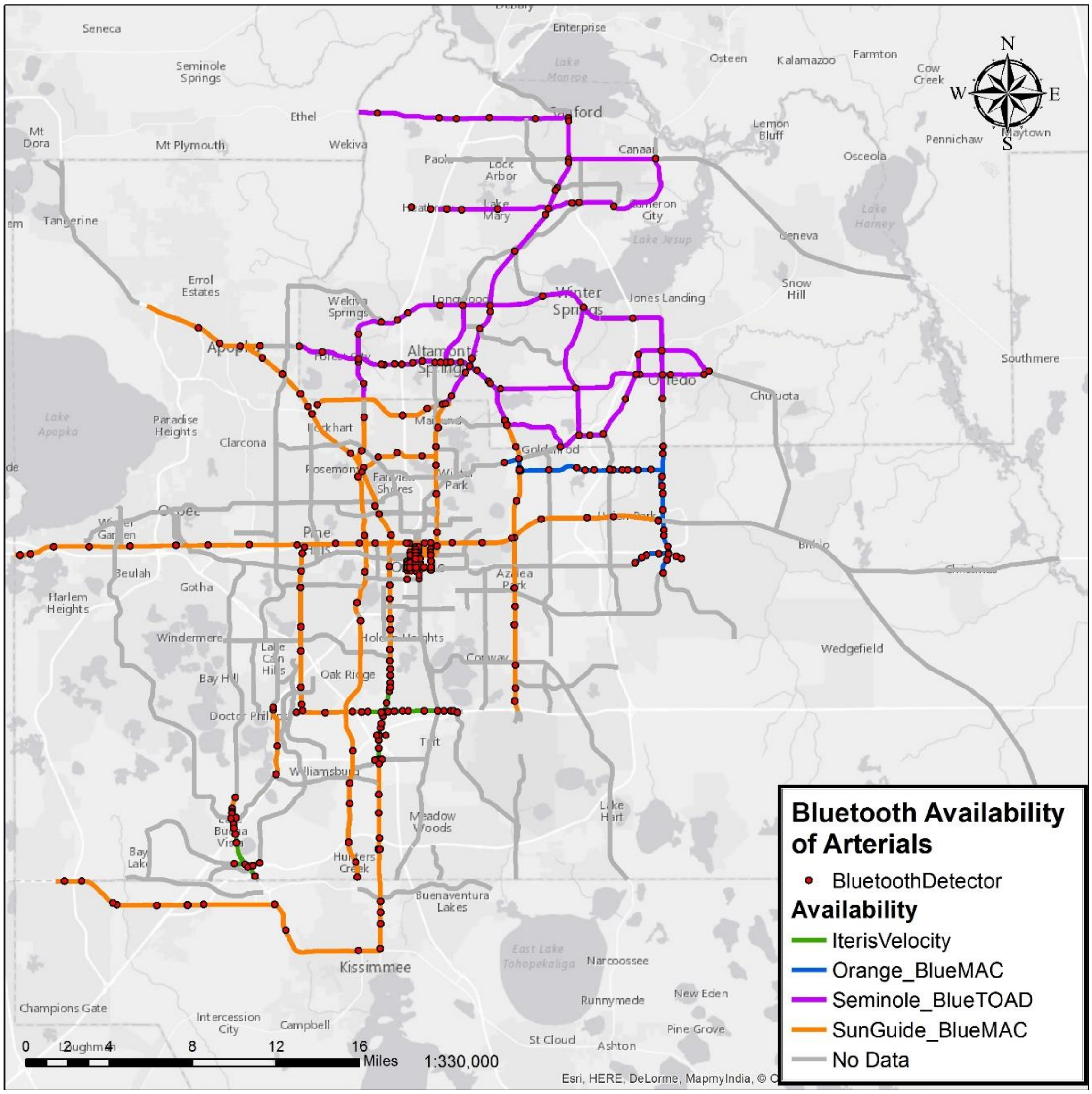


Figure 81. Bluetooth data availability on arterials

While Bluetooth data has a limited spatial coverage, HERE data are almost available for all arterials. Figure 82 illustrates the availability of HERE data for arterials in the study area. According to the figure, HERE data are unavailable for only several specific segments of serval roadways such as SR-535 North and CR-419. Hence, it could be concluded that travel time data from HERE are available for most of all arterials while the travel time data from Bluetooth are only available on arterials in Seminole County, major arterials in Orange County, and both arterials and collectors in Downtown Orlando.

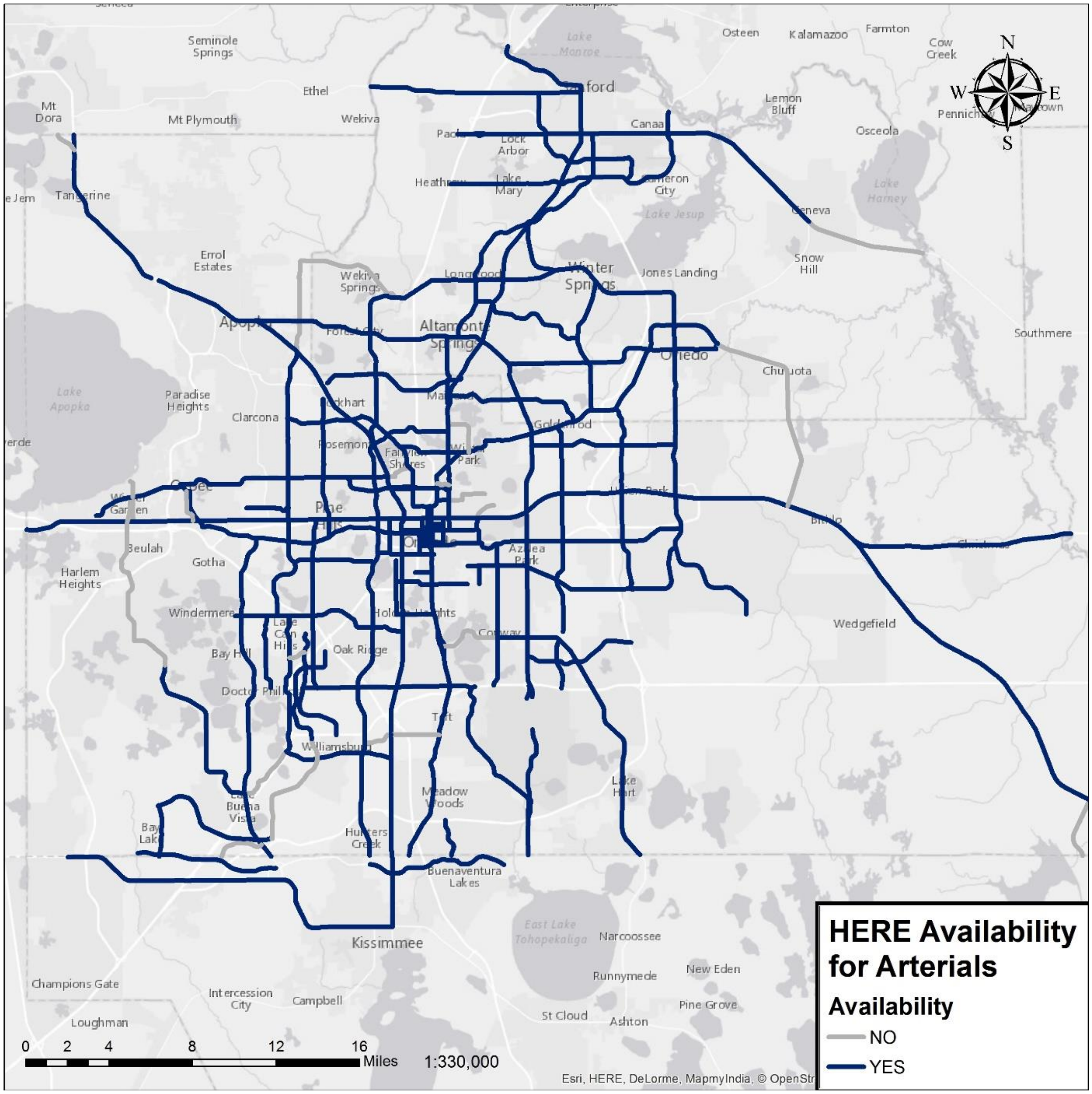


Figure 82. Bluetooth data availability on arterials

Both Bluetooth and probe vehicles could not collect traffic volume data. Instead, the volume data are collected by detectors of adaptive signal control system, whose locations are shown in Figure 83. It is shown that ATSPM data could cover almost all arterials in Seminole

County while InSync® adaptive signal control system is only available on several arterials in other areas. In that case, almost all arterials in Seminole County could have volume data while only several arterials in other areas have volume data.

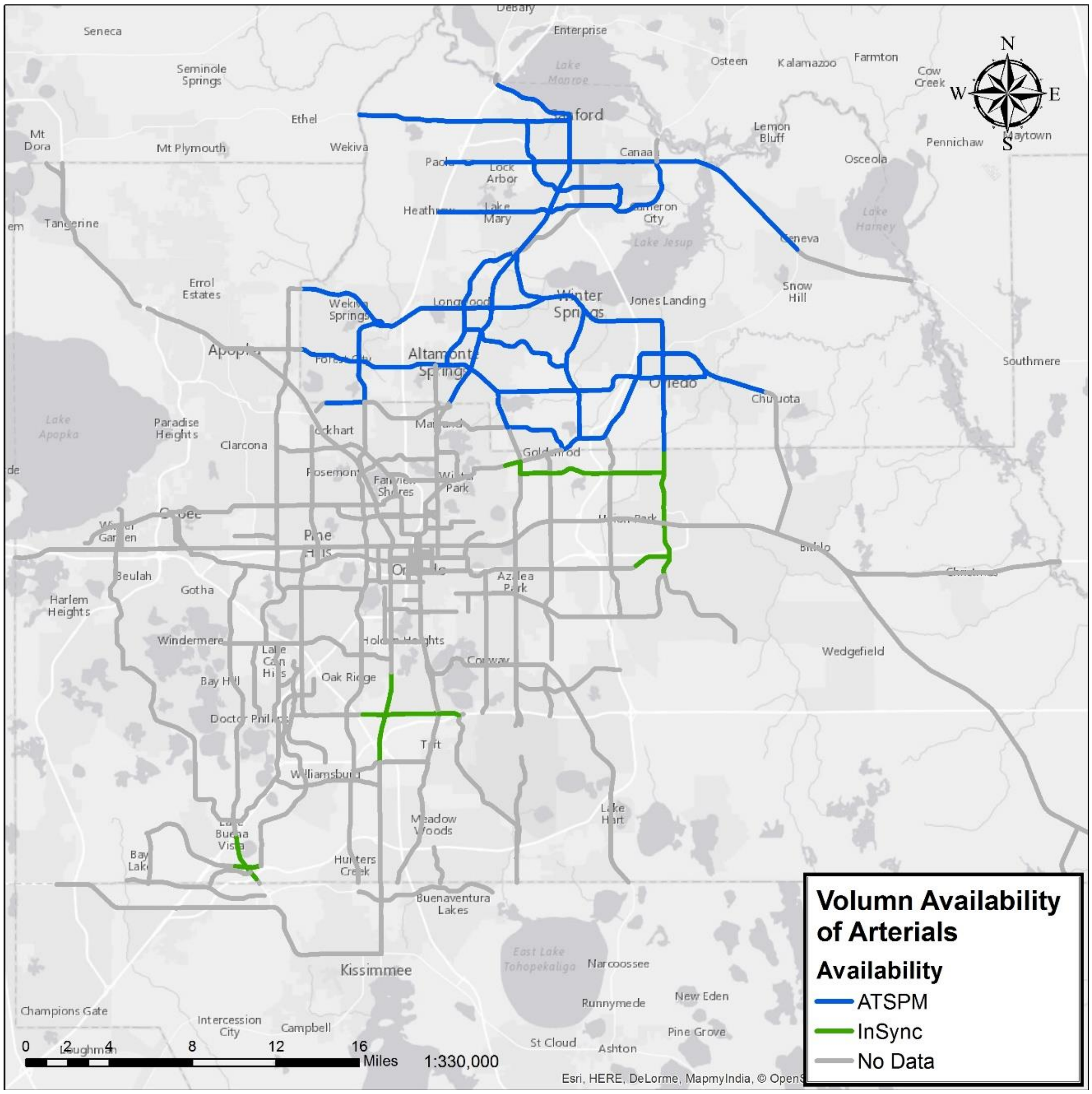


Figure 83. ATSPM and InSync® data availability on arterials

5.4. Summary

Managing Traffic data plays crucial roles in the development of the IATM system. In this project, different data such as the speed or travel time, traffic volume, density, signal control system data, dynamic message signs, and crowed source data detected by different data collection technologies have been collected from multiple data agencies.

Figure 84 summarizes the information of different data collection agencies and the collected datasets. As shown in Figure 84, the research team has devoted much effort and time to coordinate seven agencies to collect a wide range of different dataset. In order to manage, store, and utilize the collected big data efficiently, the research team has purchased two high-end computing servers with in-house funding. Based on the comprehensive data collection process and review of different data characteristics, the data availability and implementability could be checked for the roadway of interest in the study area.

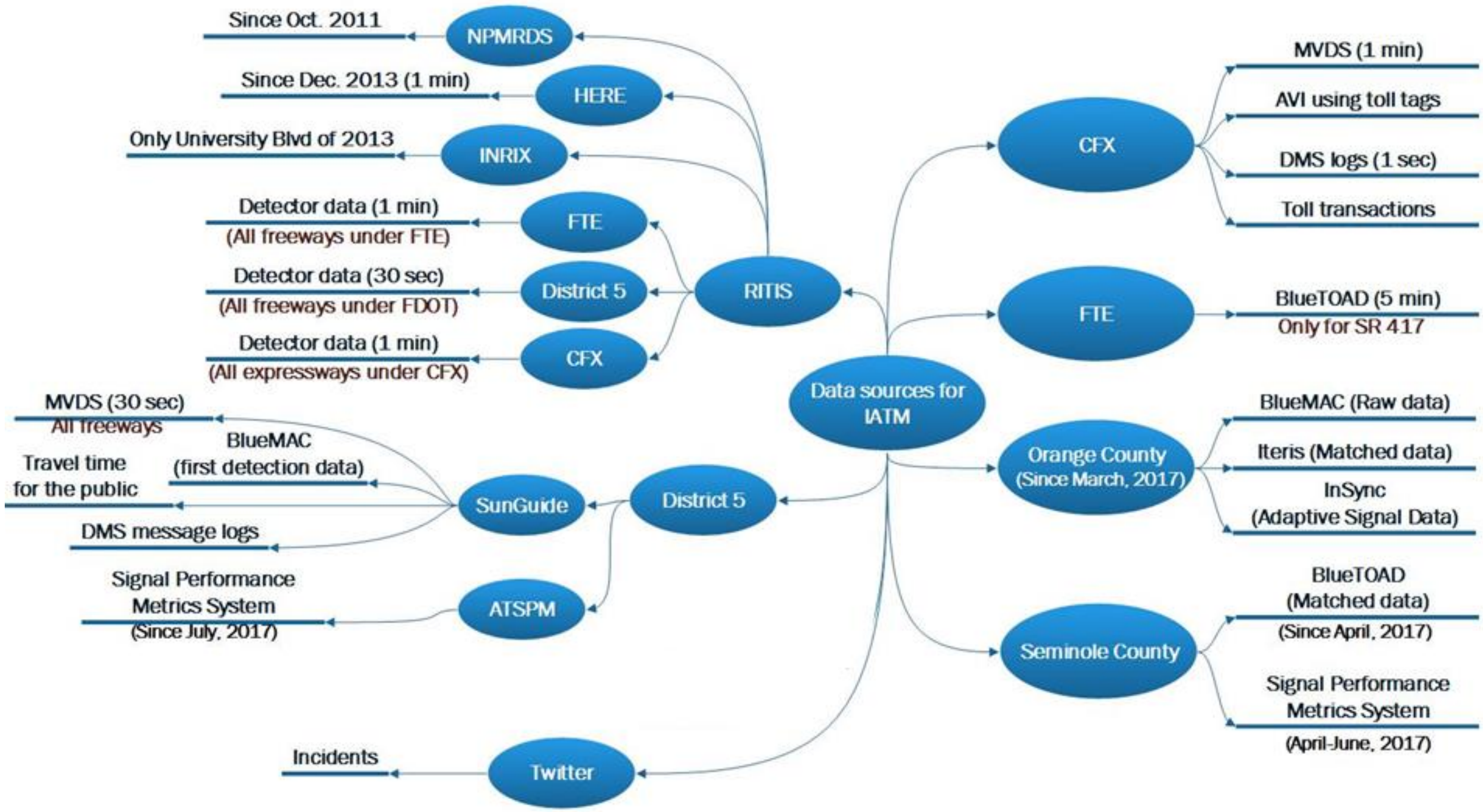


Figure 84. Summary of data collection technology and agency

Since travel time reliability is the focus of IATM, travel time data should be the essential data for this project. The availability of travel time on roadway networks in the study area is presented in Figure 85. As shown in the figure, most of roadways have at least one data type for the travel time. All freeways/expressways at least could have travel time from HERE and MVDS. Most of expressway could even have travel time from AVI while some freeways/expressways (e.g., I-4 North, SR-417 North) could obtain travel time from Bluetooth. On the other hand, nearly half of arterials have only travel time data from HERE system. Meanwhile, arterials in Seminole County, major arterials in Orange County, arterials and collectors in Downtown Orlando have two types of data, i.e., HERE and Bluetooth.

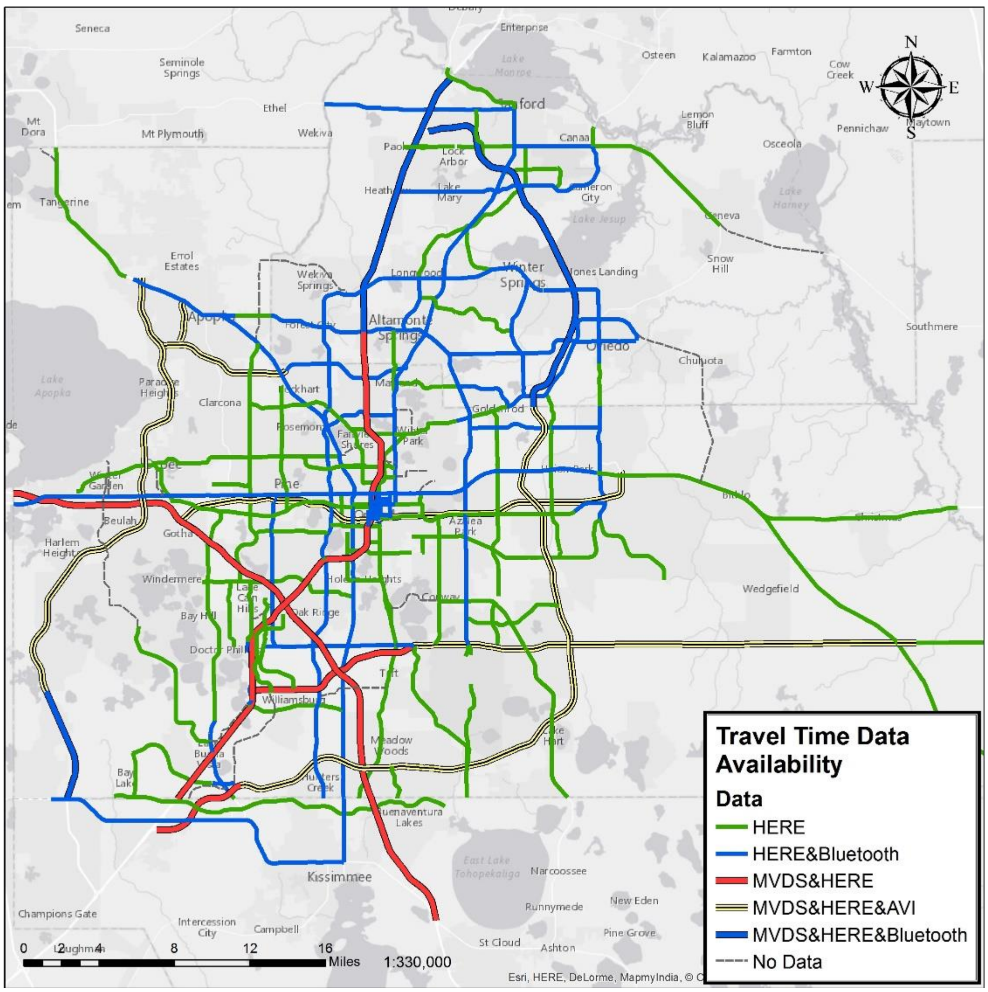


Figure 85. Travel time data availability

Besides the travel time, the volume data should also be important in this project. The data availability of volume in the study area is presented in Figure 80. The figure shows that all freeways/expressways could have volume data through MVDS. However, only arterials in Seminole county and few arterials in Orange County could have volume data through ATSPM or InSync®.

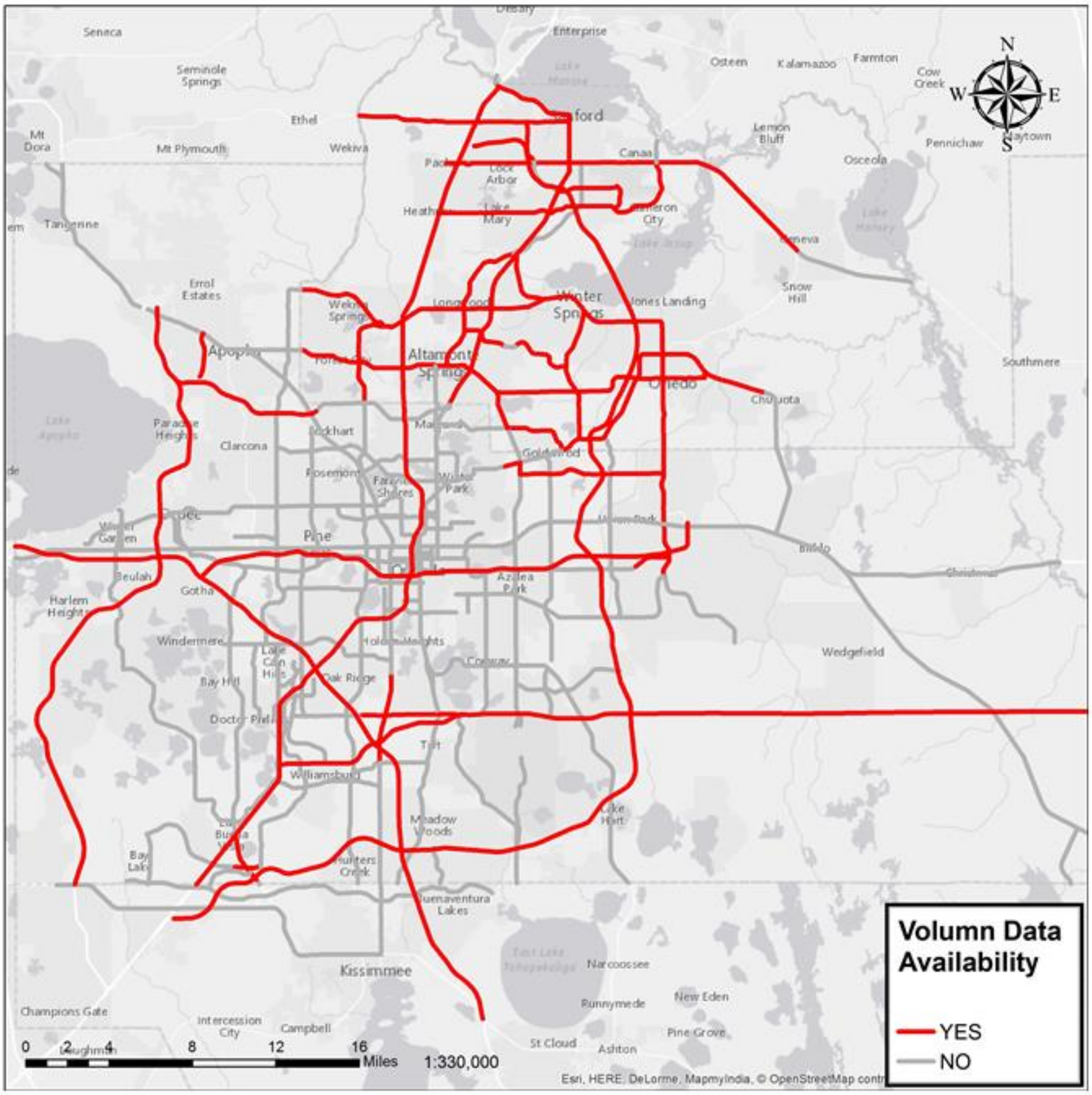


Figure 86. Volume data availability

CHAPTER 6. DATA EVALUATION AND FUSION

6.1. Overview

All available traffic data in the study area were collected. The availability of travel time on the roadway network is presented in the last Chapter. Based on the availability of data on the roadway network, the research team conducted multiple comparative studies to assess the reliability of all data sources on freeways, expressways and arterials.

Section 6.2 comprehensively analyzes the data reliability for freeways and expressways. Travel time data from different types of traffic data sources, including MVDS (Microwave Vehicle Detection System), AVI (Automatic Vehicle Identification), HERE, NPMRDS (National Performance Measure Research Data Set), and Bluetooth were evaluated. Beside traffic time data, the penetration rate of AVI detection was assessed.

Section 6.3 checked the data reliability for arterials with two types of data sources, i.e., HERE and Bluetooth. Three experimental studies were conducted to test the three different types of Bluetooth data, separately.

In Sections 6.4 and 6.5, fusion algorithms were suggested to improve the reliability of travel time data for freeways/expressways and arterials. With the proposed algorithm, more trustworthy data are expected to be achieved in the study area. Section 6.6 summarizes the data related efforts and suggests the plan for the following tasks.

6.2. Data Evaluation for Freeways and Expressways

Freeways and expressways in Orlando metropolitan area can use five kinds of traffic data sources, which are MVDS (Microwave Vehicle Detection System), AVI (Automatic Vehicle Identification), HERE, NPMRDS (National Performance Measure Research Data Set), and

Bluetooth. Depending on authorities, different combinations of the traffic data sources are being operated. MVDS, AVI, and Bluetooth are deployed on FDOT's freeways. MVDS and AVI are installed on CFX's expressways. FTE is operating MVDS and Bluetooth. HERE and NPMRDS systems are collecting travel time and speeds of all freeways and expressways through their own probe vehicles using AVL (Automatic Vehicle Location) devices. These multiple data sources would provide good opportunity for freeway and expressway traffic managers to realize the integrated active traffic management for freeways, expressways, and arterials.

Before using the multiple data sources, it is required to recognize how accurate travel time or speeds, and traffic volume can be obtained for our IATM project because they will be used as input data of performance measures and traffic simulations. For the evaluation of MVDS, time mean speeds and traffic volume were used. For HERE, NPMRDS, and Bluetooth system, speeds were used instead of travel time because accuracy of speeds can be checked consistently through the existing evaluation criteria such as AASE (Average Absolute Speed Error) and SEB (Speed Error Bias). Representatively, these measures are being used to evaluate and validate the traffic data of HERE, INRIX, and TomTom at Vehicle Probe Project (VPP), which began in 2008 to provide the I-95 Corridor Coalition members with reliable travel time and speed data for their roadways without additional sensors and other devices (Hamedi and Aliari, 2017). AVI data were used as ground truth data in this project. The AVI system used by CFX can provide high-accurate travel time and speeds than the Bluetooth because it has smaller communication range of toll tag reader and higher penetration rates of toll tag than the Bluetooth system. The travel time and speeds from AVI tag data were estimated by matching toll tags according to the travel time data collection handbook (Turner et al., 1998).

6.2.1. Travel Time

6.2.1.1. Performance Evaluation Measures

AASE and SEB were used to evaluate the speed obtained from MVDS, HERE, NPMRDS, and Bluetooth. The AASE is the same as the mean absolute error (MAE) between the mean speed from the evaluation system and the ground truth mean speed. It is assessed that the speed data are in a maximum AASE range of 10 mph in each of four speed ranges: 0-30 mph, 30-45 mph, 45-60 mph, and more than 60 mph. The four speed ranges are recommended in the guideline for evaluating the accuracy of travel time and speed data (Turner et al., 2011a). The SEB is the average speed error without the absolute value in each speed range. In this project, SEB was checked to determine whether the speeds of the evaluated system are within a maximum SEB of ± 5 mph in the four speed ranges (Hamedi and Aliari, 2017).

$$AASE = \frac{1}{n}\sum_{i=1}^{n} abs(x_i - \mu_i)$$

$$SEB = \frac{1}{n}\sum_{i=1}^{n}(x_i - \mu_i)$$

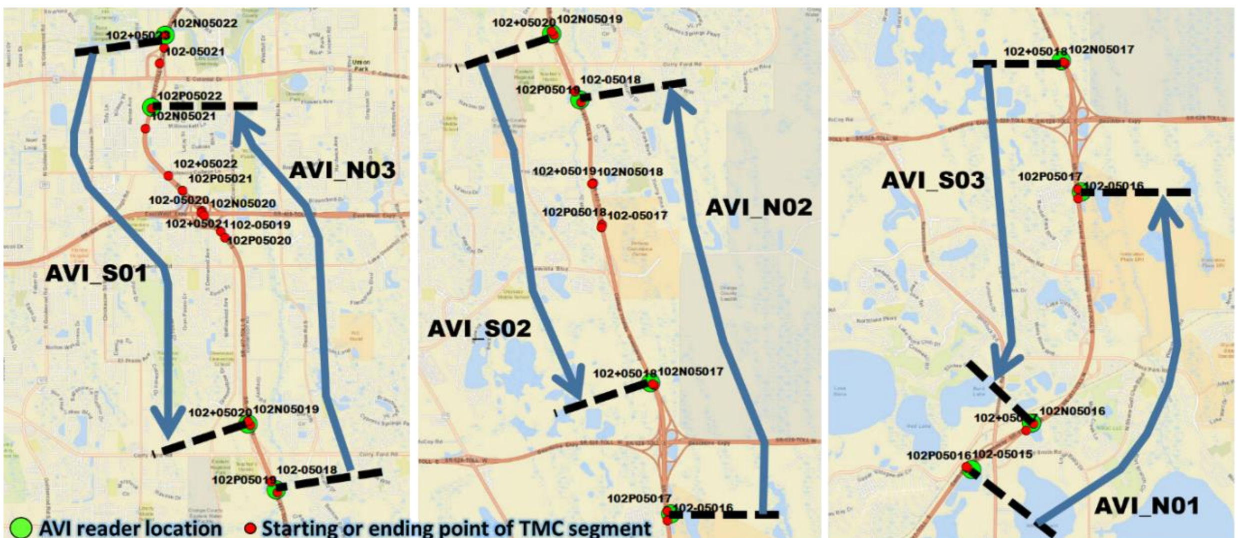
where μ_i = ground true speed for the *i*th comparison (mph);

x_i = the ith estimated speed;

n = number of estimate-to-benchmark comparisons.

6.2.1.2. Study Location

For the evaluation of MVDS, HERE, and NPMRDS, six segments on Florida State Road 417 (SR4- 417) managed by Central Florida Expressway (CFX) Authority operating with the speed limit of 70 mph were selected for the analysis because it was found that the locations of AVI readers are practically identical with the starting or ending points of TMC (Traffic Message Channel) segments (see Figure 87 and Table 32). The TMC segments are link elements for delivering traffic and travel information to drivers. All traffic data of HERE and NPMRDS are based on the TMC segments. Each AVI segment contains two to six TMC segments and has an average length of about 4 miles. The node information of TMC segments for NPMRDS and HERE was collected from the Regional Integrated Transportation Information System (RITIS).



AVI Segment	Direction	Distance (Miles)		Difference (Miles)	Here Segments
		AVI	HERE		
AVI_S01	SB	4.56	4.53	(0.038)	6
AVI_N03	NB	4.53	4.55	0.015	6
AVI_S02	SB	3.92	3.95	0.036	4
AVI_N02	NB	4.62	4.52	(0.109)	4
AVI_S03	SB	4.20	4.14	(0.054)	2
AVI_N01	NB	3.60	3.64	0.038	2

Figure 87. AVI and TMC segments for HERE and NPMRDS on Florida SR-417

Table 32. TMC segments for validation of NPMRDS and HERE in AVI segments

AVI					NPMARDS/HERE	
Segment ID	Start Name	End Name	Distance	Direction	TMC ID	Distance
AVI_N01	AVI-0417N-Narcoossee	AVI-0417N-SR528	3.599	NB	102P05016	0.780
					102+05017	2.882
AVI_N02	AVI-0417N-SR528	AVI-0417N-CurryFordRd	4.624	NB	102P05017	1.366
					102+05018	2.016
					102+05019	1.140
AVI_N03	AVI-0417N-CurryFordRd	AVI-0417N-EColonialDr	4.530	NB	102P05019	0.767
					102+05020	2.159
					102P05020	0.633
					102+05022	1.006
AVI_S01	AVI-0417S-EColonial	AVI-0417S-CurryFordRd	4.564	SB	102N05022	0.336
					102-05020	1.870
					102N05020	0.329
					102-05019	2.015
AVI_S02	AVI-0417S-CurryFordRd	AVI-0417S-SR528	3.917	SB	102N05019	0.719
					102-05018	1.248
					102-05017	1.951
AVI_S03	AVI-0417S-SR528	AVI-0417S-NarcoosseeRd	4.196	SB	102N05017	1.494
					102-05016	2.698

Considering MVDS locations and start/end points of AVI, new small MVDS segments were defined and allocated in each corresponding AVI segment (see Tables 33 and 34).

Table 33. MVDS segments (north bound) for validation of MVDS in AVI segments

AVI		MVDS				
Segment ID	Distance	Start MP	End MP	Distance	MVDS ID	MVDS MP
AVI_N01	3.599	21.132	21.650	0.518	TMS-417-21.3-NB	21.3
		21.650	22.250	0.600	TMS-417-22.0-NB	22.0
		22.250	22.750	0.500	TMS-417-22.5-NB	22.5
		22.750	23.300	0.550	TMS-417-23.0-NB	23.0
		23.300	23.750	0.450	TMS-417-23.6-NB	23.6
		23.750	24.200	0.450	TMS-417-23.9-NB	23.9
		24.200	24.731	0.531	TMS-417-24.5-NB	24.5
AVI_N02	4.624	24.731	24.750	0.019	TMS-417-24.5-NB	24.5
		24.750	25.550	0.800	TMS-417-25.0-NB	25.0
		25.550	26.500	0.950	TMS-417-26.1b-NB	26.1
		26.500	27.100	0.600	TMS-417-26.9-NB	26.9
		27.100	27.600	0.500	TMS-417-27.3-NB	27.3
		27.600	28.000	0.400	TMS-417-27.9-NB	27.9
		28.000	28.300	0.300	TMS-417-28.1-NB	28.1
		28.300	28.600	0.300	TMS-417-28.5-NB	28.5
		28.600	29.100	0.500	TMS-417-28.7-NB	28.7
		29.100	29.355	0.255	TMS-417-29.5-NB	29.5
AVI_N03	4.530	29.355	29.850	0.495	TMS-417-29.5-NB	29.5
		29.850	30.700	0.850	TMS-417-30.2-NB	30.2
		30.700	31.550	0.850	TMS-417-31.2-NB	31.2
		31.550	32.600	1.050	TMS-417-31.9-NB	31.9
		32.600	33.450	0.850	TMS-417-33.3-NB	33.3
		33.450	33.800	0.350	TMS-417-33.6-NB	33.6
		33.800	33.885	0.085	TMS-417-34.0-NB	34.0

Table 34. MVDS segments (South Bound) for validation of MVDS in AVI segments

AVI		MVDS				
Segment ID	Distance	Start MP	End MP	Distance	MVDS ID	MVDS MP
AVI_S01	4.564	34.797	34.650	0.147	TMS-417-34.8-SB	34.8
		30.700	30.233	0.467	TMS-417-30.2-SB	30.2
		31.550	30.700	0.850	TMS-417-31.2-SB	31.2
		32.500	31.550	0.950	TMS-417-31.9-SB	31.9
		33.350	32.500	0.850	TMS-417-33.1-SB	33.1
		34.050	33.350	0.700	TMS-417-33.6-SB	33.6
		34.650	34.050	0.600	TMS-417-34.5-SB	34.5
AVI_S02	3.917	30.233	29.850	0.383	TMS-417-30.2-SB	30.2
		26.500	26.316	0.184	TMS-417-26.1-SB	26.1
		27.100	26.500	0.600	TMS-417-26.9-SB	26.9
		27.600	27.100	0.500	TMS-417-27.3-SB	27.3
		28.000	27.600	0.400	TMS-417-27.9-SB	27.9
		28.300	28.000	0.300	TMS-417-28.1-SB	28.1
		28.600	28.300	0.300	TMS-417-28.5-SB	28.5
		29.100	28.600	0.500	TMS-417-28.7-SB	28.7
		29.850	29.100	0.750	TMS-417-29.5-SB	29.5
AVI_S03	4.196	26.316	25.500	0.816	TMS-417-26.1-SB	26.1
		22.600	22.120	0.480	TMS-417-22.2-SB	22.2
		23.100	22.600	0.500	TMS-417-23.0-SB	23.0
		23.350	23.100	0.250	TMS-417-23.2-SB	23.2
		23.850	23.350	0.500	TMS-417-23.5-SB	23.5
		24.350	23.850	0.500	TMS-417-24.2-SB	24.2
		24.700	24.350	0.350	TMS-417-24.5-SB	24.5
		25.500	24.700	0.800	TMS-417-24.9-SB	24.9

For the performance evaluation of the Bluetooth system, six segments on SR4- 417 under the FTE management were defined by the combination of Bluetooth segments, which can contain several TMC segments based on NPMRDS within small distance difference (see Figure 88). Table 35 shows that the defined segments include several Bluetooth pairs IDs, which were provided by the FTE's Bluetooth system. Likewise, Table 36 shows that the segments are linked to TMC segments of NPMRDS.

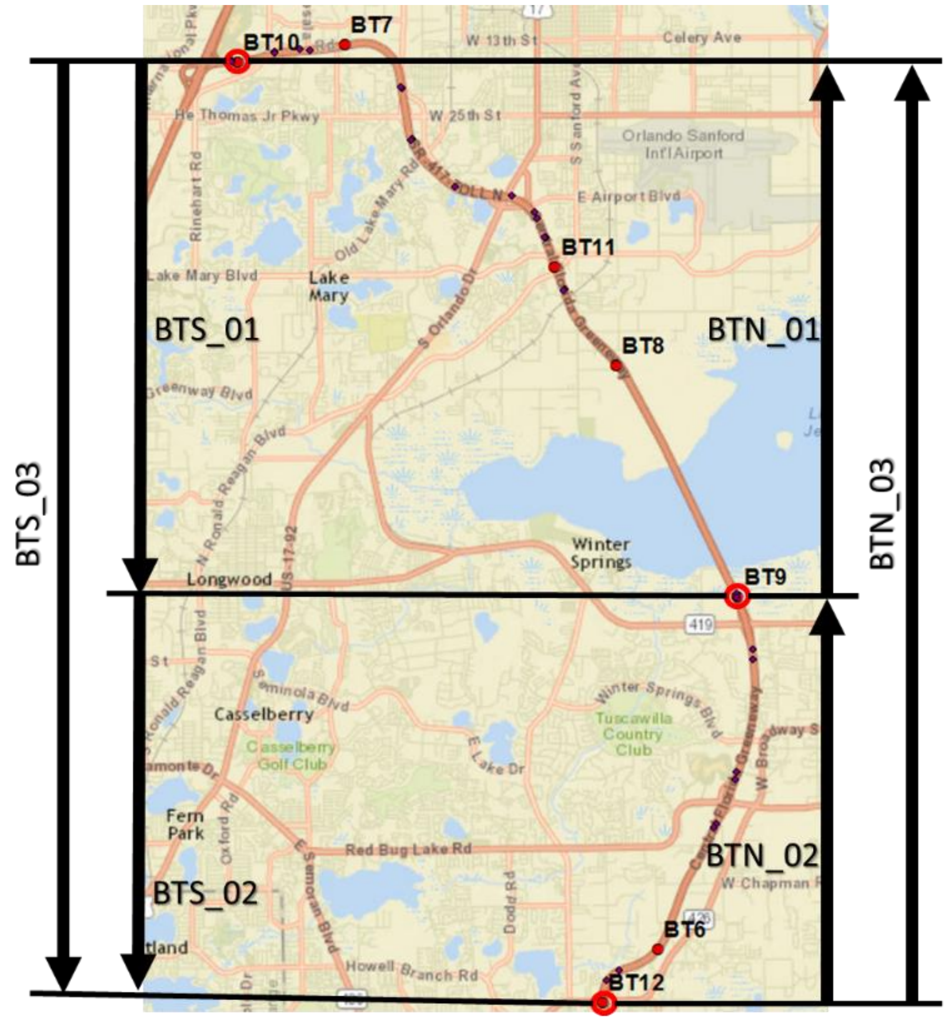


Figure 88. Six segments including segments of bluetooth and TMC

Table 35. Bluetooth pairs ID in six segments

Segment ID	Bluetooth pairs ID	Distance	Segment ID	Bluetooth pairs ID	Distance
BTS_01	FT-25940	1.44	BTN_01	FT-25933	3.42
	FT-25938	4.54		FT-25935	1.53
	FT-25936	1.53		FT-25937	4.54
	FT-25934	3.42		FT-25939	1.44
BTS_02	FT-25930	1.10	BTN_02	FT-25931	4.89
	FT-25932	4.89		FT-25929	1.10
BTS_03	FT-26171	16.92	BTN_03	FT-26170	16.92

Table 36. TMC Segments in Six Segments

Segment ID	TMC ID	Distance	Segment ID	TMC ID	Distance
BTS_01	102-05530	0.62	BTN_01	102+05531	0.54
BTS_01	102N05530	0.47	BTN_01	102P05530	0.40
BTS_01	102-05529	1.56	BTN_01	102+05530	1.69
BTS_01	102N05529	0.77	BTN_01	102P05529	0.69
BTS_01	102-05029	0.79	BTN_01	102+05529	1.60
BTS_01	102N05029	1.22	BTN_01	102P05029	0.41
BTS_01	102-05028	0.23	BTN_01	102+05029	0.31
BTS_01	102N05028	0.80	BTN_01	102P05028	0.77
BTS_01	102-05027	4.63	BTN_01	102+05028	4.53
BTS_02	102N05027	0.84	BTN_02	102P05027	0.83
BTS_02	102-05026	1.50	BTN_02	102+05027	1.71
BTS_02	102N05026	0.79	BTN_02	102P05026	0.67
BTS_02	102-05025	2.54	BTN_02	102+05026	2.37
BTS_02	102N05025	0.63	BTN_02	102P05025	0.86
BTS_03	102-05530	0.62	BTN_03	102+05531	0.54
BTS_03	102N05530	0.47	BTN_03	102P05530	0.40
BTS_03	102-05529	1.56	BTN_03	102+05530	1.69
BTS_03	102N05529	0.77	BTN_03	102P05529	0.69
BTS_03	102-05029	0.79	BTN_03	102+05529	1.60
BTS_03	102N05029	1.22	BTN_03	102P05029	0.41
BTS_03	102-05028	0.23	BTN_03	102+05029	0.31
BTS_03	102N05028	0.80	BTN_03	102P05028	0.77
BTS_03	102-05027	4.63	BTN_03	102+05028	4.53
BTS_03	102N05027	0.84	BTN_03	102P05027	0.83
BTS_03	102-05026	1.50	BTN_03	102+05027	1.71
BTS_03	102N05026	0.79	BTN_03	102P05026	0.67
BTS_03	102-05025	2.54	BTN_03	102+05026	2.37
BTS_03	102N05025	0.63	BTN_03	102P05025	0.86

6.2.1.3. Data Preparation

For the travel time evaluation, five data sources were prepared from February, 2017 to July, 2017.

A. AVI Data

AVI data were obtained from CFX's AVI system archiving the encrypted tag IDs and the passage timestamps of vehicles with toll tags. Uncapped raw AVI data, which is not adjusted by the speed limit, were archived for this research and used because more tangible travel time can be estimated as ground-truth data. AVI data were prepared through three steps: matching toll tag IDs, estimating two kinds of travel time, and filtering abnormal travel time (see Figure 89).

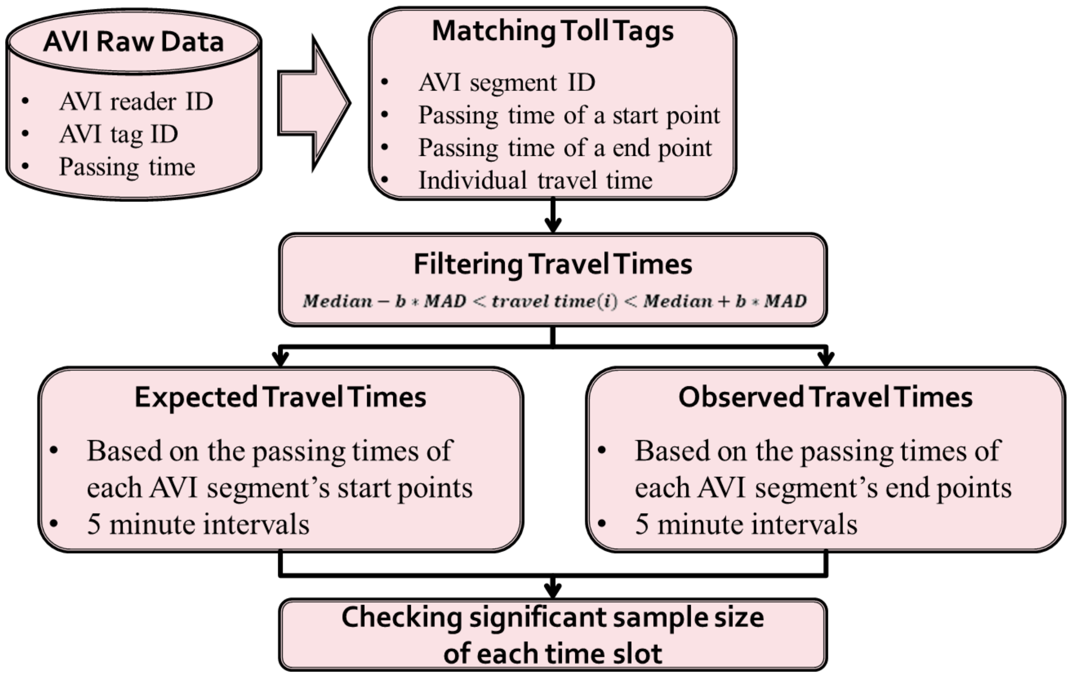


Figure 89. Flow chart of AVI data preparation

After matching AVI tags based on the new six AVI segments, two kinds of travel time were calculated from AVI data (see Figure 90). One is based on the passing time of the start points of AVI segments. Another is based on the passing time of the end points of AVI segments. The former is assumed as ground truth, which is the expected travel time when vehicles pass the starting points of AVI segments. The latter is the past travel time, which are collected in real time by AVI systems.

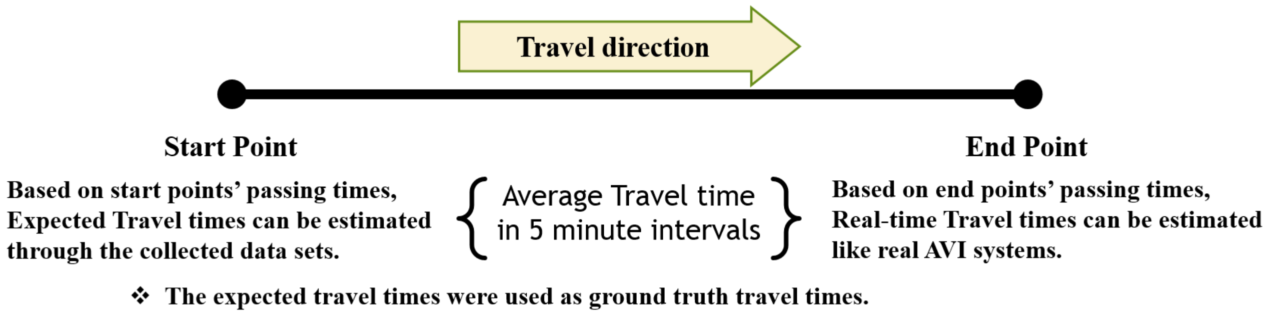


Figure 90. Two aspects related to AVI travel time

The uncapped raw AVI data were aggregated in five-minute intervals and their outliers were eliminated through the median absolute deviation (MAD) approach. The MAD approach provides a high accuracy and low computational effort (Leys et al., 2013). The removal criterion of outliers becomes:

$$Median - b * MAD < travel\ time(i) < Median + b * MAD$$

where b is a threshold, in which 3 was applied very conservatively (Miller, 1991). In addition, it was confirmed whether the count of the data used in each aggregation period satisfy the required sample size, which is estimated by the following equation (May, 1990):

$$n = \left(\frac{ts}{\varepsilon}\right)^2$$

where n = required sample size;

s = standard deviation, which was estimated in each five-minute aggregation;

ε = user-specified allowable error, in which 5 mph was applied;

t = 1.96 at 95 percent confidence was used.

If the number of data in 5-minute increments is less than the required sample size, the corresponding time periods were removed.

B. NPMRDS and HERE data

NPMRDS and HERE data are based on the same TMC segments and collected from probe vehicles with AVL devices. The NPMRDS was created as a tool for performance measurement for states and metropolitan planning organizations (MPOs). So, the NPMRDS data contain only raw observed data without any data modeling, filtering, blending, or smoothing. If no field data are observed, no data will be recorded. However, the HERE data are reported to provide best estimates of speed and travel time for all time periods. Thus, if there is insufficient observed data, other historical data or estimation techniques may be used.

The travel time of NPMRDS and HERE, which were aggregated in 5-minute intervals, were downloaded via the RITIS platform without any processing and manipulation (Vandervalk, 2014). The downloaded NPMRDS data included travel time of passenger cars and trucks. Finally, on the basis of the AVI or Bluetooth segments, each travel time of TMC segments was added at 5-minute interval and transformed into speeds.

C. MVDS data

MVDS collects volume, occupancy, and time mean speed at one-minute or 30-second intervals. The data were aggregated at 5-minute intervals in this project. Each AVI segment has multiple MVDSs (see Figure 91). To estimate traffic volume, speed, and occupancy for the AVI segments, new virtual segments were defined, which are called virtual nodes and links in this report. Based on the virtual nodes and links, all MVDS stations were connected to AVI segments. Average speeds were estimated through weighted harmonic average of speed, considering distances and volumes on virtual links. Volume representing AVI segments was calculated by the summation of all traffic volume of MVDSs in each AVI segment. Occupancy of AVI segments was computed by the volume-weighted average. Originally, occupancy referred to the percentage of time that there is a vehicle over the detector. In this project, there are more than two MVDS detectors in each AVI segment, and it is required to estimate representative occupancy of each AVI segment. So, the volume-weighted average method was used to estimate the representative occupancy of each AVI segment.

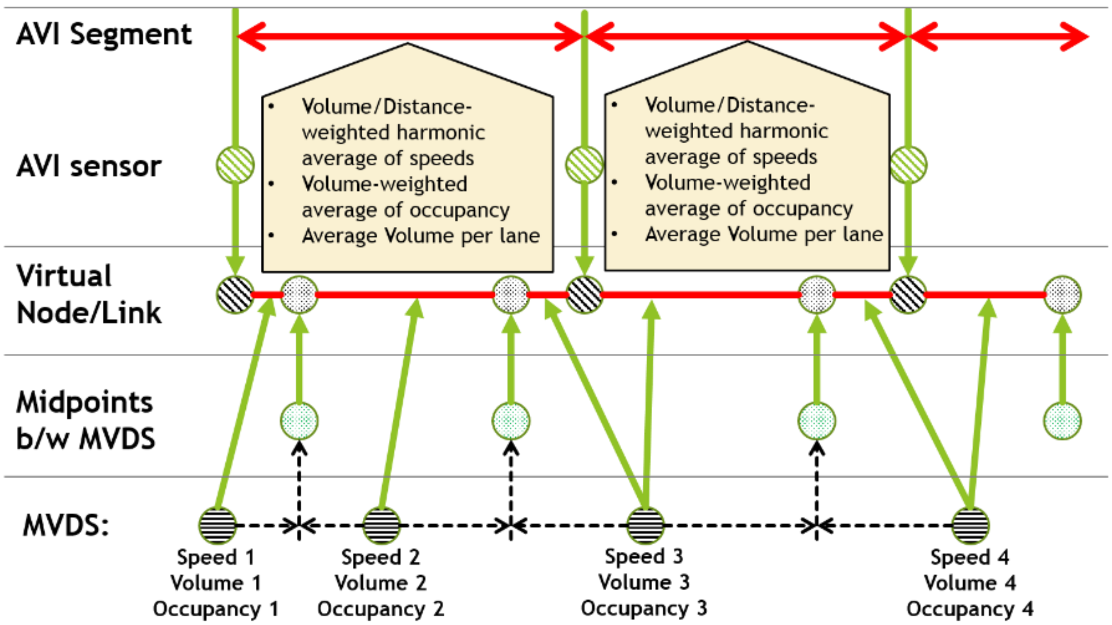


Figure 91. Relationship between AVI segments and MVDS stations

D. Bluetooth data

Travel time and speeds based on segments of Bluetooth (BT) were obtained from FTE. The data were aggregated and smoothed at five-minute intervals on the basis of FTE's own segments, which have paired IDs. The travel time based on the paired IDs was added into the new BT segments and transformed to speeds of each BT segment.

E. INTRIX

The research team also devoted efforts to evaluate INRIX data. Since INRIX data is not available for the study area of our project, two INRIX/HERE segments (ID: 102N04157 and 102P04157) of I-95 near Palm Beach Airport of and two MVDS detectors along the segments were selected for evaluation. Figure 92 shows the study site. The two green dots are the MVDS detectors used for validation and the red lines are the common TMC "segment" of INRIX and HERE. Seven months' (from January 2017 to July 2017) space mean speed data which were aggregated in 5 minutes were used for the evaluation.

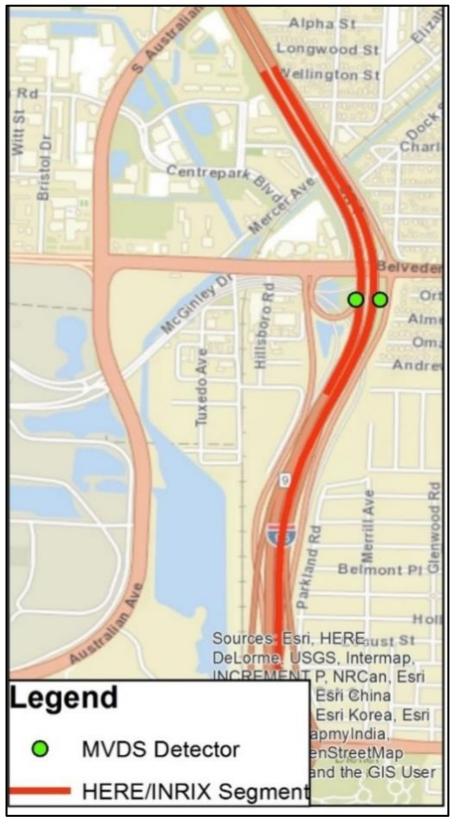


Figure 92. Segments used for INRIX evaluation

6.2.1.4. Results of Speed Evaluation

A. HERE, NPMRDS, and MVDS

Travel time validation of HERE, NPMRDS, and MVDS was conducted by using the data collected on six AVI segments on SR4- 417 managed by CFX. Travel time of all data sources including AVI was transformed into speeds to use AASE and SEB. By using six months between February 2017 and July 2017, speeds of HERE, NPMRDS, and MVDS were evaluated on the basis of AVI's expected speeds, which were derived from the expected travel time. As seen in Table 37, HERE and MVDS do not have acceptable results. Especially, there are many failures with single or double asterisk sign in the range less than 45 mph. According to MVDS's results, it is obvious that simple distance and volume weighted average or segment definition of MVDS are not suitable to estimate travel time by using only MVDS. Furthermore, it shows that HERE data should be monitored and adjusted constantly in order to evaluate the ability to capture the traffic condition with the low frequency such as non-recurring congestion. In this validation, AVI_N01, AVI_N02, AVI_S02, and AVI_S03 have the low frequency with the speed less than 45 mph. So, through temporary validation, it will be difficult to catch the exact performance considering the traffic conditions less than 45 mph. Hence, current VPP (Vehicle Probe Project) evaluation methods may not be able to capture these kinds of results reflecting non-frequent traffic conditions because they are using benchmark data of the short time periods. Finally, NPMRDS shows reasonable results although it is a little biased in terms of SEB. This means that NPMRDS can be used to evaluate travel time and speeds instead of AVI data when AVI data are not available.

Table 37. Evaluation results of HERE, NPMRDS, and MVDS

Segment ID	Speed Range	HERE		NPMRDS		MVDS		Count
		AASE	SEB	AASE	SEB	AASE	SEB	
AVI_N01	> 60 mph	2.56	-0.02	4.04	-2.37	2.22	1.75	32,792
AVI_N01	45-60 mph	8.06	5.68*	4.33	-0.22	7.87	7.05*	359
AVI_N01	30-45 mph	14.75**	12.30*	4.80	0.46	14.94**	14.45*	81
AVI_N01	0-30 mph	17.02**	16.21*	8.61	6.86*	27.39**	27.39*	58
AVI_N02	> 60 mph	5.52	-5.29*	6.09	-5.79*	1.94	-1.13	32,372
AVI_N02	45-60 mph	10.96**	-8.25*	7.33	-6.70*	8.97	8.02*	379
AVI_N02	30-45 mph	7.19	-0.18	5.39	-3.43	14.53**	14.24*	127
AVI_N02	0-30 mph	12.83**	8.07*	8.36	2.87	30.77**	30.77*	48
AVI_N03	> 60 mph	2.81	-0.07	3.63	-2.50	2.66	1.78	2,967
AVI_N03	45-60 mph	7.42	1.77	3.51	-1.45	8.75	8.36*	233
AVI_N03	30-45 mph	4.08	3.15	2.44	-1.73	13.45**	13.45*	645
AVI_N03	0-30 mph	5.42	4.78	2.94	-0.99	15.73**	15.73*	85
AVI_S01	> 60 mph	2.64	-1.67	4.49	-4.12	1.76	-1.08	4,041
AVI_S01	45-60 mph	5.35	3.58	2.77	-1.76	7.43	7.20*	298
AVI_S01	30-45 mph	6.89	5.52*	2.54	0.08	15.04**	15.04*	85
AVI_S01	0-30 mph	12.51**	9.13*	4.80	-0.26	24.61**	24.61*	15
AVI_S02	> 60 mph	2.80	-1.90	4.27	-3.57	1.71	1.21	41,167
AVI_S02	45-60 mph	8.58	1.58	3.83	-1.20	8.21	6.95*	228
AVI_S02	30-45 mph	8.89	5.28*	3.28	0.14	14.46**	14.26*	50
AVI_S02	0-30 mph	21.64**	17.97*	13.22*	6.53*	35.37**	35.37*	10
AVI_S03	> 60 mph	2.72	-1.61	4.54	-3.51	1.69	1.03	36,280
AVI_S03	45-60 mph	8.79	3.64	4.38	0.13	8.79	8.09*	237
AVI_S03	30-45 mph	11.13**	8.68*	4.30	0.42	15.65**	15.49*	90
AVI_S03	0-30 mph	17.25**	16.84*	7.37	4.62	27.65**	27.65*	99
The number of failure		8/24	12/24	1/24	4/24	12/24	18/24	-

** Failure: AASE more than 10 mph
* Failure: SEB not between 5 mph and -5 mph

B. Bluetooth

Based on the NPMRDS data, Bluetooth data on SR4- 417 managed by FTE were also assessed through AASE and SEB. It is assumed that the NPMRDS data are the ground truth speeds. According to the evaluation results (see Table 38), the smoothed and processed Bluetooth data are not acceptable because there are many differences in the results between NPMRDS and Bluetooth. Under the free-flow speed over 60 mph, the Bluetooth data provide reliable speed. However, when the average speed of segments is lower than 60 mph, most speeds of Bluetooth are inaccurate in the case of AASE or SEB. These problems may not be easily recognized by traffic operators because the traffic condition of all segments is in free-flow speed. Therefore, there is a need to evaluate and improve the travel time estimation algorithm of the Bluetooth system periodically.

Table 38. Evaluation results of Bluetooth

Segment ID	Group	AASE	SEB	Count	Segment ID	Group	AASE	SEB	Count
BTN_01	> 60 mph	4.42	3.09	44,890	BTS_01	> 60 mph	5.09	4.19	44,499
BTN_01	45-60 mph	10.72**	-8.83*	246	BTS_01	45-60 mph	13.26**	-3.62	191
BTN_01	30-45 mph	22.72**	-22.72*	88	BTS_01	30-45 mph	20.10**	-17.87*	53
BTN_01	0-30 mph	37.41**	-36.87*	46	BTS_01	0-30 mph	39.71**	-39.71*	2
BTN_02	> 60 mph	4.39	2.88	41,529	BTS_02	> 60 mph	5.21	3.80	42,689
BTN_02	45-60 mph	13.53**	-11.74*	712	BTS_02	45-60 mph	9.48	-4.36	243
BTN_02	30-45 mph	26.76**	-26.37*	536	BTS_02	30-45 mph	18.40**	-15.81*	112
BTN_02	0-30 mph	40.74**	-40.05*	100	BTS_02	0-30 mph	44.59**	-44.59*	46
BTN_03	> 60 mph	4.26	3.37	47,480	BTS_03	> 60 mph	4.48	3.69	46,539
BTN_03	45-60 mph	8.06	-1.51	317	BTS_03	45-60 mph	6.07	0.04	896
BTN_03	30-45 mph	14.83**	-11.61*	48	BTS_03	30-45 mph	9.57	-5.69*	167
BTN_03	0-30 mph	11.63**	-10.61*	23	BTS_03	0-30 mph	9.75	-7.43*	13
The number of failure		8/12	8/12	-	The number of failure		5/12	6/12	-
** Failure: AASE more than 10 mph * Failure: SEB not between 5 mph and -5 mph									

C. INRIX

Table 39 shows the evaluation results of INRIX, together with HERE data on the same segments. The results showed that data from HERE and INRIX are reliable for high speed ranges (>50 mph) while the data from HERE preforms slightly better than that from INRIX. The deviations of both HERE and INRIX to the ground truth in low speed ranges (<50 mph) are relatively high. However, the quality of the data source is still acceptable since the percentage of low speed readings is only 1.21%. In addition, the distributions (Figure 93) of INRIX and HERE data showed that INRIX capped the reported speed at 75 mph, 10 mph above the maximum speed limit, while both HERE and INRIX do not report speed lower than 30 mph whereas the MVDS validation data set does.

Hence, there is no large difference between INRIX and HERE data. However, HERE data is a little closer to MVDS than INRIX.

Table 39. Evaluation results of INRIX with HERE

Speed	Count	Segment 102N04157				Segment 102P04157			
		HERE		INRIX		HERE		INRIX	
		AASE	SEB	AASE	SEB	AASE	SEB	AASE	SEB
0-30 mph	122	22.41**	22.41*	24.85**	24.85*	21.58**	21.58*	24.73**	24.73*
30-50 mph	535	9.83	9.68*	11.49**	11.43*	9.80	9.65*	11.46**	11.40*
50-65 mph	1,757	5.45	1.71	6.01	4.4	5.46	1.72	6.02	4.40
>65 mph	51,901	2.29	-0.03	2.55	0.52	2.29	-0.03	2.55	0.52
Overall	54,315	2.52	0.17	2.8	0.81	2.51	0.17	2.80	0.81

** Failure: AASE more than 10 mph
* Failure: SEB not between 5 mph and -5 mph

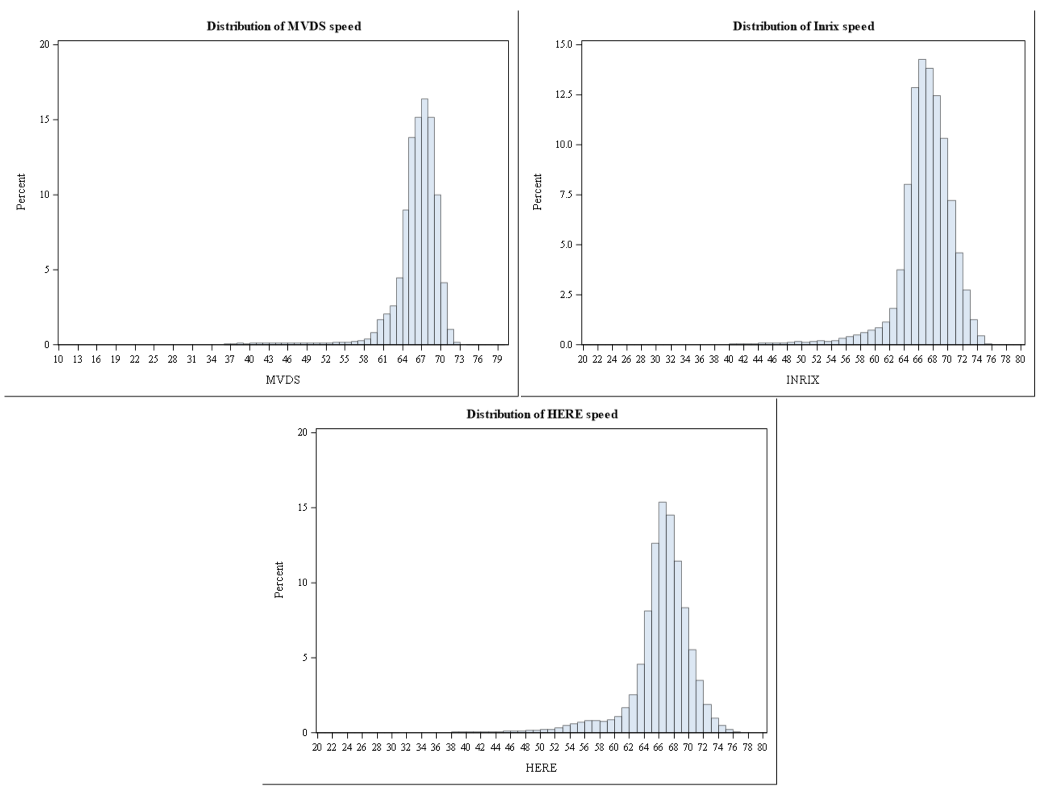


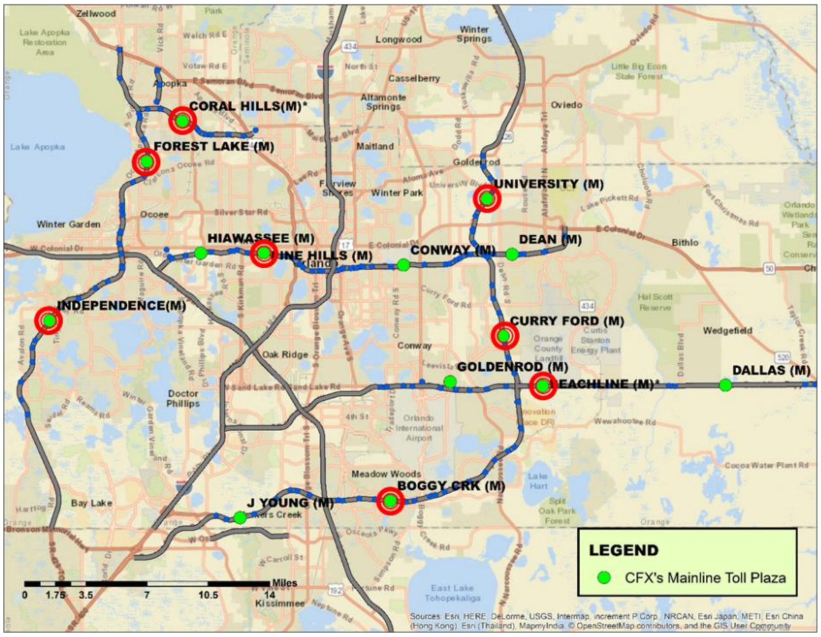
Figure 93. Speed distribution of INRIX, HERE, and MVDS

6.2.2. Penetration Ratio and Detection Rate Analysis of Toll Tags for AVI

In this project, AVI data were used as ground truth data of travel time and speeds. Reliability of the AVI data can also be confirmed through penetration ratio of transponders for toll collection and their detection rate. A toll transaction data set during September 2016 was collected through the cooperation with CFX. The toll transaction data set contains the following data elements:

- Road name
- Toll plaza name
- Toll plaza type: M (Mainline) and R (Ramp)
- Encrypted Vehicle ID
- Transaction date and time

CFX is operating 14 mainline toll plazas during December 2017 (see Figure 94). Among the 14 mainline toll plazas, 8 locations were selected to analyze the penetration ratio because there are more than one pair of MVDSs at upstream and downstream of the locations and also AVI of at least one pair without any exit and entrance of traffic flow (see Figure 95). Table 40 shows pairs of AVI and MVDS of each toll plaza. The analysis segment of each toll plaza has one pair of AVI and several pairs of MVDS. Based on the daily traffic volume of MVDS, daily total transaction data, and daily total toll tag IDs of AVI, the penetration ratio of transponders for toll collection and their detection rate were analyzed.



- SR 408
  - Hiawassee
  - **Pine Hills (※)**
  - Conway
  - Dean
- SR 417
  - **University (※)**
  - **Curry Ford (※)**
  - **Boggy Creek (※)**
  - John Young
- SR 414
  - **Coral Hills (※)**
- SR 419
  - **Forest Lake (※)**
  - **Independence (※)**
- SR 528
  - Goldenrod
  - **Beachline (※)**
  - Dallas

Figure 94. Locations of mainline toll plaza managed by CFX

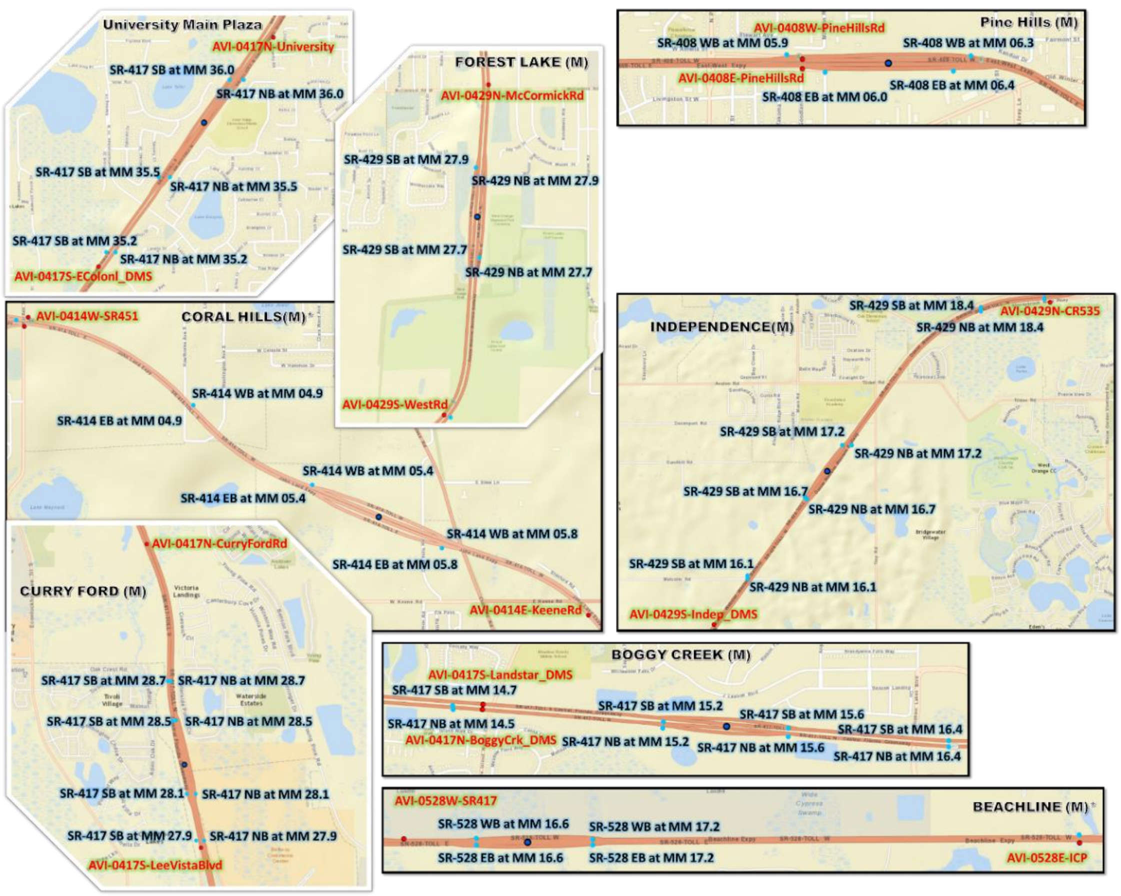


Figure 95. Locations of MVDS and AVI based on the eight mainline toll plazas

Table 40. Pairs of AVI and MVDS of each toll plazas

Toll Plaza	Paired AVI IDs		Paired MVDS locations	
Pine Hills	AVI-0408E-PineHillsRd	AVI-0408W-PineHillsRd	SR-408 EB at MM 06.0	SR-408 WB at MM 05.9
			SR-408 EB at MM 06.4	SR-408 WB at MM 06.3
University	AVI-0417S-EColonl_DMS	AVI-0417N-University	SR-417 SB at MM 35.2	SR-417 NB at MM 35.2
			SR-417 SB at MM 35.5	SR-417 NB at MM 35.5
			SR-417 SB at MM 36.0	SR-417 NB at MM 36.0
Curry Ford	AVI-0417S-LeeVistaBlvd	AVI-0417N-CurryFordRd	SR-417 SB at MM 27.9	SR-417 NB at MM 27.9
			SR-417 SB at MM 28.1	SR-417 NB at MM 28.1
			SR-417 SB at MM 28.5	SR-417 NB at MM 28.5
			SR-417 SB at MM 28.7	SR-417 NB at MM 28.7
Boggy Creek	AVI-0417S-Landstar_DMS	AVI-0417N-BoggyCrk_DMS	SR-417 SB at MM 14.7	SR-417 NB at MM 14.5
			SR-417 SB at MM 15.2	SR-417 NB at MM 15.2
			SR-417 SB at MM 15.6	SR-417 NB at MM 15.6
			SR-417 SB at MM 16.4	SR-417 NB at MM 16.4
Beach line	AVI-0528E-ICP	AVI-0528W-SR417	SR-528 EB at MM 16.6	SR-528 WB at MM 16.6
			SR-528 EB at MM 17.2	SR-528 WB at MM 17.2
Coral Hills	AVI-0414W-SR451	AVI-0414E-KeeneRd	SR-414 EB at MM 04.9	SR-414 WB at MM 04.9
			SR-414 EB at MM 05.4	SR-414 WB at MM 05.4
			SR-414 EB at MM 05.8	SR-414 WB at MM 05.8
Forest Lake	AVI-0429S-WestRd	AVI-0429N-McCormickRd	SR-429 SB at MM 27.7	SR-429 NB at MM 27.7
			SR-429 SB at MM 27.9	SR-429 NB at MM 27.9
Independence	AVI-0429S-Indep_DMS	AVI-0429N-CR535	SR-429 SB at MM 16.1	SR-429 NB at MM 16.1
			SR-429 SB at MM 16.7	SR-429 NB at MM 16.7
			SR-429 SB at MM 17.2	SR-429 NB at MM 17.2
			SR-429 SB at MM 18.4	SR-429 NB at MM 18.4

According to the analyses results, penetration ratio of transponders for electronic toll collection (ETC) was about 83.0% on the basis of average daily volume of MVDS. At the same period, the average detection rate of AVI readers is about 74.9% of transactions of ETC. It was confirmed that about 62% among the average daily volume of MVDS are detected by AVI readers. This means that the AVI system can provide high reliable travel time based on their high detection rate. Among the 8 mainline toll plazas, university toll plaza has the highest detection rate of AVI, whereas Curry Ford toll plaza has the lowest detection rate of AVI (see Table 41). According the daily penetration ratio and detection rate of toll tags, during the weekend and holidays, the daily penetration ratio is less than its total average (see Table 42). A possible reason is that weekend and holidays should have more tourists who may not have transponders.

Table 41. Penetration ratio and detection rate of toll tags of eight toll plazas

Toll Plaza Name	Average Daily Volume of MVDS (1)	Average Daily Transactions of ETC (2)	Average Daily Tags of AVI (3)	Penetration Ratio of Transponder (2)/(1)*100	Detection Rate of AVI (3)/(2)*100
BEACHLINE	56,940	45,562	33,162	80.0%	72.8%
BOGGY CREEK	60,306	48,757	43,123	80.8%	88.4%
CORAL HILLS	28,365	23,606	14,544	83.2%	61.6%
CURRY FORD	87,826	73,903	43,010	84.1%	58.2%
FOREST LAKE	46,950	39,042	27,156	83.2%	69.6%
INDEPENDENCE	29,411	23,794	17,006	80.9%	71.5%
PINE HILLS	75,669	64,696	48,519	85.5%	75.0%
UNIVERSITY	86,596	72,542	66,947	83.8%	92.3%
Average	59,008	48,988	36,683	83.0%	74.9%

Table 42. Daily penetration ratio and detection rate of toll tags

Date	Average Daily Volume of MVDS (1)	Average Daily Transactions of ETC (2)	Average Daily Tags of AVI (3)	Penetration Ratio of Transponder (2)/(1)*100	Detection Rate of AVI (3)/(2)*100
9/1/2016	60,258	50,612	33,112	84.0%	65.4%
9/2/2016	62,546	51,771	38,737	82.8%	74.8%
9/3/2016*	48,156	37,887	28,811	78.7%*	76.0%
9/4/2016*	40,880	32,790	25,771	80.2%*	78.6%
9/5/2016*	43,132	33,887	26,268	78.6%*	77.5%
9/6/2016	64,723	54,092	40,990	83.6%	75.8%
9/7/2016	63,972	53,787	39,502	84.1%	73.4%
9/8/2016	66,453	55,595	41,573	83.7%	74.8%
9/9/2016	70,794	58,413	39,447	82.5%	67.5%
9/10/2016*	52,423	41,588	31,616	79.3%*	76.0%
9/11/2016*	41,150	32,430	25,908	78.8%*	79.9%
9/12/2016	62,543	52,508	39,939	84.0%	76.1%
9/13/2016	60,280	51,708	39,332	85.8%	76.1%
9/14/2016	62,930	53,306	40,284	84.7%	75.6%
9/15/2016	66,593	56,185	41,386	84.4%	73.7%
9/16/2016	71,990	59,356	44,087	82.5%	74.3%
9/17/2016*	54,651	43,358	33,073	79.3%*	76.3%
9/18/2016*	43,795	34,564	27,552	78.9%*	79.7%
9/19/2016	62,339	53,089	40,682	85.2%	76.6%
9/20/2016	62,484	52,901	38,967	84.7%	73.7%
9/21/2016	64,089	54,375	39,576	84.8%	72.8%
9/22/2016	65,688	56,127	40,281	85.4%	71.8%
9/23/2016	69,440	58,241	43,406	83.9%	74.5%
9/24/2016*	52,987	42,112	31,843	79.5%*	75.6%
9/25/2016*	43,967	34,890	27,112	79.4%*	77.7%
9/26/2016	61,053	52,048	40,927	85.2%	78.6%
9/27/2016	63,110	53,927	39,452	85.5%	73.2%
9/28/2016	63,800	54,432	42,281	85.3%	77.7%
9/29/2016	66,208	56,002	42,931	84.6%	76.7%
Average	59,049	49,034	36,719	83.0%	74.9%
* Penetration ratio during weekend or holidays is less than its total average.					

6.2.3. Travel Time Reliability of HERE

Recently, FDOT is trying to use multiple data sources for mobility performance measures, such as travel time reliability, travel time variability, vehicle hours of delay and so on (Chung et al., 2018; FDOT, 2015b). In terms of data availability, cost-effectiveness, and usability of the multiple data sources, the National Performance Measure Research Dataset (NPMRDS) and HERE, instead of TomTom and INRIX, were chosen for the mobility performance measures of Florida. This study aims to compare travel time reliability of HERE's data with the actual truthful system, the AVI system, which differs with the previous research using Bluetooth. The AVI system uses toll tags, which provide much better, stable, and qualified data than Bluetooth. For comparison, it explores travel time reliability performance measures based on several analysis scenarios including each weekday of the year, time period of an average weekday, day of the week, and time of day of an average weekday.

6.2.3.1. Data preparation

The same six AVI segments, which are used in the validation of travel time of section 4.2.1, were used and the same data processing was applied. Different from the evaluation of travel time of multiple data sources, this study used AVI and HERE data of 2016 because usually travel time reliability is evaluated based on the one-year data.

6.2.3.2. Travel time reliability measures

Travel time reliability metrics were selected within four classifications, which are statistical range measures, buffer time measures, tardy-trip measures, and probabilistic measures. Currently, several agencies are using different travel time reliability measures considering their own mobility policies. These measures can also be distinguished by robust statistics, which are insensitive to the effects of outliers or events, and non-robust statistics. The robust statistics are based on medians instead of means and use more information from the center than from the outlying data (Huber, 2017). A skew statistic, width statistic, buffer index based on median and probabilistic measures use robust statistics.

A. Statistical Range Measures

Statistical range measures include standard deviation (SD), coefficient of variation (CV), skew statistic (λ^{skew}) and width statistic (λ^{var}), which are an attempt to quantify travel time reliability in a statistical perspective. The CV is one metric to measure data variability, which can be used to identify links or corridors to experience the higher travel time variation over long periods of time than other links (Turner et al., 2011a). The skew statistic and the width statistic follow the concept that asymmetric, wider, and larger distribution relative to median will be able to be unreliable (Van Lint and Van Zuylen, 2005). Thus, the two statistics should be considered together for travel time reliability.

$$CV = \frac{SD}{mean(\mu)} \times 100$$

$$\lambda^{skew} = \frac{TT_{90th} - TT_{50th}}{TT_{50th} - TT_{10th}}; \lambda^{var} = \frac{TT_{90th} - TT_{10th}}{TT_{50th}}$$

where TT_{90th}, TT_{50th}, and TT_{10th} stand for the 90^{th}, 50^{th}, and 10^{th} percentile travel time, respectively. Although FHWA does not recommend to use statistical range measures since it is not easy for the public to understand, this study used these measures to recognize specific difference of travel time reliability between AVI and HERE.

B. Buffer Time Measures

As buffer time measures, buffer index (BI) based on average, BI based on median, and planning time index (PTI) were selected. The BI implies that as a traveler should allow an extra percentage of travel time to arrive at a destination on time, and the PTI provides an expected travel time budget, which could be used as a trip planning measure for journeys that require punctuality (Lomax and Margiotta, 2003). FHWA, Georgia Regional Transportation Authority, Georgia Department of Transportation (DOT), and Maryland State Highway Administration (MSHA) introduced BI and PTI to represent travel time reliability (FHWA, 2006). Florida DOT and the National Transportation Operations Coalition (NTOC) are using BI (Turner et al., 2011b). Washington State DOT chose PTI to provide the best time for travelers to leave (WSDOT, 2017).

$$BI_{mean} = \frac{TT_{95th} - Average\ Travel\ Time}{Average\ Travel\ Time} \times 100(\%)$$

$$BI_{median} = \frac{TT_{95th} - Median\ Travel\ Time}{Median\ Travel\ Time} \times 100(\%)$$

$$PTI = \frac{TT_{95th}}{TT_{free\ flow\ or\ posted\ speed\ limit}}$$

C. Tardy Trip Measures

Tardy trip measures can explain the unreliability of travel time through late-arrival trips. Misery Index (MI) and On-Time Arrival (OTA) were used in this study. The MI focuses on the extra delay that occurred during the worst trip (Lomax and Margiotta, 2003). The OTA measure can be estimated by the proportion of travel times less than a designated travel time, which can be defined on “speed limit – 10 mph” (OTA(a)) or “1/3 × speed limit” (OTA(b)) speed (Elefteriadou and Cui, 2007).

$$MI = \frac{Average\ Travel\ Time\ for\ the\ longest\ 20\%\ of\ trips - Average\ Travel\ Time}{Average\ Travel\ Time}$$

D. Probabilistic Measures

This study adopts the probabilistic measure used by the Dutch Ministry of Transport, Public Works and Water Management (Van Lint et al., 2008). It calculates the probability that the observed travel times happen greater than α times predefined travel time threshold, which in this case is the median travel time on a given time of day or day of week. For this study, the parameter α is chosen as 1.2, which means the probability that travel time is larger than the median travel time + 20% (Van Lint et al., 2008).

$$PR(a) = P(TT_i \geq \alpha TT_{50th})$$

6.2.3.3. Analysis scenarios

Travel time reliability measures can be calculated according to various viewpoints. For example, the travel time reliability measures of each segment or corridor can be aggregated by day of week (DOW), time period (TP) such as AM peak, PM peak, Mid-day, and late PM of an average weekday, and time of day (TOD) of an average weekday. They can also be separated and analyzed depending on events including weather, incidents, and so on, but the events were not distinguished in this study. With reference to previous research (Lomax and Margiotta, 2003), several analysis scenarios were established as follow:

- Average travel time reliability by DOW of the whole year: the travel time reliability measures are aggregated for each DOW and analysis section.
- Average travel time reliability by TP (AM Peak, Mid-day, PM Peak, and Late PM) of an average weekday
- Average travel time reliability by TOD in an-hour intervals of an average weekday
- Average travel time reliability by TOD in 15-minute increments of an average weekday

- Average travel time reliability by TOD in 5-minute increments of an average weekday

To analyze the difference of travel time reliability measures between the two data sources, it is necessary to confirm whether travel time reliability measures derived from two data sources are equal statistically. As a general statistical method, the paired t-test was applied.

6.2.3.4. Analysis results and discussions

By using travel times and rates of 2016 on SR4- 417 based on the analysis scenarios, four types of travel time reliability measures between AVI and HERE were compared through the paired t-test. As with the review of travel rate distributions, the paired t-test was conducted by distinguishing southbound and northbound direction. The null hypothesis is that there is no significant mean difference of travel time reliability performance measures between AVI and HERE.

According to the results of the paired t-test of all data regardless of driving direction and segments (see Table 42), SD, CV, MI, and OTA(a) represent that AVI and HERE are statistically significantly different in all test scenarios. However, the skew statistics, the width statistics, BI based on median, and PR (1.2) show that AVI and HERE are not different until TOD in an hour increment. It seems that this kind of separation caused by characteristics of robust statistics. Considering various travel time distribution under different traffic conditions (Guessous et al., 2014), this result showed that travel time reliability measures with robust statistics can explain the relationship better between different data sources having the same purpose.

Table 43. All paired t-test results of travel time reliability measures between AVI and HERE

Test scenarios		Statistical range measure				Buffer time measure			Tardy trip measure			PR(1.2)
		SD	CV	λ_{skew}	λ_{var}	BI_{mean}	BI_{median}	PTI	MI	OTA(a)	OTA(b)	
DOW	p-value	0.000	0.000	0.292 *	0.060 *	0.313 *	0.502 *	0.478 *	0.002	0.623 *	0.000	0.456 *
	t-value	7.230	6.690	1.070	1.950	-1.030	0.680	-0.720	3.470	0.500	-4.440	0.760
	Δ	0.812	0.224	0.171	0.038	-1.040	1.102	-0.015	0.041	0.003	-0.001	0.003
	CI	0.582	0.155	-0.155	-0.002	-3.113	-2.216	-0.057	0.017	-0.009	-0.001	-0.006
		1.042	0.292	0.497	0.078	1.033	4.420	0.027	0.065	0.014	0.000	0.012
	DF	29	29	29	29	29	29	29	29	29	29	29
TP	p-value	0.000	0.000	0.718 *	0.699 *	0.110 *	0.586 *	0.041	0.040	0.181 *	0.021	0.442 *
	t-value	6.120	5.880	-0.360	-0.390	-1.650	-0.550	-2.130	2.150	1.370	-2.440	-0.780
	Δ	0.754	0.211	-0.054	-0.004	-1.516	-0.710	-0.037	0.021	0.014	0.000	-0.004
	CI	0.502	0.138	-0.354	-0.024	-3.395	-3.348	-0.072	0.001	-0.007	-0.001	-0.015
		1.006	0.284	0.247	0.016	0.364	1.929	-0.002	0.041	0.035	0.000	0.007
	DF	29	29	29	29	29	29	29	29	29	29	29
TOD (Hour)	p-value	0.000	0.000	0.043 *	0.933 *	0.003	0.421 *	0.000	0.000	0.079 *	0.000	0.180 *
	t-value	7.290	7.360	-2.040	-0.080	-3.020	-0.810	-4.330	4.450	1.770	-3.800	-1.350
	Δ	0.629	0.171	-0.178	0.000	-1.203	-0.444	-0.032	0.027	0.008	-0.001	-0.003
	CI	0.458	0.125	-0.350	-0.009	-1.991	-1.533	-0.046	0.015	-0.001	-0.001	-0.006
		0.799	0.217	-0.006	0.009	-0.416	0.644	-0.017	0.039	0.018	0.000	0.001
	DF	143	143	143	143	143	143	143	143	143	143	143
TOD (15-min)	p-value	0.000	0.000	0.000	0.565 *	0.000	0.060 *	0.000	0.000	0.001	0.000	0.017 *
	t-value	8.860	9.230	-4.430	-0.580	-5.590	-1.880	-8.530	6.620	3.300	-5.350	-2.400
	Δ	0.454	0.120	-0.175	-0.001	-1.176	-0.474	-0.032	0.026	0.008	-0.001	-0.002
	CI	0.353	0.095	-0.253	-0.005	-1.589	-0.969	-0.039	0.019	0.003	-0.001	-0.004
		0.555	0.146	-0.097	0.003	-0.762	0.021	-0.024	0.034	0.013	0.000	0.000
	DF	575	575	575	575	575	575	575	575	575	575	575
TOD (5-min)	p-value	0.000	0.000	0.000	0.175 *	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	t-value	10.290	10.980	-7.390	-1.360	-9.450	-4.170	-15.440	8.070	5.580	-6.820	-3.690
	Δ	0.318	0.081	-0.181	-0.002	-1.225	-0.614	-0.033	0.023	0.008	-0.001	-0.002
	CI	0.258	0.066	-0.229	-0.004	-1.479	-0.903	-0.037	0.017	0.005	-0.001	-0.003
		0.379	0.095	-0.133	0.001	-0.970	-0.325	-0.029	0.029	0.011	0.000	-0.001
	DF	1,727	1,727	1,727	1,727	1,727	1,727	1,727	1,727	1,727	1,727	1,727

* This indicates no rejection of the null hypothesis, there is no mean difference between paired measures, at $\alpha = 0.05$.
Δ: Mean difference

CI: Confidence Interval
DF: Degreed of Freedom
OTA(a): speed limit – 10 mph
OTA(b): 1/3 × speed limit

In the next analysis, the travel time reliability measures were compared by driving directions. Table 43 shows the comparison results of the southbound direction and Table 44 is about the northbound direction. Among statistical range measures of Tables 43 and 44, the standard deviation and the coefficient of variance are statistically significantly different between AVI and HERE in all test scenarios, whereas the width statistic (λ_{var}) are not statistically different in most test scenarios except for TOD (5-minute). However, the skew statistic (λ_{skew}) shows conflicting results in two different travel rate distributions. At least, the ratio of the range of travel times between 90th percentile travel time and 10th percentile travel time and the median is statistically consistent in AVI and HERE in all test scenarios except for TOD (5-minute).

Table 44. Paired t-test results of travel time reliability measures between AVI and HERE of the southbound direction

Test scenarios		Statistical range measure				Buffer time measure			Tardy trip measure			PR(1.2)
		SD	CV	λ_{skew}	λ_{var}	BI_{mean}	BI_{median}	PTI	MI	OTA(a)	OTA(b)	
DOW	p-value	0.000	0.000	0.045	0.262 *	0.156 *	0.828 *	0.000	0.007	0.000	0.004	0.373 *
	t-value	6.150	5.750	2.200	-1.170	-1.500	0.220	-6.000	3.160	7.870	-3.500	0.920
	Δ	0.829	0.233	0.191	-0.006	-0.847	0.138	-0.036	0.027	0.007	-0.001	0.001
	CI	0.540	0.146	0.005	-0.017	-2.057	-1.200	-0.049	0.009	0.005	-0.001	-0.002
		1.118	0.320	0.377	0.005	0.363	1.477	-0.023	0.045	0.009	0.000	0.005
	DF	14	14	14	14	14	14	14	14	14	14	14
TP	p-value	0.002	0.002	0.115 *	0.737 *	0.658	0.589 *	0.009	0.022	0.001	0.005	0.451 *
	t-value	3.800	3.690	1.680	-0.340	-0.450	0.550	-3.010	2.570	4.470	-3.360	0.780
	Δ	0.657	0.186	0.311	-0.003	-0.458	0.654	-0.033	0.024	0.008	-0.001	0.002
	CI	0.286	0.078	-0.086	-0.021	-2.629	-1.880	-0.056	0.004	0.004	-0.001	-0.004
		1.028	0.295	0.709	0.015	1.712	3.187	-0.009	0.043	0.012	0.000	0.009
	DF	14	14	14	14	14	14	14	14	14	14	14
TOD (Hour)	p-value	0.000	0.000	0.947 *	0.770 *	0.021	0.486 *	0.000	0.001	0.000	0.000	0.868 *
	t-value	4.990	4.980	-0.070	-0.290	-2.360	-0.700	-6.430	3.530	3.900	-4.850	-0.170
	Δ	0.529	0.147	-0.005	-0.001	-1.112	-0.366	-0.038	0.022	0.007	-0.001	0.000
	CI	0.317	0.088	-0.168	-0.011	-2.051	-1.408	-0.049	0.010	0.003	-0.001	-0.003
		0.740	0.206	0.157	0.008	-0.173	0.676	-0.026	0.035	0.010	0.000	0.002
	DF	71	71	71	71	71	71	71	71	71	71	71
TOD (15-min)	p-value	0.000	0.000	0.485 *	0.399 *	0.000	0.403 *	0.000	0.000	0.000	0.000	0.828 *
	t-value	6.570	6.670	-0.700	-0.840	-3.920	-0.840	-11.370	5.110	5.730	-6.740	0.220
	Δ	0.400	0.108	-0.030	-0.002	-1.024	-0.244	-0.037	0.021	0.007	-0.001	0.000
	CI	0.280	0.076	-0.114	-0.007	-1.539	-0.818	-0.043	0.013	0.004	-0.001	-0.002
		0.521	0.140	0.054	0.003	-0.509	0.330	-0.030	0.030	0.009	-0.001	0.002
	DF	287	287	287	287	287	287	287	287	287	287	287
TOD (5-min)	p-value	0.000	0.000	0.282 *	0.096 *	0.000	0.031	0.000	0.000	0.000	0.000	0.784 *
	t-value	7.630	8.030	-1.080	-1.660	-6.750	-2.160	-20.060	5.910	8.900	-8.540	0.270
	Δ	0.285	0.074	-0.029	-0.003	-1.099	-0.368	-0.038	0.019	0.007	-0.001	0.000
	CI	0.212	0.056	-0.082	-0.005	-1.419	-0.703	-0.042	0.013	0.005	-0.001	-0.001
		0.358	0.092	0.024	0.000	-0.779	-0.034	-0.034	0.026	0.008	-0.001	0.001
	DF	863	863	863	863	863	863	863	863	863	863	863

[a] This indicates no rejection of the null hypothesis, there is no mean difference between paired measures, at $\alpha = 0.05$.
Δ: Mean difference

CI: Confidence Interval
DF: Degreed of Freedom
OTA(a): speed limit – 10 mph
OTA(b): 1/3 × speed limit

Table 45. Paired t-test results of travel time reliability measures between AVI and HERE of the northbound direction

Test scenarios		Statistical range measure				Buffer time measure			Tardy trip measure			PR(1.2)
		SD	CV	λ_{skew}	λ_{var}	BI_{mean}	BI_{median}	PTI	MI	OTA(a)	OTA(b)	
DOW	p-value	0.001	0.002	0.636 *	0.053 *	0.544 *	0.532 *	0.874 *	0.024	0.912 *	0.016	0.568 *
	t-value	4.310	3.930	0.480	2.110	-0.620	0.640	0.160	2.530	-0.110	-2.730	0.580
	Δ	0.796	0.214	0.151	0.081	-1.233	2.065	0.007	0.055	-0.001	-0.001	0.005
	CI	0.400	0.097	-0.519	0.163	-5.487	-4.845	-0.081	0.008	-0.025	-0.001	-0.013
		1.192	0.331	0.821	-0.001	3.021	8.976	0.094	0.102	0.023	0.000	0.024
	DF	14	14	14	14	14	14	14	14	14	14	14
TP	p-value	0.000	0.000	0.045	0.793 *	0.113 *	0.380 *	0.240 *	0.316 *	0.354 *	0.421 *	0.304 *
	t-value	4.780	4.540	-2.200	-0.270	-1.690	-0.910	-1.230	1.040	0.960	-0.830	-1.070
	Δ	0.851	0.236	-0.419	-0.006	-2.573	-2.073	-0.041	0.018	0.020	0.000	-0.011
	CI	0.469	0.124	-0.827	0.043	-5.836	-6.980	-0.113	-0.019	-0.024	-0.001	-0.032
		1.232	0.347	-0.010	-0.055	0.690	2.834	0.031	0.056	0.064	0.000	0.011
	DF	14	14	14	14	14	14	14	14	14	14	14
TOD (Hour)	p-value	0.000	0.000	0.024	0.446 *	0.049	0.593 *	0.061 *	0.003	0.289 *	0.114 *	0.173 *
	t-value	5.370	5.430	-2.310	0.770	-2.000	-0.540	-1.900	3.040	1.070	-1.600	-1.380
	Δ	0.729	0.195	-0.350	0.007	-1.295	-0.523	-0.026	0.031	0.010	0.000	-0.005
	CI	0.458	0.123	-0.653	0.026	-2.583	-2.465	-0.052	0.011	-0.009	-0.001	-0.012
		1.000	0.266	-0.047	-0.012	-0.007	1.419	0.001	0.052	0.029	0.000	0.002
	DF	71	71	71	71	71	71	71	71	71	71	71
TOD (15-min)	p-value	0.000	0.000	0.000	0.081 *	0.000	0.088 *	0.000	0.000	0.043	0.021	0.004
	t-value	6.160	6.480	-4.890	1.750	-4.020	-1.710	-3.980	4.640	2.030	-2.330	-2.910
	Δ	0.507	0.132	-0.320	0.007	-1.328	-0.704	-0.026	0.032	0.010	0.000	-0.005
	CI	0.345	0.092	-0.449	0.016	-1.978	-1.512	-0.040	0.018	0.000	-0.001	-0.008
		0.669	0.172	-0.191	-0.001	-0.678	0.105	-0.013	0.045	0.020	0.000	-0.002
	DF	287	287	287	287	287	287	287	287	287	287	287
TOD (5-min)	p-value	0.000	0.000	0.000	0.011	0.000	0.000	0.000	0.000	0.001	0.004	0.000
	t-value	7.130	7.640	-8.290	2.550	-6.690	-3.580	-7.310	5.710	3.460	-2.880	-4.360
	Δ	0.351	0.087	-0.332	0.006	-1.350	-0.859	-0.028	0.027	0.010	0.000	-0.005
	CI	0.255	0.065	-0.411	0.011	-1.747	-1.330	-0.035	0.017	0.004	-0.001	-0.007
		0.448	0.110	-0.253	0.001	-0.954	-0.388	-0.020	0.036	0.016	0.000	-0.002
	DF	863	863	863	863	863	863	863	863	863	863	863

[a] This indicates no rejection of the null hypothesis, there is no mean difference between paired measures, at $\alpha = 0.05$.
Δ: Mean difference

CI: Confidence Interval
DF: Degreed of Freedom
OTA(a): speed limit – 10 mph
OTA(b): 1/3 × speed limit

In the buffer time measures, BI based on mean and BI based on median show a consistent result in the two distributions. The BI based on mean has no difference between AVI and HERE in the only DOW and TP test scenarios, but the BI based on median has no difference in the DOW, TP, TOD (Hour) and TOD (15-minute). On the other hand, PTI has no statistical difference between AVI and HERE in only the North Direction's travel time distribution. The BI based on median using one of the robust estimators shows that there is no difference between AVI and HERE till the test scenarios from DOW to TOD (15-minute). This is the same result as the width statistic. The only difference is that the width statistic uses 90th, 10th, and 50th percentile travel time, and the buffer index is based on the median and uses the 95th and 50th percentile travel time.

Furthermore, it was found that all tardy travel measures are not different between AVI and HERE in only the northbound travel time distribution with DOW, TP, and TOD (Hour) test scenarios. Finally, the probabilistic measure, PR(1.2), had the same results in three test scenarios, DOW, TP and TOD (Hour), on the distribution of both directions. PR(1.2) also uses the 50th percentile travel time.

Finally, the comparison of travel time reliability measures between AVI and HERE was conducted for each segment (see Table 45). For this test, DOW and TP test scenarios were not included because the sample size is too small. When the size of the interval of time of day is decreased, the number of measures, representing two distributions are not different, is decreased. Based on Table 45, travel time reliability measures of HERE are not different with AVI at most segments except for SB02 in TOD (Hour). The SB02 does not have any measure with p-value more than 0.05 in all TOD, which means AVI and HERE data in the SB02 segment is definitely different or there may be some error between AVI and HERE.

Table 46. Paired t-test results of travel time reliability measures between AVI and HERE of the northbound direction

Test scenarios		Statistical range measure				Buffer time measure			Tardy trip measure			PR(1.2)
		SD	CV	λ_{skew}	λ_{var}	BI_{mean}	BI_{median}	PTI	MI	OTA(a)	OTA(b)	
TOD (Hour)	NB01	0.002	0.002	0.051 *	0.664 *	0.012	0.380 *	0.600 *	0.009	0.381 *	0.002	0.406 *
	NB02	0.060 *	0.043	0.091 *	0.323 *	0.042	0.093 *	0.000	0.808 *	0.050 *	0.838 *	0.053 *
	NB03	0.001	0.001	0.309 *	0.079 *	0.763 *	0.462 *	0.251 *	0.031	0.086 *	0.855 *	0.972 *
	SB01	0.010	0.010	0.332 *	0.061 *	0.468 *	0.185 *	0.333 *	0.005	0.112 *	0.003	0.412 *
	SB02	0.000	0.000	0.001	0.003	0.000	0.000	0.000	0.028	0.000	0.004	0.000
	SB03	0.136 *	0.131 *	0.452 *	0.617 *	0.145 *	0.220 *	0.000	0.730 *	0.006	0.047	0.349 *
TOD (15-min)	NB01	0.000	0.000	0.000	0.360 *	0.000	0.116 *	0.328 *	0.000	0.111 *	0.000	0.159 *
	NB02	0.034	0.020	0.015	0.064 *	0.000	0.003	0.000	0.495 *	0.000	0.988 *	0.000
	NB03	0.001	0.001	0.009	0.000	0.846 *	0.403 *	0.043	0.003	0.003	0.795 *	0.425 *
	SB01	0.000	0.000	0.164 *	0.002	0.102 *	0.005	0.144 *	0.000	0.019	0.000	0.096 *
	SB02	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000
	SB03	0.038	0.035	0.163 *	0.247 *	0.009	0.030	0.000	0.605 *	0.000	0.006	0.154 *
TOD (5-min)	NB01	0.000	0.000	0.000	0.128 *	0.000	0.003	0.053 *	0.000	0.019	0.000	0.080 *
	NB02	0.009	0.003	0.000	0.001	0.000	0.000	0.000	0.533 *	0.000	0.913 *	0.000
	NB03	0.001	0.001	0.000	0.000	0.827 *	0.371 *	0.002	0.001	0.000	0.891 *	0.292 *
	SB01	0.000	0.000	0.045	0.000	0.047	0.000	0.002	0.000	0.000	0.000	0.008
	SB02	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	SB03	0.043	0.037	0.244 *	0.050 *	0.000	0.000	0.000	0.710 *	0.000	0.004	0.093 *

* This indicates no rejection of the null hypothesis, there is no mean difference between paired measures, at $\alpha = 0.05$.
OTA(a): speed limit – 10 mph
OTA(b): 1/3 × speed limit

According to the statistical test results of the two groups, it was confirmed that the results were different depending on elements of performance measures. It is shown that SD and CV, which are representative of non-robust estimators using an average, have statistically significant differences between AVI and HERE. In addition, most of the PTI, MI, and OTA using non-robust estimators, average travel time, did not provide consistent evaluation results in AVI and HERE, although BI based on mean travel times shows that the two data sources are not different in travel time reliability of day of week and time periods of an average weekday.

On the other hands, it was found that there is no statistical difference between AVI and HERE in terms of travel time reliability using day of the week, time periods, and time of day in an hour unit according to the test results of the width statistic, buffer index based on median, and PR (1.2), which are using the robust estimator, although the skew statistic did not yield a consistent conclusion in both distributions. However, the travel time reliability measures calculated from the two different data sources at 5-minute and 15-minute units can also yield different results. It is obvious that HERE data as a real-time feed will have differences with AVI data since the HERE data can be estimated for all time periods through unopened modeling methods including smoothing, filtering, and imputation using historical data when the collected data are insufficient. The differences will be revealed more obviously when the aggregation time span shortens. However, if raw traffic data without modeling will be used, the differences will be reduced although there might be irreducible errors. In conclusion, on the basis of the average-based BI, PTI, and OTA, which are currently used by public agencies in the USA, AVI and HERE cannot estimate consistent travel time reliability measures in real time.

6.2.4. Discussions

Freeways and expressways in the Orlando Metropolitan region are operated and managed by three agencies: FDOT, CFX, and FTE. The three authorities are monitoring traffic conditions through MVDS, AVI, and Bluetooth on their own. In addition, HERE as a representative of a private company is collecting traffic information for all freeways and expressways. Based on the AVI raw data, uncapped travel times were estimated. The uncapped travel times were used as ground truth data for the evaluation of MVDS and HERE. Comparing NPMRDS with AVI data, it was found that NPMRDS is also close to AVI data. Thus, the NPMRDS was also utilized ground truth travel time for the evaluation of Bluetooth data although it is not a real-time traffic data collection system. In addition, the reliability of AVI was confirmed indirectly through the penetration of toll tags, which is about 83%, and their detection rate of AVI readers, which is about 75%. The evaluation of MVDS, Bluetooth, and HERE was conducted through AASE and SEB, which are used in the VPP (Vehicle Probe Project) to validate travel time and speed of HERE, INRIX, and TOMTOM. According to the evaluation results of MVDS, HERE, and Bluetooth data, all of them showed inaccurate speeds and travel time when the average speed is less than 60 mph. Therefore, data fusion algorithm of multiple data sources should be proposed for the freeways and expressways have MVDS, HERE, or Bluetooth but do not have AVI data or reliable toll tag penetration. The fusion algorithm will be discussed in Section 4.4.

6.3. Data Evaluation for Arterials

In terms of travel time, there are two data sources available on the arterial network in the study area. One is infrastructure-based Bluetooth Detection System (BDS) provided by several different vendors. Traffic data from BDS were frequently used as the benchmark "ground truth" data to validate (Hu et al., 2016; Wang et al., 2014; Zhang et al., 2015). However, there are several systematical errors of BDS due to the inherent drawbacks of its mechanism. Section 4.3.1 will discuss the systematical errors of BDS comprehensively and propose possible approaches to eliminate them. Beside BDS, Florida Department of Transportation (FDOT) also purchased speed and travel time data from private sector traffic service company, i.e., HERE. HERE utilized probe vehicles tracking technologies to estimate travel time for an extensive roadway network. However, the data quality should be checked since the exact data source and processing algorithms are proprietary.

In order to evaluate to quality of both data sources, a "ground truth" validation dataset, which includes High-resolution GPS trajectories, was collected in the field. Several volunteer drivers were asked to record their trajectories when they drove along the whole or part of the corridor by smart phone GPS tracking applications. The applications record the geographical coordinates of the vehicle (or precisely, the smart phone) every one to two seconds, which provide a high-resolution trajectory data to calculate the ground truth travel time and space mean speed data.

As shown in Table 47, different BDS vendors provide different types of data. The research group collected raw detection log and filtered travel time of individual vehicles from BlueMAC for 4 arterial corridors in Orange County from Orange County Traffic Engineering Office. Beside the 4 arterial corridors, we also collected the first detection of BlueMAC data for some major arterials in Orange County and collectors in City of Orlando from SunGuide System of District 5. Both Orange County Traffic Engineering Office and SunGuide System of District 5 also provide filtered travel time of individual vehicles for these roads. In addition, Orange County Traffic Engineering Office could provide the filtered travel time of individual vehicles from Vantage Velocity® for two other arterials in Orange County. Furthermore, the filtered travel time of individual vehicles for all arterials in Seminole County from BlueTOAD were collected from Seminole County Traffic Engineering Office. In summary, there are three types of Bluetooth data available in the study area: raw data on 4 arterial corridors in Orange County, first detection data, and filtered travel time on arterials and collectors. Hence, three different studies were conducted to evaluate the three different types of BDS data, separately. To specify, a study on Alafaya Trail, Orange County evaluated the segment space mean speed estimated from the raw detections from BlueMAC and the corresponding speed data from HERE, which will be elaborated on in Section 6.3.2. Besides, one study on Mitchell Hammock Road, Seminole County evaluated the segment space mean speed estimated from the filtered travel time of individual vehicles from BlueTOAD and the corresponding speed data from HERE, which will be elaborated on in Section 6.3.3. Lastly, Section 6.3.4 will extend the evaluation to urban collectors. Segment space mean speed of several collectors in Downtown Orlando estimated by both first detections by BlueMAC and travel time of individual vehicles. Meanwhile, the corresponding speed data from HERE were evaluated.

Table 47. Information of bluetooth detection system

Data Type	Data Source	Collection Agency	Roadway
Raw detection	BlueMAC	Orange County	4 arterial corridors
First detection	BlueMAC	District 5	Major arterials in Orange County and Collectors in City of Orlando
Filtered travel time of individual vehicle	BlueMAC	Orange County & District 5	Major arterials in Orange County and Collectors in City of Orlando
	BlueTOAD	Seminole County	All arterials
	Vantage Velocity®	Orange County	2 arterial corridors

6.3.1. Discussion on Systematical Errors of the Bluetooth Detection System

Bluetooth Detection System (BDS) employs the vehicle identification and re-identification concept to estimate the travel time of a specific vehicle between two BDS detectors. BDS employed the Bluetooth communication process to detect a specific vehicle with Bluetooth devices. The Media Access Control (MAC) address is employed to identify the vehicles. Then the detected MAC address and its associated detection timestamp could be matched with the detection of the same vehicle by another detector. The difference of the timestamps is the estimated travel time. The following equation gives the fundamental mechanism of AVI travel time estimation.

$$TT_{i,u,d} = t_{i,d} - t_{i,u}$$

where, $TT_{i,u,d}$ is the travel time of the vehicle i between upstream detector and downstream detector; $t_{i,d}$ is the timestamp when the vehicle i was detected by the downstream detector; $t_{i,u}$ is the timestamp when the vehicle i was detected by the upstream detector.

Figure 96 shows three basic steps of the travel time estimation process by BDS. With the steps and estimation method, several errors could occur corresponding to each step.

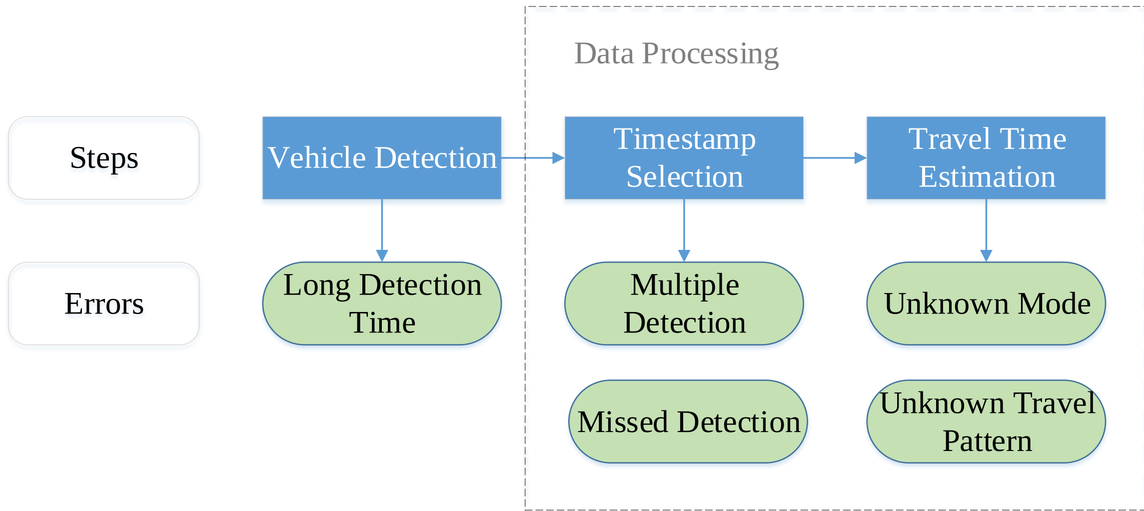


Figure 96. Travel time estimation process of BDS

6.3.1.1. Long Detection Time

The basic mechanism of the vehicle detection is a two-way communication process between Bluetooth detectors and the Bluetooth devices, including hands-free devices and smartphones. Based on the Bluetooth protocol (Bluetooth Special Interest Group, 2017), the time recommended for the whole process is 10.24 s. Kasten and Langheinrich (2001) investigated the distribution of time needed for the process. The probability of detecting a device in 1.910 s, 4.728 s, and 5.449 s is 50%, 95% and 99%, respectively. In short, it could take a long time to detect a vehicle for the BDS, which would lead to uncertainty of the location where the vehicle was first detected.

6.3.1.2. Multiple and Missed Detection

Due to the long detection time issue, detectors used in the BDS need a rather large detection range in order to detect enough vehicles for a better travel time estimation. For instance, for an arterial with the speed limit of 50mph, the detection range should be at least 346 feet to detect 95% of vehicles based on the time of the detection process. In the field, Class-1 devices with a theoretical detection range of at least 330 feet (100 m) are utilized as the detectors of BDS (Bhaskar and Chung, 2013; Digiwest, 2016). A field experiment conducted by the research team found that the real detection range of BlueMAC devices could reach 500 feet.

A large detection zone could increase the probability of a vehicle to be detected, since the vehicle could stay within the zone for a relatively lone time period. However, at the same time, it could lead to a serious issue called "multiple detections". Assume a vehicle running at 50mph was detected when it just entered the detection zone and the radius of the zone is 330 feet. Therefore, the vehicle had been staying within the detection zone for four seconds. If the granularity of reported timestamps is one second, the detector would report the MAC address associated with the vehicle at least 4 times. As the fundamental mechanism of AVI travel time estimation required a unique timestamp to calculate the travel time, a good strategy to select the "unique" timestamp among multiple detections is crucial for BDS travel time estimation.

The "multiple detections" issue would be even more serious for arterials. In order to ensure the power supply and network connectivity of the BDS, transportation agencies typically install the BDS detectors within or close to the signal controller cabinet, which is located at the corner of a signalized intersection. Figure 97 shows an illustration of the detection zone of a BDS detector installed at the northwest corner of the intersection of Alafaya Trail and Lake Underhill Drive in Orange County. A 330-ft detection zone is able to cover four legs of the intersection.

Thus, one detector is enough to monitor the traffic from four ways of intersection, which reduces the cost of the BDS system. However, the vehicles approaching the intersection should stop during the red time. Then, the time period for staying in the detection zone will be longer than the assumption above and the reported detections would be more. In addition, the detection range is also not consistent for the 4 legs as the detector is installed at one corner of the intersection.

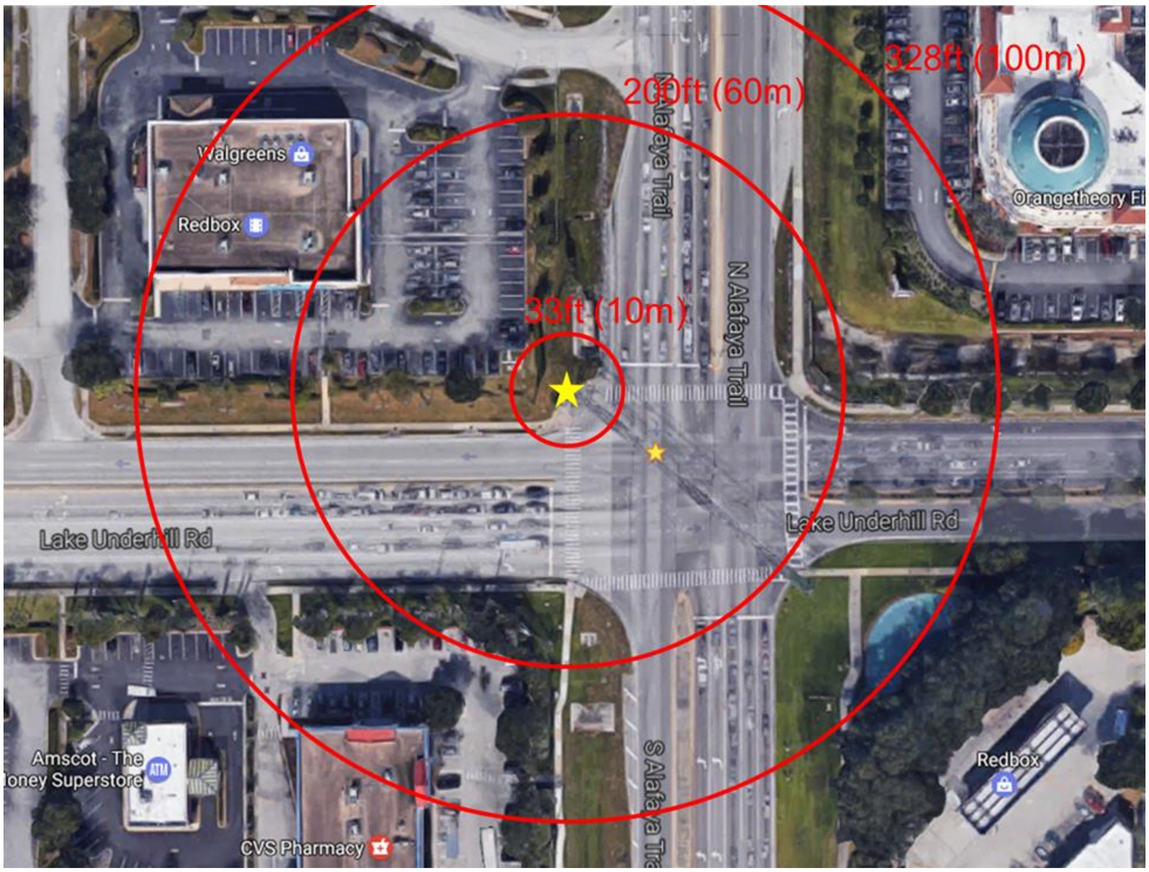


Figure 97. Illustration of bluetooth detection range

The "multiple detections" issue could make it difficult to identify the exact location which is closest to the detectors. For example, the measured distance between the location associated with the first upstream detection and that associated with the last downstream detection should be longer than the measured distance between the location associated with last upstream detection and that associated with first downstream detection. Thus, a consistent detection selection strategy should be applied, which will be discussed later.

Although the BDS detectors have a relatively large detection zone, it is not guaranteed that all vehicles could be detected. The missed detection would reduce the sample size for travel time estimation, which may lead to inconsistency for travel time estimation "segment". On the other hand, the wrong match could be caused by the missed detection, which could be a problem for automatic estimation algorithms.

6.3.1.3. Unknown Mode and Unknown Travel Pattern

BDS utilized the Bluetooth communication process to detect the vehicles with a discoverable Bluetooth device. However, if a pedestrian or a bicyclist carrying a smartphone or Bluetooth wireless headphone, the travel time of pedestrian and bicycle mode could also be detected by the BDS. If one is interested in the travel time of a specific mode, an appropriate method should be utilized to separate different modes. Some BDS used statistical data filtering algorithms. Díaz et al. (2015) employed Dedicated Inquiry Access Code (DIAC) of the devices to select only the detections associated with "Hands-free Device" to estimate the travel time of vehicles only. However, not all BDS detectors are capable to detect DIAC of the Bluetooth devices. As a result, for areas with significant pedestrian and bicycle activities, such as downtown and a university campus, only statistical data filtering algorithms might not be sufficient. In addition, the BDS detectors are only able to detect the vehicle behavior within its detection zone. Hence, the travel patterns between the zones such as detour and parking, whose travel time is significantly different from those of vehicles traversing the segment, should be taken into consideration.

6.3.2. Bluetooth Data Processing Method

6.3.2.1. Detection Selection Methodology

As discussed above, in order to calculate "segment" travel time, a "unique" timestamp among multiple detections should be selected. Figure 98 is an illustration of the trajectory of a vehicle traversing upstream and downstream intersections. The yellow horizontal bold lines indicate the stop line at the intersection. According to the figure, the vehicle runs through the upstream intersection during the green light and stops at the downstream due to the red light. Several different methods were proposed for detection selection, including (1) first-first matching using the first detection ($t_{i,f}$, $i \in \{u, d\}$); (2) last-last matching using the last detection ($t_{i,l}$, $i \in \{u, d\}$); (3) max-max matching, and (4) improved max-max matching using the detection associated with the maximum Received Signal Strength Indicator (RSSI) ($t_{i,m}$, $i \in \{u, d\}$) and stop-stop matching using the detection of the vehicle exactly at the stop line ($t_{s,l}$, $i \in \{u, d\}$). The timestamps of the aforementioned four selection methods are also labelled in Figure 92.

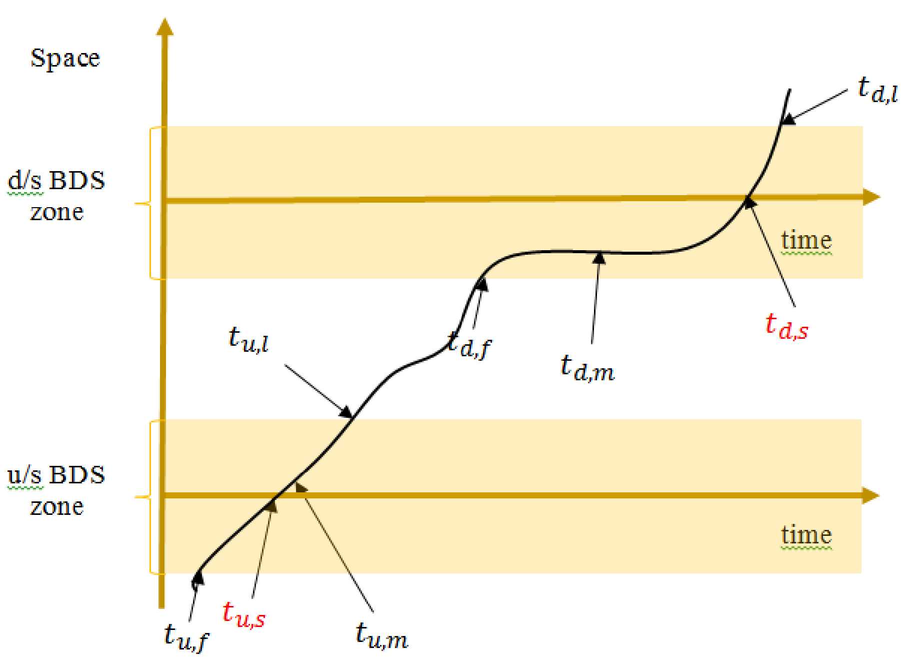


Figure 98. Illustration of detection selection methodologies

The last two methods aim at eliminating the errors caused by long detection time and location ambiguity caused by multiple matching. The last method (the stop-stop matching) could theoretically eliminate the error and uniformly catch the control delay of the downstream intersection, since they used a unique and predefined location. However, it is only available in the traffic simulation not the field because it is impossible to find out the exact location without the vehicle's real geographical trajectory. It should be noted that the travel time for validation extracted from GPS trajectories are estimated by stop-stop matching method, since the timestamp when the vehicle is exactly at the stop line could be known from the trajectories.

The mechanism behind the max-max matching is that RSSI is an approximate indicator of distance between Bluetooth detectors and discoverable devices. The higher the RSSI, the closer for the device to the detector will be. The detection with the max RSSI should indicate that the corresponding vehicle is detected very close to the detector. Since the travel time for a vehicle to cross an intersection is only one to two seconds, the detection with the max RSSI should also indicate the time when the corresponding vehicle is very close to the stop line. Therefore, the max-max matching is a field-feasible approximation of the stop-stop matching. However, according to the field study conducted by our research team, the detection with the max RSSI ($t_{d,m}$) is less likely to be the detection of the vehicle exactly at the stop line if the vehicle stops during red light, which might lead to some errors. It is worth to mention that the third method is only feasible when the BDS detector is capable to catch and provide the RSSI. Hence, this method is only applicable for BlueMAC in Orange County among the three vendors in our study area.

The first-first matching and last-last matching are not the approximations of stop-stop matching. The systematic errors of the two methods are relatively higher than max-max matching since the first or last detection is not necessary the timestamp the vehicle entering or exiting the theoretical 330 feet detection zone. Therefore, the measured distance between two detections are not the same as the distance between stop lines. The error of the abovementioned two methods could be expressed as:

$$TT_{f,f} = t_{d,f} - t_{u,f} = TT_f + \varepsilon_{ldt,d} - \varepsilon_{ldt,u} + \varepsilon_{dr,d} - \varepsilon_{dr,u} + d_u$$
$$TT_{l,l} = t_{d,f} - t_{u,f} = TT_f + \varepsilon_{dr,d} - \varepsilon_{dr,u} + d_d$$

where, $TT_{f,f}$,$TT_{l,l}$ are travel time of first-first matching and last-last matching; TT_f is free flow travel time; $\varepsilon_{ldt,i}, i \in \{u, d\}$ is error caused by long detection time; $\varepsilon_{dr,i}, i \in \{u, d\}$ indicates error caused by uncertain size of detection zone; $d_i, i \in \{u, d\}$ is the control delay.

The research team conducted a study to examine the magnitude of the error of first detection. The timestamps of the first detections were compared with the "Ground Truth" timestamp when the vehicle entering the theoretical 330 feet detection zone was extracted from GPS trajectories. The reason to choose first detection since it is the matching method used by all vendors in our study area. The study was conducted in October 2017 in Downtown Orlando. Data from 8 detectors were used and totally 176 detections were collected. Figure 93 shows the distribution of the difference between the timestamp of the first detection and that when the vehicle enters the theoretical 330-ft detection zone. The mean difference is 48.76 seconds and the median is 15 seconds. In short, the magnitude of the error is quite large. The details about the study including the study site will be discussed in Section 4.3.5.

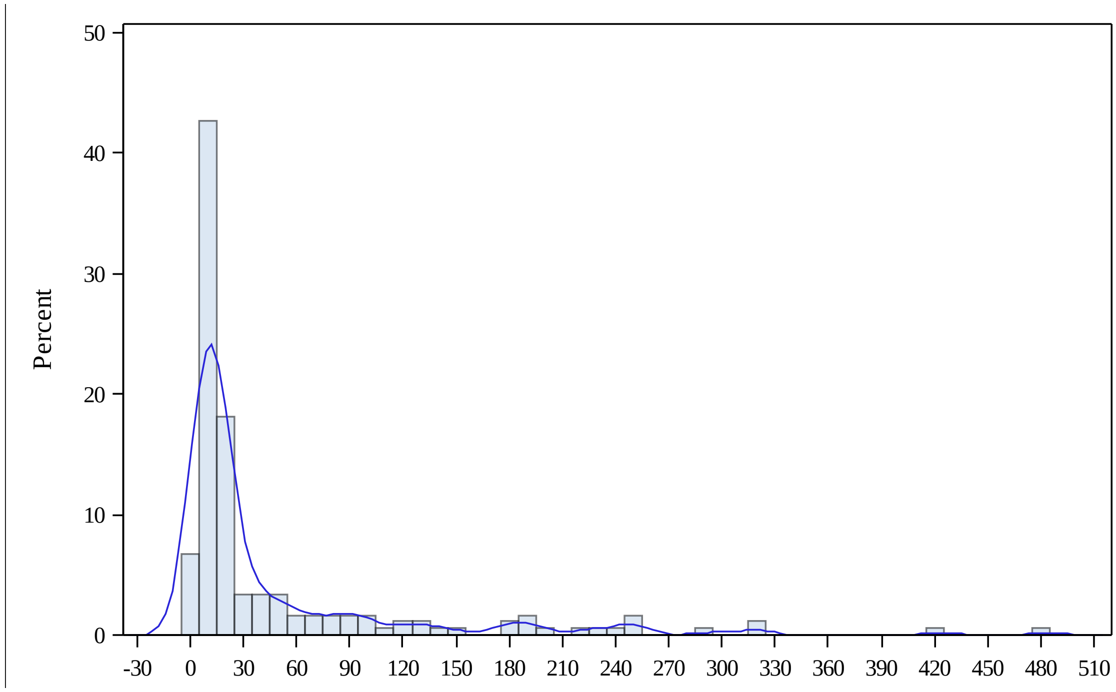


Figure 99. Magnitude of error of first detection

However, relatively small difference between travel time estimated by the first-first detection and the "Ground truth" GPS travel time data is found. It may be because the difference may be cancelled out during the estimation of travel time if the error terms are consistent at the upstream and downstream. This finding shades light on the feasibility of using first-first or last-last matching when the BDS detector is not able to record the RSSI information. The details will be discussed in Section 3.5. In addition to the theoretical discussion about the error term, the research team compared the segments' space mean speed of individual vehicles estimated by first-first matching, last-last matching, and max-max matching of BlueMAC data on Alafaya Trail with those from the GPS validation dataset. A total of 194 observations of individual travel time were evaluated. Table 48 shows the absolute error between the estimated travel time and the ground truth travel time. According to the table, the max-max matching approach has the best accuracy. As a consequence, the max-max matching method was chosen as the detection selection method in this project.

Table 48. Absolute error between estimated travel time and ground truth

Variable	Mean	Std Dev
First-First Matching	8.817	10.144
Last-Last Matching	4.688	8.335
Max-Max Matching	4.377	8.561

6.3.2.2. Outlier Filtering Algorithm

Missed detection, unknown node and unknown travel pattern would lead to unrealistic travel time data. An appropriate filtering algorithm should be applied to eliminate outliers.

The BlueMAC system utilizes absolute values to eliminate extremely low or high travel time. However, the minimum lower bound was set to 30 seconds which is too long for short segments. For example, for Alafaya Trail in Orange County, the free flow travel time of over 60% of segments is less than 30s while the minimum one is only 17 seconds. Thus, the valid travel time will be "filtered out" by the filtering algorithm. As a result, the travel time obtained directly from the BlueMAC systems will not be used in this project. Instead, the research team decided to use the raw detection logs to estimate travel time and apply mathematical filtering algorithms.

Mathematical filtering algorithms such as Moving Median filter, Median Absolute Deviation (MAD) filter, Box-and-Whisker filter, etc. were suggested (Lomax and Margiotta, 2003). In this project, a Moving Median Absolute Deviation (MAD) filtering algorithm was adopted to eliminate outliers. First, the median of all space mean speed readings with a nine-minute moving window was calculated (Elefteriadou and Cui, 2007). Then, the upper bound value (UBV) and lower bound value (LBV) could be calculated as:

$$v_{ub} = Med + \hat{\sigma} f \tag{15}$$

$$v_{lb} = Med + \hat{\sigma}f \quad (16)$$

$$\hat{\sigma} = 1.4826 * MAD \quad (17)$$

$$MAD = median(|v_i - median(v)|) \quad (18)$$

where, v_{ub} and v_{lb} is the UBV and LBV; Med is the median space mean speed of the speed observations among the moving time window; MAD is the median absolute deviation from the Med; $\hat{\sigma}$ is the standard deviation from MAD. f value indicates the variance level of speed data. A smaller f gives a higher confidence, yet several valid data might be filtered out if the variance is relatively large. In this study, 1.5 is selected as the f value.

6.3.3. Evaluation of BlueMAC and Corresponding HERE

6.3.3.1. Study Site

A 5.4-mile segment of a principal arterial corridor-Alafaya Trail-in Orange County was selected. The map of the study corridor is presented in Figure 100. The segment is between McCulloch Road and Curry Ford Road with a posted speed limit of 45 mph.

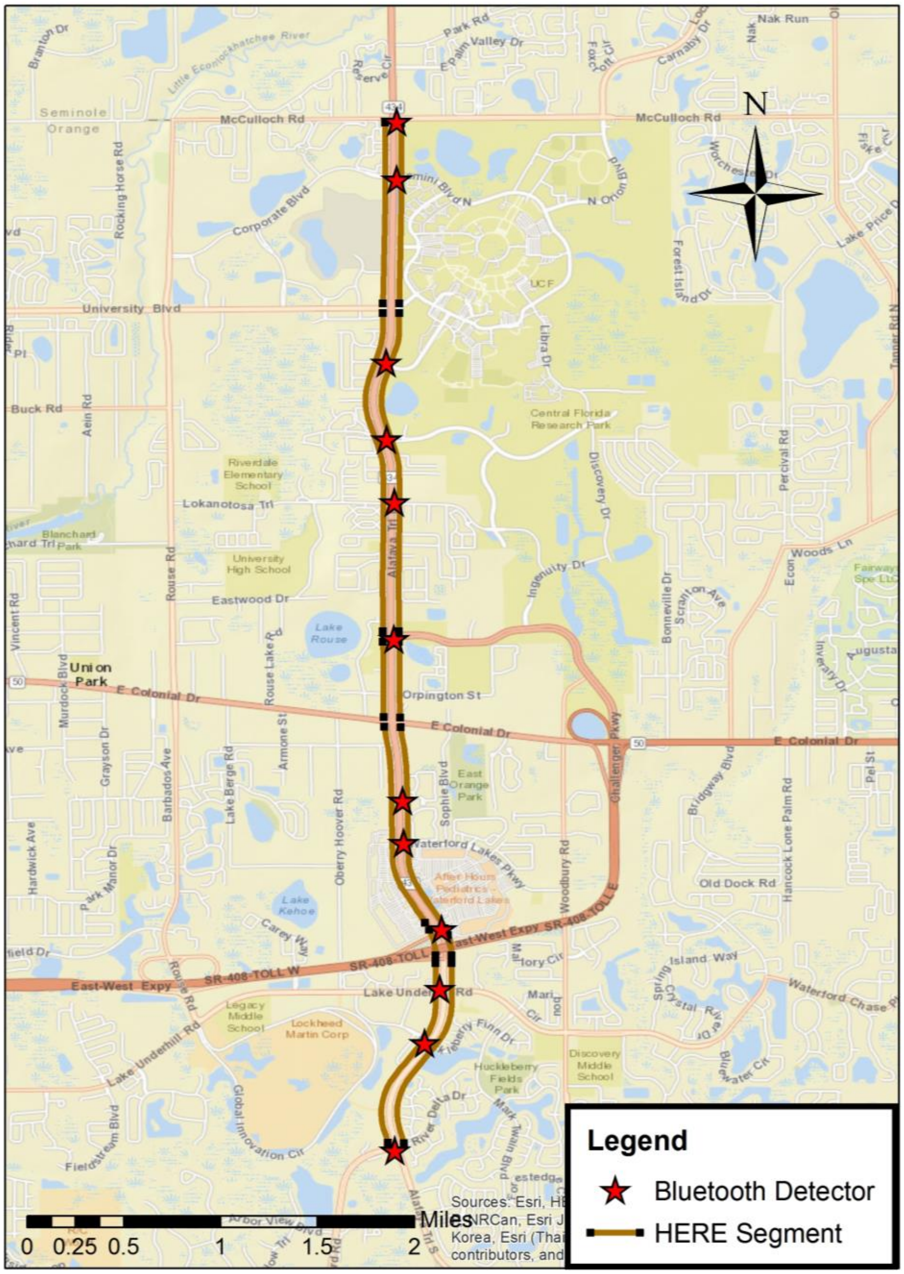


Figure 100. HERE links and bluetooth detectors of study site

6.3.3.2. Data Collection and Preparation

HERE reports one-minute space mean speed and average travel time at Traffic Message Channel (TMC) codes, which is a predominant standard roadway segment referencing system. On arterials, TMC segments break primarily at major intersections, whereas minor intersections are contained within a single TMC Segment. Figure 95 shows the TMC segments (HERE Links) of the study site. Some TMC segments might refer to isolated intersections, whose length is too short (about 50 feet) for segment travel time or space mean speed to be estimated by other data sources. Thus, these segments were excluded in this study. As a consequence, data from six TMC segments for each direction were utilized in this study.

As discussed in Section 4.3.1, the filtered individual travel time directly retrieved from BlueMAC system is not valid. Thus, BDS raw detection readings retrieved from BlueMAC detectors archived by Orange County Traffic Engineering were utilized. The locations of Bluetooth detectors are presented in Figure 95. There are a total of 12 detectors monitoring traffic in both directions.

Travel time and space mean speed of an individual vehicle from upstream Bluetooth detector to downstream detector was estimated using max-max matching. The segment between two adjacent Bluetooth detectors is defined as a BDS segment. In order to efficiently evaluate the accuracy of travel time of different segments, the space mean speed was utilized for evaluation instead of travel time. Then, as mentioned in Section 4.3.2, the calculated space mean speed is filtered by a MAD filter.

Evaluating traffic data from one data source by another requires spatial and temporal alignment of both data sources. Both HERE and BDS traffic data are reported at the segment level. However, as shown in Figure 101, the segmentations of HERE data and BDS data are not consistent with each other. Hence, a spatial alignment methodology shown in Figure 95 was adopted. In this project, the space mean speed from BDS of a single HERE segment was estimated by a weighted average value of the speed of the same period from all BDS segments fully and partially within the HERE segment by length.

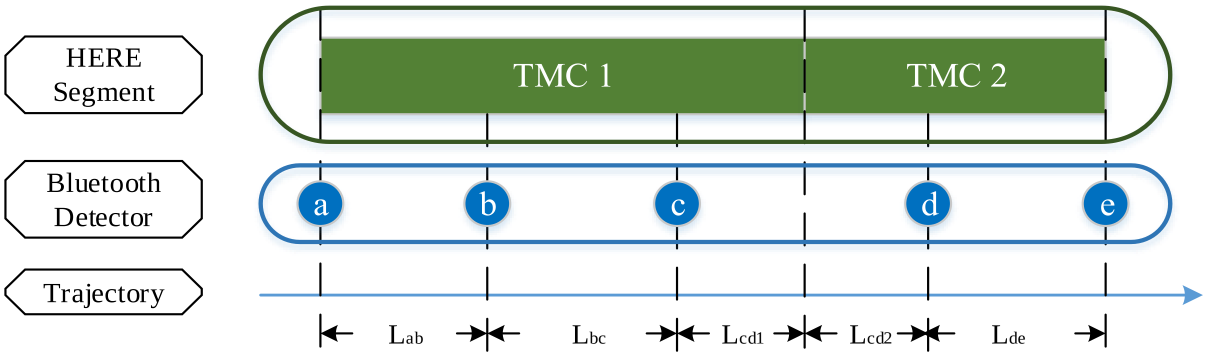


Figure 101. Spatial Matching of Three Data Sources

For example, the space mean speed of TMC1 from BDS was estimated as:

$$v_1 = v_{ab}\frac{L_{ab}}{L_1} + v_{bc}\frac{L_{bc}}{L_1} + v_{cd}\frac{L_{cd1}}{L_1} \tag{19}$$

where, v_1 is the space mean speed from BDS of segment TMC1; v_{ij} is the space mean speed of the roadway segment between Bluetooth detectors *i* and *j*; L_1 is the length of segment TMC1.

Note that L_{cd1} is not the distance between Detectors c and d, but is the length of the overlaying part of TMC1 and segment between Bluetooth detectors c and d. As mentioned above, high-resolution GPS trajectory data was utilized as the "Ground truth" to evaluate the two data sources. The travel time and space mean speed from the validation dataset (i.e., data from GPS probe vehicles) at HERE segment level were calculated directly by the similar method as BDS travel time estimation.

The space mean speed, which represents the travel time, is reported in one-minute aggregation level for HERE data and in individual vehicle level for BDS and GPS data. In order to evaluate data sources at the same temporal aggregation level, individual space mean speed observations in a five-minute time interval were aggregated to generate the average speed corresponding to that time interval. HERE data were aggregated based on its reported time stamp, whereas BDS and GPS data were aggregated based on the time stamp when the individual vehicle ended the trip. Then, the average space mean speeds from the three data sources were matched with each other based on the same roadway segment and the same reported time interval. HERE data and BDS data were collected from April 2017 to June 2017. Ground truth GPS trajectory data were collected on some specific days in the same period.

6.3.3.3. Comparison Criteria

The basic logic of data evaluation in this study is to assess whether a specific data source is able to provide reliable and credible travel time (space mean speed) information to individual travelers or not. Thus, the average speed of five-minute intervals from HERE and BDS were compared with the corresponding GPS ground truth data, which is the space mean speed (travel time) of the "actual" trips. Although the size of the validation data sets is not very large, it should be efficient to represent the travel time of the actual trips. Two metrics were utilized as the quantitative measurements of the deviation of a specific data source from the ground truth: one is the Average Absolute Speed Error (AASE) and the other is Speed Error Bias (SEB).

6.3.3.4. Results

Table 49 shows the AASE and SEB of the two data sources from the GPS ground truth for each segment. In terms of AASE, data from BDS are always closer to the GPS ground truth than data from HERE, which indicates that the BDS data have better accuracy. The only segment whose AASE of BDS data is greater than 10 mph is segment "102N10190". A possible reason is that this segment is the part of an arterial between the on-ramp and off-ramp of a limited-access toll expressway. The traffic on the segment includes the vehicles from the off-ramp and to the on-ramp. A careful examination of the volunteers' trajectories showed that no drivers had ever travelled from or to the expressway using this off-ramp. Therefore, the validation dataset may have some bias from the actual traffic. As a rule of thumb, the reliability of a data source is acceptable if its AASE is less than 10 mph and SEB is less than ±5 mph. The BDS data is reliable for most of the segments (10 out of 12, and the SEB of segment “102-10186” is -5.07, which is slightly higher than the criteria), while the HERE data is reliable for only four segments. In addition, the signs of SEB show that there is no consistent positive or negative deviation from the ground truth. Interestingly, for most of the segments (9 out of 12), the speed from HERE is less than the corresponding speed from BDS.

Table 49. AASE and SEB of speed from HERE and BDS compared with ground truth

HERE_ID	HERE		BlueMAC	
	AASE	SEB	AASE	SEB
102+10187	11.60**	2.08	9.13	-2.88
102+10188	7.56	-1.85	6.38	-0.01
102+10189	6.05	0.02	1.59	-0.82
102+10190	7.26	-3.74	6.55	1.86
102+10191	9.05	-3.32	7.37	-2.60
102-10186	9.85	7.04*	7.70	-5.07*
102-10187	11.57**	-8.70*	8.05	0.41
102-10188	10.77**	-0.81	6.96	1.85
102-10189	13.21**	-9.89*	8.66	3.44
102-10190	9.41	-7.14*	8.03	-1.66
102N10190	12.82**	-11.04*	10.70**	6.45*
102P10190	11.13**	6.50*	6.49	1.14
** Failure: AASE more than 10 mph * Failure: SEB not between 5 mph and -5 mph				

In summary, compared to HERE data, BlueMAC could provide more accurate travel time. Hence, the data from BlueMAC is recommended if both HERE and BlueMAC are available for a specific arterial corridor.

6.3.4. Evaluation of BlueTOAD and Corresponding HERE

6.3.4.1. Study Site and Data Preparation

A 1.7-mile segment of an arterial corridor- Mitchell Hammock Rd-in Seminole County was selected. The segment is between Alafaya Trail and Lookwood Blvd with the posted speed limit of 45 mph. The BlueTOAD system is only able to provide filtered travel time of individual vehicles. Thus, the travel time is directly employed for the evaluation. Two segments (1 per each direction) were utilized in this study. For temporal alignment and the derivation of ground truth travel time, the study utilized the same methodologies mentioned in Section 4.2.2.2. HERE data and BlueTOAD data were collected in August 2017 and the GPS trajectory data were collected in the same period.

6.3.4.2. Results

Table 50 shows the comparison results with AASE and SEB, the same quantitative metrics used in Section 3.3. According to the reliability criteria mentioned above, the BlueTOAD data are reliable for both segments. However, the HERE data are only reliable for one segment, which indicates that BlueTOAD data is more reliable than HERE data. Hence, if both HERE and BlueTOAD are available for a specific arterial corridor, the processed data from BlueTOAD is recommended. Nevertheless, more accurate detection results might be obtained if BlueTOAD could provide raw data.

Table 50. Evaluation results of HERE and BlueTOAD

HERE_ID	HERE		BlueTOAD	
	AASE	SEB	AASE	SEB
102+10361	7.14	-0.50	5.19	2.42
102-10360	9.31	-8.13*	7.69	-1.26
* Failure: SEB not between 5 mph and -5 mph				

6.3.5. Evaluation of BlueMAC and Corresponding HERE on Urban Collectors

Collectors and local roads play an important role in traffic in populous urban areas. It would be beneficial to consider some collectors in the Downtown area during the development of the Integrated Active Traffic Management System. However, the conclusion from data evaluation of arterials could not directly transfer to the urban collectors. First, the travel patterns of collectors are more complicated than those of arterials. Especially for BDS, the huge amount of non-motorized travel, the overlapping detection zones caused by extremely short segments, and the frequent detour and parking could significantly increase the systematic errors. Meanwhile, the research team is only able to get the first detection rather than all the raw detections from SunGuide for the downtown area until November 2017. In other words, only the first-first matching method, whose error is the largest among all three matching methods, could be used to estimate the travel time.

6.3.5.1. Study Site and Data Preparation

Three busy collectors in Downtown Orlando area were selected for evaluation: Orange Avenue running southbound from Robinson Street to South Street, Garland Avenue running northbound from South Street to Robinson Street, and Robinson Street running westbound from Garland Avenue to Robinson Street. It should be noted that the first two collectors allow only one-way traffic. Figure 102 shows the map of the three corridors. This study totally includes three HERE segments with one HERE segment (Brown Line) corresponding to each collector road. In addition, 12 BlueMAC detectors are implemented in this area, however, only 8 (Green Point) of them could collect data currently. Two types of BlueMAC data were evaluated in this study. The one is filtered travel time of individual vehicles directly from SunGuide TSS subsystem. The other is travel time estimated by using the first-first matching method since the current BlueMAC in

Downtown Orlando only provided the first detections. The study utilized the same methodologies mentioned in Section 3.3 for the alignments and the derivation of ground truth travel time. HERE data and BlueMAC data were collected in October 2017 and ground truth GPS trajectory data were collected in the same time period.

Figure 102. Segments used for collector evaluation

6.3.5.2. Results

Figure 103 shows the agreements of filtered speed of individual vehicles from BlueMAC detectors versus GPS ground truth (Left) and HERE versus GPS ground truth (Right). It is that the GPS speed and the BlueMAC speed are not consistent. One possible reason is the timestamps provided by the SunGuide is not accurate. Meanwhile, only some of the HERE speed data agree with the Ground truth.

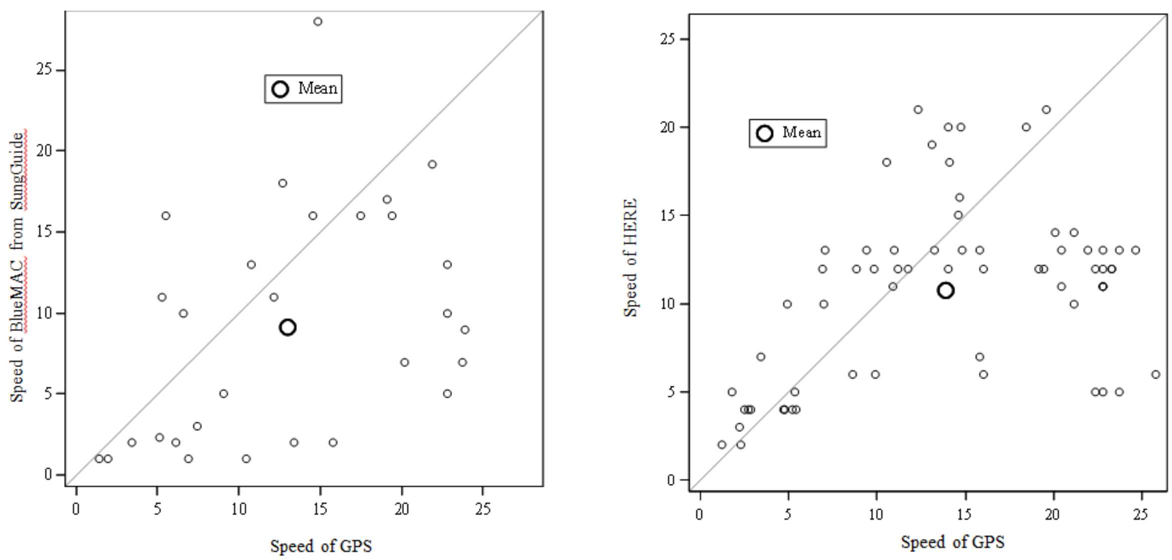


Figure 103. Agreement of BlueMAC and HERE speed versus GPS ground truth

The travel time estimated using first-first matching by the research team highly agrees with the ground truth data (Figure 104). That means the timestamps provided by first detections is accurate and the error of first-first matching is acceptable.

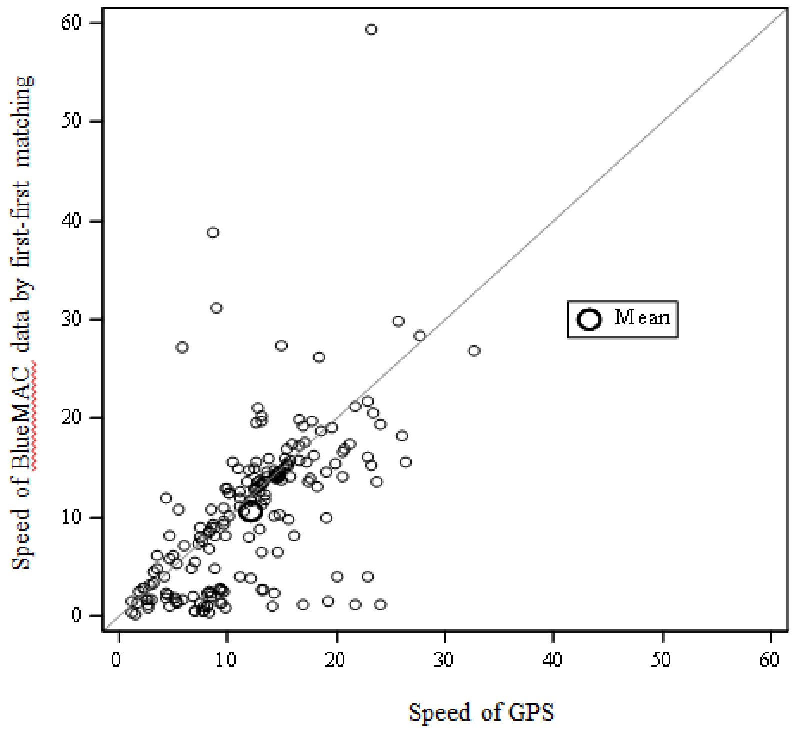


Figure 104. Agreement of BlueMAC speed by matching and the ground truth

However, as shown in Table 51, the detection rate of BlueMAC in downtown area is extremely low. The average detection rate is only 40.74% and the lowest one is only 25.86%. Given that low detection rate, further study found that for the 8 investigated segments, there are only 4.6 travel time records per hour per segment. Thus, the BDS data of Downtown Orlando is not able to capture the traffic dynamics in 5-minute granularity.

Table 51. Detection rate by intersections

Intersection	Passed	Detected	Rate
Orange Ave and Robinson St	58	31	53.45%
Orange Ave and Jefferson St	58	33	56.90%
Orange Ave and Washington St	58	19	32.76%
Orange Ave and Central Blvd	58	15	25.86%
Orange Ave and South St	58	23	39.66%
Garland Ave and Pine St	54	16	29.63%
Garland Ave and Washington St	54	25	46.30%
Garland Ave and Robinson St	54	14	25.93%
Average	**54**	**22**	**40.74%**

For the downtown Orlando area, the most reliable data source is the first detection of BlueMAC in terms of accuracy. However, the data could not provide 5-minute traffic data in real time. Thus, HERE is the only choice if the system development requires short-term real-time strategy.

6.3.6. Discussions

The evaluation of three different scenarios showed that the three types of BDS consistently could provide more reliable travel time data compared with data from private sector, HERE. However, using BDS data to measure the real-time performance of the traffic on urban collectors is not recommended since the granularity of the data is not enough to provide even 5-minute traffic dynamics. Hence, it is recommended to use BDS data for the future study of the project on arterials if BDS data are available. If urban collectors are considered in the future study, the data from HERE should be utilized. In addition, HERE data would be used if segments only have HERE data.

6.4. Data Fusion for Freeways and Expressways

According to the evaluation results of travel time of HERE, MVDS, and Bluetooth in Section 4.2, they have inaccurate data on the basis of AVI and NPMRDS. Thus, it will be improper to fuse them through a simple average of multiple data sources. In addition, the simple average method would not be able to reflect the expected travel time, which was described in Chapter 2. Based on the Automatic Vehicle Identification (AVI) system, two kinds of AVI travel time can be estimated (see Figure 105). One is the observed travel time, which is collected from the AVI system in real time on the basis of the end point of AVI segments when drivers passed the AVI segments. The other is the expected travel time, which can be computed from the historical data of the AVI system. The expected travel time mean the time that drivers entering the start point of AVI segment will experience when passing the AVI segments. Usually, most of traffic management centers for freeways and expressways are using the observed travel time to provide travel time for drivers. Therefore, the travel time have irreducible errors. This means drivers are receiving travel time observed 5 minutes before on the basis of the processing time without any adjustment about the time lag.

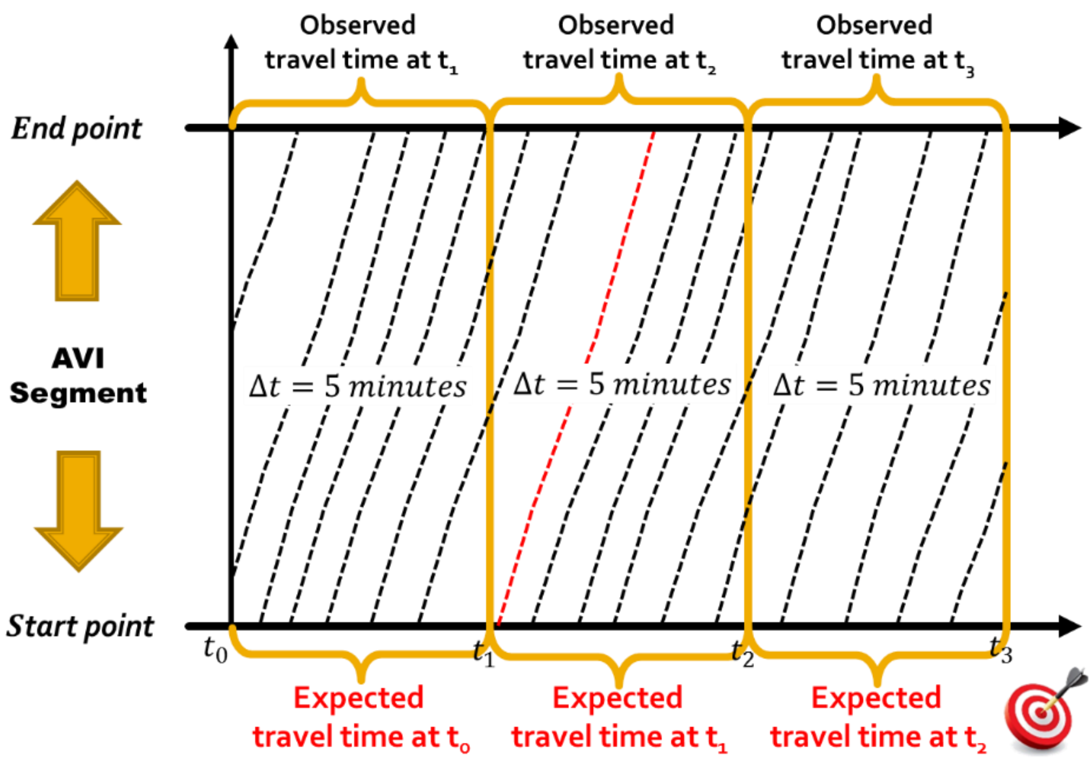


Figure 105. Two aspects of AVI travel time

6.4.1. Data Fusion Method

The same locations as the evaluation of travel time for freeways and expressways were selected. Instead of the simple average of multiple data sources, KNN (K Nearest Neighbors) regression was used to build non-parametric regression models regardless of time and space such as segments. A simple implementation of KNN regression is to compute the average of the numerical target variables of the K nearest neighbors.

Many traffic engineers and experts studied and used the KNN approach in the last decades. Bajwa et al. studied it in detail by using the speed of a single data source (Bajwa et al., 2005; Chung and Kuwahara, 2004; Ul et al., 2003). Bajwa et al. (2005) considered historical data set of speeds in temporal and spatial aspects based on time of day. The optimal size of the historical data set was estimated through the genetic algorithm to minimize the error in travel time prediction. To calculate the final predicted travel time, nearest-distance weighted inverse speed was used after filtering outliers using an interquartile range technique. Recently, KNN approach predicting travel time through multiple data sources was developed. Myung et al. (2011) used KNN with combination of VDS (Vehicle Detection System) and ATC (Automatic Toll Collection) data. Tak et al. (2014) developed travel time prediction algorithm for long-distance trips using layered KNN and utilized multiple data source, VDS using inductive loop detectors, TCS (Toll Collection System), and DSRC (Dedicated Short Range Communication) data.

Optimal K values for the KNN regression were found through k-fold cross validation (k=5). Although many KNN regression models may be developed according to classification criteria such as the day of week, time of day, and segments, it is inefficient to build all cases of KNN regressions.

6.4.2. Data Fusion Types

According to the travel time data availability analysis, freeways and expressways have the following data available:

- HERE and Bluetooth
- MVDS and HERE
- MVDS, HERE, and AVI

A KNN regression model to fuse HERE and Bluetooth data was developed by using six segments managed by FTE (see Figure 82). The six segments are BTS_01, BTS_02, BTS_03, BTN_01, BTN_02, and BTN_03. The KNN model for HERE and Bluetooth data fusion is based on the assumption that NPMRDS is a ground truth travel time. KNN regression models for the other cases were developed by using six segments: AVI_S01, AVI_S02, AVI_S03, AVI_N01, AVI_N02, and AVI_N03, managed by CFX (see Figure 81). All segments are located on SR4-417. Other KNN regression models are based on the assumption that the expected travel times from AVI are ground truth travel times.

6.4.3. Data Preparation

For the development of the data fusion algorithm, four kinds of data sources were used: AVI, MVDS (Microwave Vehicle Detection System), HERE, and NPMRDS (National Performance Management Research Data Set). The observed and expected travel time were estimated by matching individual toll tag IDs from CFX's AVI system. MVDS collects traffic volume, occupancy (%), and speed (mph) at 30-second or 1-minute interval. HERE provides the processed travel time by TMC segments, which are based on probe vehicles' GPS locations. NPMRDS was made from the unprocessed travel time from a private sector source, which are also based on GPS.

To integrate four different data sources, data were processed the same as in the evaluation of travel time for freeways and expressways. Finally, two historical data sets were prepared (see Figure 106). One is based on AVI data of 2016 and includes HERE and MVDS data. Another is based on NPMRDS between June 2016 and December 2016 and also includes Bluetooth and HERE data. In addition, for the test of the KNN regression models, test data sets were prepared from January 2017 to February 2017. Instead of using travel time directly, travel time index (TTI, minute per mile) was used. For example, objective functions based on AVI data have five variables in the training data set and test data set as follows:

$$TTI_e(t) = f(TTI_o(t), TTI_h(t), TTI_m(t), VOL_m(t), OCC_m(t)) \tag{20}$$

where, $TTI_e(t)$, which is the expected TTI of AVI at 5-minute intervals;

$TTI_o(t)$, which is the observed TTI of AVI at 5-minute intervals;

$TTI_h(t)$, which is TTI of HERE at 5-minute intervals;

$TTI_m(t)$, which is TTI of MVDS at 5-minute intervals;

$VOL_m(t)$, which is average traffic volume per lane on each AVI segment;

$OCC_m(t)$, which is average occupancy on each AVI segment.

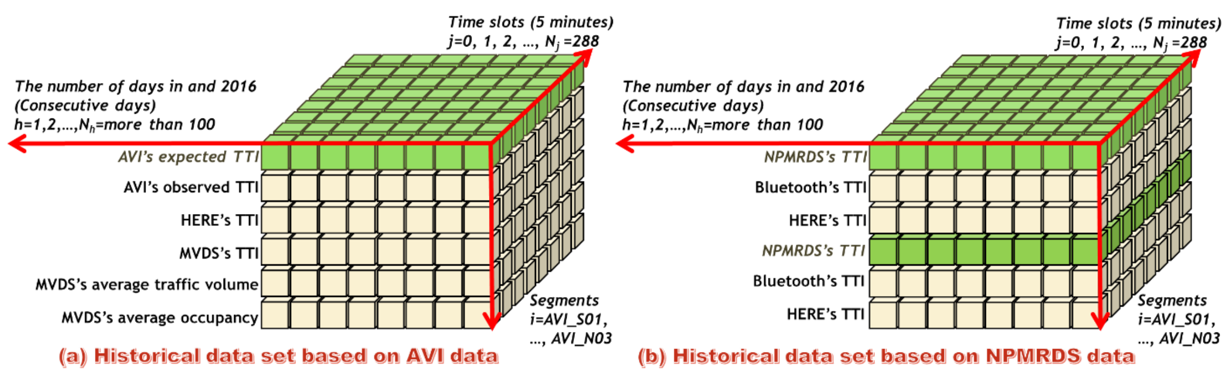


Figure 106. Two types of historical data sets

According to the scatter plot of the prepared data (Figure 107), it seems that four TTIs have a linear relationship with each other. As shown in the right bottom of the figure, the aggregated MVDS data having volume, occupancy, and speed show good relationships in terms of the traffic flow theory. For example, volume and occupancy have the parabolic relationship used in the kinematic wave model. The scatter plot between volume and speed is consistent with the relationship explained in HCM (Highway Capacity Manual). The plotting of occupancy and speed makes obvious the linear relationship. All variables except for $TTI_e(t)$ were normalized through z-score standardization.

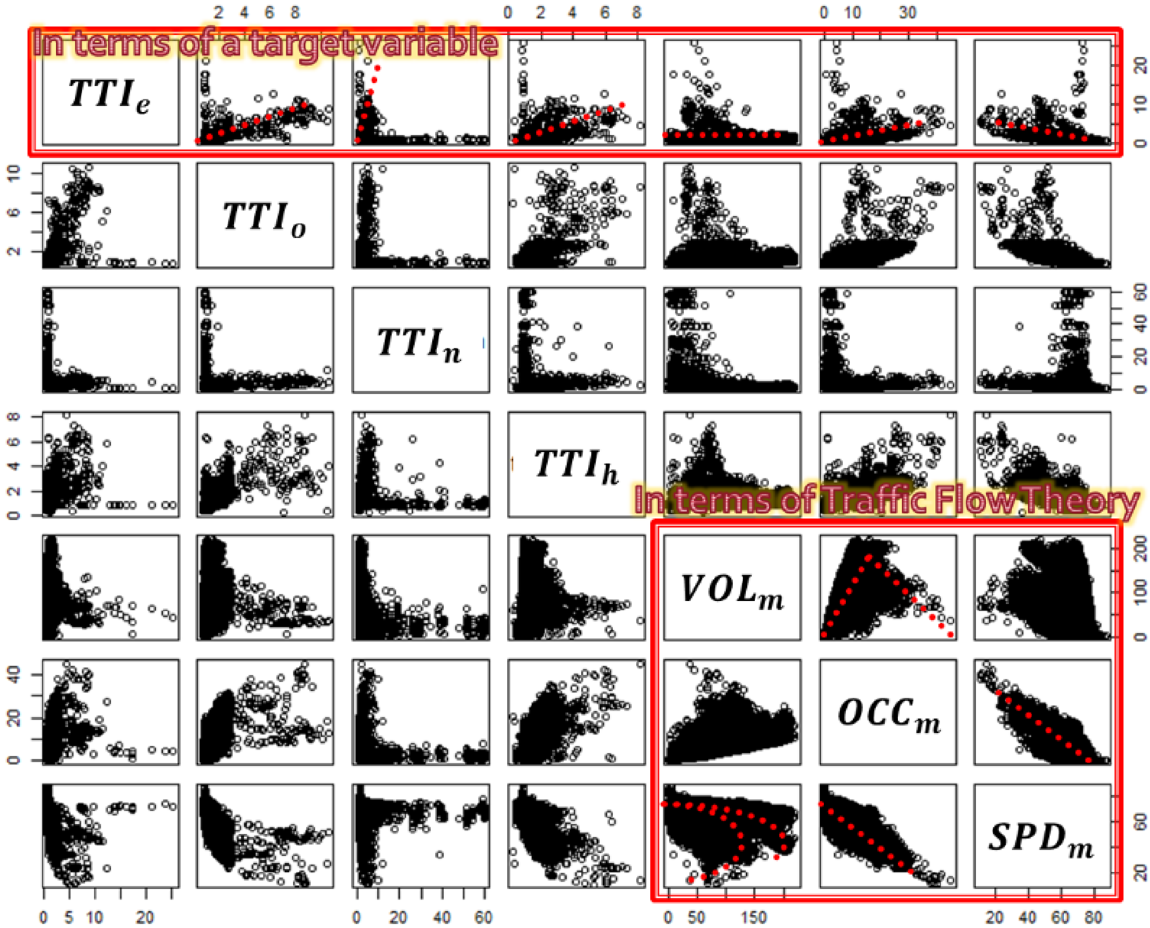


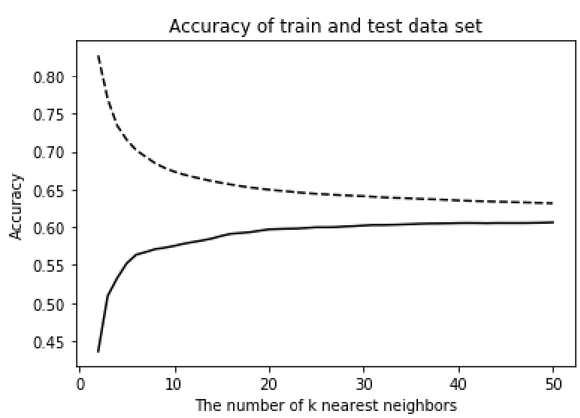
Figure 107. Scatter plot of all variables in historical data

6.4.4. Data Fusion Results

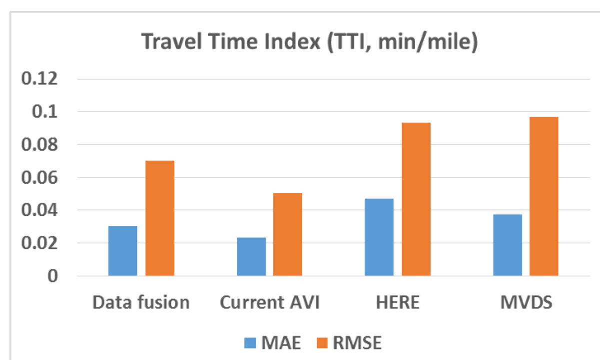
Based on travel time index (TTI, minute/mile), data fusion results were evaluated through two performance measures: MAE (Mean Absolute Error), and RSME (Root Squared Mean Error).

6.4.4.1. Data Fusion of AVI, MVDS and HERE

Through the cross validation, the optimal K value was found as 40 based on the accuracy. By using K=40 and the prepared test data set, the KNN regression was tested. According to the results of MAE and RMSE, it is obvious that TTI values fused by the KNN regression model are better than only HERE or only MVDS data. However, the model cannot provide better data fit than the current AVI data, which are based on the observed TTI. Therefore, when the observed AVI data are available in real time, it will be better to use the observed AVI data without any data fusion (see Figure 108).



(a) Accuracy by K values



(b) MAE and RMSE of each data source

Figure 108. Data fusion result of AVI, MVDS, and HERE

In more details, daily trends of TTI were checked through Segment AVI_N03. Seeing Figure 109, it is obvious that there are time lag errors between the observed TTI and expected TTI. MVDS's TTI is the most inaccurate among three data sources. In addition, HERE and Fusion data are not perfect to follow the expected TTI of AVI. However, it shows that well-built historical data set can provide more reliable TTI, which requires further investigation.

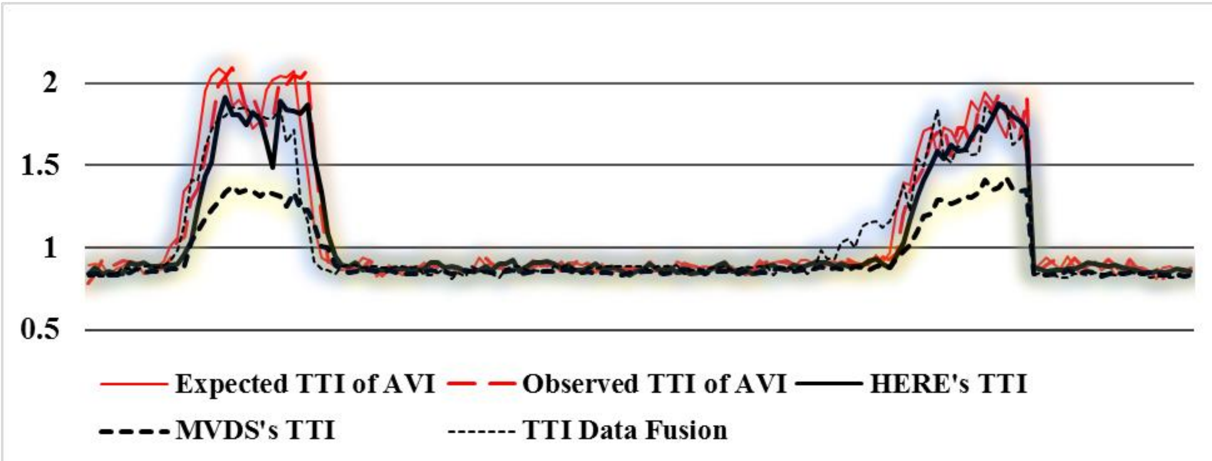
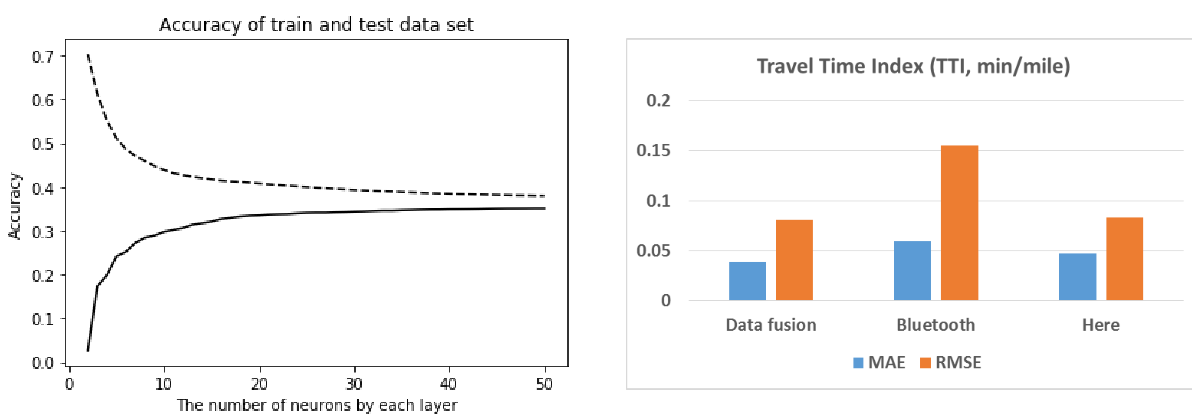


Figure 109. TTI's change during a day at AVI_N03 segment

6.4.4.2. Data Fusion of HERE and Bluetooth

Through the cross validation, the optimal K value was found as 50 based on the accuracy. By using K=50 and the prepared test data set, the KNN regression was tested. According to the results of MAE and RMSE, TTI values fused by the KNN regression model are better than only HERE or only Bluetooth data (see Figure 110).



(a) Accuracy by K values (b) MAE and RMSE

Figure 110. Data fusion result of AVI, MVDS, and HERE

In more detail, daily trends of TTI were checked on Segment BTS-02. Seeing Figure 111, it is obvious that there are time lag errors between NPMRDS' and Bluetooth's TTI. However, data fusion results and HERE data follow the trends of NPMRDS closely. Thus, it shows that well-built historical data set with HERE and Bluetooth can be used to estimate more reliable TTI.

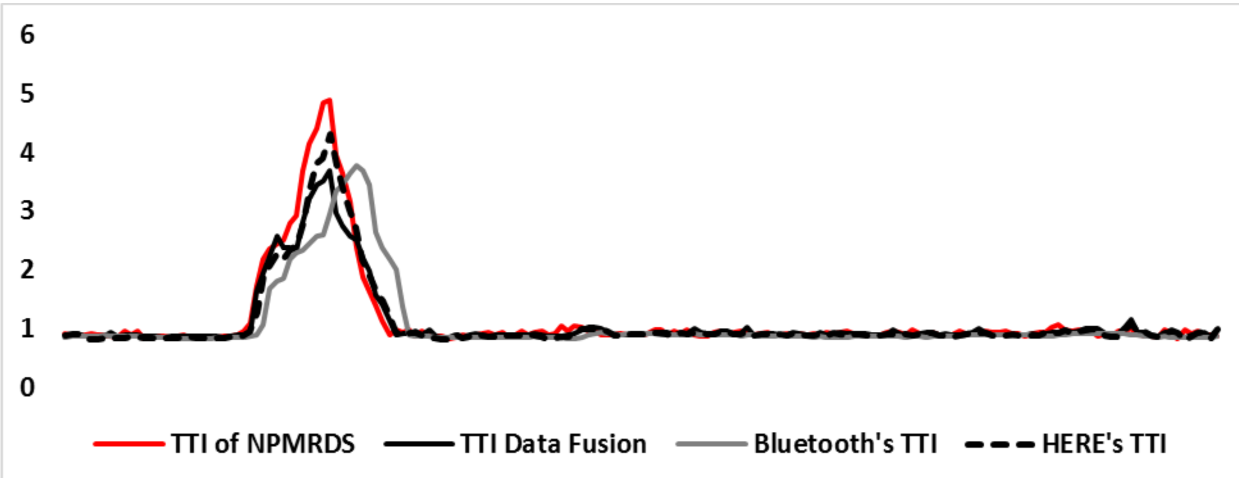
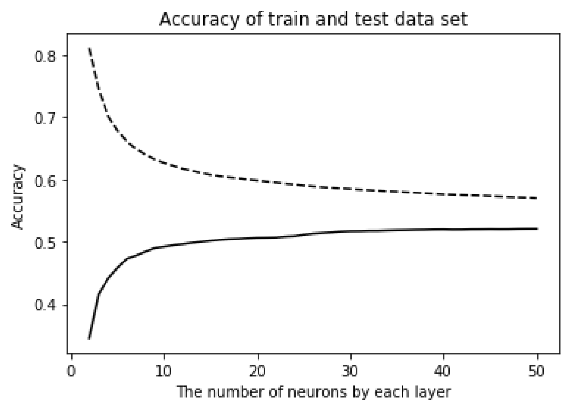


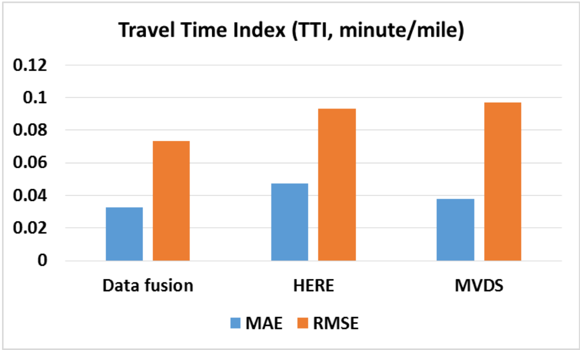
Figure 111. TTI's change during a day at BTS_02 segment

6.4.4.3. Data Fusion of MVDS and HERE

Through the cross validation, the optimal K value was found as 45 based on the accuracy. By using K=45 and the prepared test data set, the KNN regression was tested. According to the results of MAE and RMSE, TTI values fused by the KNN regression model are better than only HERE or only MVDS data (see Figure 112).



(a) Accuracy by K values



(b) MAE and RMSE

Figure 112. Data fusion result of MVDS, and HERE

In more detail, daily trends of TTI were checked through AVI_N03 segment. Seeing Figure 113, it is obvious that there are time lag errors between the expected TTI of AVI and HERE's TTI. However, data fusion results and HERE data follow the trends of AVI's TTI closely. Thus, it shows that well-built historical data set with HERE and MVDS data can be used to estimate more reliable TTI.

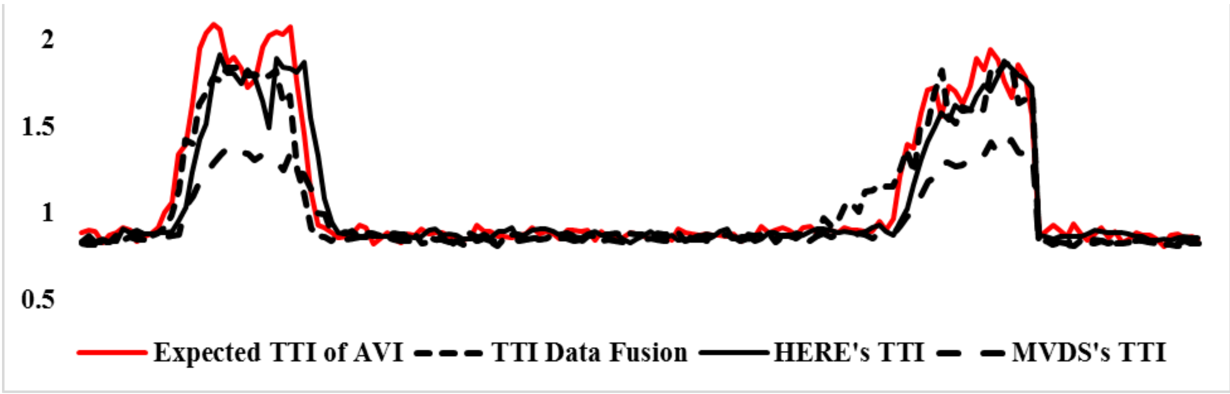


Figure 113. TTI's change during a day at AVI_N03 segment

6.4.5. Discussions

Based on the available data sources on freeways and expressways, three kinds of travel time data fusion were conducted:

- AVI, MVDS, and HERE
- Bluetooth and HERE
- MVDS and HERE

Plotting TTIs of the above data sources according to time slots of 5-minute intervals, they have similar trends with each other. However, there are accuracy and timeliness issues, and finally it could not be explained by one relationship. A nonparametric approach was considered to combine multiple data sources. Among many nonparametric approaches, KNN regression method was used. According to the data fusion results, the KNN regression shows more improved accuracy of TTI than cases using only one among MVDS, Bluetooth, and HERE.

6.5. Data Fusion for Arterials

6.5.1. Improving the Accuracy of BlueMAC Travel Time Data

To eliminate the errors of BDS travel time estimation caused by long detection time and multiple detections, several detection selection methods were proposed. Among those, the stop-stop matching, theoretically, could eliminated the error and uniformly capture the control delay of the downstream intersection. However, it is only available in the traffic simulation since it is impossible to find out the exact location without the vehicle's real geographical trajectory. The max-max matching is a field-feasible approximation of the stop-stop matching, However, if the vehicle is stopped by a red light, the detection with the max RSSI ($t_{d,m}$) is less likely to be the detection of the vehicle exactly at the stop line, which might lead to some errors. In order to eliminate the error of the max-max matching, the research team tried to propose a new matching method called green max-max matching. Basically, the green max-max matching selects the detection with the maximum RSSI during the green period rather than that during the whole detection period. Then a preliminary study was conducted to evaluate the accuracy of the matching method.

6.5.1.1. Methodology

Figure 114 shows the illustration of detection selection methods including green max-max matching. The proposed green max-max matching assumes that the vehicle stopped by a red light was waiting in the queue until the light turned to green. After the traffic light turns green, the vehicle starts to proceed to the intersection and crosses the stop line. Thus, the detection with the maximum RSSI after the vehicle start running or during the green period indicates the time stamp when the vehicle crossed the stop line.

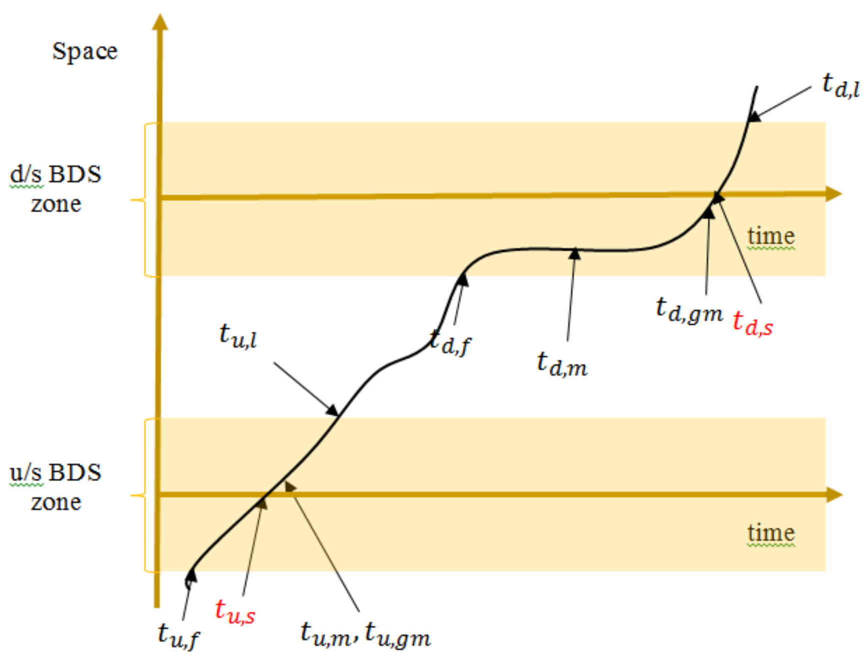


Figure 114. Illustration of detection selection method

where, *u,d*: upstream and downstream intersections

f,l,m,s,mg: Selection method: first, last, max, stop and max-green

$t_{i,j}$: The selected timestamp, where $i \in \{u, d\}$ and $j \in \{f, l, m, s, mg\}$

In order to find out "stop and go" behavior of the vehicle, the real-time status of the traffic signal of its approach is assigned to each detection to determine the status of the traffic signal at the specific time stamp. Then, the green period is defined as the time period from the first detection with green status to the last detection with green or yellow status (effective green). Finally, the detection with the max RSSI during the green period was selected.

6.5.1.2. Field Limitation

The operation logs of the InSync adaptive signal system were employed to determine the status of approaching signal. The system operation logs provide the phase combination, phase duration, the maximum waiting time, and queue length of each phase collected from InSync® data archiving system which serves as the historical traffic signal timing information and the signal performance measures. In this study, only the historical traffic signal timing information was utilized.

The BlueMAC BDS data could not identify which legs the detected vehicles drove on since BlueMAC BDS were only implemented on several corridors not the whole roadway network. Hence, although InSync system is able to provide the signal status of all approaching directions, it is impossible to find out where the vehicle comes from especially if the vehicle comes from the minor road. Therefore, it is hard to assign the right signal status of every vehicle without knowing its approaching direction. The research team is not able to track back the actual vehicle trajectory. Thus, an approximation approach was proposed.

The approximation approach is based on two assumptions:

(1) If the signal status of a specific direction of the last detection of vehicle is green or yellow (effective green), the direction is regarded as the approaching direction of the vehicle.

It is reasonable since the signal has to be green or yellow to allow the vehicle to cross the intersection. However, if the BDS detector does not record the actual last detection with green or yellow status due to its short period and the detector recorded the last detection with red status before the vehicle started to go, the method would lead to a significant error.

(2) If there are two directions whose last detection is green or yellow status, the last calculated green max detection between those directions is the best feasible approximation of the stop detection.

Since the traffic signal system of the study site only allows protected left turning phase, there should be only two scenarios which meet the aforementioned condition. The first one is when two directions are both through or left approach of the opposite directions. It will not cause any problem since the signal status of those directions change simultaneously. The timestamps of green max detection of both directions are always the same. The other one is when two directions are the left-turning and approaching directions of the same approach. There will not be any problem if the signal statuses of both directions of all detections are "green". However, if there exists red status and the signal status of those directions does not change simultaneously, there will be two situations.

First, for a vehicle which is going to make a left turn, it is first stopped by the red light and then past the intersection after the signal turned to green. Figure 115 shows signal status of the left-turn and through of the northern approach by each second after the vehicle is first detected. As the figure illustrates, the status of both left-turn signal and through signal associated with the last detection of the vehicle is “green”. Hence, the last calculated green max detection (marked as ‘Max’), which is the “green max detection” of left-turn approach, is the actual detection when the vehicle is running through the stop line. However, the other one, the green max detection of through approach, is the “max detection” when the vehicle was waiting for the green light. As a result, the last “green max detection” among those directions is selected as the “stop detection”.

Figure 115. Illustration of signal timing with a vehicle stop

Second, for a vehicle passing through the intersection without any stop, there will be several recorded detections. Figure 116 illustrates signal status of the left-turn and through of the northern approach by each second after the vehicle is first detected. According to Figure 110, the last calculated “green max detection (marked as ‘Max’)”, which is the “green max detection” of left-turn approach, is not likely the actual detection when the vehicle is running through the stop line. However, since the maximum error is only 3 seconds. Using the last calculated “green max detection” is still the best feasible approximation.

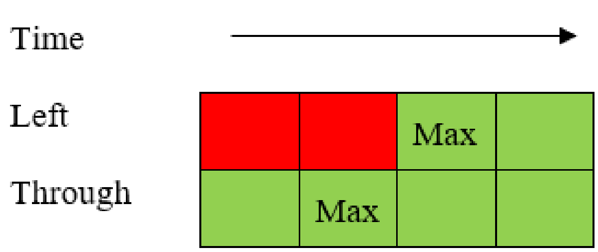


Figure 116. Illustration of signal timing with a vehicle passes

Hence, for both situations, the last calculated “green max detection” is adopted to calculate travel time.

6.5.1.3. Evaluation of the Proposed Method

The proposed method was evaluated by comparing with the max-max matching method. The segments on Alafaya Trail (SR434) in Orange County (from Curry Ford Rd to Ashton Manor Way) were selected as the test sites. Total 12 segments (6 per direction) were considered. BlueMAC data were collected in June and July 2017 and ground truth GPS trajectory data were collected in the same time period. In total, 196 travel time data of individual vehicles extracted for the study.

Table 52 shows the statistics of the absolute error between estimated space mean speed by the two methods and GPS ground truth. The results indicate that the proposed green max-max matching slightly improved the accuracy. Since there are still errors caused by the two assumptions to assign signal status, the accuracy is expected to be further improved when the BlueMAC BDS is implemented for the whole roadway network.

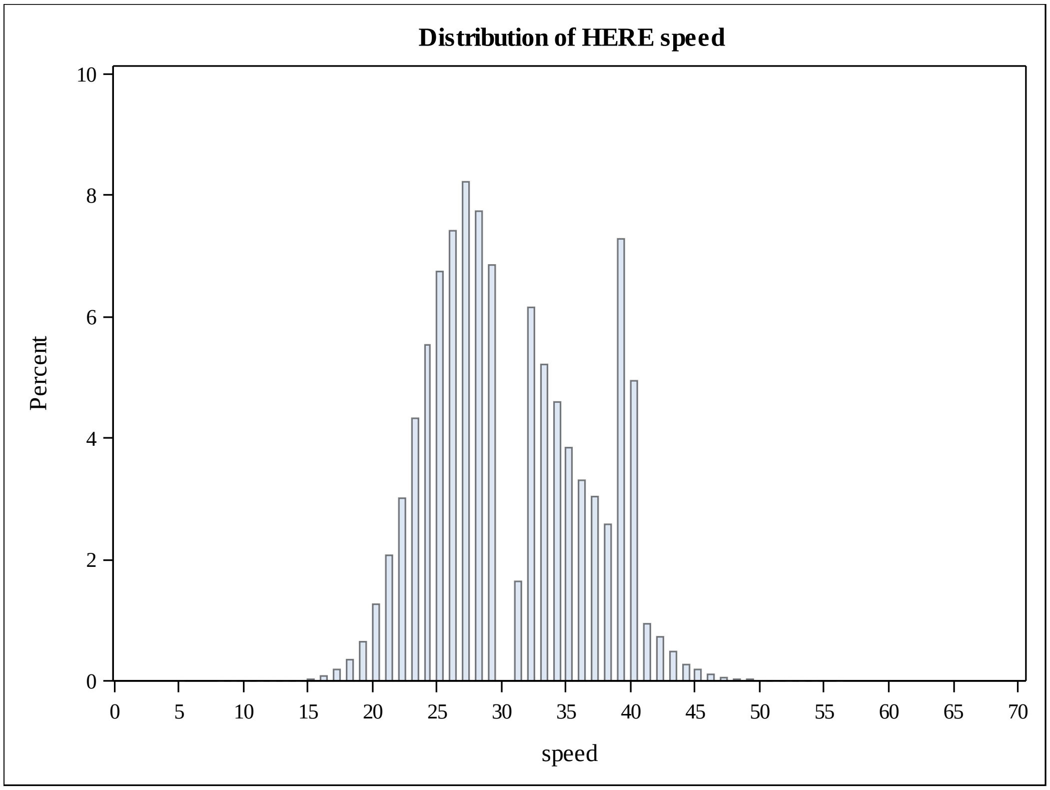
Table 52. Description statistics of absolute error between estimation and ground truth

Method	Mean	Standard Deviation	Minimum	Maximum
Max-Max Matching	4.38	8.56	0	54.85
Green Max-Max Matching	3.90	8.25	0	54.54

6.5.2. Improving the Accuracy of HERE Space Mean Space Data

According to the evaluation results in Chapter 3, data from BDS are more reliable than those form HERE. However, one of the advantages of the private sector data is its large geographical coverage compared with field detectors. For our study area, BDS data are only available for some of the arterial corridors, whereas HERE data are available for all the principal arterials and most of the minor arterials. Thus, for an area where only HERE data are available, a proper augmentation framework is needed.

A possible augmentation approach is using the extra information (e.g., historical BDS data) regarding the traffic flow pattern from a more reliable data source (Gong, 2018). Figure 117 shows the distributions of raw data of HERE and BDS data for the same segment (Note that the magnitude of percentage is different for better illustration). The BDS data clearly present the bimodal flow caused by traffic signals- a "slower mode" represents vehicles stopped by a red signal and waiting for the green phase and a "faster mode" indicates those vehicles traveling through the corridor without stopping. However, HERE data fail to provide such information. In addition, the speed from HERE does not reflect either "faster mode" or "slower mode". Instead, it illustrates a pseudo mode whose expected speed is between the speed of the aforementioned two modes, which means that that HERE company utilized algorithms to adjust the speed observations to create an "average" speed information. The evaluation results in Section 4.3 showed that the effectiveness of the adjustment is not optimal on the study corridor.



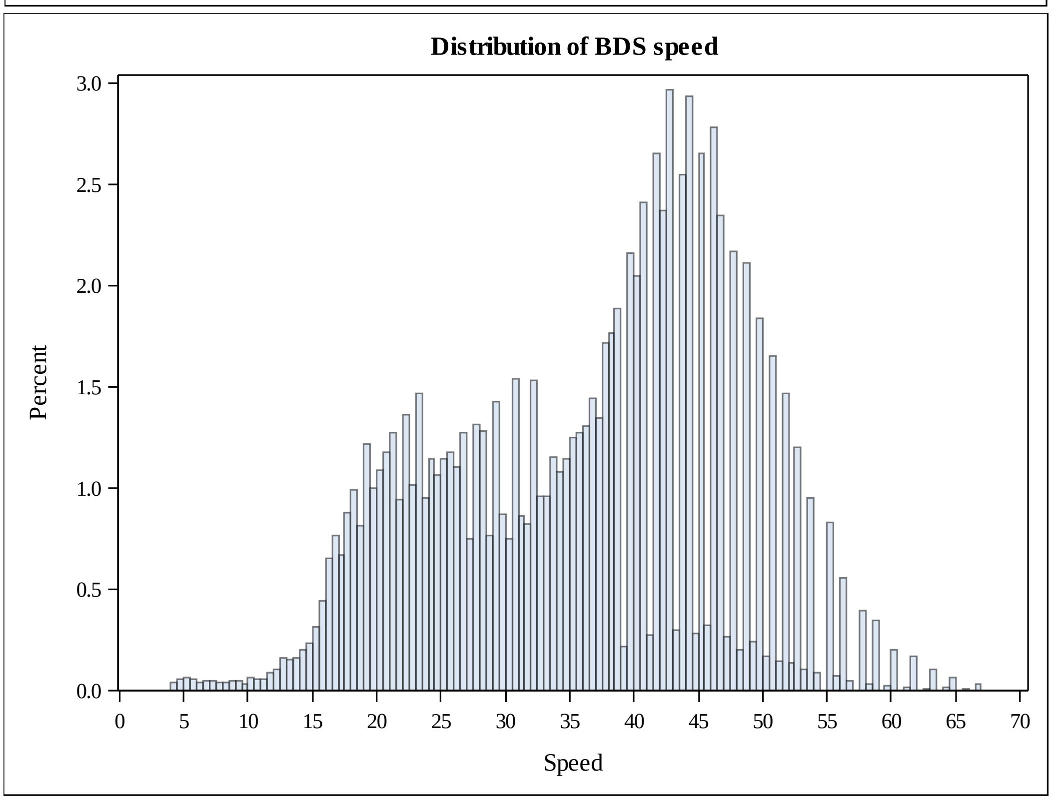


Figure 117. Distributions of speed from HERE (up) and BDS (down)

In addition, for most of the segments, the speed from HERE is less than the corresponding speed from BDS. A possible reason is that two data sources have different estimations of compliance of the posted speed limit. HERE tended to optimistically estimate the compliance of the posted speed limit, which lead to a bias estimation of free flow travel time.

In order to extract the extra information regarding the bimodal traffic flow pattern from the historical BlueMAC data, a finite mixture model was utilized. Then, a Bayesian inference is proposed to enhance the quality of the private sector data, HERE.

6.5.2.1. Methodology

A. Estimation of Bimodal Traffic Flow Pattern by Finite Mixture Model

Assume the distribution of space mean speed of a segment is the summation of two normal distributions: a distribution of "slower" speed $N(\mu_s, \sigma_s^2)$ and a distribution of "faster" speed $N(\mu_f, \sigma_f^2)$, where $\mu_i, \sigma_i^2, i \in \{s, f\}$ denote the mean and variance of the distribution i. μ_f represents the expected space mean speed (travel time) of vehicles traveling through the corridors without stopping and σ_f^2 represents the speed variance of individual vehicles. μ_s represents the expected space mean speed (travel time) of vehicles stopped by a red signal and waiting for the green phase and the σ_s^2 indicates the variance of delay. The probability density function (PDF) of mixture model $P(v)$ is defined as:

$$P(v) = w_s P(v_s) + w_f P(v_f)$$

where $P(v_s), i \in \{s, f\}$ is the PDF of the distribution $N(\mu_i, \sigma_i^2)$; $w_i, i \in \{s, f\}$ is the weight of the distribution i.

The parameters of the finite mixture models were estimated by SAS® software based on all data from BDS during the study period. In order to provide more precise information, the model was estimated separately for 12(segments)×2(weekend/weekday) ×18(hours, from 5 am to 9 pm) scenarios. Note that the bimodal flow pattern was not observed during the night time (10 pm to 4 am), thus the mixture model collapses to a model with the only "faster" mode.

B. Augmentation based on Bayesian Inference

The space mean speed (travel time) of a segment follows a mixture of "faster" distribution and "slower" distribution. Assume that a specific HERE speed observation was taken from one of the two distributions. A Bayesian inference framework was proposed to estimate average space mean speed of 5-minute time intervals considering the bimodal traffic flow pattern. The estimated finite mixture model parameters serve as the "prior" information of the bimodal pattern, and the posterior distribution $P(v|v_H)$ is given as:

$$P(v|v_H) = w_s \frac{P(v_H|v_f)P(v_f)}{P(v_H)} + w_f \frac{P(v_H|v_s)P(v_s)}{P(v_H)}$$

where w_s, $P(v_f)$, w_f, $P(v_s)$ is given by Equation (21); v_H is the speed observation from HERE; the likelihood function $P(v_H|v_f)$ and $P(v_H|v_s)$ is given as:

$$P(v_H|v_{s/f}) = \frac{1}{\sqrt{2\pi\sigma_H^2}} \exp(-\frac{(v_H - v_{s/f})^2}{2\sigma_H^2})$$

where the σ_H^2 denotes the variance of HERE speed data, which is not able to be observed. Thus, it is estimated by all HERE data during the study period for different scenarios developed by the same manner as the bimodal information estimation process.

Since the space mean speed v_H, v_f and v_s all follow the normal distributions, the three distributions are conjugated with each other. Therefore, the mean value of the posterior distribution, which is the augmented HERE speed, is given as:

$$\mu = w_s(\mu_s \frac{\sigma_H^2}{\sigma_H^2 + \sigma_s^2} + \mu_H \frac{\sigma_s^2}{\sigma_H^2 + \sigma_s^2}) + w_f(\mu_f \frac{\sigma_H^2}{\sigma_H^2 + \sigma_f^2} + \mu_H \frac{\sigma_f^2}{\sigma_H^2 + \sigma_f^2})$$

6.5.2.2. Evaluation of the Proposed Method

Table 53 shows the deviation of the original and augmented HERE speed compared with the GPS ground truth for each segment. The accuracy of most segments (10 of 12) has improved in terms of AASE. Moreover, 2 segments ("102-10186" and "102P10190") turned acceptable (AASE ⩽ 10 mph and SEB ⩽ ±5 mph) after the augmentation. The accuracy of segment "102N10190" and "102N10190" was not improved. A possible reason is that the validation data set may have some biases since these two segments are connected with expressway ramps while there were no probe vehicle drivers that had traveled from or to the expressway during the study period.

Table 53. Deviation of original and augmented HERE speed with the ground truth

HERE_ID	Original		Augmented	
	AASE(mph)	SEB(mph)	AASE(mph)	SEB(mph)
102+10187	11.60**	2.08	11.06**	1.30
102+10188	7.56	-1.85	7.09	-1.47
102+10189	6.05	0.02	5.57	-1.51
102+10190	7.26	-3.74	7.40	-4.46
102+10191	9.05	-3.32	8.94	-2.83
102-10186	9.85	7.04*	8.71	4.66
102-10187	11.57**	-8.70*	11.21**	-8.57*
102-10188	10.77**	-0.81	10.45**	-5.67*
102-10189	13.21**	-9.89*	12.76**	-9.96*
102-10190	9.41	-7.14*	8.88	-5.23*
102N10190	12.82**	-11.04*	13.73**	-11.91*
102P10190	11.13**	6.50*	9.34	2.51

** Failure: AASE more than 10 mph
* Failure: SEB not between 5 mph and -5 mph

6.5.2.3. Discussions

To improve the accuracy of the data sources available on arterials, two different "fusion" frameworks were proposed. The first one aims at proposing a green max-max matching method to improve the travel time detection by integrating the corresponding traffic signal status. Given the limitation of the field implementation of BDS, some assumptions and approximations were used to determine the exact status of the approaching signal. The result of the evaluation by the GPS ground truth probes indicated that the method improved the accuracy of the travel time estimated from BDS raw detections. If the BDS data would be available for the road network, the exact green time when a vehicle passes the stop line can be determined. Thus, the error caused by the approximations would be eliminated. Therefore, a better accuracy of the travel time estimation is expected.

The second one aims at enhancing the accuracy of the private sector data by the reliable estimated traffic flow pattern. In this study, the traffic flow pattern was estimated from historical BDS data by finite mixture models. Then, the information regarding the traffic flow pattern was fused with the HERE speed by a Bayesian inference framework. The evaluation results also showed that the proposed data augmentation framework is effective for most of the roadway segments.

6.6. Summary

In this task, the research team has evaluated the reliability of traffic data from multiple data sources in the study area. By conducting the comparative studies for the roadway network, the most reliable data have been determined for different segments on freeways, expressways, and arterials. In addition, fusion algorithms were suggested to combine different available data to generate more trustworthy data in the study area. With the data evaluation and fusion process, the most reliable traffic data could be obtained to reflect the traffic status of the roadway network in the study area. Based on the identified traffic status, the efficient algorithms for IATM strategies will be developed and the proposed strategies will be evaluated by conducting traffic simulations.

CHAPTER 7. ROADWAY EVALUATION AND SELECTION FOR IATM CONTROLS

7.1. Overview

All available traffic data in the study area was evaluated in Chapter 4. As shown in Table 54, different freeways/expressways, arterials, and collectors have different data availability. For all freeways/expressways, microwave vehicle detection system (MVDS) was the only system providing traffic volume. For arterials, Signal Performance Measures (SPM) could provide volume data for arterials in Seminole County while InSync system collected volume data for part of arterials in Orange County. In Orange County, part of arterials and collectors don't have volume data. Hence, the only available volume data will be used for different study purposes (i.e., simulation, road evaluation, and real-time traffic condition monitoring). On the other hand, different systems including Automatic Vehicle Identification (AVI), National Performance Management Research Data Set (NPMRDS), HERE, and Bluetooth data could provide travel time data for different roadways. According to the evaluation results, the most appropriate data sources were recommended for different data availability conditions and study purposes. For example, the roadways having travel time data provided by HERE, Bluetooth, and NPMRDS systems, travel time from NPMRDS system is used for the simulation and road evaluation while fused data is used for real-time traffic monitoring.

The Integrated Freeway/Arterial Active Traffic Management (IATM) control is intended to implement strategies to increase corridor throughput and improve travel time reliability. Hence, the IATM control should be conducted at the corridor level by integrating freeways/expressways and arterials together. To achieve IATM successfully and efficiently, it is necessary to conduct the roadway evaluation analysis to select the corridors for IATM controls. The selected corridors should include both freeways/expressways and arterials, with priority to those that experience traffic congestion and unreliable travel time. In this task, all main roadways and segments having available travel time data were evaluated. According to the data availability, the best source which could provide the most reliable data will be used for the evaluation. Specifically, Automatic Vehicle Identification (AVI) and National Performance Management Research Data Set (NPMRDS) data are used for freeways/expressways and Bluetooth and NPMRDS data are employed for arterials.

Table 54. Summary of data evaluation results

Roadway Type	County	Data Availability	Volume Data	Travel Time Data		
				Simulation	Road Evaluation	Real-Time Traffic Monitoring
Freeways/expressways	All	AVI, MVDS, HERE, NPMRDS	MVDS	AVI	AVI	AVI
	All	MVDS, HERE, Bluetooth, NPMRDS	MVDS	NPMRDS	NPMRDS	Data fusion results
	All	MVDS, HERE, NPMRDS	MVDS	NPMRDS	NPMRDS	Data fusion results
Arterial	Seminole	SPM, Bluetooth, HERE, NPMRDS	SPM	Bluetooth	Bluetooth	Bluetooth (Imputed by fused HERE)
	Orange	HERE, Bluetooth, InSync	InSync	Bluetooth	Bluetooth	Bluetooth (Imputed by fused HERE)
	Orange	HERE, NPMRDS	----	NPMRDS	NPMRDS	HERE
Collector	Orange	Bluetooth, HERE, NPMRDS	----	NPMRDS	NPMRDS	HERE
	Orange	HERE, NPMRDS	----	NPMRDS	NPMRDS	HERE

Section 5.2 presents the evaluation analysis to identify the critical roadways and segments considering traffic congestion and travel time reliability. Different measures including travel time index (TTI), planning time index (PTI), and buffer time index (BTI) are calculated at the segment level. All measures were aggregated at the roadway level. The three measures are combined to identify critical roadways and segments having serious congestion and unreliable travel time.

In Section 5.3, we select critical corridors for IATM controls. The corridors integrate freeways/expressways and arterials based on criteria including data availability for IATM, critical segments, and detour routes. Section 5.4 recommends alternative IATM control strategies for the selected critical corridors. The recommendation of strategies mainly considers the identified critical segments experiencing traffic congestion and unreliable travel time while other factors such as traffic safety might also be considered. It is expected that the recommended strategies would release the traffic congestion and unreliability problems for both freeways/expressways and arterials in the selected corridors. Section 5.5 concludes the roadway evaluation effort and suggests the plan for the following simulation and strategy analysis tasks.

7.2. Identifications of Critical Roadways and Segments

7.2.1. Identification Methods

It is necessary to find critical roadways and segments with high potential benefits related to the implementation of the integrated active traffic management systems. In general, the roadways and segments with high potential for improvement would have significantly high traffic congestion and unreliability. Thus, the critical roadways and segments are investigated through the traffic congestion and reliability analysis. The segments of roadways were defined depending on the data source. Expressways managed by CFX or arterials covered by Bluetooth systems were segmented on the basis of AVI or Bluetooth readers' locations. Whereas, the segmentation of other freeways/expressways and arterials was based on NPMRDS, which is standardized as Traffic Message Channel (TMC) segments used to deliver and share traffic information among traffic management centers. In order to quantify the traffic congestion and reliability from the segment level to roadways and network level of freeways/expressways and arterials, the following evaluation methods were considered:

- Selection of performance measures in terms of traffic congestion and reliability
- Aggregation of each performance measure by direction of roadways
- Normalization and combination of performance measures to identify critical roadways
- Categorization and combination of performance measures to identify critical segments

7.2.1.1. Performance Measures

In Chapter 6, travel time and speed of freeways, expressways, and arterials have been collected and archived. Especially, there has been various research that addressed travel time to analyze both traffic congestion and reliability. Therefore, performance measures related to the travel time were selected as follows

- Travel Time Index (TTI)
- Planning Time Index (PTI)
- Buffer Time Index (BTI)

Currently, FHWA and most of states including Florida are using the above three measures to evaluate the performance of roadways (Chen, 2010; FDOT, 2015a; FHWA, 2006; Heery, 2016; Turner et al., 2011b; WSDOT, 2017).

The traffic congestion of roadways and their segments can be measured by the travel time index (TTI). The TTI is defined as the ratio of average travel time to a free-flow or speed-limit travel time:

$$\text{TTI} = \frac{Average\ Travel\ Time}{Travel\ Time_{free\ flow\ or\ speed\ limit}}$$

The TTI represents how much longer travel time is spent on average on the basis of the ideal traffic condition.

Related to the reliability, travel time reliability can be used and estimated by various measures. Particularly, it is well-known that reliability measures can capture the benefits of traffic management well. In this project, planning time index (PTI) and buffer time index (BTI) were selected to assess the travel time reliability according to the FWHA's recommendation (FHWA, 2006). The PTI is defined as the ratio of the 95th travel time to a free-flow or speed-limit travel time (USDOT):

$$\text{PTI} = \frac{95th\ percentile\ Travel\ Time}{Travel\ Time_{free\ flow\ or\ speed\ limit}}$$

The PTI provides an expected travel time budget, which could be used as a trip planning measure for journeys that require punctuality (Lomax and Margiotta, 2003).

Instead of considering the total travel time to preserve punctuality of travelers, the additional travel time can be used as the difference between the 95th percentile and the average travel time. Usually, the additional travel time is named as buffer time. The BTI is the ratio of the buffer time to the average travel time:

$$\text{BTI} = \frac{95th\ percentile\ Travel\ Time - Average\ Travel\ Time}{Average\ Travel\ Time}$$

The BTI implies that as a traveler should allow an extra percentage of travel time to arrive at a destination on time.

To calculate TTI and PTI, it is required to determine the ideal travel time of each segment. The ideal travel time can be based on the free flow speed or speed limit. In this project, speed limits will be used to estimate TTI and PTI. In summary, TTI is used for evaluating traffic congestion and PTI and BTI are used for evaluating travel time reliability.

7.2.1.2. Performance Measure Estimation by Direction of Roadways

After the performance measures were calculated at each segment on the basis of analysis time slots, each performance measure was aggregated based on the direction of roadways through the VMT (Vehicle Miles Traveled)-weighted average of all segments as follows:

$$TTI_{mean\ by\ direction} = \frac{\sum_{i=1}^{n}(TTI_i * VMT_i)}{\sum_{i=1}^{n} VMT_i}$$

$$PTI_{mean\ by\ direction} = \frac{\sum_{i=1}^{n}(PTI_i * VMT_i)}{\sum_{i=1}^{n} VMT_i}$$

$$BTI_{mean\ by\ direction} = \frac{\sum_{i=1}^{n}(BTI_i * VMT_i)}{\sum_{i=1}^{n} VMT_i}$$

The analysis time slots of 288 were determined based on 5-minute intervals, from 00:00:00 to 23:59:59. To estimate VMT, traffic volume of 5-minute intervals was collected from MVDS for freeways and expressways. Whereas, in the case of arterials, Annual Average Daily Traffic (AADT) was used to estimate the VMT because there are no traffic volume collection systems collecting traffic volume in 5-minute intervals. Thus, the same VMT of each segment on arterials was applied throughout all analysis time slots. Figure 118 shows the estimated three performance measures of westbound Interstate 4 (I-4) based on one-year data of 2017.

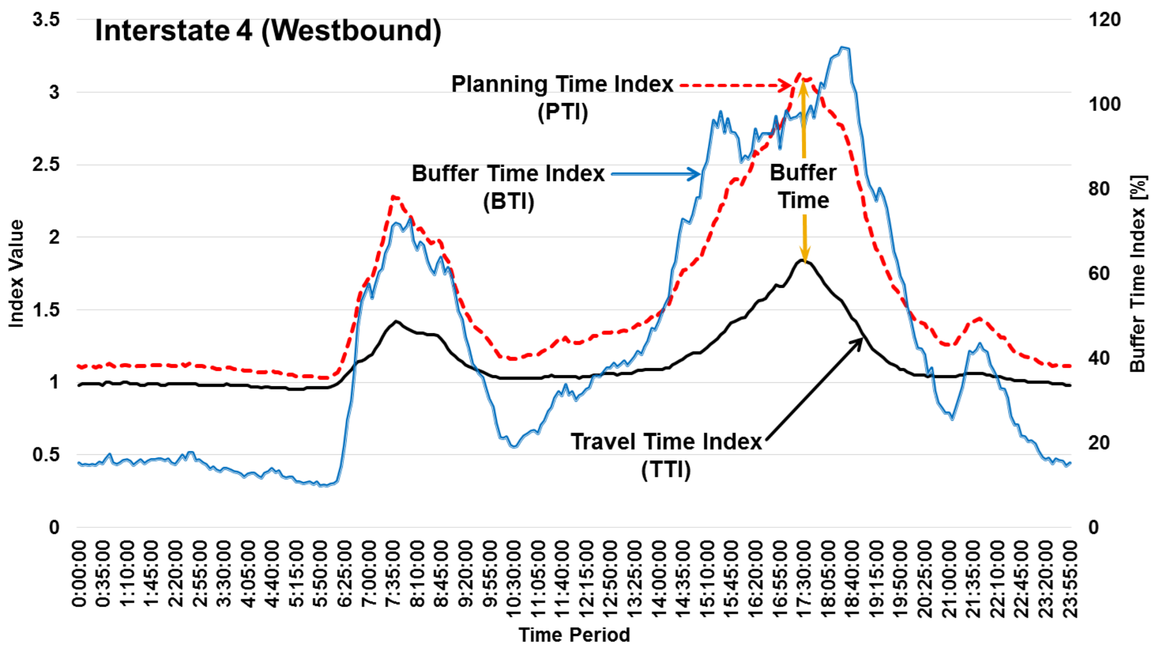


Figure 118. The relationship among TTI, PTI, and BTI of 2017

7.2.1.3. Normalization and Combination of Performance Measures

Before the three measures (i.e., TTI, PTI, and BTI) are combined, it is required to normalize them because they have different data scale. Among many normalization methods, the min-max normalization method was applied to transform the data of the three measures into a new range as follows:

$$x' = \frac{x - \min(X)}{\max(X) - \min(X)}$$

where, x indicates an observation of X variable,

x' indicates the transformed observation of x,

$\min(X)$ is the minimum value among values of X variable,

$\max(X)$ is the maximum value among values of X variable,

By normalization, three measures could have the same scale, which ranges from 0 to 1. Figure 119 shows the normalized TTI, PTI, and BTI of westbound I-4 as an example. Comparing with Figure 118, Figure 119 provides a clearer view of the three variables, and we can notice that they have similar trends or fluctuations according to the time series. In this case, TTI and PTI have very similar trends and normalized values, but BTI is a little different than TTI and PTI. Finally, the normalized values were combined through a simple average method.

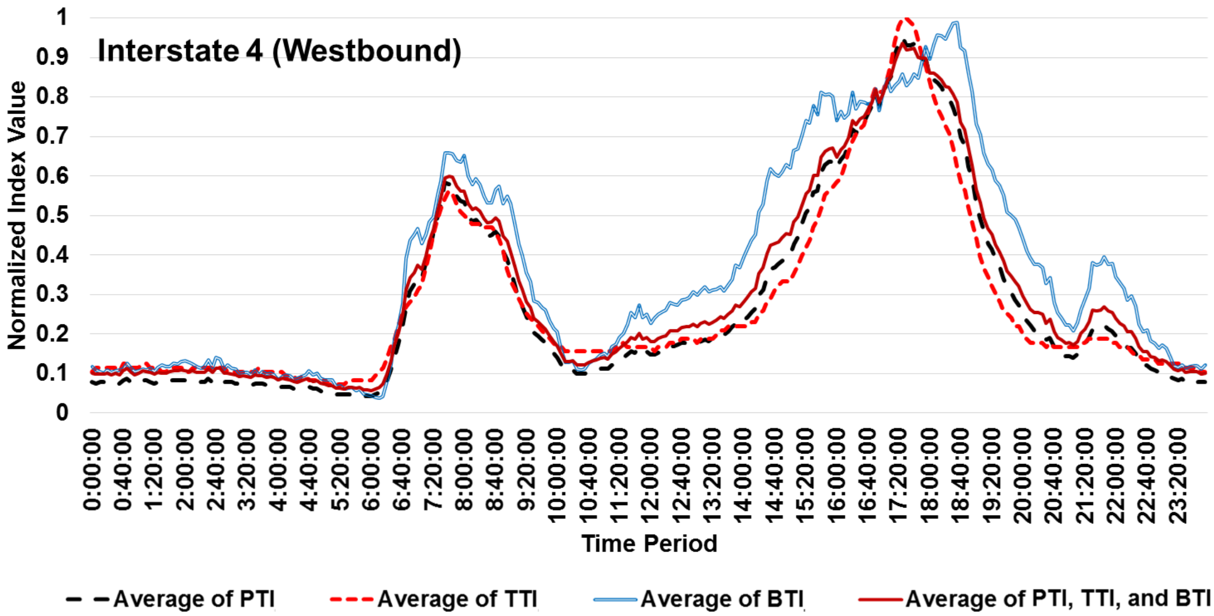


Figure 119. Normalized TTI, PTI, and BTI of 2017

7.2.1.4. Categorization and Combination of Performance Measures

Categorization of performance measures was applied to identify the critical segments with moderate and high categories. Regardless of freeways and arterials, the selected performance measures were categorized in three groups by considering the following values:

- Low congestion or High reliability (Green): less than the 50th percentile
- Moderate congestion or Moderate reliability (Yellow): greater than or equal to the 50th percentile and less than the 75th percentile
- High congestion or Low reliability (Red): greater than or equal to the 75th percentile value

Considering to using 50 % and 75% of speed to group speeds of RITIS, this research determined the 50th percentile and 75th percentile as criteria to distinguish the low, medium, and high levels. Figure 120 shows the 50th and 75th percentile value of performance measures: TTI, PTI, and BTI. The distributions of TTI, PTI, and BTI included all data of freeways/expressways and arterials. Values in parentheses were applied as criteria to categorize TTI, PTI, and BTI. It should be noted that the criteria of TTI is not significantly different from the previous research on freeways, in which three types of congestion levels are classified on the basis of TTI: less than 1.25, greater than or equal to 1.25 and less than 2.00, and greater than or equal to 2.00. So, the categorization of TTI is consistent with the criteria of previous research (Griffin, 2011).

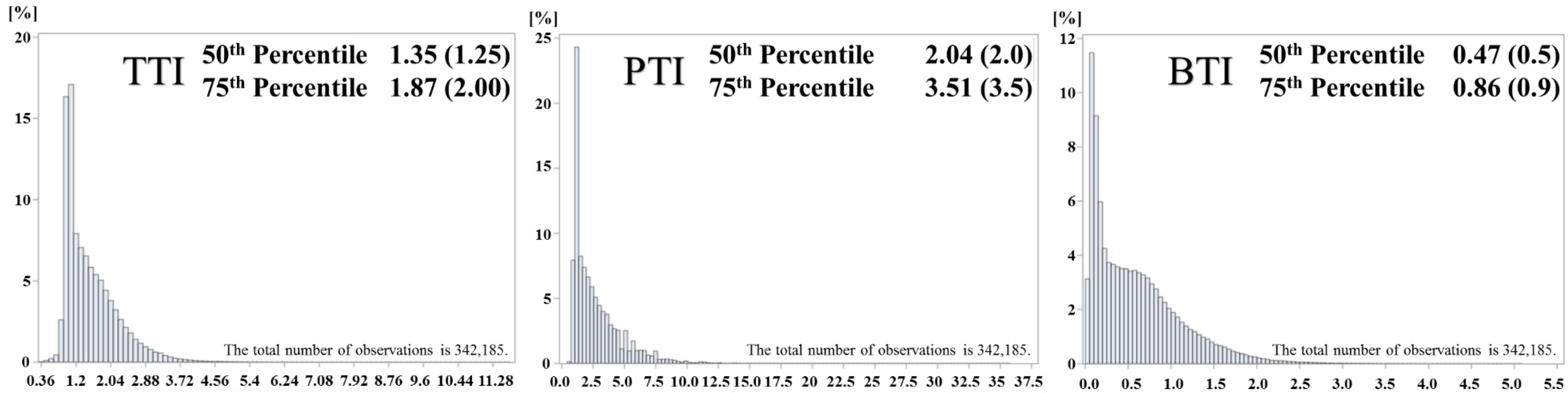


Figure 120. 50th and 75th percentile of performance measures: TTI, PTI, and BTI

For each measure, a scoring paradigm is used for the three categories:

Category	Score
Low congestion or High reliability	1
Moderate congestion or Moderate reliability	2
High congestion or Low reliability	3

Finally, the comprehensive score could be obtained by calculating the average of scores of the three measures (i.e., TTI, PTI, and BTI). Since the average scores have a decimal point, the final scores were rounded to be assigned into three levels (i.e., 1, 2, and 3). Then, the critical segments with medium and high categories were indicated if the rounded final average scores are greater than or equal to 2.

7.2.2. Data Preparation

Three types of data in 2017 were prepared: travel time data, traffic volume data, and geometry data. To estimate more actual traffic conditions, various data sources of freeways, expressways, and arterials were used. If multiple data sources are available for one segment, the data source with the best performance is selected based on the evaluation results in Chapter 4. The travel time data of expressways and arterials covered by the AVI systems of CFX or Bluetooth system were estimated from their raw data. Otherwise, the travel time data of other freeways and arterials were acquired from NPMRDS. Figure 121 demonstrates the data source used for each segment. Note that several segments without any available data are also included to ensure the completeness of the roadways.

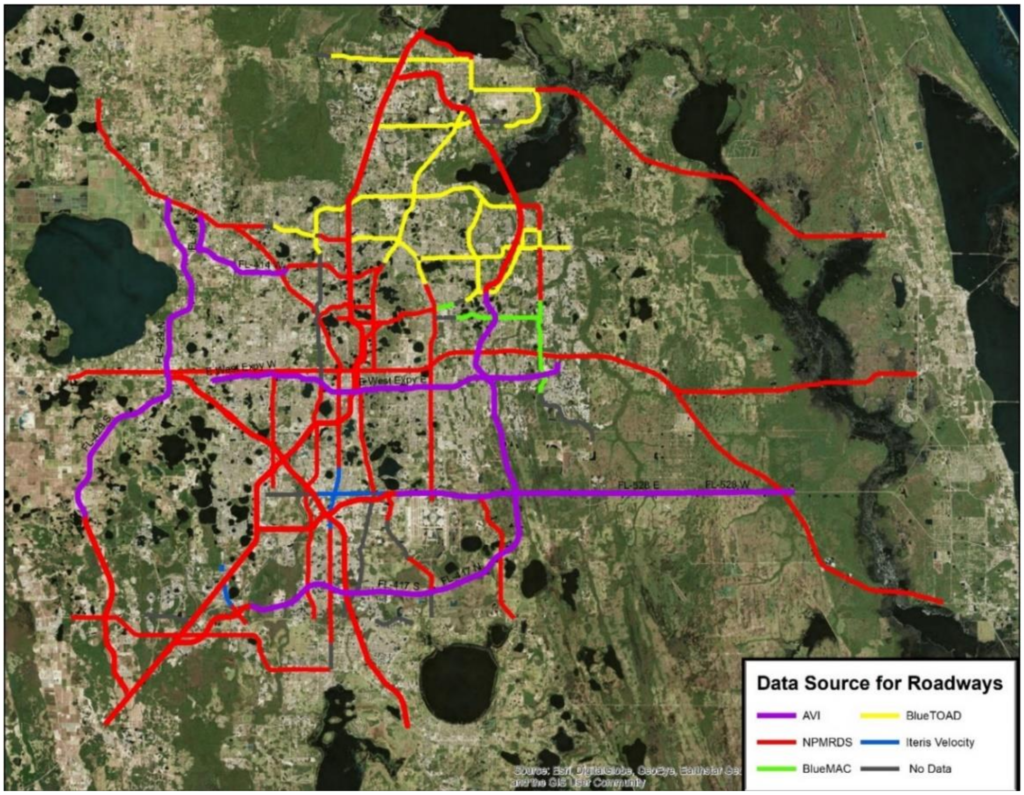


Figure 121. Travel time data sources used for roadways

Related to the traffic volume data, MVDS data of RITIS archived at 5-minute interval was used for expressways (CATT, 2008; 2018). However, traffic volume of other arterials and freeways, which are not monitored by MVDS, was derived from Annual Average Daily Traffic (AADT) of NPMRDS. Finally, related to the geometry data, speed limits and the number of lanes of each segment were collected from the Roadway Characteristics Inventory (RCI) of FDOT.

After considering the functional classification and data availability, a total of 6 freeways/ expressways and 21 arterials were selected in our study area. Totally, travel time from around 600 miles of roadways (around 1,200 segments) were evaluated. Table 55 lists the information of the studied roadways including roadway type, roadway name, length, number of segments of both directions, minimum and maximum speed limits along the roadway. It should be noted that speed limit varies across segments for a roadway. Hence, minimum and maximum speed limits of all segments on each are listed.

Table 55. List of the evaluated roadways

Roadway Type	Roadway Name	Length per direction (mile)	Number of Segments*	Speed Limit	
				Min	Max
Freeway	I-4	54.68	136	50	65
	Florida's Turnpike	29.28	31	70	70
	SR 408	23.63	43	55	65
	SR4- 417	61.91	84	55	70
	SR 429	37.11	46	70	70
	SR 528	35.56	44	55	70
Arterial	SR 46	37.22	22	40	55
	Lake Mary Blvd	11.49	19	35	45
	SR 434	35.02	69	35	50
	US 17-92 North	22.83	51	35	55
	Red Bug Lake Rd-Mitchell	9.12	12	45	45
	SR 436	25.41	73	35	50
	Tuskawilla Rd	5.66	4	45	45
	SR 426	14.53	43	30	45
	Maitland Blvd	5.97	14	45	55
	SR 423-CR 423	21.38	70	35	55
	US 441 N	22.3	56	35	55
	US 17-92-441	17.17	71	35	55
	SR 527	18	44	30	45
	SR 50	50.11	116	30	65
	Kirkman Rd	6.76	35	35	50
	Narcoossee Rd	7.75	9	40	45
	SR 527 A	8.13	13	35	55
	Sand Lake-Mc Coy Rd	7.09	22	45	55
	US 192	16.57	30	40	55
	SR 535	3.79	12	40	50
	University Blvd	6.07	20	45	45
Total	-	594.54	1,189	-	-

* Two directions in total

7.2.2.1. Travel Time of Segments on CFX's Expressways

In this project, AVI raw data including the passing time of the encrypted toll tag IDs at each AVI readers is a very important data source because it is assumed that the processed travel time is ground-truth data which is not adjusted by the speed limit (see Chapter 4). Because of the encryption of transponders' ID, some noise in the data were included in the AVI raw data. Therefore, through three steps, the mean travel times of segments were estimated (see Figure 122).

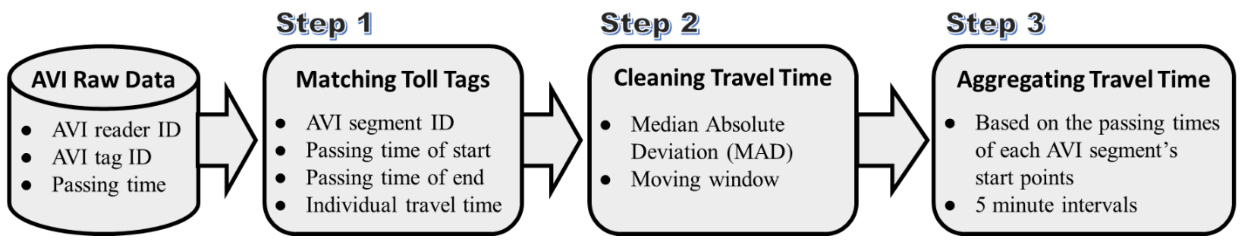


Figure 122 Segment travel time estimation steps from AVI raw data

By matching the encrypted toll tag IDs between an AVI reader and its adjacent AVI reader, individual vehicle's travel time was calculated through the passing time difference between two readers. One constraint was considered: the maximum travel time of each segment will not exceed two hours because it will be extremely rare to take more than two hours to pass a segment with the average length of 1.5 miles. The constraint could help efficiently avoid many duplicated matching results of transponders.

Next, outliers among individual vehicle's travel time were identified and eliminated through a moving-window implementation of the Hampel identifier based on the median absolute deviation (MAD) approach (Davies and Gather, 1993). Twenty consecutive observations were used as the size of a window. The MAD approach could provide high accuracy with low computational effort. The removal criterion of outliers is as follows:

$$abs(travel\ time(i) - Median(i)) \leq b * MAD$$

where b is a threshold, in which 3 was applied conservatively (Miller, 1991). Figure 123 shows the plot of individual travel times before and after removing outliers at a specific segment.

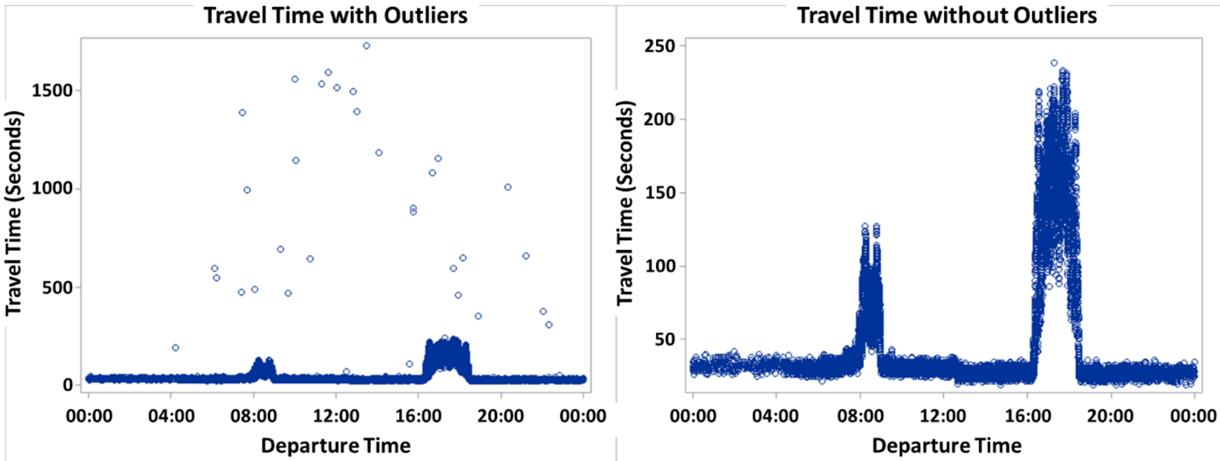


Figure 123. Individual travel times before/after removing outliers

Finally, segment mean travel time was aggregated at 5-minute intervals on the basis of the departure time of individual vehicles at each AVI segment's start point.

7.2.2.2. Travel Time of I-4 and Florida Turnpike

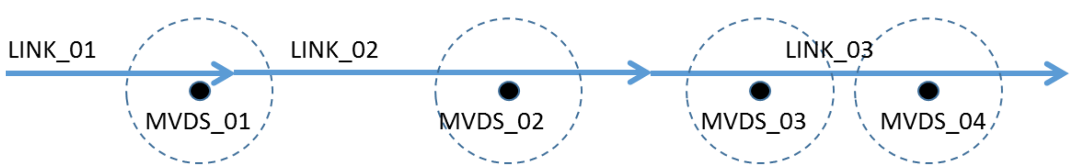
Although there are many methods to estimate segment travel times through MVDS data, the methods have limitations to estimate the true travel time. For instance, the travel time estimation method using spot mean speeds of MVDS detectors cannot include actual speed variation at different locations within segments. I-4 and FTE are using Bluetooth readers, but the travel time estimated from the Bluetooth system cannot represent actual drivers' travel time because of the smoothing or prediction algorithms. Whereas, NPMRDS' travel time can be used as the segment travel time ground truth of I-4 and FTE expressways because it is based on only raw observed probe-based traffic data including passenger cars and trucks regardless of data modeling and smoothing. Besides, it is a useful data source to evaluate the existing roadway performance such as travel time reliability. Therefore, travel time was collected 5-minute intervals for -4 and FTE. The data included both trucks and passenger vehicles.

7.2.2.3. Travel time of Arterials

Travel time data from Bluetooth Detection System (BDS) and NPMRDS were collected to evaluate the performance of arterials. Travel time of an individual vehicle detected by BDS was extracted from three BDS vendors: BlueMAC, BlueTOAD, and Iteris Velocity. Their coverage was showed in Figure 121. Then, the raw travel time data were aggregated at 5-minute intervals to be consistent with travel time of freeways/expressways. Similarly, NPMRDS' travel time was collected at 5-minute aggregation level for other major arterials which lack BDS data.

7.2.2.4. MVDS Data

I-4 and all expressways are covered by MVDS to collect traffic flow, occupancy, and spot speed. The MVDS data aggregated at 5-minute intervals were downloaded via the Regional Integrated Transportation Information System (RITIS) (CATT, 2008). Each MVDS was connected to segments of AVI and NPMRDS through the spatial join within 100 meters radius on the basis of the location of the MVDS (see Figure 124). Based on the matching table between segments and MVDSs, the traffic volume of each segment was calculated through the simple average of traffic volume of MVDSs connected to each segment, and the occupancy and speed of each segment were computed through the volume-weighted average of MVDSs.



Link_ID	MVDS_ID
LINK_01	MVDS_01
LINK_02	MVDS_01
LINK_02	MVDS_02
LINK_03	MVDS_03
LINK_03	MVDS_04

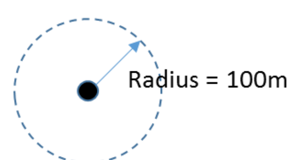


Figure 124. Spatial join with segments and MVDS

7.2.2.5. Geometry Features

Many geometry features such as speed limits, and the length of a segment were included in this study. The speed limits were used to estimate TTI and PTI. Whereas, the length of a segment was used to calculate VMT. The geometry features were collected from the Roadway Characteristics Inventory (RCI) database of FDOT.

7.2.3. Evaluation Results

Before ranking roadways and identifying critical segments, analysis was conducted to investigate the overall traffic conditions in the study area. As shown in Figure 125, there are obvious AM and PM peak periods during the day at the freeway/expressway network level. The overall traffic volume of AM and PM peak periods are not significantly different, but the trends of travel time are significantly different: travel time performance of the PM peak periods gets much worse than the AM peak periods. Likewise, arterials at a network level have two peak time periods: AM and PM (see Figure 126). Overall, arterials have higher values of overall TTI, PTI, and BTI than the freeways/expressways, which means that traffic conditions of arterials are worse than freeways/expressways. The TTI at the freeway/expressway network level has low congestion range between 1 and 1.3, whereas the TTI of the arterial network is between about 1.3 and 2.1 corresponding to the medium and high congestion levels. In the case of PTI, the freeway/expressway network has high travel time reliability which is between 1 and 2. On the other hand, the arterial network has higher records between 2 and 4, corresponding to the medium travel time reliability during the non-peak hours and the low travel time reliability during peak hours. In terms of BTI, the freeway/expressway network is in the range of high travel time reliability (between 0.1 and 0.4), but the arterial network has medium travel time reliability which is between 0.5 and 0.8.

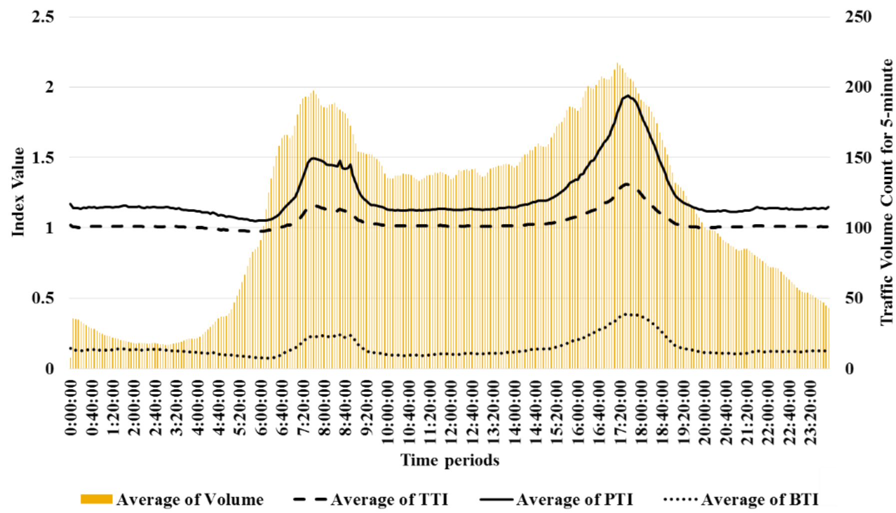


Figure 125. TTI, PTI, and BTI at the freeway/expressways network level

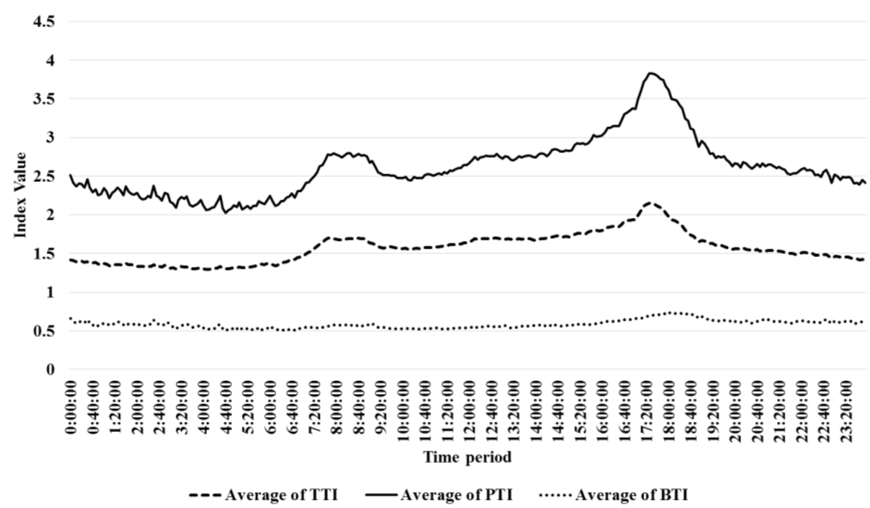


Figure 126. TTI, PTI, and BTI at the arterial network level

Based on the overall trends, critical roadways and segments were analyzed by using the collected data during AM and PM peak periods, when the network has the most serious problem. By considering the change of the average volume of freeways/expressways network (see Figure 119), the AM and PM peak periods were determined as follows:

- AM peak period: 06:00-09:00
- PM peak period: 16:00-19:00

7.2.3.1. Identification of Critical Roadways

Critical roadways were identified through ranking roadways based on the normalization and combination of performance measures by direction of roadways. Table 56 shows the results related to ranking freeways/expressways. Based on the AM and PM peak periods, TTI, PTI, and BTI by the direction of each roadway were estimated. The estimated values were normalized by using the minimum and maximum values of each measure. The normalized values correspond to AM (Normalization) and PM (Normalization) columns. The normalized six variables were combined through the simple average. The rank of freeways/expressways were prioritized in descending order. According to the analysis results, it is indicated that both directions of Interstate 4 are mostly congested and unreliable, followed by Florida turnpike (SR 91) and SR 408. It was revealed that the most uncongested and reliable roadway is SR 414 and SR 429, which are in the western outskirts and the west-northern outskirts of Orlando city, respectively.

Table 56. Ranking results of freeways/expressways

Roadway	Dir.	AM			PM			AM (Normalization)			PM (Normalization)			Mean	Rank
		TTI	PTI	BTI	TTI	PTI	BTI	TTI	PTI	BTI	TTI	PTI	BTI		
Interstate-4	WB	1.24	1.79	36.99	1.61	2.75	65.56	0.85	0.96	1.00	1.00	1.00	0.98	0.96	1
Interstate-4	EB	1.24	1.68	28.67	1.55	2.70	66.85	0.83	0.82	0.72	0.90	0.98	1.00	0.88	2
Turnpike	NB	1.30	1.83	31.26	1.16	1.63	38.16	1.00	1.00	0.81	0.37	0.38	0.52	0.68	3
Turnpike	SB	1.11	1.28	13.58	1.41	2.10	40.42	0.53	0.35	0.21	0.72	0.64	0.56	0.50	4
SR 408	WB	1.13	1.47	26.45	1.14	1.46	23.07	0.56	0.58	0.64	0.35	0.29	0.27	0.45	5
SR 408	EB	1.05	1.36	22.54	1.13	1.60	34.24	0.37	0.45	0.51	0.33	0.36	0.46	0.42	6
SR4- 417	SB	1.08	1.27	15.60	1.12	1.49	29.44	0.44	0.35	0.28	0.32	0.30	0.38	0.34	7
SR4- 417	NB	1.02	1.12	7.77	1.19	1.63	31.46	0.30	0.17	0.01	0.41	0.38	0.41	0.28	8
SR 528	WB	1.01	1.20	15.74	1.09	1.41	21.41	0.27	0.26	0.28	0.28	0.26	0.25	0.27	9
SR 528	EB	0.98	1.09	10.88	1.10	1.45	25.95	0.19	0.13	0.12	0.29	0.28	0.32	0.22	11
SR 429	SB	1.06	1.20	12.51	1.08	1.32	17.88	0.39	0.27	0.17	0.26	0.21	0.19	0.25	10
SR 429	NB	1.02	1.10	7.47	1.06	1.22	14.40	0.30	0.14	0.00	0.23	0.15	0.13	0.16	12
SR 414	EB	0.96	1.03	8.30	0.94	1.03	9.40	0.14	0.07	0.03	0.08	0.05	0.05	0.07	13
SR 414	WB	0.90	0.98	8.68	0.89	0.95	6.65	0.00	0.00	0.04	0.00	0.00	0.00	0.01	14

Like the ranking of freeways/expressways, arterials were also prioritized. Table 4 shows the ranking results of 21 arterials separated by the main road direction. It should be noted that the directions change along SR 434 and the corresponding directions are N-W-SB (North-West-South Bound) and N-E-SB (North-East-South Bound). The columns of AM and PM are the actual estimated values of TTI, PTI, and BTI of the two peak periods and AM (Normalization) and PM (Normalization) are the normalized values through the min-max method. Finally, the arterials distinguished by their main direction were ranked after the normalized values were averaged.

According to the ranking results of arterials (see Table 57), the critical arterials in the top 10 ranks were identified as follows: Kirkman Road (Southbound and Northbound), SR 527 (Southbound and Northbound), Maitland Boulevard (Eastbound), University Boulevard (Eastbound and Westbound), SR 423-CR 423 (Westbound), and SR 50 (Eastbound and Westbound of Colonial Road). Except for University Boulevard, most critical arterials pass through near the central business district or amusement parks in Orlando city. In addition, it was revealed that arterials in the bottom 10 ranks are as follows: Red Bug Lake Rd-Mitchell Hammock Road (Eastbound and Westbound), Lake Mary Boulevard (Eastbound and Westbound), SR 46 (Eastbound and Westbound), Tuskawilla Road (Southbound and Northbound), US 441 N (Northbound), and US 17-92 North (Southbound), which are located in Oviedo city or in the suburban area of Orlando.

Table 57. Ranking results of arterials

Roadway	Dir.	AM			PM			AM (Normalization)			PM (Normalization)			Mean	Rank
		TTI	PTI	BTI	TTI	PTI	BTI	TTI	PTI	BTI	TTI	PTI	BTI		
Kirkman Rd	NB	1.92	3.6	0.86	2.65	5.36	1.00	0.71	0.89	1.00	0.99	1.00	0.97	0.93	1
Kirkman Rd	SB	1.99	3.73	0.83	2.13	4.12	0.91	0.77	0.94	0.96	0.67	0.70	0.86	0.82	2
SR 527	SB	1.81	3.22	0.76	2.46	4.83	0.94	0.62	0.75	0.86	0.87	0.87	0.90	0.81	3
Maitland Blvd	EB	2.27	3.89	0.65	2.47	4.22	0.67	1.00	1.00	0.69	0.88	0.72	0.57	0.81	4
SR 527	NB	1.91	3.39	0.75	2.19	4.27	0.93	0.70	0.81	0.85	0.71	0.74	0.89	0.78	5
University Blvd	EB	1.69	3.32	0.86	1.97	4.18	1.03	0.52	0.78	1.00	0.58	0.71	1.00	0.77	6
SR 423-CR 423	WB	1.71	2.96	0.70	2.52	4.8	0.87	0.54	0.65	0.76	0.91	0.86	0.82	0.76	7
University Blvd	WB	1.63	3.07	0.79	2.15	4.34	0.97	0.48	0.69	0.90	0.68	0.75	0.93	0.74	8
SR 50	WB	1.83	3.26	0.74	2.14	4.02	0.85	0.64	0.76	0.83	0.68	0.68	0.80	0.73	9
SR 50	EB	1.73	3.02	0.71	2.23	4.32	0.91	0.56	0.67	0.79	0.73	0.75	0.86	0.73	10
SR 423-CR 423	EB	1.85	3.29	0.72	2.12	3.95	0.83	0.66	0.77	0.80	0.67	0.66	0.76	0.72	11
Maitland Blvd	WB	1.71	2.81	0.58	2.48	4.66	0.89	0.54	0.59	0.58	0.88	0.83	0.84	0.71	12
US 17-92-441	SB	1.62	2.56	0.57	2.67	4.95	0.84	0.47	0.50	0.57	1.00	0.90	0.78	0.70	13
US 17-92-441	NB	1.79	3	0.61	2.25	4.19	0.81	0.61	0.66	0.64	0.75	0.72	0.74	0.69	14
SR 434	N-E-SB	1.65	2.84	0.63	2.09	3.95	0.75	0.49	0.60	0.66	0.65	0.66	0.67	0.62	15
SR 535	SB	1.27	2.09	0.58	2.29	4.55	0.95	0.18	0.32	0.58	0.77	0.80	0.91	0.60	16
SR 434	N-W-SB	1.6	2.77	0.64	1.95	3.52	0.70	0.45	0.58	0.67	0.56	0.56	0.61	0.57	17
US 192	EB	1.53	2.5	0.60	2.04	3.74	0.78	0.39	0.48	0.62	0.62	0.61	0.71	0.57	18
SR 436	NB	1.66	2.65	0.56	2.17	3.63	0.63	0.50	0.53	0.57	0.70	0.58	0.53	0.57	19
SR 426	EB	1.52	2.58	0.63	2.15	3.63	0.63	0.39	0.51	0.66	0.68	0.58	0.53	0.56	20
US 192	WB	1.51	2.36	0.53	2.04	3.8	0.79	0.38	0.42	0.52	0.62	0.62	0.72	0.55	21
Sand Lake-Mc Coy Rd	EB	1.38	2.18	0.58	2.01	3.76	0.84	0.27	0.35	0.59	0.60	0.61	0.78	0.54	22
Narcoossee Rd	SB	1.5	2.39	0.57	1.82	3.42	0.81	0.37	0.43	0.58	0.48	0.53	0.74	0.52	23
SR 436	SB	1.65	2.59	0.52	2.01	3.37	0.63	0.49	0.51	0.50	0.60	0.52	0.52	0.52	24
Narcoossee Rd	NB	1.52	2.58	0.66	1.7	3.04	0.76	0.39	0.51	0.70	0.41	0.44	0.68	0.52	25
Sand Lake-Mc Coy Rd	WB	1.61	2.55	0.56	1.81	3.18	0.70	0.46	0.49	0.56	0.48	0.47	0.61	0.51	26
SR 535	NB	1.46	2.23	0.47	1.77	3.39	0.92	0.34	0.37	0.42	0.45	0.52	0.87	0.50	27
SR 426	WB	1.56	2.51	0.54	1.75	2.92	0.61	0.42	0.48	0.53	0.44	0.41	0.50	0.46	28
US 17-92 North	NB	1.45	2.28	0.51	1.9	3.21	0.63	0.33	0.39	0.48	0.53	0.48	0.53	0.46	29
US 441 N	SB	1.58	2.48	0.53	1.57	2.64	0.63	0.43	0.47	0.51	0.33	0.34	0.52	0.44	30
SR 527 A	SB	1.42	2.08	0.46	1.65	3.09	0.79	0.30	0.32	0.42	0.38	0.45	0.72	0.43	31
SR 527 A	NB	1.5	2.28	0.48	1.58	2.62	0.61	0.37	0.39	0.45	0.34	0.34	0.51	0.40	32
US 17-92 North	SB	1.49	2.26	0.47	1.69	2.75	0.55	0.36	0.38	0.42	0.41	0.37	0.43	0.40	33
US 441 N	NB	1.41	2.12	0.47	1.76	2.88	0.58	0.30	0.33	0.43	0.45	0.40	0.46	0.40	34
SR 46	WB	1.27	1.63	0.28	1.58	2.27	0.42	0.18	0.15	0.14	0.34	0.25	0.27	0.22	35
Lake Mary Blvd	EB	1.27	1.71	0.30	1.45	1.93	0.30	0.18	0.18	0.18	0.26	0.17	0.13	0.18	36
Red Bug Lake Rd-Mitchell Hammock Rd	EB	1.28	1.56	0.21	1.56	2.09	0.32	0.19	0.12	0.05	0.33	0.21	0.16	0.17	37
Tuskawilla Rd	SB	1.37	1.71	0.24	1.48	1.86	0.26	0.26	0.18	0.09	0.28	0.15	0.08	0.17	38
Tuskawilla Rd	NB	1.31	1.64	0.24	1.46	1.85	0.27	0.21	0.15	0.09	0.27	0.15	0.09	0.16	39
SR 46	EB	1.29	1.63	0.26	1.36	1.79	0.31	0.20	0.15	0.12	0.21	0.14	0.14	0.16	40
Lake Mary Blvd	WB	1.24	1.64	0.29	1.37	1.8	0.28	0.16	0.15	0.16	0.21	0.14	0.10	0.15	41
Red Bug Lake Rd-Mitchell Hammock Rd	WB	1.25	1.59	0.25	1.34	1.68	0.24	0.16	0.13	0.10	0.19	0.11	0.05	0.13	42

7.2.3.2. Identification of Critical Segments

Although the critical roadways with high normalized numeric index will have most of the critical segments indicated by medium and high categories, several critical segments can be located on other roadways. In order to find critical segments, all segments on freeway/expressways and arterials in study area were analyzed through categorization of TTI, PTI, and BTI according to the defined criteria in Figure 115. Segments with medium and high categories were indicated to critical segments.

The classification of TTI, PTI, and BTI for all segments was conducted for both AM and PM peak periods. As shown in Figure 127, it is clear that arterials have much more critical segments and more critical segments could be identified during the PM peak period.

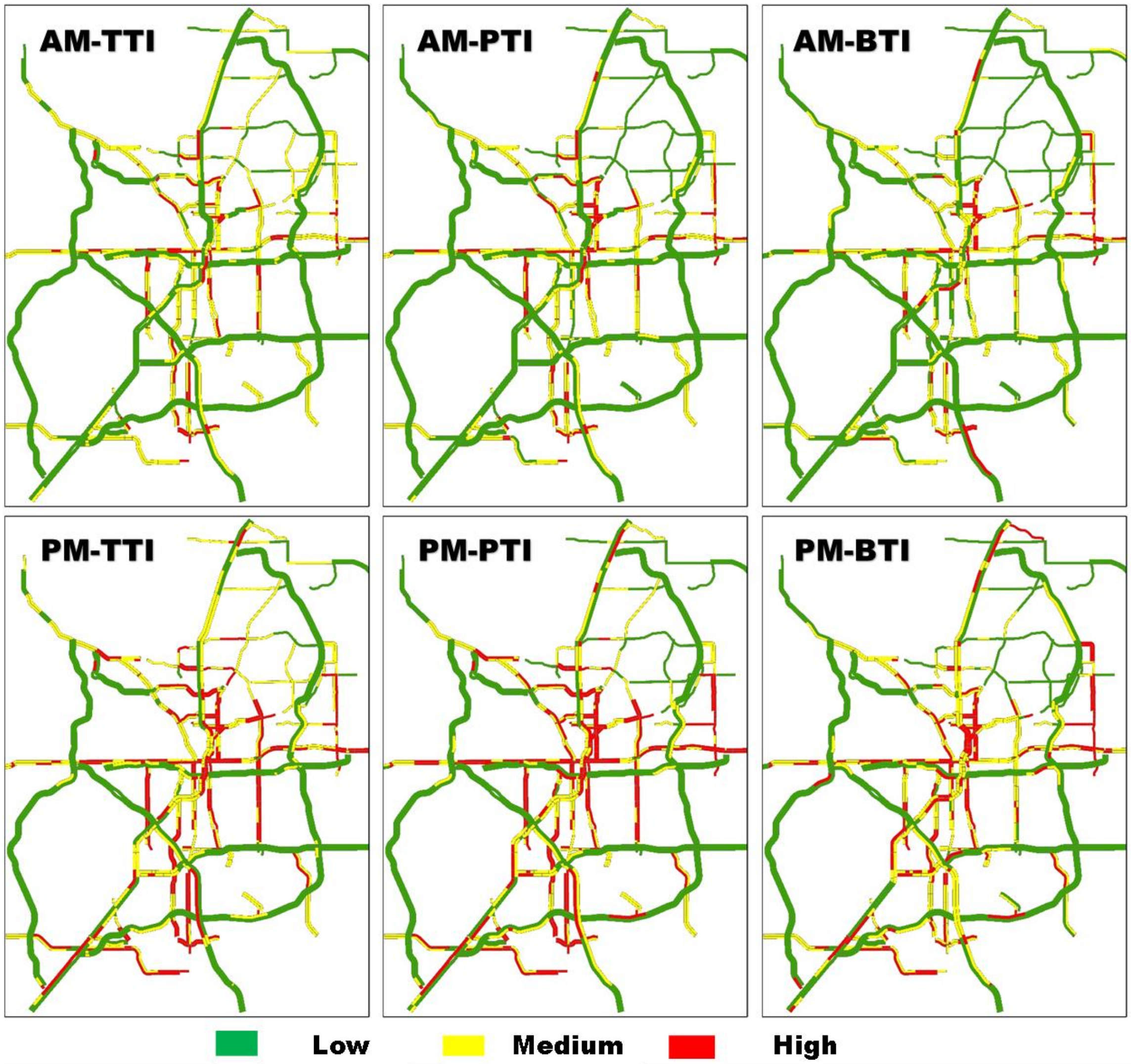


Figure 127. Categorization of TTI, PTI, and BTI on segments for AM and PM peak periods

To obtain comprehensive results related to the critical segments, all category values of the above were aggregated through the simple average for both AM and PM periods. Figure 128 shows clearly critical segments on freeway/expressways and arterials. The overall length of critical segments by each freeway/expressway is similar to the ranking results of freeway/expressways. Especially, I-4 has the longest critical segments, followed by Turnpike (SR-91). SR-408, SR-528, and SR-417 appear to have a similar critical segment length. Finally, SR-429 has only two critical segments near major junctions, but SR-414 does not have any critical segment. Likewise, major arterials have more critical segments. Arterials in Oviedo city have less critical segments than Orlando city during peak periods. Arterials near CBD, universities, amusement parks, and Orlando airport have many critical segments. Most of the segments on SR-50, which is a major east - west arterial in the study area, are critical segments.

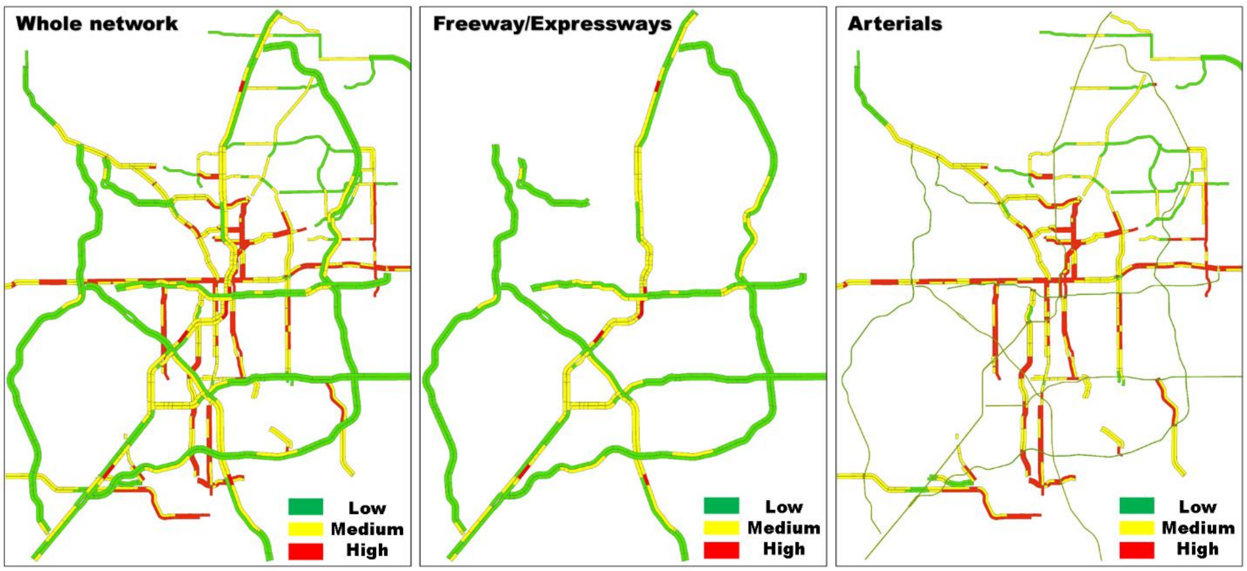


Figure 128.

7.2.4. Discussions

To evaluate roadways and segments in the study area, three measures including TTI, PTI, BTI which could reflect traffic congestion and reliability levels were calculated for all segments. A wide array of data sources was used to compute the measures. The calculated measures were aggregated for each roadway by using the VMT weighted average approach. By normalization and categorization, the different measures were combined to evaluate all roadways and segments comprehensively. For freeways/expressways, the evaluation results indicated that I-4, Turnpike, and SR-408 have the most serious problems. For arterials, the roadways across the downtown Orlando area experience traffic congestion and unreliable travel time while the roadways in the

Oviedo area have good traffic performance. IATM controls should be first implemented for the identified critical roadways and segments.

7.3. Selection of Study Corridors

Two major study corridors are selected in the study area for implementing IATM strategies. The selection of the study corridors is based on the objectives of the IATM project, the evaluation results, roadway network structures, locations of roadways. In other words, the identified critical roadways which need improvement and could be treated by IATM strategies are selected. There are 7 freeways/expressways in total considered in this project: I-4, Turnpike, SR-408, SR-528, SR-417, SR-429, and SR-414. The selection of roadways for corridors considered the freeways/expressways and arterials at the same time. Besides, some important collectors are also included in the corridors.

According to the evaluation results in Chapter 7.2, I-4 is experiencing serious problems, especially in the Orlando Metropolitan area. It suffers from frequent congestion and unreliable travel time. Meanwhile, there are plenty of arterials and even major collectors which could serve as its alternative and detour routes. Further, I-4 plays such an important role in connecting downtown Orlando with other cities (e.g. Sanford, Altamonte Springs and Winter Park) and major attractions (Walt Disney World and Universal Studio Orlando). I-4 is an ideal freeway to implement IATM strategies. Fortunately, aiming to release its congestion, the ongoing I-4 Ultimate project (FDOT, 2017a) is reconstructing and widening I-4 in the study area. It is expected that traffic on I-4 will be significantly improved after the construction. Hence, both I-4 current and future conditions will be considered in the following tasks. The selected I-4 corridor is shown in Figure 129. The length of the selected I-4 is around 6 miles, across the Greater Orlando Metropolitan Area. The surrounding arterials and collectors most of which have critical congestion and travel time reliability problems are included in the corridor. Meanwhile, the part of SR-408 is also included in the I-4 corridor.

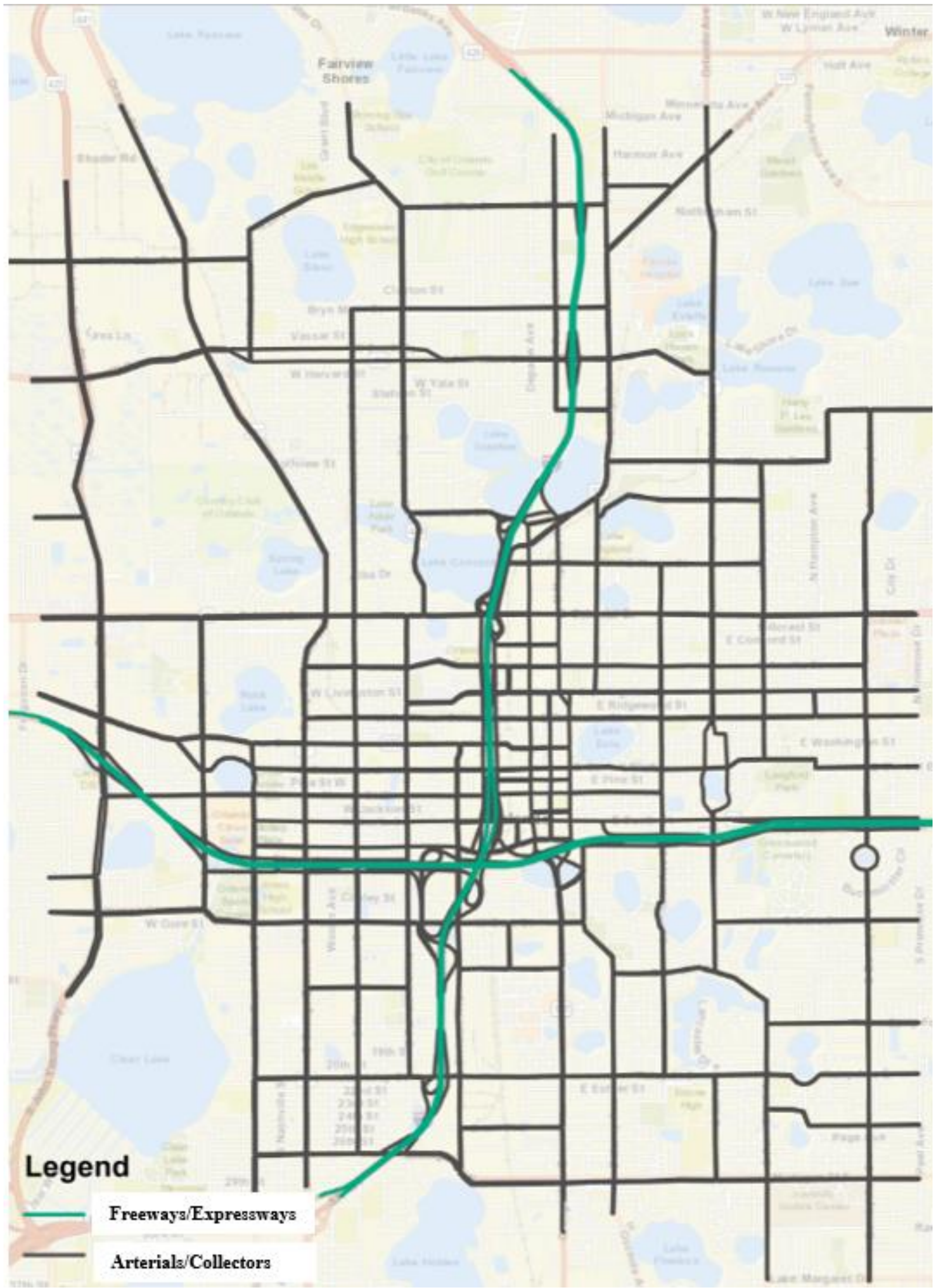


Figure 129 Selected I-4 corridor

In addition to I-4, the north section of SR-417 has several critical segments. Meanwhile, the north SR-417 is near the University of Central Florida (UCF), where high traffic demands are expected. During big events, the demand might be over the capacities of the surrounding roadways. Hence, roadways (both freeways/expressways and arterials) are selected along SR-417 in the East Orlando Area are selected for the corridor management. As shown in Figure 130, the selected SR-417 north runs north-south from Winter Springs, south through Oviedo and University of Central Florida (UCF), to the interchange with SR-408. Three arterials/collectors along the expressway are included. The first arterial/collector roadway is the northern part of SR-426 and the northern part of SR-551 (Goldenrod Road). The second arterial/collector roadway is Tuskawilla Road and Dean Road and it shares the small common stretch of SR-426 with the first arterial/collector roadway. The third arterial/collector roadway is SR-434, from Winter Spring to Waterford Lakes. It serves travelers who travel from northern Greater Orlando to UCF, Siemens Energy, and Central Florida Research Park. Meanwhile, some connectors are included in the corridor as well.

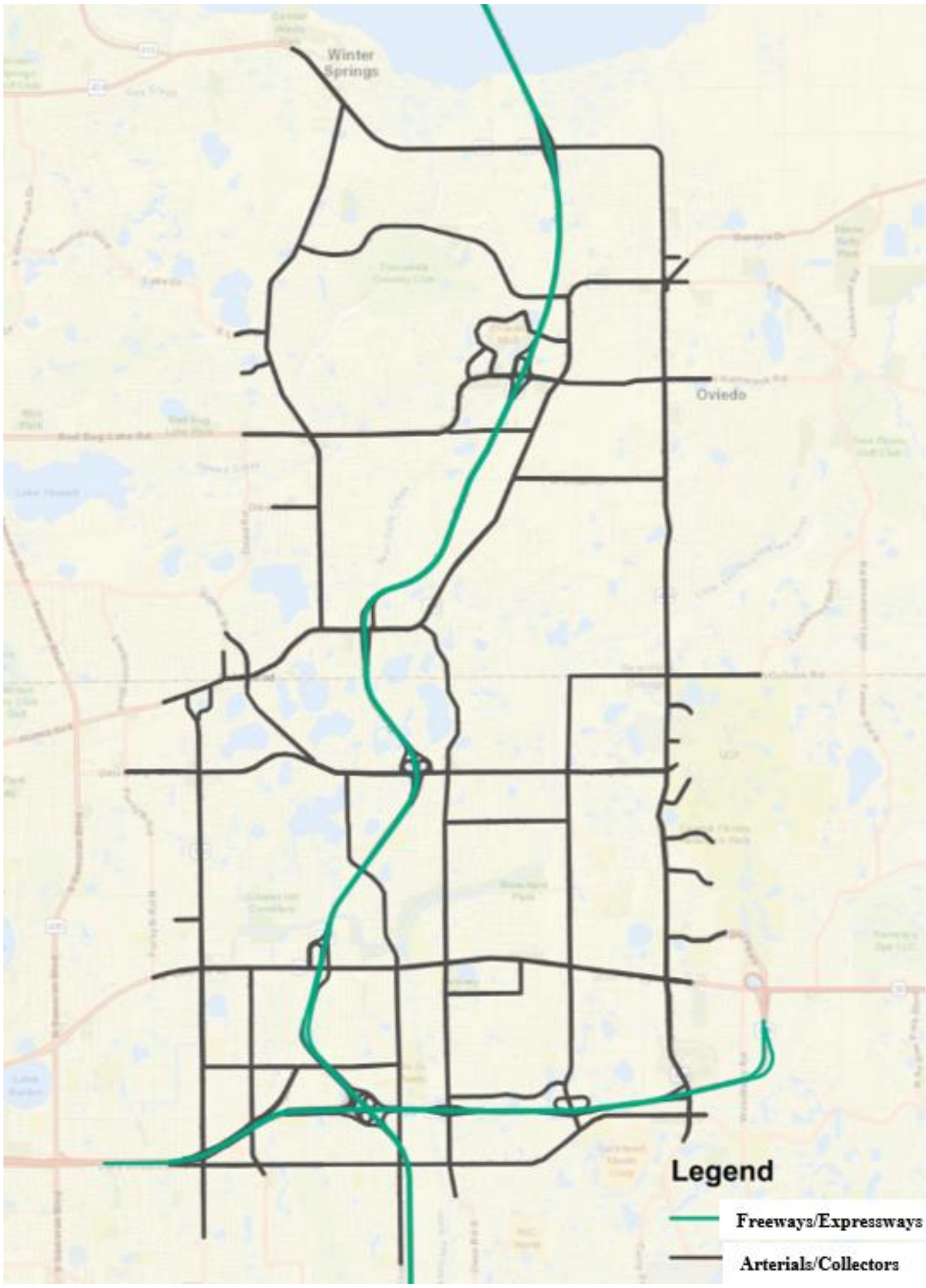


Figure 130 Selected SR-417 north corridor

In summary, a total of 2 corridors integrating freeways/expressways and arterials are selected to build and evaluate IATM strategies. It should be noted that there are several segments of the arterials that lack data. They are still included since they will play an important role in connecting freeways/expressways and arterials. It is expected that the most efficient IATM controls could be obtained on the selected corridors.

7.4. Alternative IATM Strategies

For two major corridors determined in Section 7.3, IATM strategies will be selected for critical segments by considering the following aspects:

- Policy consistency with the master plan
- Technical integration among IATM strategies
- Spatial continuity and consistency of IATM services by considering crash rates

According to the ITS (Intelligent Transportation Systems) master plan of FDOT District 5, FDOT District 5 identified implementable regional ITS strategies and local strategies related to the active traffic management (ATM) and traffic control. The implementable regional ITS strategies are as follows:

- Active Arterial Management (AAM) including traffic signal operation and Bluetooth data
- Adaptive Ramp Metering
- Dynamic Routing

As the local strategies regardless of regional cooperation, the following ATM and traffic control strategies were identified:

- Active Traffic Management: Dynamic Merge Control and Queue Warning
- Traffic Control: Adaptive Signal Control

Based on the FDOT District 5 ITS master plan, the following strategies were considered:

- Queue Warning (QW)
- Dynamic Lane Use Control (DLUC) in conjunction with Dynamic Merge Control (DMC) and Dynamic Speed Limits (DSpL)
- Dynamic Routing
- Ramp Metering

Considering continuity and consistency for IATM strategies along with roadways, it is required to connect the critical segments along the direction of expressways. As a condition to connect the critical segments, crash rates were considered. If there are segments with high and medium crash rates between the critical segments, the segments were also selected for the IATM control.

By using the crash data of 2017, the crash rates were estimated on the basis of one thousand VMT per lane. Like the selection of the categorization criteria of TTI, PTI, and BTI, the normalized crash frequency was categorized on the basis of 50^{th} percentile crash frequency (1.15) and 75^{th} percentile crash frequency (2.56) (see Figure 131). Figure 132 shows crash rates on freeways/expressways. The crash rates were used to determine the segments for some IATM strategies.

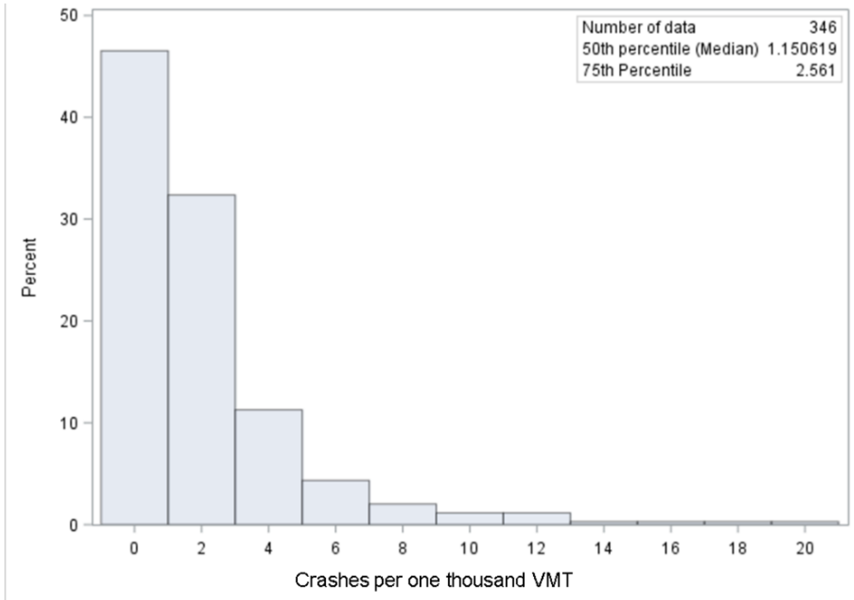


Figure 131. Crash rate distribution of freeway/expressways

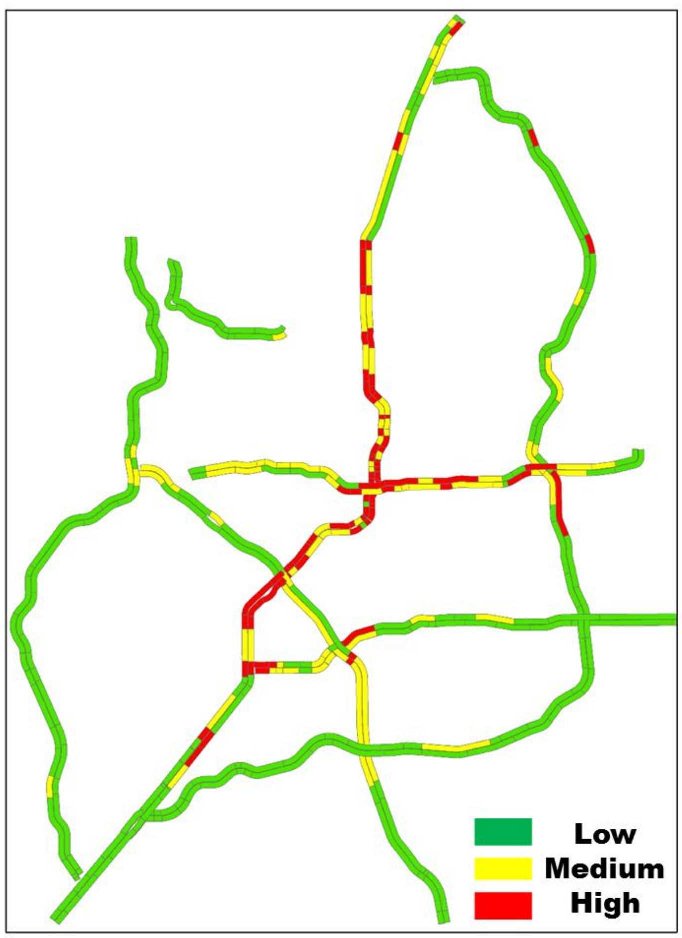


Figure 132. Crash rate by segments

7.4.1. Variable Speed Limits

Variable speed limits (VSL) adjusts speed limits based on real-time traffic, roadway, and/or weather conditions. DSpL can either be enforceable (regulatory) speed limits or recommended speed advisories. They can be applied to an entire roadway segment or individual lane (Neudorff and McCabe, 2015). In an ATDM approach, real-time and anticipated traffic conditions are used to adjust the speed limits dynamically to meet an agency's goals/objectives for safety, mobility, or environmental impacts. The DSpL has the following potential benefits:

- Reduce difference between posted speed versus actual speed
- Reduce speed variability
- Reduce spatial extent of congestion
- Reduce temporal extent of congestion
- Reduce crash rates
- Reduce crash severity

In terms of the effectiveness maximization of the ATM strategies, integration and continuity of ATM strategies on freeway/expressways are critical considerations to determine strategic segments. Considering benefits and compatibility among QW and VSL, they are in a mutually complementary relationship (Kuhn et al., 2017). So, it will be more beneficial if these strategies can be operated for drivers through a composite gantry.

7.4.2. Queue Warning

QW involves real-time displays of warning messages (typically on dynamic message signs and possibly coupled with flashing lights) along a roadway to alert drivers that queues or significant slowdowns are ahead. Then, drivers approaching at the end of the queues could reduce their speed in advance and drive carefully to proactively avoid rear-end crashes. Drivers' adjustment will reduce shockwaves, which are additional speed reduction caused by the combination of traffic congestion and queueing. Hence, the efficiency of the whole segment could get improved. In an active transportation and demand management (ATDM) approach, as the traffic conditions are monitored continuously, the warning messages are dynamic based on the location and severity of the queues and slowdowns. QW has high compatibility with DLUC, and DSpL. QW has the following benefits:

- Reduce rear-end crashes where the warning is in effect
- Increase travel speeds
- Reduce speed variance

7.4.3. Ramp Metering

Ramp meters, or ramp signals, are traffic signals installed on freeways/expressways on-ramps to control volume merging into the freeways/expressways. Ramp metering allows efficient use of freeway mainline capacity by managing the volume of vehicles entering into the freeway. It also helps to reduce the crash risk of freeway merging area by breaking up platoons of vehicles entering the freeway, which are competing for the limited gaps in mainline traffic.

Ramp metering (RM) is a ramp metering approach, which controls the meter by using traffic responsive or adaptive algorithms based on real-time and/or anticipated traffic conditions. It yields greater benefits than the simple pre-timed algorithms, especially for the non-recurrent traffic issues.

With all the aforementioned benefits of RM, it might be applicable for every segment of freeway. Since RM is mitigating freeway problems by controlling on-ramp traffic volume, a freeway segment might benefit from RM if the on-ramp traffic volume is high. Unfortunately, there is no volume data available for on-ramps in the study area. Therefore, a qualitative pre-screening will be conducted to select potential locations to implement RM. Then, RM will be deployed on the selected ramps to test its effectiveness based on several performance measures such as travel time and throughput. The pre-screening process are based on several intuitive rules:

- Freeway Problems (at least one of two):
  - The segment is experiencing congestion during peak time and/or unreliable travel time
  - The crash rate of the segment is higher than average crash rate than average
- High On-Ramp Volume Implication (at least one of two):
  - There is congestion on the specific freeway segment but no congestions observed at the upstream
  - There is congestion on the upstream arterial segment which connected to on-ramp but no congestions observed at the downstream

7.4.4. Discussions

This section discussed the potential alternative IATM control strategies for the selected corridors. Seven types of control strategies were discussed, including dynamic speed limits, queue warning, ramp metering, and etc. Considering the traffic problems for the selected corridors, it is expected the alternative strategies could help enhance traffic performance. For each segment, the specific selection of control strategies should be selected based on the individual traffic problem, geometric design, available control devices, etc. In addition, the final recommendation of IATM control strategies should be based on simulation analysis results in the future task.

7.5. Summary

In this task, the research team has conducted a comprehensive analysis to select roadways for IATM controls. The selection flowchart is presented in Figure 133. First, around 600 miles of roadways with around 1,200 segments in total were evaluated by using multiple data sources. Three measures (i.e., TTI, PTI, and BTI) were used for the evaluation considering the traffic congestion and the travel time reliability. The critical roadways and segments were identified based on the evaluation results. Second, two most critical corridors integrating freeways/expressways and arterials were determined for IATM controls considering data availability for IATM controls, identified critical roadways and segments. Finally, considering the traffic problems that the selected corridors experienced, several alternative control strategies were recommended. In the traffic simulation, the recommended control strategies will be selectively evaluated for the selected corridors.

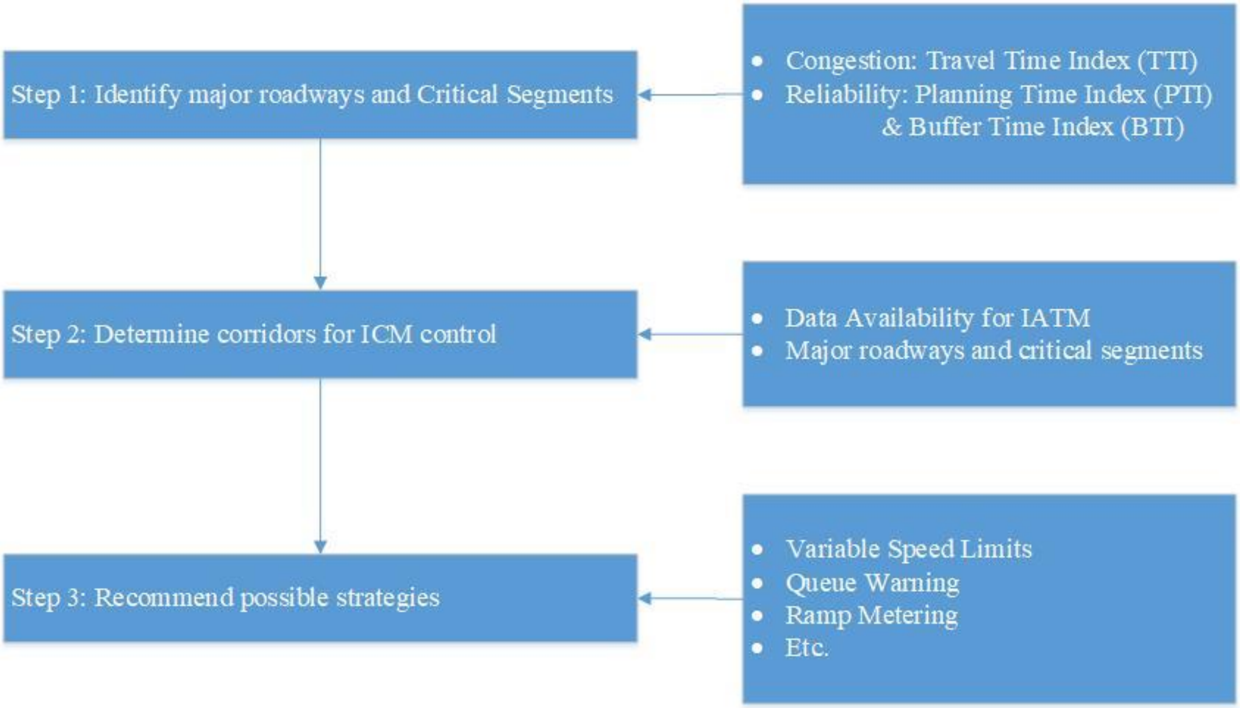


Figure 133. Flowchart for identifying corridors for IATM controls

CHAPTER 8. CONSTRUCTION OF TRAFFIC SIMULATION

8.1. Overview

In Chapter 7, it was conducted the roadway evaluation analysis to select the two critical corridors for the integrated active traffic management (IATM) controls. To test different control strategies, the microsimulation was developed in Aimsun for the study corridors. Meanwhile, it was recommended the most appropriate available data sources for different conditions and study purposes in the study area. According to the evaluation results, these most appropriate data were extensively used in the construction of the Dynamic Traffic Assignment (DTA) based simulation model in this task. In this chapter, the research team developed a data intensive framework for deployment, calibration, and validation of a dynamic traffic assignment model for the Orlando metropolitan area, using Multi-Resolution Modelling (MRM) framework. The detailed simulation calibration and validation process is presented in the following chapters. The final calibrated and validated large scale DTA model provides an effective tool to replicate traffic patterns in the greater Orlando metropolitan area and support the future applications of the model for various transportation operations such as integrated active traffic management strategies and decision support system.

Section 8.2 presents the overview of DTA based simulation model using multiresolution modelling framework. Existing state-of-the-art and state of practice of large-scale dynamic traffic assignment models have been thoroughly reviewed. Study area selection for the mesoscopic DTA model, input data for model development, and the overview of modelling techniques are presented in this chapter.

In Section 8.3, the team developed and calibrated the macroscopic simulation model from the regional traffic demand model. This is the first step of building any DTA based simulation model. The origin-destination matrix estimation has been conducted using observed traffic counts for developing the dynamic traffic assignment model.

Section 8.4 shows the development of the mesoscopic area from the results of the macroscopic simulation model. The research team extracted Orange and Seminole Counties as the mesoscopic area to develop the mesoscopic DTA model from the macroscopic model. In this task, the team calibrated and validated the mesoscopic DTA model using 15 minutes traffic counts and the travel time, respectively.

In Section 8.5, two microsimulation areas within the large-scale mesoscopic area were selected in order to develop the DTA based microscopic traffic simulation model. In particular, more accurate geometry and signal timing were coded for microscopic simulation areas to develop the microscopic DTA models. In this chapter, the simulation network was also calibrated and validated based on widely accepted guidelines in the literature.

Section 8.6 summarizes the calibration and the validation of various resolution levels (from macroscopic to microscopic) in dynamic traffic assignment models.

8.2. Review of the Dynamic Traffic Assignment-Based Simulation Model

8.2.1. Simulation Approach

There are mainly four modeling approaches that have already been developed to analyze the transportation systems for both operational and planning purposes: macroscopic, mesoscopic, microscopic, and hybrid. The Regional Travel Demand Model (RTDM) focuses on only major roadways and intersections referred to as links and nodes, respectively. The important parameters of the macroscopic model are link speed, capacity, and assigned traffic volume. However, vehicles are not individually modeled but are aggregated into the link demand as origin-destination (OD) matrix (Zitzow et al., 2015). Nevertheless, macroscopic models have some key limitations in terms of incident management, infrastructure development, active traffic management, and decision support system. Unlike macroscopic models, microscopic models have a high level of resolution for variables such as car following, lane changing, and other driving behavior models incorporating a fixed time-step framework. Detailed geometry, traffic, and signal timing information are needed to accurately represent traffic statues such as queuing at intersections and congestion throughout the network. Calibration of the microscopic models is computationally intensive for a large area network. Due to the computational intensity of microscopic models and the limitations of macroscopic models, mesoscopic models bridge the gap between these two extremes (Mahut, 2002; Shafiei et al., 2018). Mesoscopic models use macroscopic rules to represent each individual vehicle in the network, which needs much less time than the microscopic model. Compared to macroscopic models, mesoscopic models are not limited to analyze infrastructure development, active traffic management, and decision support system. Despite of the advantages and disadvantages of macroscopic, mesoscopic, and microscopic models, sometimes transportation modelers concurrently apply the microscopic model in selected areas and the mesoscopic in the remainder of the large network. This specification is called a hybrid simulation model. The hybrid model is recommended for large-scale networks with specific areas that require a microscopic level of detail but with a global network evaluation. Running the entire network at the microscopic level would increase the computation time, so a mesoscopic model is used outside of the areas where micro is strictly needed to increase the size of the model without impacting too heavily on the runtime (Aimsun, 2018).

The MRM framework is an essential practice to simulate the DTA based simulation model. MRM refers to a modeling framework that combines microscopic, mesoscopic, and macroscopic representations of traffic flow in the modeling effort of a single project. The Federal Highway Administration (Sloboden et al., 2012) classified MRM into partial MRM and full MRM, as shown in Figure 134. The former one is to use demand forecasting models to provide initial demand estimates to mesoscopic or microscopic modeling tools. The latter one utilizes a mesoscopic simulation-based DTA models for a large sub-area using trip demands from the demand models and produce input data (Davis and Bigelow, 1998). Furthermore, the microscopic models can be used to provide detailed analyses of selected sub-areas, corridors, or facilities. The full MRM approach is used in the network in which the initial demand matrices are estimated based on the approved regional travel demand model (RTDM) and then wide area diversion and bottleneck impacts are modeled using mesoscopic DTA models, followed by detailed analysis of traffic operations using microscopic models. Recently, researchers are implementing the MRM technique to develop a dynamic traffic assignment based mesoscopic and/or microscopic simulation models utilizing large-scale networks (Fakharian Qom, 2016; Hadi et al., 2015; Luo and Joshua, 2011; Massahi, 2017; Mirchandani et al., 2018; Tokishi and Chiu, 2013). However, none of the studies consider the MRM technique to test the active traffic management strategies in the DTA based simulation model except the study by Tokishi and Chiu (2013).

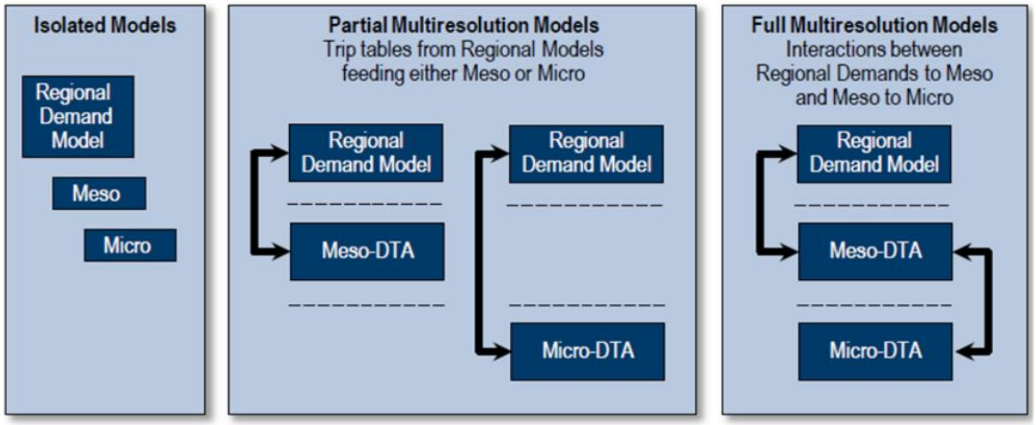


Figure 134. Examples of MRM structure

Simulation-based dynamic traffic assignment (DTA) is an effective tool to analyze transportation systems for both operational and planning purposes (Ben-Akiva et al., 2012; Mahmassani, 2001; Ziliaskopoulos et al., 2004). In recent years, the DTA based hybrid models have become widely accepted, which commonly combine macroscopic or mesoscopic models with microscopic models. This framework allows for the modeling of large areas, such as entire cities or counties, while simultaneously maintaining details in areas of interest. Very few attempts have been made at large-scale hybrid DTA model for major metropolitan regions across the world. The first large-scale hybrid model was used to evaluate a variety of traffic system management strategies for a fifty-mile segment of US 101 in California (Pravinvongvuth and Loudon, 2011). The hybrid simulation model was successfully calibrated with the base-year according to the recommended calibration guidelines of the Federal Highway Administration (FHWA). However, the model was not validated to achieve high degree of assurance of both mesoscopic and microscopic area which is needed to develop a successful deployment of hybrid simulation model. Zitzow et al (2015) developed a large-scale hybrid model incorporating components of both microscopic and macroscopic modeling to achieve high resolution required along the light rail corridor in Minneapolis–Saint Paul, Minnesota. However, the research team calibrated the DTA model using the R-square value of regression line between the real and simulated counts. But, the validation of the large scale DTA models was overlooked for both mesoscopic and the microscopic levels. Moreover, Tokishi and Chiu (2013) considered a multi-resolution modelling technique to evaluate consistency of a DTA based hybrid simulation model along with the calibration of the large-scale network. The results of this study demonstrated that the MRM technique for a hybrid simulation model could be made more consistent with its parent model. However, none of the studies considered validation of the calibrated DTA model for every level of simulation: macroscopic, mesoscopic, and microscopic. In this task, the research team developed a large-scale DTA based simulation model for all three levels.

8.2.2. Study Area

The regional model along with the mesoscopic and microscopic study areas are presented in Figure 138. The regional model named Orlando Urban Area Transportation Study (OUATS) with base year 2009 extracted from Cube Voyager to develop hybrid DTA based simulation model using the full MRM framework. It is worth mentioning that the OUATS covers Orange, Osceola, Seminole, and Lake Counties. In addition, the western portion of Volusia County and the northeastern part of Polk County are also included. The main reason for selecting the 2009 macroscopic model is the unavailability of a recent year travel demand model which is generally conducted every 10 or 15 years. The OUATS network covers over 6,732 miles section lengths and contains 2,438 Traffic Analysis Zones (TAZs), 26,094 links, 11,585 nodes, and 2,702 signalized intersections. In addition to the network data, the demand data is required as an important input for the modeling tools to run the traffic assignment procedure in DTA model. The Origin-Destination (OD) matrices from the Cube model were imported and used as a baseline initial matrix in the model development. To develop a mesoscopic DTA model, the team have selected the two largest counties in the region: Orange and Seminole Counties, as the large subarea network from the regional model, which have 1,416 Traffic Analysis Zones (TAZs) and 4,264 miles roadways. The roadways include 18,350 segments and 8,942 nodes, which include 2,417 signalized intersections. Two subareas/corridors (1) Downtown Orlando Area (including I-4, SR408, SR50 etc.) (2) East Orlando Area (including SR417, SR434 etc.), were utilized as the microsimulation areas to develop the microscopic DTA model. Figure 135 (a) corresponds to the regional OUATS model indicating the larger subarea network by border including Orange and Seminole County for the development of DTA model. Furthermore, Figure 135 (b) illustrates the subnetwork selected for the mesoscopic simulation. Among the road networks in the mesoscopic simulation, two selected corridors (Downtown Orlando area and East Orlando area) were selected for the microscopic simulation (Figure 135 (c)). The DTA based mesoscopic and microscopic simulation model were developed for 2 hours in the morning peak (07:00 to 09:00 AM) using real dataset of October 2017, with a total of eight time-intervals 15 minutes each.

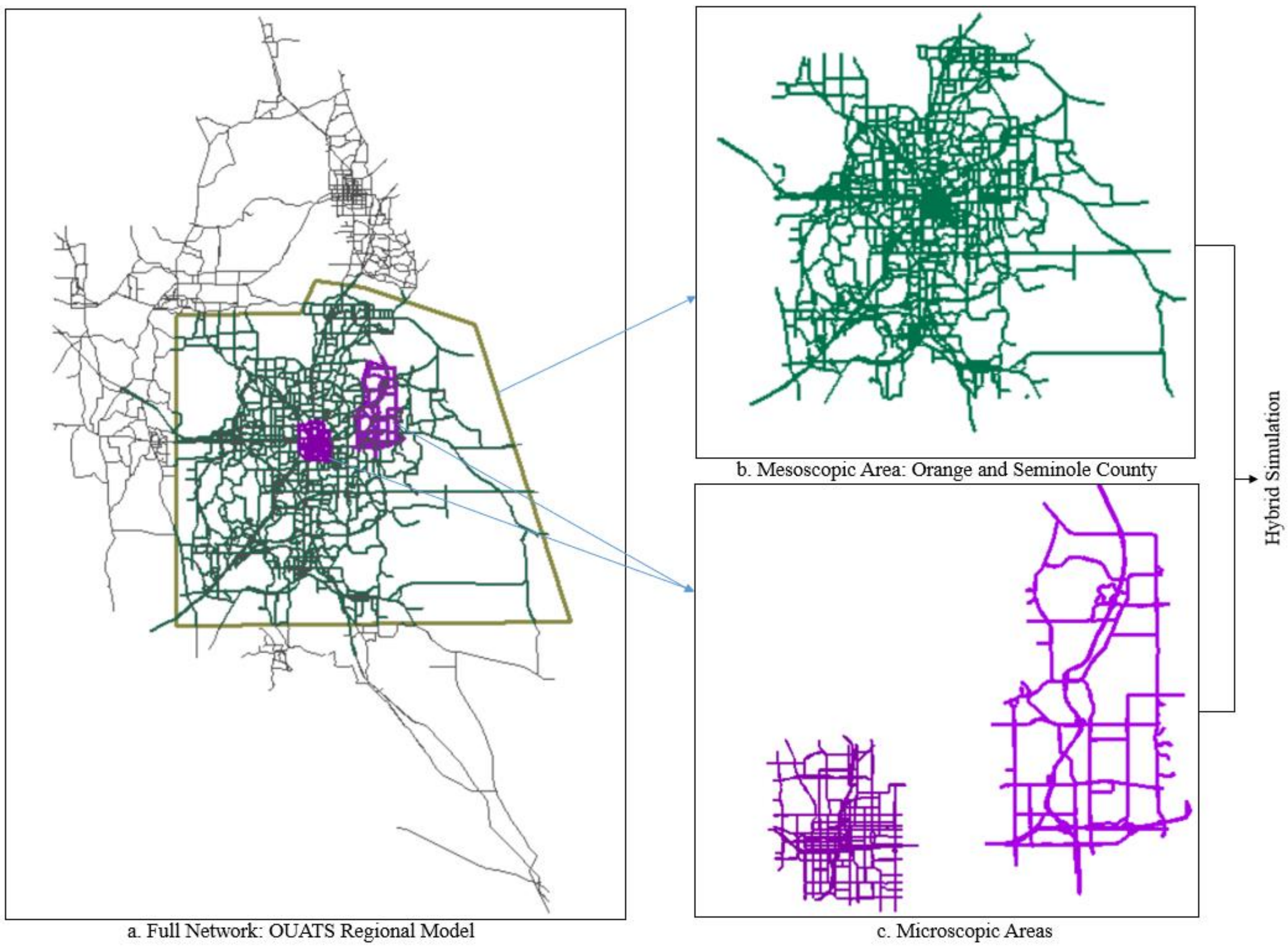


Figure 135. Study area: (a) full network OUATS regional model (b) mesoscopic area (Orange and Seminole County) (c) microscopic areas.

The network attributes of the full OUATS, mesoscopic, and microscopic areas are presented in Table 58.

Table 58. Network attributes of OUATS model including mesoscopic and microscopic areas

Network Level	Attributes Name	Number
Full OUATS Model	Links	26,094
	Nodes	11,585
	Traffic analysis zone	2,438
	Signalized Intersection	2,702
Mesoscopic Area	Links	18,350
	Nodes	8,942
	Traffic analysis zone	1,416
	Signalized Intersection	2,417
Microscopic Area (Downtown Orlando)	Links	1,628
	Nodes	707
	Traffic analysis zone	179
	Signalized Intersection	197
Microscopic Area (East Orlando)	Links	808
	Nodes	428
	Traffic analysis zone	128
	Signalized Intersection	89

8.2.3. Input Data for Model Development

In this project, data from multiple sources and agencies were collected and processed to develop, calibrate, and validate the DTA model. This data was extensively used in this study for demand estimation, model calibration, and model validation. The data contains records of traffic counts, speeds, and travel time which are aggregated at 15-minute intervals. The available data collection systems for freeways and arterials are different. The research team has devoted much effort and time to collect all available traffic data in this large-scale study area. Freeways and expressways in the Orlando metropolitan area are using seven kinds of traffic data sources, which are MVDS (Microwave Vehicle Detection System), AVI (Automatic Vehicle Identification), ATSPM (Automated Traffic Signal Performance Measures), Insync, NPMRDS (National Performance

Measure Research Data Set), HERE, and Bluetooth. Before using the multiple data sources, it is required to recognize how accurate travel time or speeds, and traffic volume can be obtained for building large-scale simulation model because they are used for demand estimation, model calibration, and model validation in the DTA modelling framework. By conducting the comparative studies for the roadway network, the research team used the most reliable data for different segments on freeways, expressways (Chung et al., 2018), and arterials (Gong, 2018). For roads with different data availability, the data used for the simulation is summarized in Table 59. It is worth mentioning that data from various sources need to be combined to produce final OD matrices of good quality representing the base year traffic demand.

Table 59. Summary of data used for simulation

Roadway Type	County	Data Type	Simulation Data	
			Volume	Travel time
Freeway	All	AVI, MVDS, HERE, NPMRDS	MVDS	AVI
	All	MVDS, HERE, Bluetooth, NPMRDS	MVDS	NPMRDS
	All	MVDS, HERE, NPMRDS	MVDS	NPMRDS
Arterial	Seminole	HERE, Bluetooth, SPM	SPM	Bluetooth
	Orange	HERE, Bluetooth, InSync	InSync	Bluetooth
	Orange	HERE	----	HERE
Collector	Orange	Bluetooth, HERE	----	HERE
	Orange	HERE	----	HERE

8.2.4. Overview of Modelling Techniques

The modelling method used to develop the large-scale DTA based simulation model using MRM framework is summarized in Figure 136. The research team developed this workflow which was followed step by step to build such large-scale simulation model. The first step of this framework was to update the available regional travel demand model (OUATS) to the existing condition based on the roadway network and traffic volumes of 2017. Then, the two Counties (Orange and

Seminole) were extracted from the regional model. This subarea network was used to develop the mesoscopic DTA model which was refined in terms of roadways, zones, and intersections to bring it as close as possible to the real-world. Regional travel demand models were traditionally designed for daily model that can only produce daily trip matrices. Hence, the OUATS model has only the daily trip matrices whereas the peak-hour traffic is simulated in this project. To achieve a reasonable trip matrix during the peak hour, two steps were conducted. First, the daily matrices were converted to 2-hour OD matrices by multiplying a peak factor. Then, an origin destination matrix estimation (ODME) process was performed to calibrate the 2 hours OD matrices at macroscopic level using the available real-word traffic count dataset. ODME is a procedure for adjusting a prior OD matrix based on the input traffic counts. The solution algorithm is based on a bi-level model solved heuristically by a gradient algorithm using Aimsun Next which is beyond the scope of this study (Aimsun, 2018). Furthermore, the time dependent OD matrices were adjusted to set traffic counts slicing into shorter time intervals (15 or 30 minutes). Towards this end, static origin-destination departure adjustment step was performed to divide the whole 2-hour peak period demand to eight 15-minutes sliced demand. In this step, the team split the demand into different vehicle composition (i.e., cars and trucks). The split was based on the MVDS detectors. MVDS detector contains seven important variables including volume, speed, and lane occupancy for each lane at 1 min interval, and also categorizes vehicles into four types according to their length; type 1: vehicles 0 to 10 ft. in length, type 2: vehicles 10–24 ft. in length, type 3: vehicles 24–54 ft. in length, type 4: vehicles over 54 ft. in length. The vehicles were classified into two categories: (1) Car and (2) Truck. A vehicle was considered as a passenger car (PC) if its length is equal to or less than 24 ft. (type 1 and type 2) (Shi, 2014; Wang, 2016). Based on the

MVDS detectors in the study area, the overall percentages of cars and trucks are 90% and 10%, respectively. Hence, the percentages were employed in the simulation model.

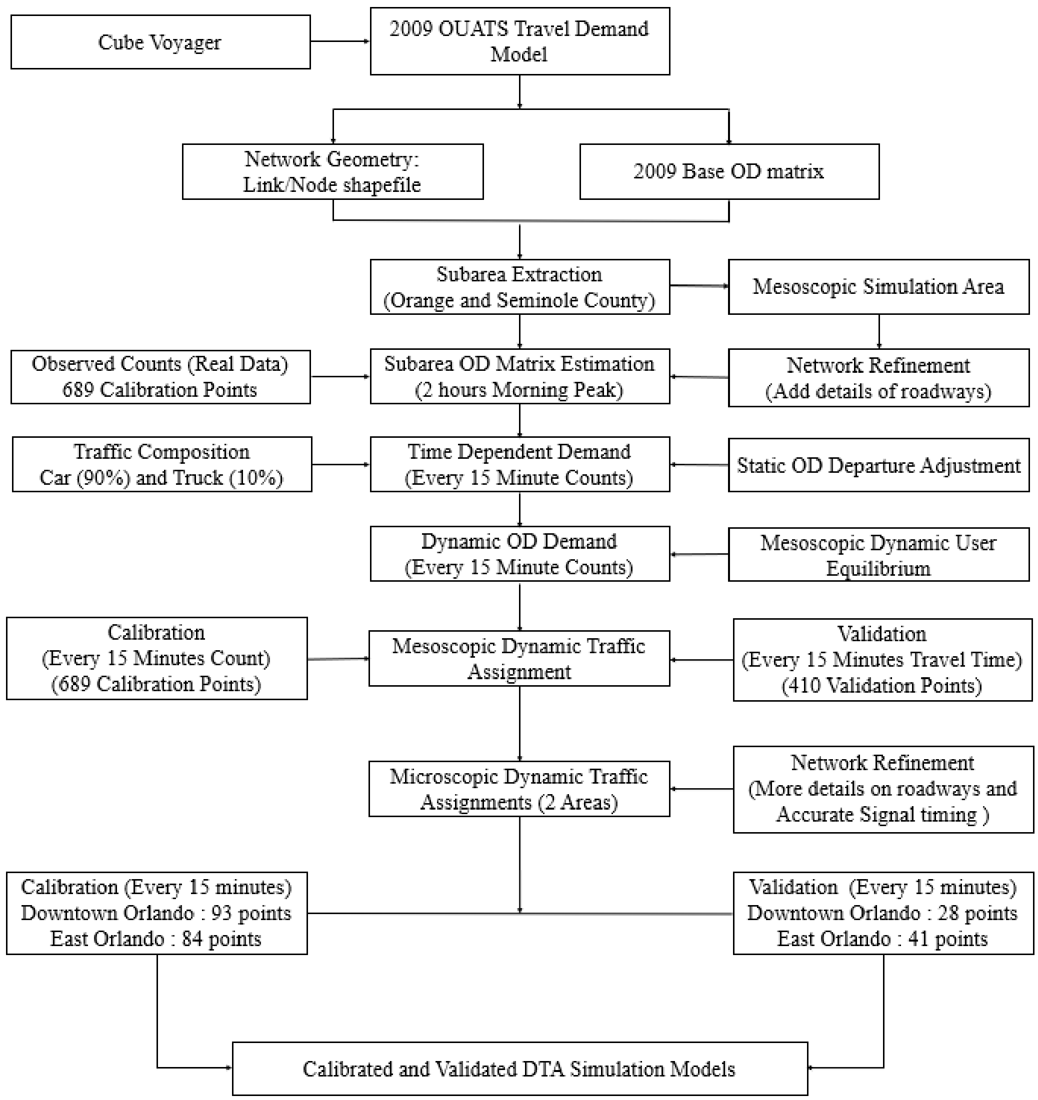


Figure 136. Modeling methods for the DTA-based simulation model.

To make the model dynamic, mesoscopic Dynamic User Equilibrium (DUE) step was performed for which the saved path file was utilized in the mesoscopic dynamic traffic assignment model. This step mainly focuses on the dynamic path assignment of all the vehicles throughout the entire mesoscopic area. In DTA, the path assignment of vehicles in the network is a very important and complex process based on the prevailing traffic condition for large-scale simulation model. The probability of choosing a path k in the DTA model can be obtained with any random utility model such as proportional, multinomial logit, and C-logit. The multinomial logit (MNL) model is preferred route choice model due to the closed form representation and easy estimation. However, the underlying modelling hypothesis of logit models are based on a critical assumption of Identical and Independent Distribution (IID) for the random terms in the utility functions. This assumption implies the independence of irrelevant alternatives (IIA) property which does not often hold in real-size networks because of the high correlation among various routes between any OD pair (Ben-Akiva et al., 1998; Cascetta, 2009). In other words, the multinomial logit model is unable to distinguish between two alternative routes when there is a high degree of overlapping resulting of the overestimation of choice probability. To overcome this issue, the C-logit model (Cascetta, 2009) is implemented to modify the MNL model by adding a term called 'commonality factor'. This term is inversely proportional to path k's degree of independence from other paths and is equal to zero if no other path shares links with path k (Barceló, 2010). The commonality factor is directly proportional to the degree of overlapping of path k with other alternative paths presented as follows:

$$CF_k = ln(1 + \sum_{l \neq k} \frac{L_{lk}}{\sqrt{L_l L_k}})$$

Where L_l and L_k are the cumulative values of the cost attribute over the links in path l and k, respectively, and L_{lk} is the cumulative value of the cost attribute over the links that are shared by the two paths. Therefore, the C-logit model reduces the probability of choosing heavily overlapped paths and hence is a more realistic route choice model. Given CF_k, the C-logit model is formulated as follows:

$$p(k) = \frac{e(-g_k - \beta CF_k)}{\sum_{l\varepsilon K_{OD}} e(-g_k - \beta CF_k)}$$

where, $p(k)$ is the probability of choosing path k, g_k is the general cost of path k, K_{OD} is the set of paths connecting OD pairs, and β is the proportion of the commonality factor. $p(k)$ is calculated for the maximum 3 shortest paths obtained from the well-known Dijkstra label-setting algorithm (Cascetta, 2009) based on the current path costs. This specification of choosing a path selection procedure was applied in the DTA model using Aimsun Next. The above utility model was repeated in every assignment interval until all travel demand loaded into network.

After loading all the vehicles in the network, the next step was to calibrate and validate the entire mesoscopic area by using the real dataset of traffic counts and travel time, respectively. Much effort was dedicated to calibrating and validating the large-scale mesoscopic area within the DTA framework. Furthermore, two congested microsimulation areas within the mesoscopic large area were further refined to represent the accurate traffic, geometric, and signal information. The microscopic model includes a much larger number of parameters that should be calibrated which are not included in the mesoscopic model. The microscopic areas of the DTA simulation network were also calibrated and validated based on the real dataset providing a final calibrated and validated large-scale DTA based mesoscopic and microscopic model which is the last step in the proposed workflow. Furthermore, this framework can be a good platform to run the hybrid simulation model in order to test the active traffic management strategies in the microscopic model in selected areas and the mesoscopic model in the remainder of the large mesoscopic area.

8.3. Development of Macroscopic Model and Calibration

8.3.1. Overview

For any large-scale DTA application, implementing the model, analyzing the results, calibrating, and validating the model are challenging tasks. This section discusses the development of the macroscopic model from regional travel forecasting model along with the calibration. It is worth mentioning that the macroscopic model is the good starting point of any DTA based simulation model. The macroscopic model was developed to adjust the demand matrices using the regional traffic demand model incorporating with real datasets of traffic counts from multiple sets of detectors.

8.3.2. Regional Travel Demand Model

As discussed earlier, regional travel demand model or other previously developed model provide a good starting point of any dynamic traffic assignment-based simulation model. These models provide valuable information such as the origin destination matrices, average trip length, network geometry, and attributes for each link such as length, number of lanes, free-flow speed, capacity, and so on. The project team used the regional travel demand model named Orlando Urban Area Transportation Study (OUATS) with base year 2009 developed by Metroplan Orlando. Figure 140 shows the geographical coverages of OUATS model. This model includes the geographic area covered by the Orlando Urban Area (i.e., Orange, Osceola, and Seminole counties) as well as the western part of the Volusia County network, the Lake County network, and northeastern part of the Polk County network) (See Figure 137).

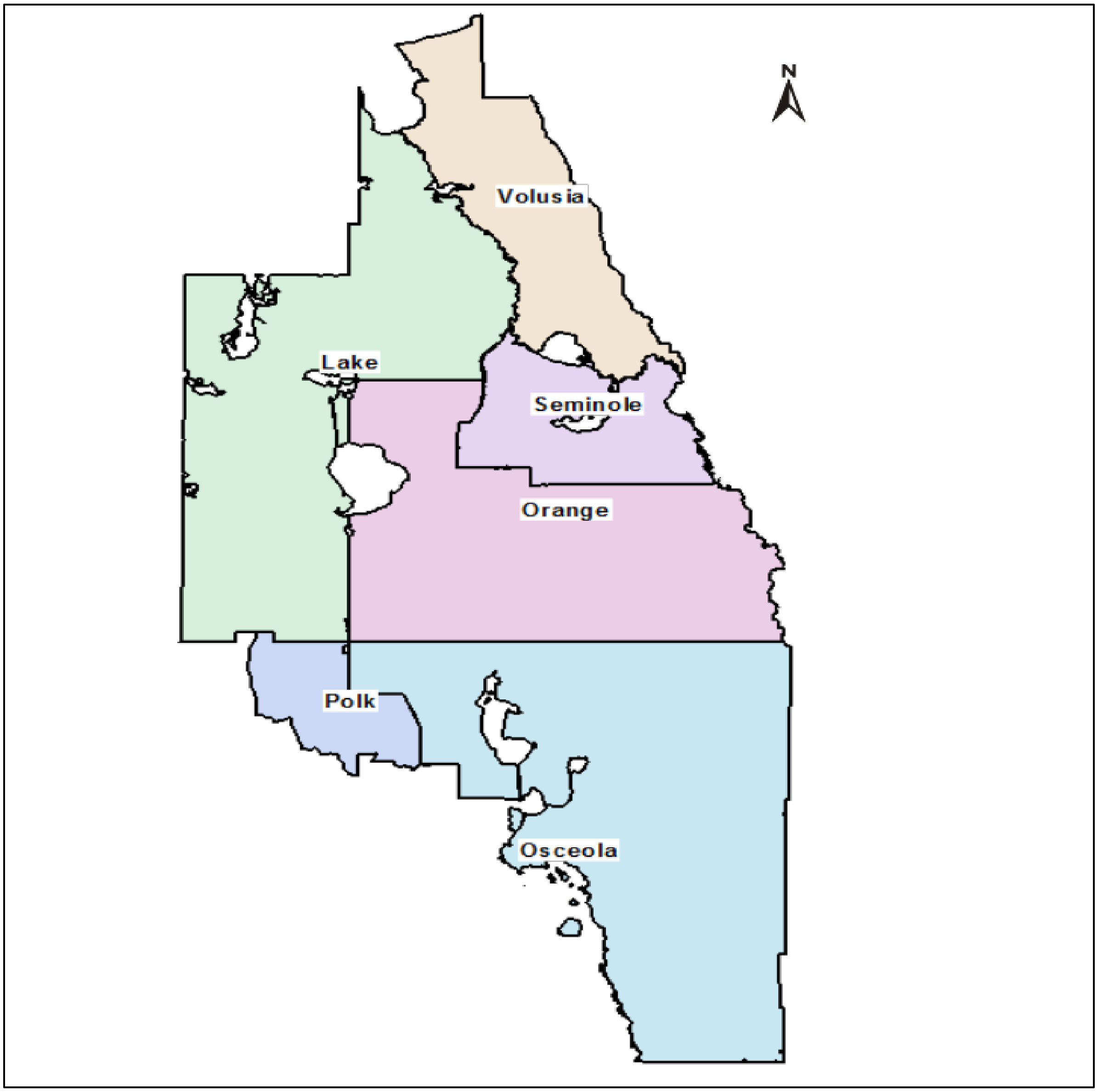
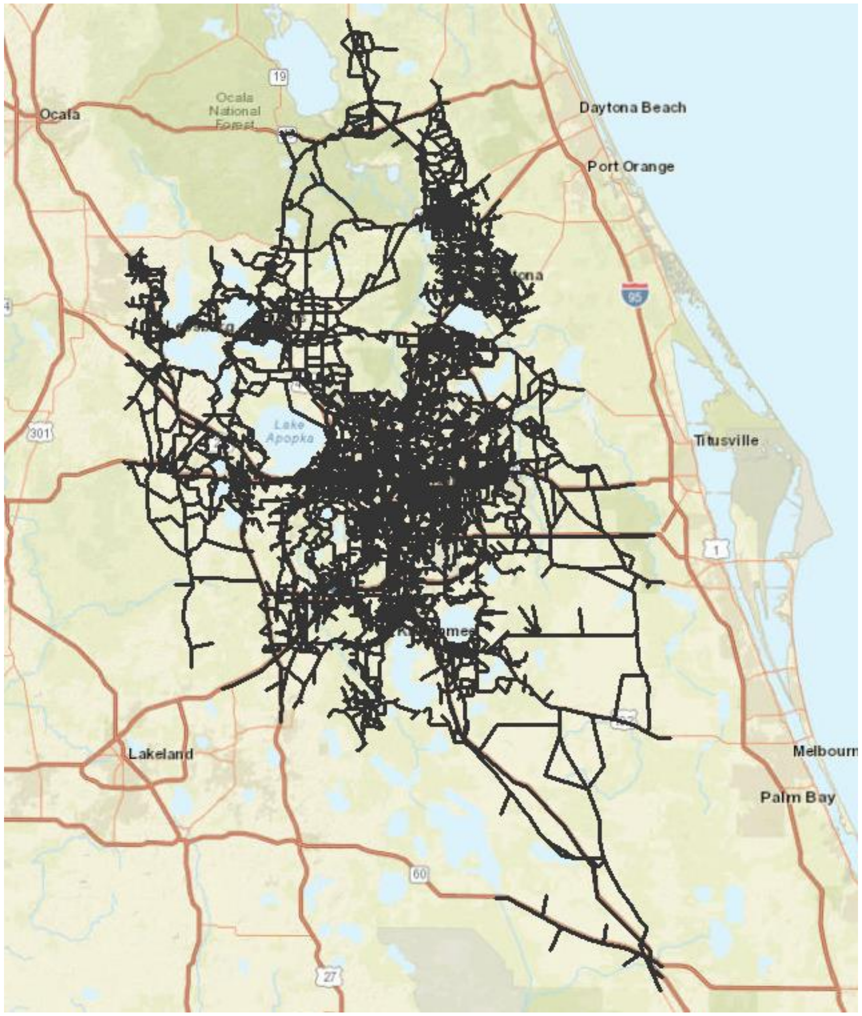
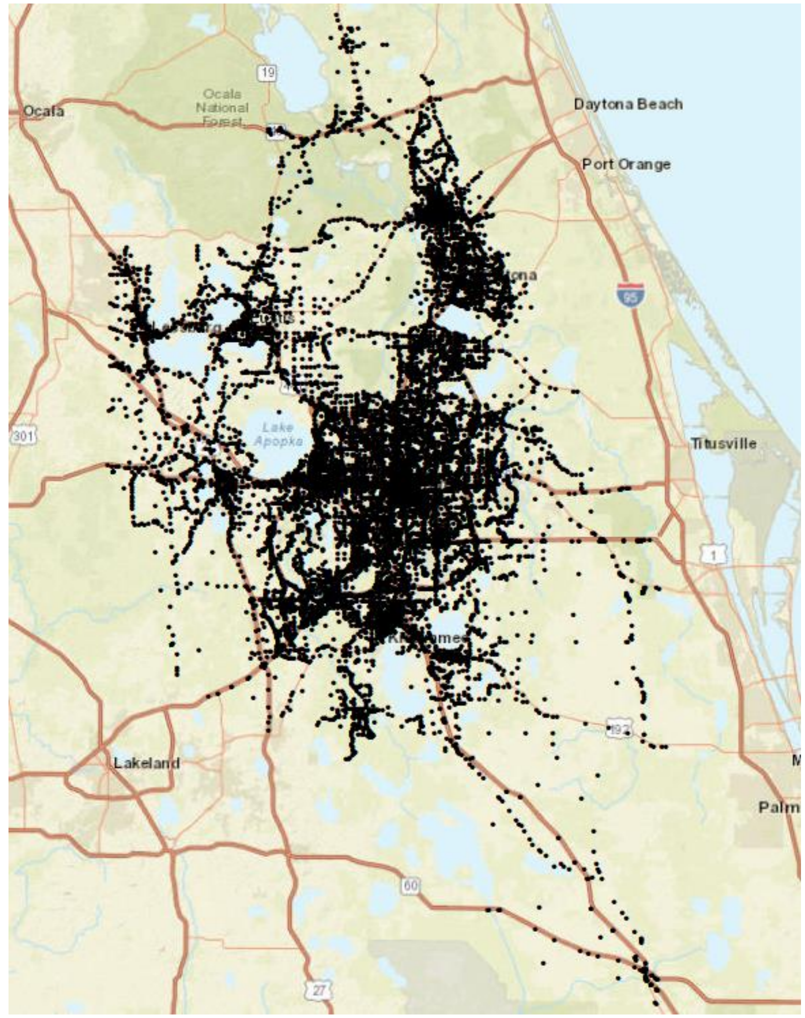


Figure 137. Geographic area covered by the OUATS model.

The regional OUATS model with base year 2009 was extracted from Cube Voyager modelling software and employed to develop the DTA simulation models using the full MRM framework. Figure 138 shows the link and node files extracted from the OUATS model.



Link files



Node Files

Figure 138. Link and node files in OUATS regional model extracted from Cube.

The important attributes from the node and link files extracted from Cube are showed in Table 60.

Table 60. Important attributes of link and node files

File Type	Attributes
Node File	Node Number
	Total number of nodes
	Latitude
	Longitude
Link File	Link ID
	Total number of links
	Link distance
	Zone Number
	Road type
	Speed Limit
	Free flow speed
	Bureau of Public Roads (BPR) coefficient
	Bureau of Public Roads (BPR) exponent

Bureau of Public Roads (BPR) curves is a type of volume-delay function used to describe the speed-flow relationships in a travel demand model network based on the available link capacity. The equation of BPR curve is formulated as follows:

$$t_i = t_{o_i}\left[1 + \alpha \left(\frac{v_i}{c_i}\right)^{\beta}\right]$$

Where, t_i= Congestion flow travel time on link i;

t_{o_i}= Free-flow travel time on link i;

v_i= Volume of traffic on link i per unit of time;

c_i= Capacity of link i per unit of time;

α = BPR coefficient;

β = BPR exponent;

Moreover, demand data are important inputs for calibration of macroscopic model from regional travel demand model. Traditionally, trip Origin-Destination (OD) matrices utilized in traffic analyses have been derived from daily or time-of-day (peak period) demand matrices produced from regional travel demand models by fine-tuning these matrices to produce acceptable assignment results. Demand data was also converted as CSV file from OUATS model using Cube. The original OD are 2438×2438 matrices. The screenshot of the OD matrices as CSV format from OUATS model is showed in Figure 139.

Production Zone

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	OD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2	1	417	65.5	69.5	5.5	10.5	8.5	5	3.5	13	1	2.5	2.5	29.5	19	1.5
3	2	65.5	825	118.5	10	20.5	17	8.5	9	21.5	1.5	1	3	35	22.5	0
4	3	69.5	118.5	1365	31.5	34.5	21	14.5	13.5	41	3.5	2.5	8.5	67.5	15	0.5
5	4	5.5	10	31.5	116	40	20	12	7	26.5	1	0	1	3.5	2	0
6	5	10.5	20.5	34.5	40	238	37	16	26.5	53.5	3.5	3	5	11	2.5	0
7	6	8.5	17	21	20	37	50	21.5	25.5	56	4.5	2	6.5	8	2.5	0
8	7	5	8.5	14.5	12	16	21.5	18	18	40.5	3.5	2	3.5	5	1.5	0
9	8	3.5	9	13.5	7	26.5	25.5	18	108	72	2.5	2	1.5	4	0.5	0
10	9	13	21.5	41	26.5	53.5	56	40.5	72	893	22.5	9.5	13.5	12	2.5	0
11	10	1	1.5	3.5	1	3.5	4.5	3.5	2.5	22.5	20	1	1.5	0	0	0
12	11	2.5	1	2.5	0	3	2	2	2	9.5	1	26	3.5	1	0.5	0
13	12	2.5	3	8.5	1	5	6.5	3.5	1.5	13.5	1.5	3.5	194	1	1	0
14	13	29.5	35	67.5	3.5	11	8	5	4	12	0	1	1	259	22.5	0.5
15	14	19	22.5	15	2	2.5	2.5	1.5	0.5	2.5	0	0.5	1	22.5	116	0
16	15	1.5	0	0.5	0	0	0	0	0	0	0	0	0	0.5	0	0
17	16	12	16.5	30.5	3.5	4	4	1.5	1	5.5	0.5	0.5	0.5	9	3	0
18	17	29.5	45	129	15.5	18	12	8.5	9.5	20.5	1.5	0.5	2	26.5	6.5	1
19	18	62.5	94	184	65	59.5	39	21	24.5	63	8.5	5	15	65.5	13.5	0.5
20	19	6	10	24.5	21	97	25	12.5	18.5	33	2	1.5	2.5	2.5	2	0
21	20	4	7	12.5	5.5	18	17	8	10.5	24	1	1	3	4.5	0.5	0
22	21	6	4.5	11.5	9.5	17.5	17.5	11	16.5	32	3	2	3.5	3.5	0.5	0
23	22	3	4	8.5	7	12.5	13	7.5	13.5	23.5	2	1.5	2	4	0.5	0
24	23	2.5	2.5	7	2.5	10.5	12.5	8.5	34	21.5	1.5	0.5	1	0.5	0.5	0
25	24	3	1.5	8.5	2.5	12.5	12.5	8	16	27	2.5	1	1	2.5	1.5	0
26	25	4.5	9	23.5	4.5	23	28.5	20	25.5	108.5	5	2.5	4.5	3	2	0
27	26	4	3.5	12.5	3.5	10.5	12	9	8.5	46.5	11	10	9.5	3.5	0	0

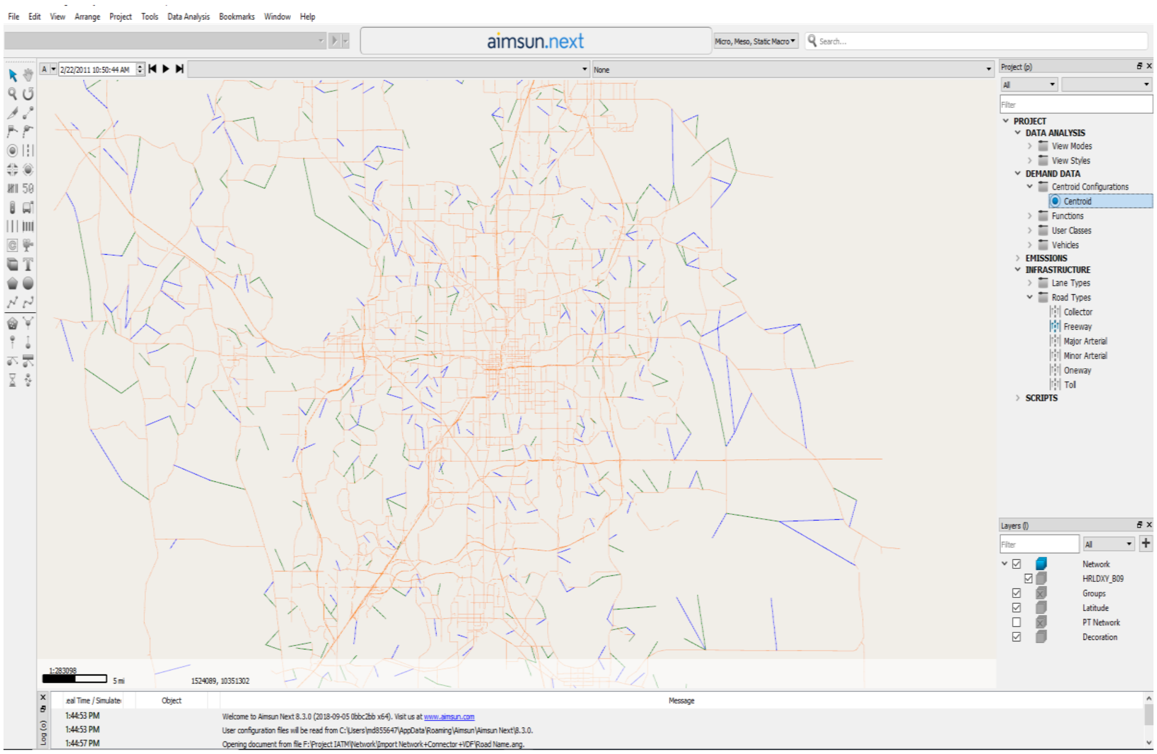
Attraction Zone

Figure 139. Screenshot of OD matrices exported from Cube

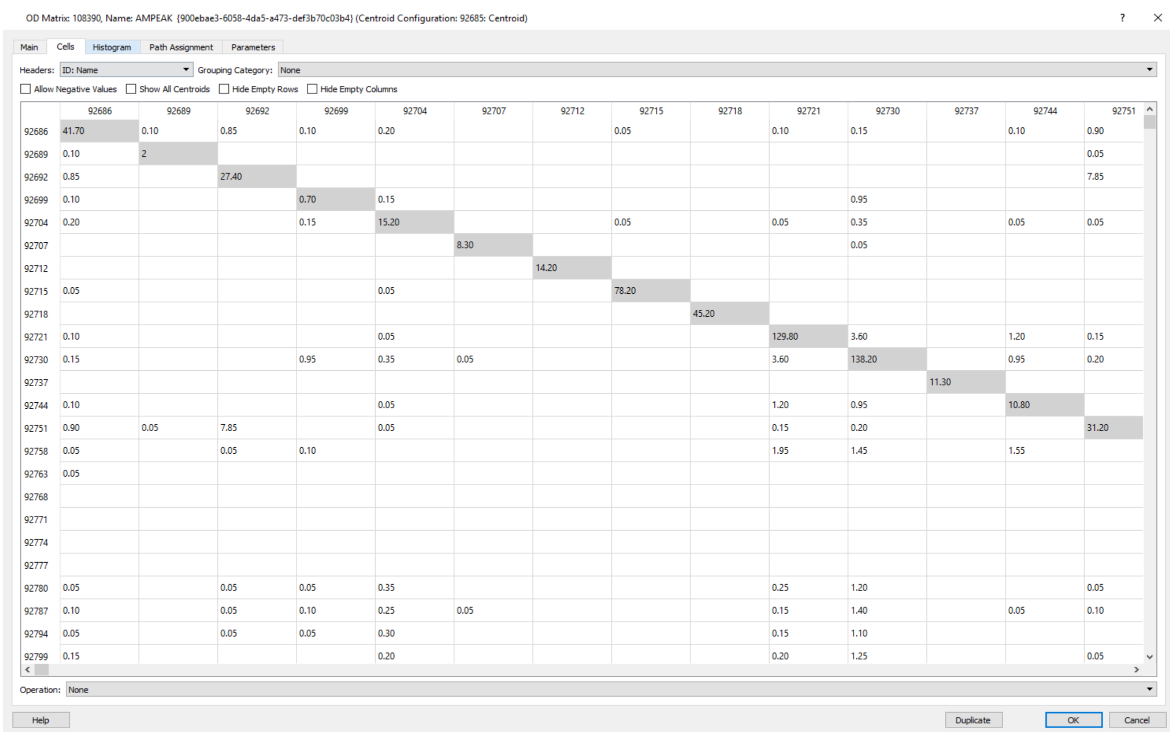
It is worth mentioning that, OD matrices include both intra (from one study zone to another study zone) and inter (from one study zone to the same zone) zonal trips while external zones are not included.

8.3.3. Network and Demand Data Conversion to Aimsun Next

The research team uses Aimsun Next, a widely implemented traffic simulation platform that has been utilized in a number of large-scale simulation models. The first step was to create a set of shapefiles (links and nodes) describing the network to be imported to Aimsun Next from Cube exported GIS file. The node and link shape files exported from the Cube model were imported into Aimsun Next, through the network importing function. The corresponding link and node attributes, such as the number of lanes, free-flow speed, link capacity, BPR coefficient, BPR exponent were configured in Aimsun Next. In addition to the network data, the demand data should be input to the modeling tools to run the traffic assignment procedure in DTA model. Therefore, the demands matrices from the Cube based OUATS model were imported to Aimsun Next and used as a baseline initial matrix in the analysis. The demand matrices were converted to the csv file format and imported into Aimsun Next through the demand input configuration. Figure 140 (a) and (b) show the final imported network and the OD matrices in Aimsun Next, respectively.



a. Network importation in Aimsun Next

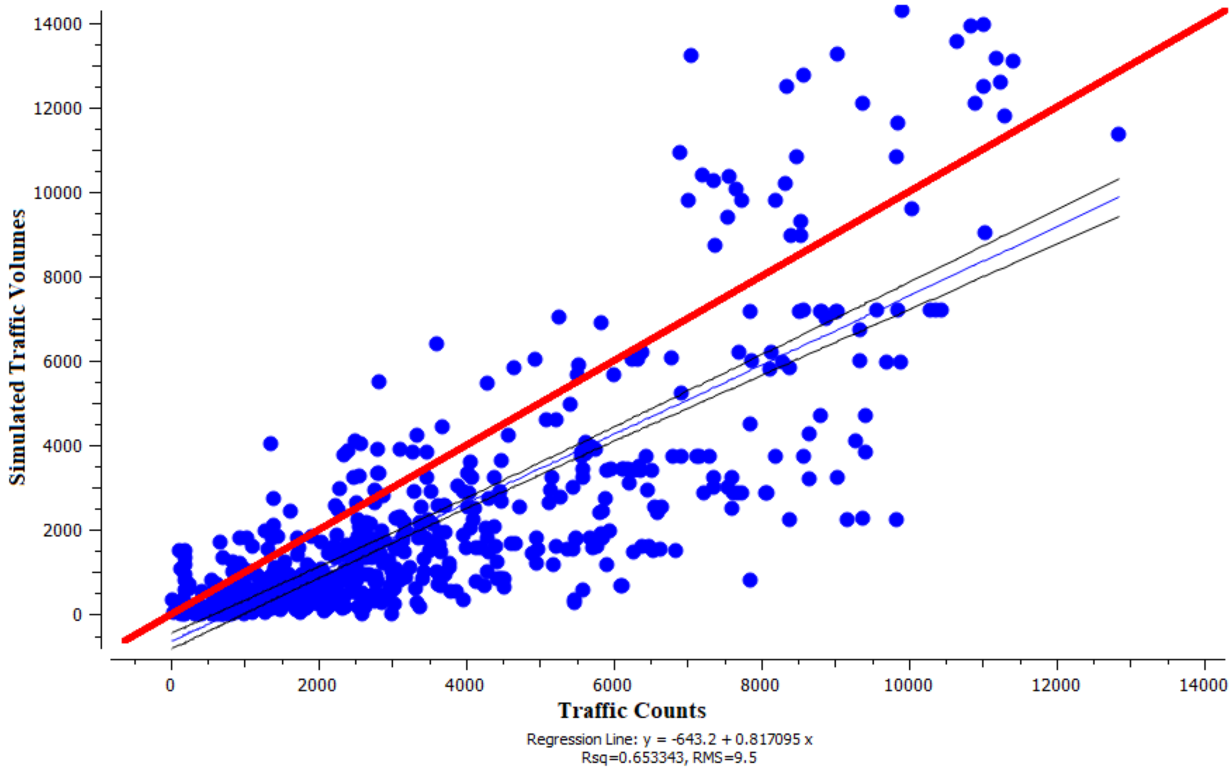


b. OD matrices importation in Aimsun Next

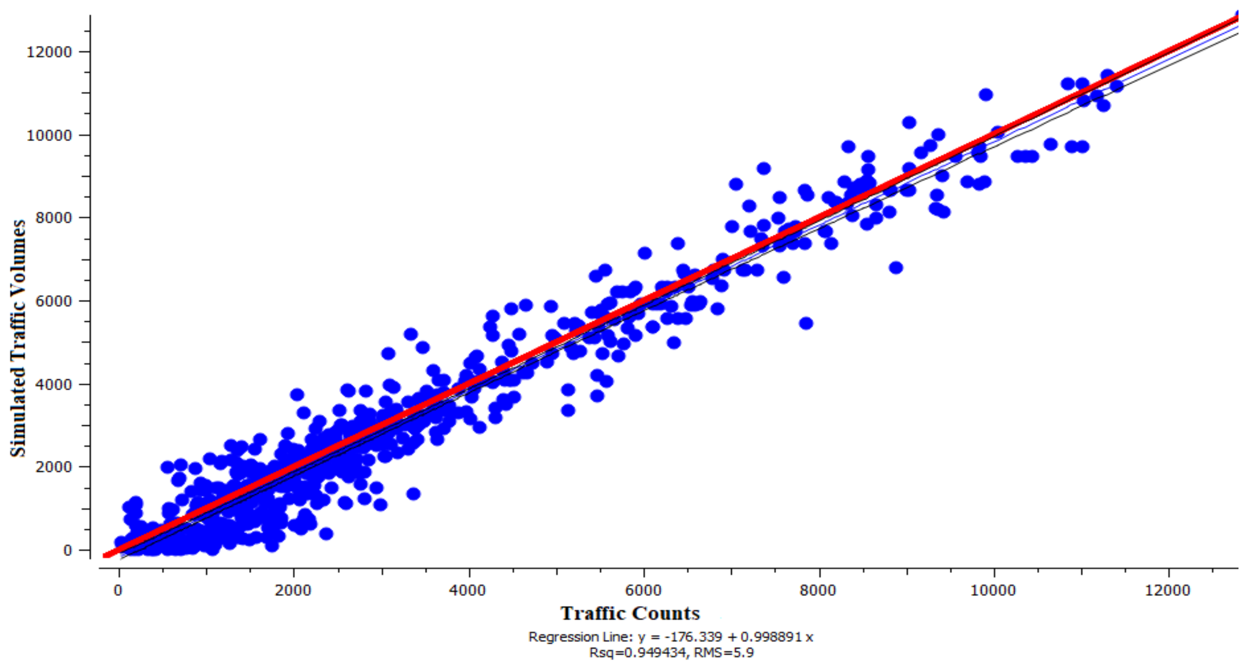
Figure 140. Final imported network and OD matrices in Aimsun Next.

8.3.4. Origin-Destination Matrix Estimation

The estimation of time-variant trip matrices is an important step in DTA-based tools. DTA analysis requires dynamic or time-variant trip matrices specified for short time intervals (e.g., 15 minutes or 30 minutes) (Hadi et al., 2016). However, regional demand models were traditionally designed for daily model that can only produce daily trip matrices. More recently transportation modelers are developing “time-of-day” models that produce trip matrices representing the peak periods demand matrices. An origin destination matrix estimation (ODME) process is needed to fill this gap by estimating the trip tables for short intervals based on an initial matrix obtained from the regional demand models combined with field data. The ODME results are presented in Figure 141 (a) and (b) with comparison of simulated link volumes with real-world traffic counts for two different sets of matrices in 2 hours using Aimsun Next optimization procedure. The first set was produced by factorizing the demand matrix extracted from the regional demand model using static assignment in Aimsun Next. The second matrix is the calibrated demand matrix produced from static adjustment results, which was obtained by the same Aimsun Next modeling software. As shown in this Figure 141 (a), the simulated link volumes cannot replicate the observed link volumes when factorization of the demand matrix was used since the corresponding R^2 is only 0.65. With calibrating the demands, the simulated link volumes get closer to the observed link volumes with a R^2 value of 0.95. Furthermore, static adjustment results showed in Figure 141 (b) that the ODME procedure generates an approximately 38% improvement (from 9.5 to 5.9) in terms of root mean square error (RMSE). The previous assignment and adjustment procedure were performed for the full regional model.



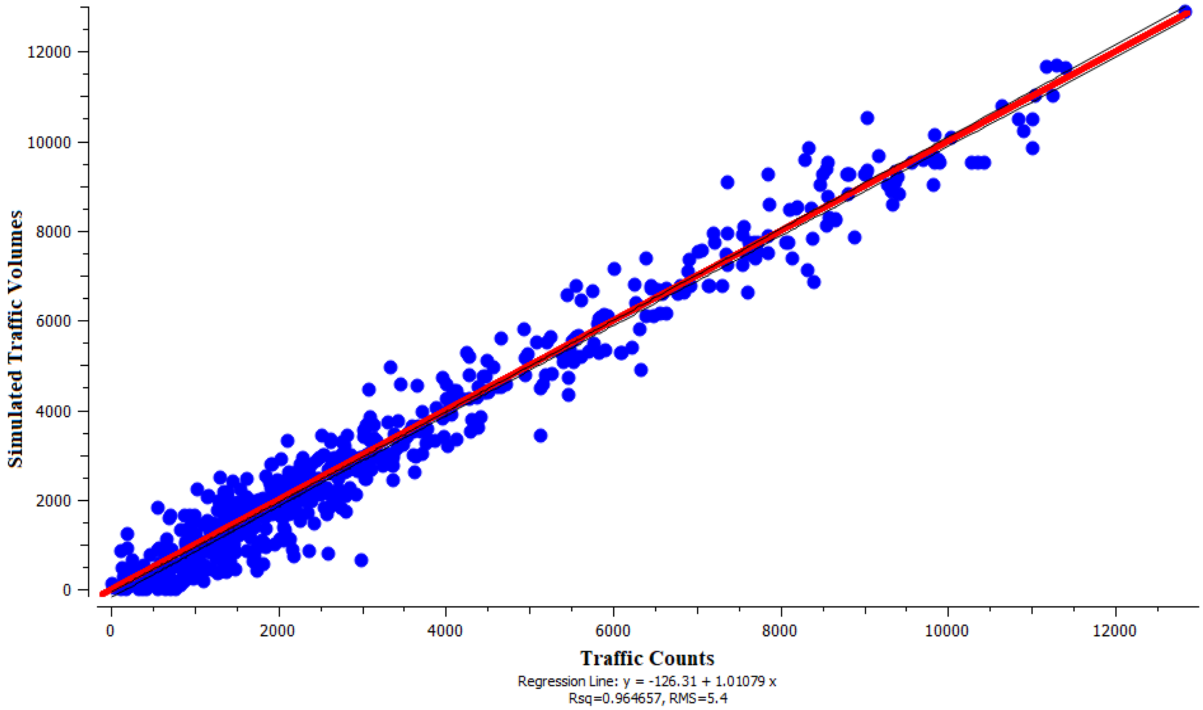
a. Static assignment of full regional network



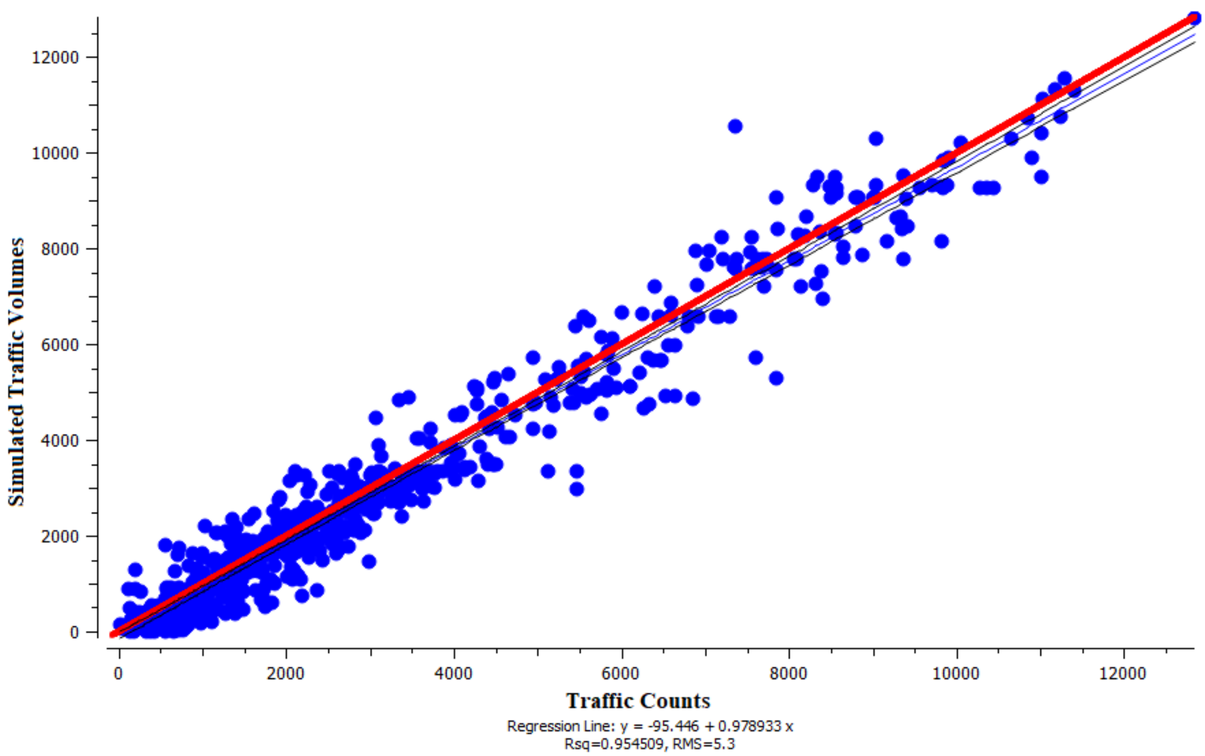
b. Static adjustment of full regional network.

Figure 141. Origin-destination matrix estimation results of OUATS model.

To develop a mesoscopic DTA model, the research team selected Orange and Seminole Counties as the subarea network from the regional model including 4,264 section lengths, 1,416 Traffic Analysis Zones (TAZs), 18,350 links, 8,942 nodes, and 2,417 signalized intersections. This subarea large network is also well calibrated by static adjustment procedures using real datasets with R^2 and RMSE value of 0.96 and 5.4, respectively. Furthermore, static assignment is performed for this subarea network (Orange and Seminole Counties) in order to get the much accurate assigned volume based on adjusted volume, which would be used for signal timing of all the 2,417 signals in the mesoscopic area network. However, those signals would be utilized as dummy signal timing for the mesoscopic simulation area, while the accurate signal timing data will be coded for the microscopic DTA simulation models within the mesoscopic area using full MRM techniques as previously described. The static adjustment and the assignment results are presented in Figures 142 (a) and (b) with comparison of simulated link volumes with real-world traffic counts. This is the final network and demand matrices which would be used for the calibration and the validation of mesoscopic simulation model. As described earlier, there are 2,417 signals in the mesoscopic area, while the total number of signals in the two microscopic areas (Downtown Orlando, East Orlando) are 286. For every signal, the research team devoted more than 30 minutes to code it in Aimsun Next. Hence, it is not practical to add the signal timing in the whole mesoscopic area. Instead, the dummy signal timing, as another alternative, was generated in Aimsun Next based on the assigned volume. The dummy signal timing is a sophisticated way to calibrate the mesoscopic area with very large number of signals. Afterwards, as the microscopic model aims to simulate the traffic in detail, the signal timing of the two microscopic areas are coded based on actual signal timing plan data (described in section 8.5.2).



a. Static adjustment of subarea network

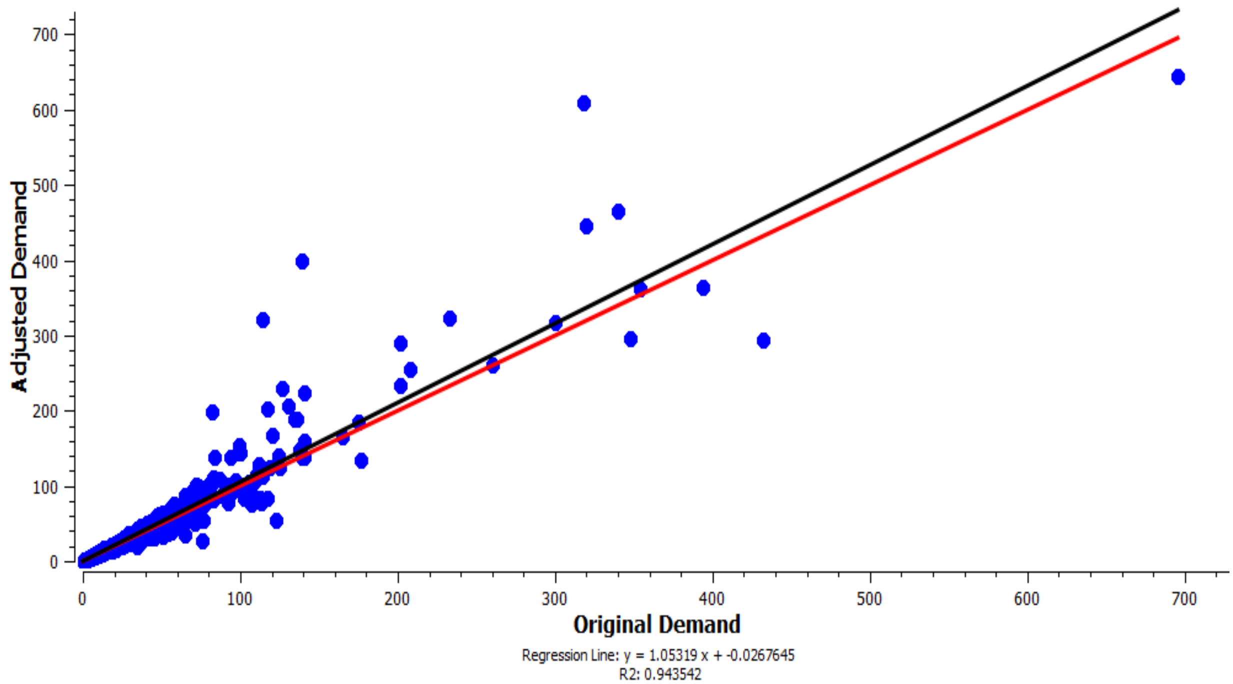


b. Static assignment of subarea network

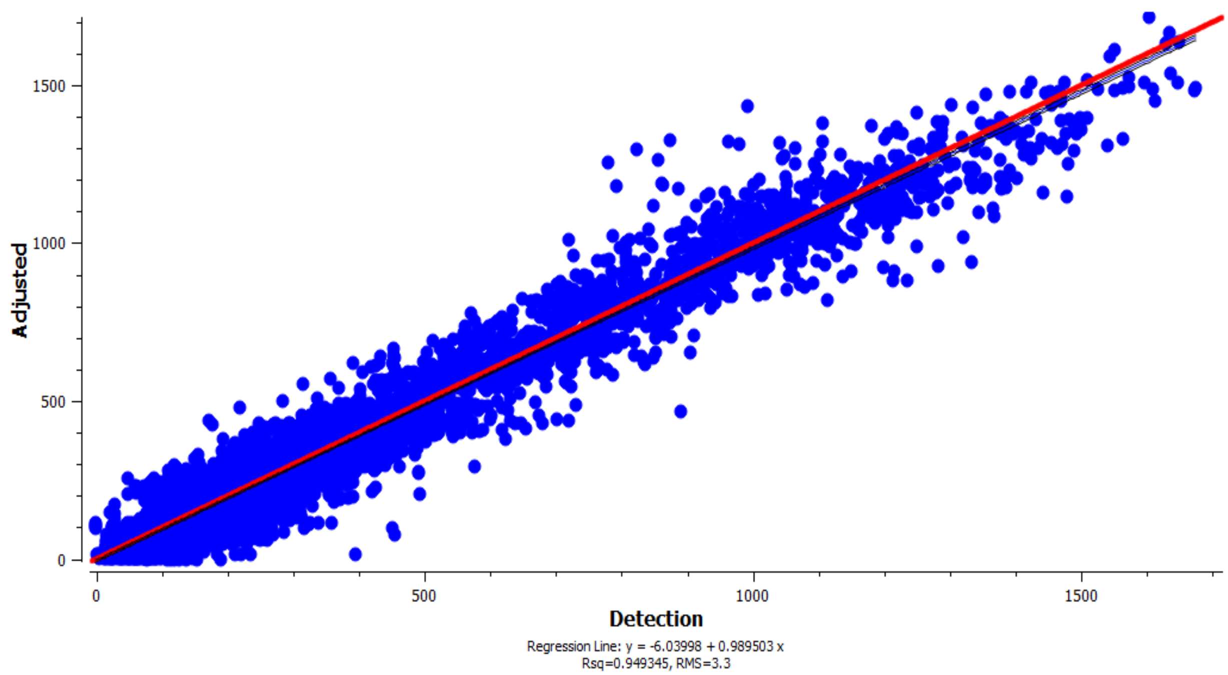
Figure 142. Origin-destination matrix estimation results of mesoscopic area model.

8.3.5. Time Dependent Origin-Destination Demand

The aforementioned ODME procedure was applied for the adjustment of initial demand matrix to peak period demand matrix with the 2-hour period. However, to prepare the demand for DTA based dynamic modelling (either mesoscopic or microscopic), it is important to adjust the set of traffic counts slicing into 15-minute intervals by departure adjustment procedure in Aimsun Next. The static adjustment process refines the total peak hour matrix, while the departure time adjustment process distributes it by each time slice. The departure time adjustment uses path assignment results of a static adjustment as input to calculate the demand matrix of each 15-minutes interval of total 2 hours AM peak period. The Static OD departure adjustment does not calculate any new assignment, it takes previously calculated fixed paths from a path assignment produced earlier and link travel time which is used to calculate the assigned number of vehicles for each time period. OD departure adjustment allows for a ‘warm-up’ period (i.e., no time is taken from the simulation and no data files are produced during this period) to load the network with vehicles in the right proportions and with the right distribution. In a large-scale DTA model, the selection of the warm up period is done by iterative process until the first 15 to 30 minutes of 2 hours dynamic simulation has a regression slope closer to 1. The optimal warm up period of this large network was found to be 45 minutes so that 2 hours 45 minutes hours OD matrices (From 6:15:00 to 9:00:00 A.M.) were obtained for each 15-minute time interval in the OD departure adjustment process. In Figure 143, the total adjusted demand is compared with the original demand in regression plots for both trips and count. With optimal warm up period of 45 minutes, the simulated trip and link counts get closer to the observed trip and link counts with a R^2 value of 0.94 and 0.95 which confirmed reasonably good results described in Figures 146 (a) and 146 (b), respectively.



a. Adjustment and observed trip counts (total 2 hours)



b. Adjustment and observed link counts (every 15 minutes)

Figure 143. Observed and adjusted demand in departure adjustment procedure.

Moreover, the traffic demand for every 15 minutes interval was obtained from the results of OD departure adjustment procedure. The 2-hour 45 minutes profiled demand is presented in Figure 144 below in which first 45 minutes are considered for the warm up period in mesoscopic DTA simulation.

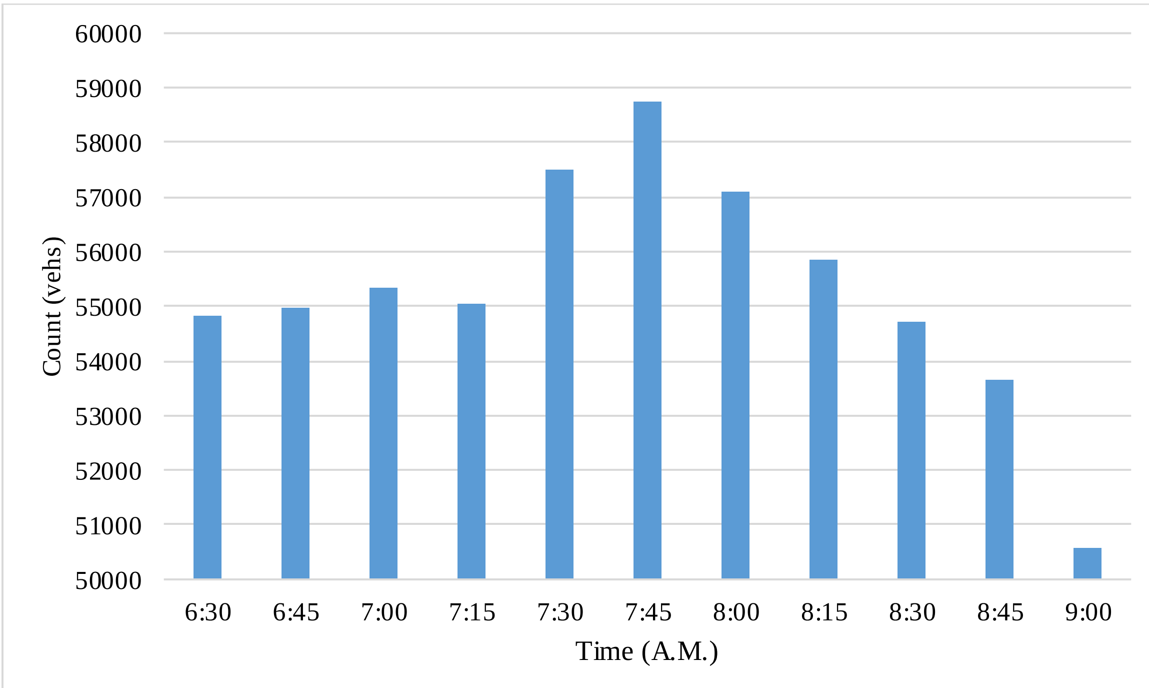


Figure 144. Profiled demand from OD adjustment procedure

However, the demand is only based on car in the simulation. Based on the real-data, two types of vehicles including car and truck were considered to apply at each 15-minutes demand matrices with proportion of 90% and 10%, respectively.

8.4. Development of Mesoscopic Area (Calibration and Validation)

8.4.1. Selection of Mesoscopic Area

As mentioned earlier, the regional model named OUATS with base year 2009 was the starting point for the development of DTA based simulation model. To develop the mesoscopic DTA model, the research team extracted Orange and Seminole Counties from OUATS model as the large subarea network counting 18,350 links, 8,942 nodes, and 2,417 signalized intersections as mesoscopic area. The screenshot of the mesoscopic area from Aimsun Next is showed in Figure 145.

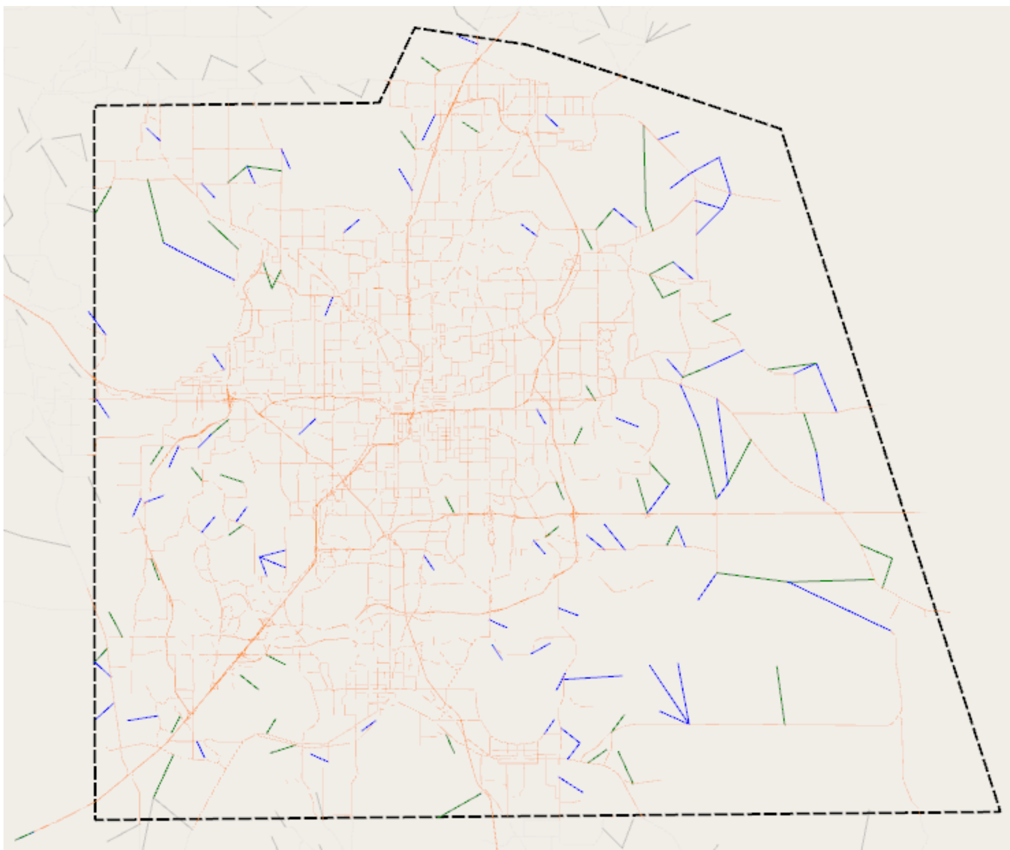


Figure 145. Screenshot of mesoscopic area from Aimsun Next

8.4.2. Calibration of the Mesoscopic Area

In general, extensive efforts are required to calibrate and validate the large-scale DTA based simulation model for both the mesoscopic and microscopic levels. First of all, it is necessary to calibrate the entire model at the mesoscopic level to build the reliable framework of microscopic DTA model. Towards this end, vehicles are loaded into the network and then select routes through a C-logit route choice model under the dynamic user equilibrium (DUE) procedure. This process means that vehicles departing simultaneously will take routes that experience equal and minimal travel times for any given origin-destination (OD) pair at any time during the simulation (Zitzow et al., 2015). To achieve this, a DTA approach is taken at each simulation step for which vehicles entering the network to calculate the shortest routes for their OD pairs according to existing link speeds and distribute themselves onto the network. As they move through the road system, link speeds are updated for the next time interval. For the large-scale DTA model, the calibration process is a high-level iterative procedure which includes running the model, comparing the output with calibration and validation points, changing the global and local parameters, identifying problem areas, comparing the model data with the real network, identifying appropriate changes, implementing the changes, and rerunning the model. The primary calibration metric used in this large-scale network was 15-minutes traffic counts throughout the whole mesoscopic area. The waves of traffic count data were acquired that resulted in 689 calibration points (265 on freeways and 424 on arterials) throughout the entire mesoscopic network from 7 to 9 A.M. with each 15-minute interval. Figure 146 shows the traffic count detector locations within the mesoscopic area. With this approach, the model underpredicted delay because of the cold start of the DTA model (i.e., the model began with an empty network). Thus, the optimal 45 minutes warm up period was utilized based on the OD departure adjustment procedure mentioned above.

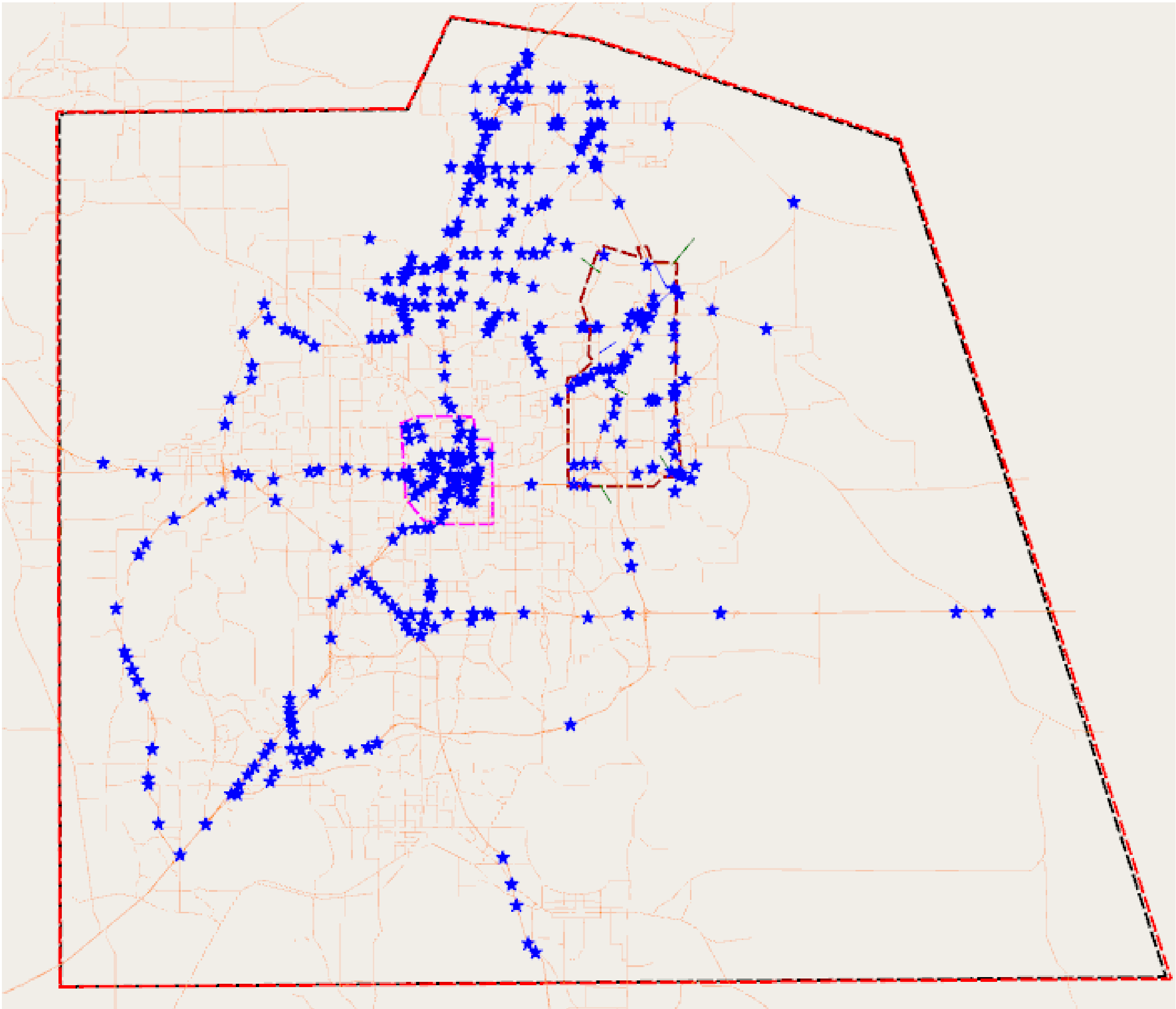
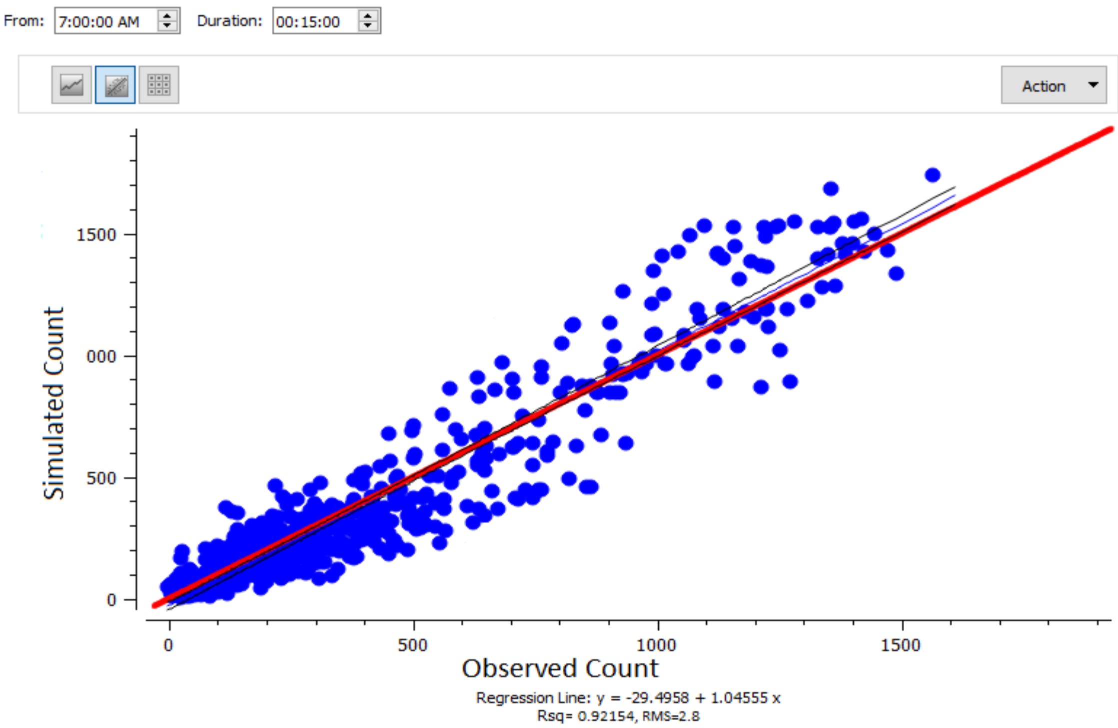


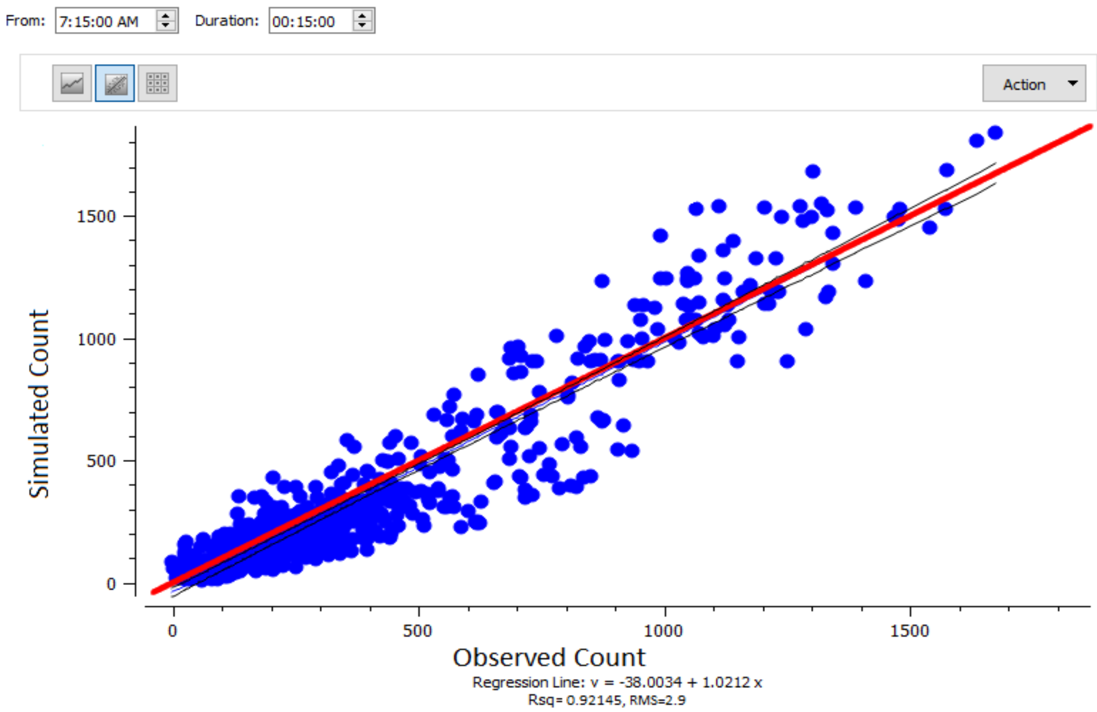
Figure 146. Location of traffic count detectors in whole mesoscopic area.

Most of the DTA based simulation studies used R^2 and Root Mean Squared Error (RMSE) values for the calibration criteria of large scale network The R^2 value of every 15 minutes simulated versus traffic counts was found to be more than 0.90 that confirmed reasonably good calibration based on previous research (Hadi et al., 2016; Shafiei et al., 2018; Zitzow et al., 2015). Figure 147 represents the regression line with R^2 value of first two 15 minutes (from 7:00:00 to 7:30:00 A.M.) time intervals out of total eight 15 minutes time intervals (from 7:00:00 to 9:00:00

A.M.). However, the research team also used the GEH statistic (named for Geoffrey E. Havers) to quantify model output, which is a weighted measure of the absolute and relative differences between the real data prediction and the model output at a certain location. The GEH statistic is common in traffic models and is usually used on a small-scale microsimulation model. However, in large-scale DTA model, some research teams were limited to using the regression line, R-Square, and RMSE as GEH is stricter in the sense that small volumes have a higher impact compared to the regression line (Hadi et al., 2016; Luo and Joshua, 2011; Shafiei et al., 2018; Zitzow et al., 2015). Generally, a GEH value of less than 10 is an acceptable match to data. However, it should be reasonable to select a larger bound of error since this project involved a much larger scale. A recent widely accepted large scale DTA model used GEH value of 10 to 25 as an acceptable range of error (Duell et al., 2015). Thus, a GEH value of 10 to 25 was considered as an acceptable error of margins and applied in the calibration of large mesoscopic area only. It is worth mentioning that, the microscopic DTA model, which is going to be used in detail for the active traffic management strategies would be well calibrated and validated based on the widely accepted criteria for small-scale microsimulation (will be explained in the microscopic calibration part).



a. Regression line for first time interval (7:00:00 AM to 7:15:00 A.M.)



b. Regression line for second time interval (7:15:00 AM to 7:30:00 A.M.)

Figure 147. Mesoscopic results for first two 15-minute intervals

Figure 148 illustrates the results for the GEH statistic on the mesoscopic network for first 15 minutes counts from 7:00:00 A.M. to 7:15:00 A.M. The green points indicate a GEH value of less than 10, the yellow points denote GEH value of between 10 and 25, and the red points represent a GEH value of greater than 25 which is considered unacceptable. Based on the mesoscopic calibration results, about 95% of all the data collection points' GEH were less than 25, and about 56% were less than 10. This project achieved better mesoscopic DTA calibration compared to previous widely accepted large-scale DTA model of which 80% of all the data measurement locations GEH were less than 25 and about 48% were less than 10. (Duell et al., 2016).

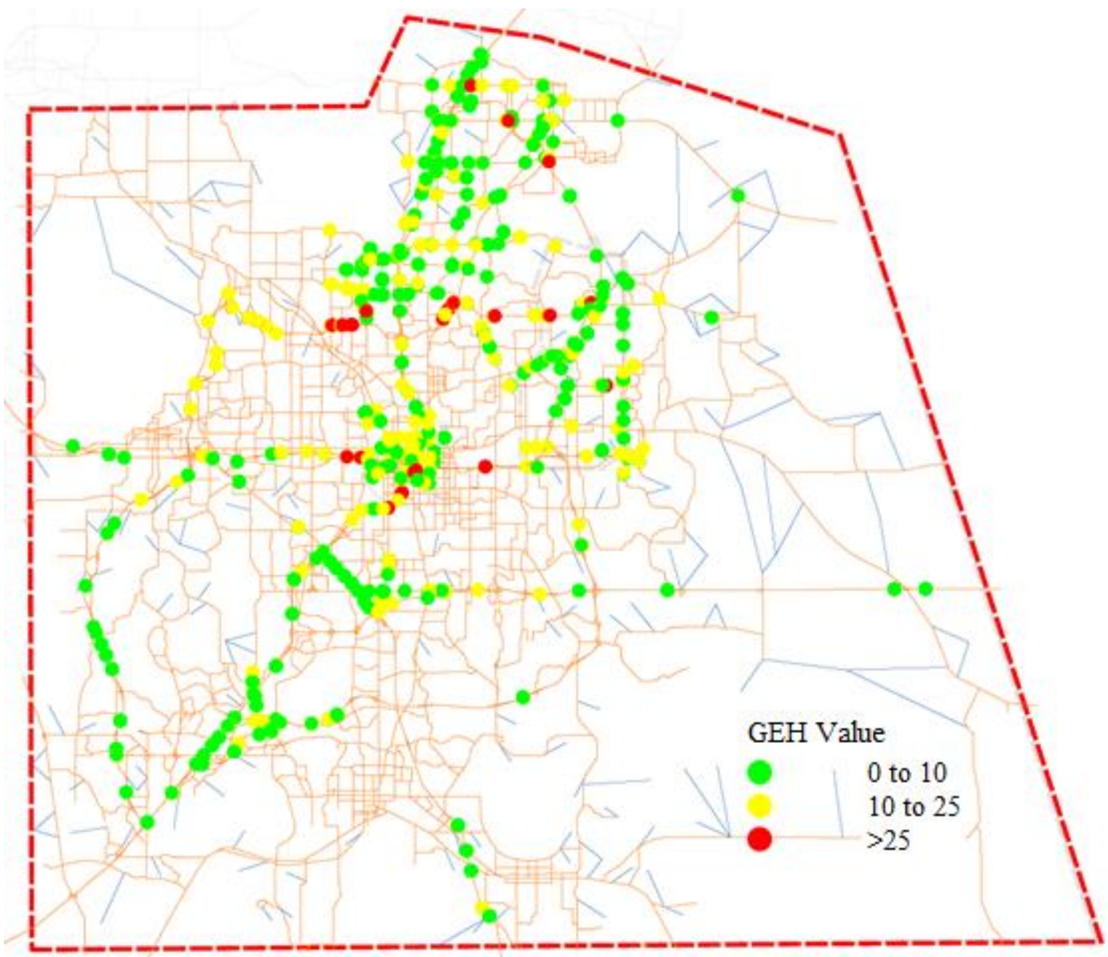


Figure 148. GEH value for model calibration (7:00:00-7:15:00 A.M.).

Table 61 shows the calibration results in terms of data collection point.

Table 61. Status of the calibration results

GEH value	Number of Detectors	Percentages	Status
<10	386	56%	Good
10-25	269	39%	Acceptable
>25	34	5%	Poor

8.4.3. Validation of Mesoscopic Simulation Area

In practice, a simulation model should be well validated to confirm the credibility of the model that represents the true behavior of the real-world closely enough for decision-making purposes. To the best of our knowledge, none of the large-scale DTA models with the MRM framework (Duell et al., 2015; Hadi et al., 2016; Shafiei et al., 2018; Zitzow et al., 2015) have considered the model validation because of the complexity of such kind of large networks except Shafiei et al (2018) which was a much smaller network in terms of mesoscopic area compared to this current study. However, previous large scale DTA models (Pravinvongvuth and Loudon, 2011; Tokishi and Chiu, 2013; Zitzow et al., 2015) performed only calibration as achievement of validation criteria is very time consuming. This research team validated the entire mesoscopic model with set of time-dependent path travel times obtained from Bluetooth, NPMRDS, HERE, and AVI detectors for both freeway and arterials. The travel time data were collected that resulted in 410 validation points with 76 on freeways and 334 on arterials throughout the network from 7 to 9 A.M. with each 15-minute time interval. On freeways and expressways, the number of available travel time detectors was less compared to traffic count detectors. A traffic count detector locates at one point in a section while a pair of detectors is needed to get travel time which needs to cover two or more sections. In the network, relatively long travel time sections were used to avoid randomness. Actually, travel time detectors cover larger area compared to traffic count detectors. Hence, the 76 travel time detectors are reasonable compared with the 265 count detectors. Figure 149 shows segments (highlighted red segment) having travel time data input in the whole mesoscopic area based on the availability of real data. FDOT provides in general guidelines of travel time validation in two ways: (1) simulated travel time should be within ±1 minute for routes with observed travel times less than seven minutes (2) simulated travel time would be within ±15% for routes with observed travel times greater than seven minutes (FDOT Systems Planning Office, 2014). There are no specific guidelines for validating the mesoscopic and microscopic network in terms of network size. Some researchers used larger bound of error to calibrate and validate the large-scale DTA model because of the complexity of such kind of networks (Duell et al., 2015; 2016). As mentioned earlier, this project covers a much larger scale, and a larger bound of error is also acceptable in mesoscopic validation. However, the microscopic DTA model would be validated by the accepted guidelines mentioned above. The research team used ±1.5 minutes and ±20% as larger bound of error for routes with observed travel times less than seven minutes and more than seven minutes, respectively, for mesoscopic validation in terms of travel time.

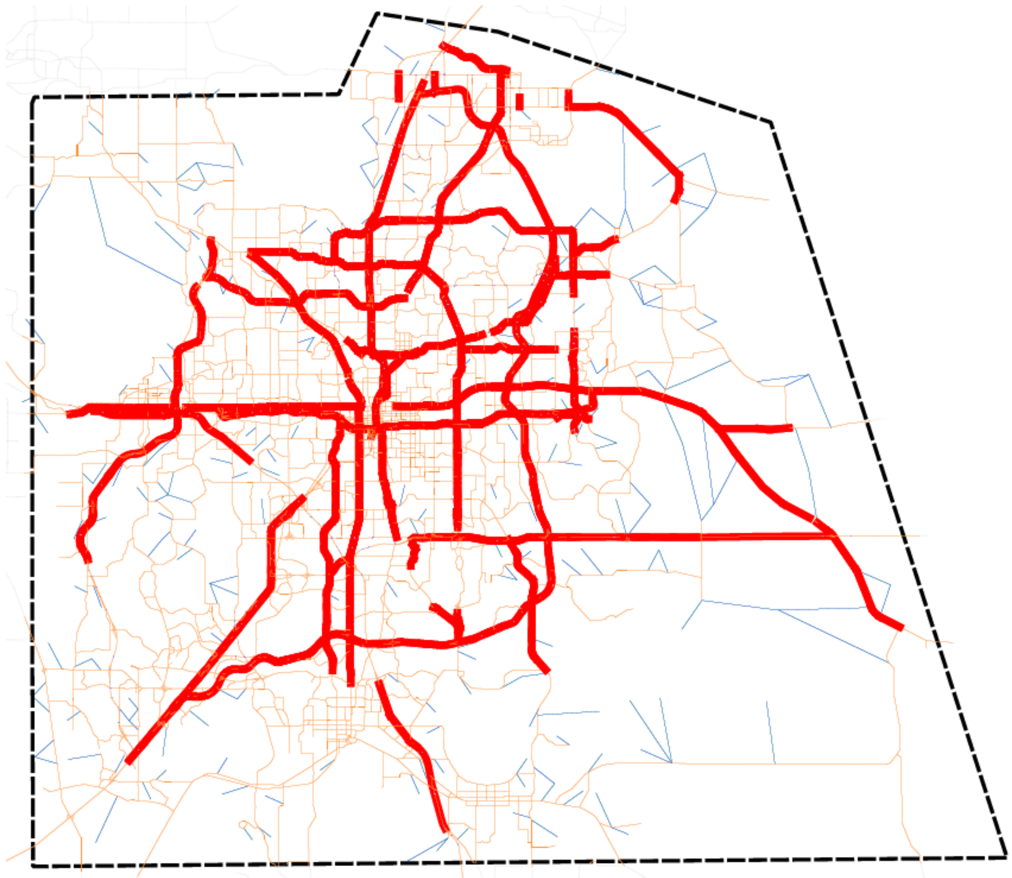


Figure 149. Travel time detector locations for the entire mesoscopic area

There are two main parts to calibrate the parameters in Aimsun Next to achieve the good validation criteria: (1) dynamic traffic assignment or route choice and (2) mesoscopic parameters (Aimsun, 2018). The network had much congestion in some corridors due to two possible reasons: (1) too many vehicles are assigned to that corridor which is governed by dynamic traffic assignment parameters; (2) the model is not properly calibrated in terms of mesoscopic parameters such as reaction time, look ahead distance, the speed acceptance for vehicle type etc. Sensitivity analysis is an acceptable practice to calibrate the simulation model based on adjusting the simulation software parameters (Rahman and Abdel-Aty, 2018; Rahman et al., 2018). Therefore, a sensitivity analysis was conducted on Aimsun Next traffic assignment parameters and mesoscopic parameters (behavioral calibration) based on engineering judgement with their allowable minimum and maximum values in the simulation model. For each parameter, a range of values between the minimum and maximum (include default value) were chosen to run the mesoscopic dynamic traffic assignment model and the corresponding percentages of travel time validation criteria were calculated. For each parameter, the maximum value of percentage locations achieving the aforementioned validation criteria is the corresponding calibrated value for that parameter. The calibrated values of both traffic assignment parameters and the mesoscopic parameters are presented with default values in Table 62.

Table 62. Aimsun Next calibration parameters for mesoscopic simulation

Parameters	Unit	Default value	Calibrated value based on Travel Time
Traffic assignment parameter			
Model selection	N/A	uniform	C-logit
Attractiveness weight	N/A	0	10
Maximum number of initial paths to consider	N/A	All	3
Maximum Paths per interval	N/A	3	10
Mesoscopic parameters			
Reaction time	s	1.2	0.9
Reaction time at traffic light	s	1.6	1.2
Look ahead distance variability	%	40	60
Speed acceptance for Car	N/A	1.1	1.5
Speed acceptance for Truck	N/A	1.0	1.4

In terms of mesoscopic behavioral calibration, look ahead distance was iteratively adjusted in various problematic sections based on the results of unrealistic congestion, missed turns etc. The combination of those parameters and adjusting the behavioral calibration provide 86% locations are within error bound ±1.5 minutes and ±20% for routes with observed travel times less than seven minutes and more than seven minutes, respectively.

Figure 150 illustrates the validation results of the mesoscopic network for eight 15-minute time intervals (2-hour simulation). The legends showed the number of validated time intervals from 1 to 8 by different colors (from red to green). For example, the red color (i.e., number of validated time interval is 1) means that the corresponding subpath is satisfied the validation criteria for only one-time interval, while the green color (i.e., number of validate time interval is 8) represent all the 8 time intervals are satisfied with the validation criteria. From the figure, it can be depicted that most of the subpaths are green, representing good validation. Therefore, the large mesoscopic network achieved the reasonable validation within the acceptable bound of errors. Finally, the calibration and the validation results indicated that the mesoscopic DTA model outputs including traffic counts and path travel time are of reasonably high accuracy given the size of the network and its congestion level. Hence, within the DTA framework, the large-scale network is well calibrated and validated by mesoscopic level of simulation.

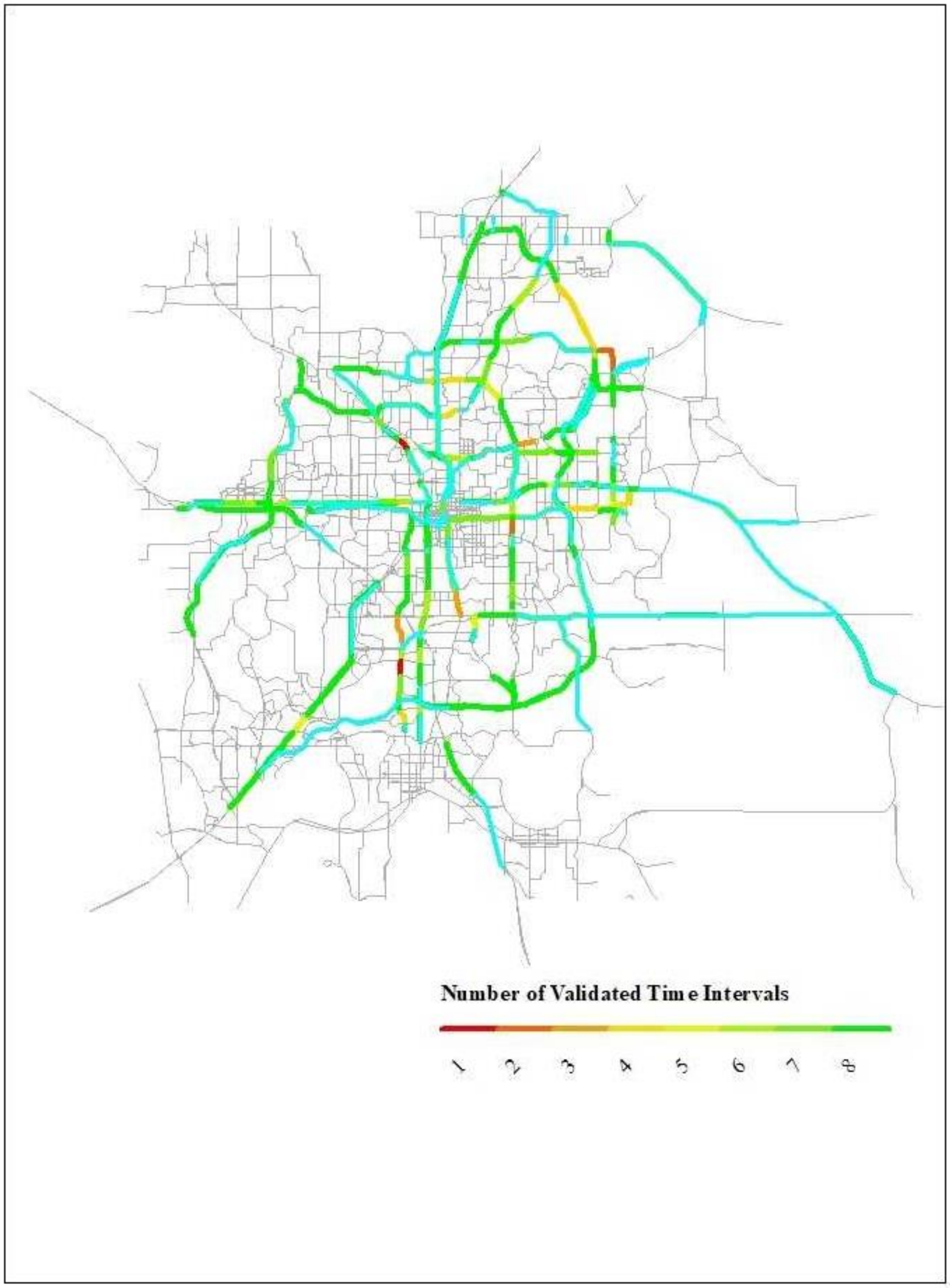
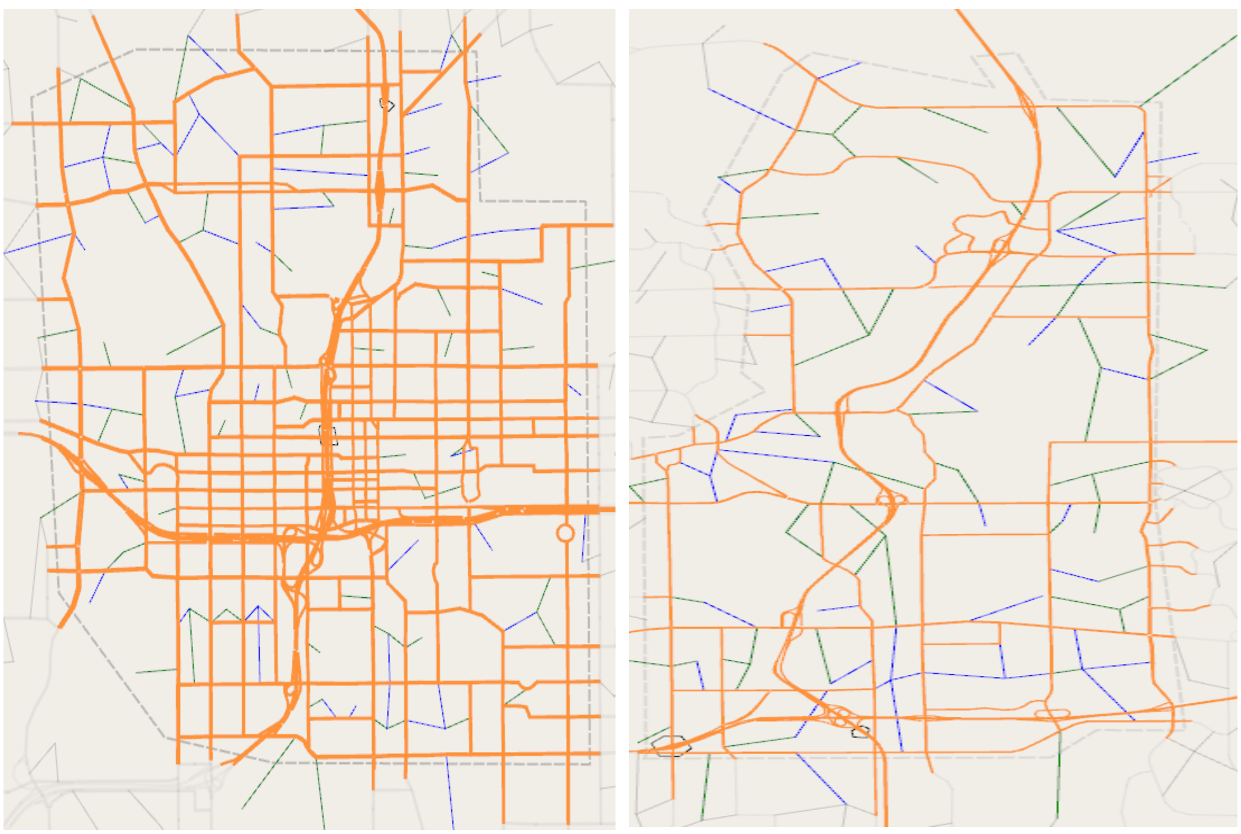


Figure 150. Travel time validation results.

8.5. Microscopic Areas' Calibration and Validation

8.5.1. Selection of Microscopic Areas

Based on the evaluation results of the previous task, the research team has selected the two critical corridors for testing integrated active traffic management (IATM) strategies in microscopic level. Towards that end, two congested subarea networks (1) Downtown Orlando (including I-4, SR408, Colonial Drive etc.) (2) East Orlando campus (including SR417, SR434 etc.) were selected as microsimulation areas to test the IATM strategies. The screenshot of two microscopic areas from Aimsun Next are presented in Figure 151.



(a) Downtown Orlando (I4, SR 408 etc.) (b) East Orlando Area (SR417, SR434)

Figure 151. Screenshot of microscopic areas from Aimsun Next.

The roadway along with the traffic control information's of the two microscopic areas are presented below in Table 63.

Table 63. Roadway and traffic control information in the microscopic areas

Attributes	Microscopic Area 1	Microscopic Area 2
	Downtown Orlando	East Orlando Area
Section length (miles)	233	248
Traffic Analysis Zones	179	128
Links	1,628	808
Nodes	707	428
Signalized Intersection	197	89

8.5.2. Importation of Signals in Microscopic Area

In the microscopic areas, more accurate geometry and signal timing were provided as the original OUATS model was a macroscopic model with less detailed geometric configuration and traffic. The research team coded signal timing information's in Aimsun Next for the microscopic area while the signals in the mesoscopic area were implemented based on assigned volume mentioned above. The signal timing data were collected from Orange County, Seminole County, and the City of Orlando engineering division. The research team coded the signal timing in Downtown Orlando and East Orlando areas (two microsimulation areas) are 197 and 89, respectively. The sample timing sheets collected from the three engineering divisions are presented in Figure 152 below.

ORANGE COUNTY TRAFFIC SIGNAL TIMING

Hazem El-Assar, P.E.

Intersection: SR 50 at CR 431 (Pine Hills Road)	Node: 67	Port:	
Equipment: Eagle	Date: 6/28/16	Address:	

BASIC TIMING

Phase	1	2	3	4	5	6	7	8
Direction	EBL	WB	SBL	NB	WBL	EB	NBL	SB
Min Green (sec)	5	15	5	5	5	15	5	5
Vehicle Gap (sec)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Max Green 1 (sec)	25	60	25	50	25	60	25	50
Max Green 2 (sec)	22	56	25	36	22	54	20	32
Yellow (sec)	4.8	4.8	4.4	4.1	4.8	4.8	4.1	4.4
All-Red (sec)	3.0	2.0	3.1	3.3	2.6	2.0	3.0	3.1
Walk (sec)		7		7		7		7
Flash Don't Walk (sec)		29		42		21		43
Recall/Memory	LK	SF/LK	LK	NL	LK	SF/LK	LK	NL
Detector Delay (sec)								
Detector Switching								
Dual Entry		Y		Y		Y		Y
Overlap								
Flash	R	Y	R	R	R	Y	R	R

(a) Signal timing sheet from Orange County

Seminole County Traffic Engineering Timing Sheet
Intersection: SR 436 @ 10-SR 434 #4276

SEMINOLE COUNTY
FLORIDA'S NATURAL CHOICE

Name	SR 436		SR 434		SR 436		SR 434									
Direction	WL	ET	NL	ST	EL	WT	SL	NT								
Channel	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Phase/OL	1	2	3	4	5	6	7	8	1	2	3	4	2	4	6	8
Type	VEH	VEH	VEH	VEH	VEH	VEH	VEH	VEH	OLP	OLP	OLP	OLP	PED	PED	PED	PED

IP	010.046.084.002	Mask	255.255.255.0
Gate	10.46.84.254	Port #	5105
Ph Mode	STD8	Com ID #	1470
Free Seq	1	Node #	4276
Date	15-Nov-16	Done By	EPrincipe

Phase Times

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Min Grn	6	17	6	8	6	17	6	8								
Passage	3	4	3	3	3	4	3	3								
Max 1	20	50	30	45	25	50	20	45								
Max 2	20	50	30	45	25	50	20	45								
Yel Clr	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8								
Red Clr	2.1	2.1	2	2	2.1	2.1	2	2								
Walk		7		7		7		7								
Ped Clr		30		35		31		34								
Red Rvrt	3	3	3	3	3	3	3	3								
Added Init																
Max Initial																
Max3 Limit																
Max3 Step																
Time B-4																
Cars B-4																
Time to																
Reduce By																
Min Gap																

Alt Phase Times 1

Assign								
Min Grn								
Passage								
Max 1								
Max 2								
Yel Clr								
Red Clr								
Walk								
Ped Clr								

Alt Phase Times 2

Assign								
Min Grn								
Passage								
Max 1								
Max 2								
Yel Clr								
Red Clr								
Walk								
Ped Clr								

(b) Signal timing sheet from Seminole County

City of Orlando Timing Sheet 10/9/2018 9:29:24 AM

Station : 202 - Lake Highland & Mills Av (Standard File)

Phase [1.1.1]

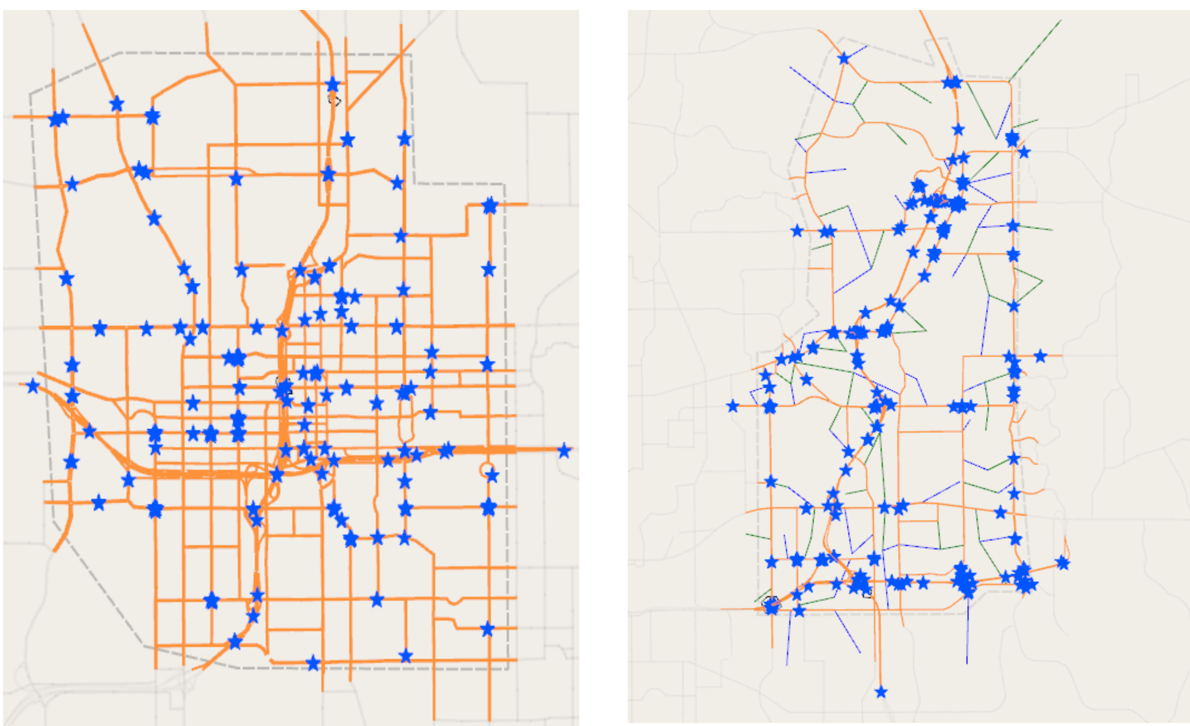
	1	2 (ST)	3	4 (WT)	5	6	7	8	9	10	11	12	13	14	15	16
Walk		7		7												
Ped Clearance		10		19												
Min Green		7		12					3		3		3		3	
Passage		4		3.5												
Max1		60		25												
Max2		45		23												
Yellow		4.2		3.5					3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Red		2		2.8					1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Red Revert	2	2	2	2	2	2	2	2								
Added Initial																
Max Initial																
Time Before Reduce																
Cars Before Reduce																
Time To Reduce																
Reduce By																
Min Gap																
Dynamic Max Limit																
Dynamic Max Step																
Auto Exit		ON														
Rest In Walk																

(c) Signal timing sheet from City of Orlando

Figure 152. Signal timing sheets from different agencies

8.5.3. Calibration and Validation of Microscopic Areas

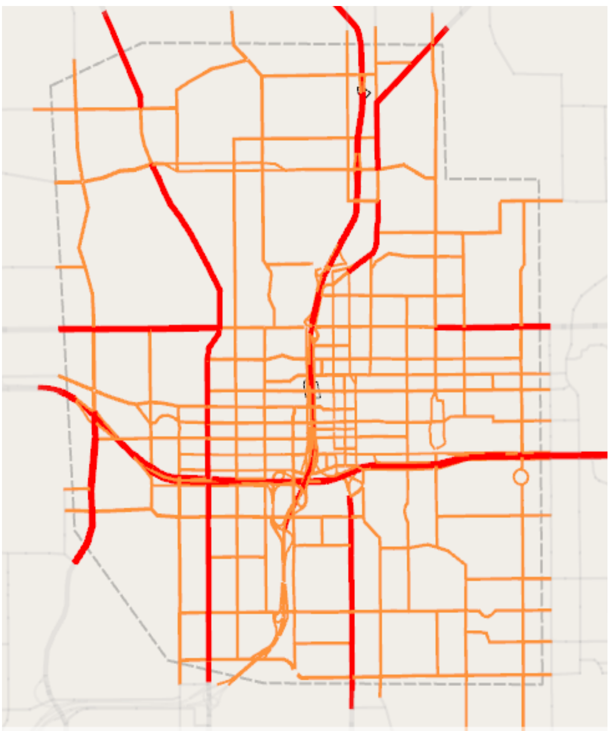
As mentioned earlier, two microscopic areas, including Downtown Orlando and East Orlando area in Central Florida, were implemented at a microscopic resolution from previously calibrated mesoscopic level using full MRM techniques. To better assess traffic impact studies in an area of interest, it is necessary to calibrate and validate the selected microscopic area with lower acceptable bound of error in accordance with the guidelines of small-scale simulation model. Traffic counts and the travel time with each 15-minutes interval were used to calibrate and the validate the microscopic area with lower acceptable bound of error, while a larger bound of error was used to calibrate and validate the model in the mesoscopic area mentioned above. Figure 153 shows the traffic count detector locations for both Downtown Orlando and East Orlando microsimulation areas.



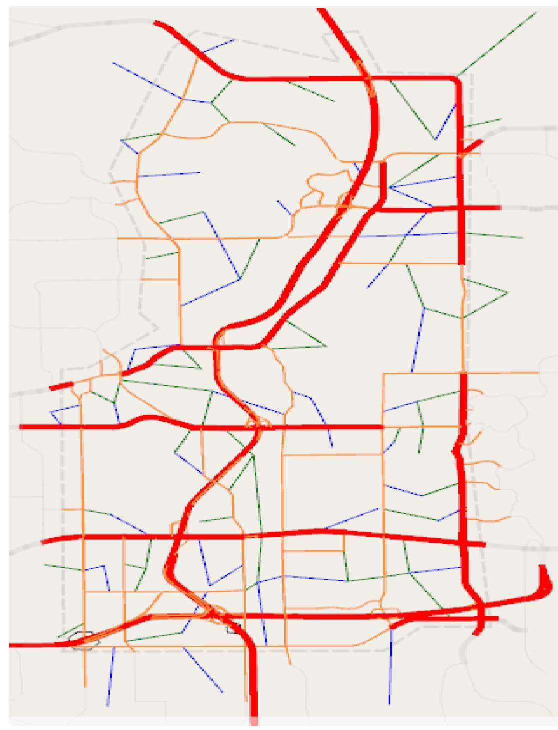
(a) Downtown Orlando (I4, SR 408 etc.) (b) East Orlando Area (SR417, SR434 etc.)

Figure 153. Locations of traffic count detectors in the microsimulation area

From Figure 154, the number of count detectors in Downtown Orlando and the East Orlando, areas are 93 and 84, respectively. Moreover, Figure 154 shows the travel time detector locations as subpath system (red segments) in Aimsun Next for both Downtown Orlando and East Orlando microsimulation areas. There are 28 and 41 pairs of travel time detectors in Downtown Orlando and the East Orlando area, respectively.



(a) Downtown Orlando (I4, SR 408 etc.)



(b) East Orlando Area (SR417, SR434 etc.)

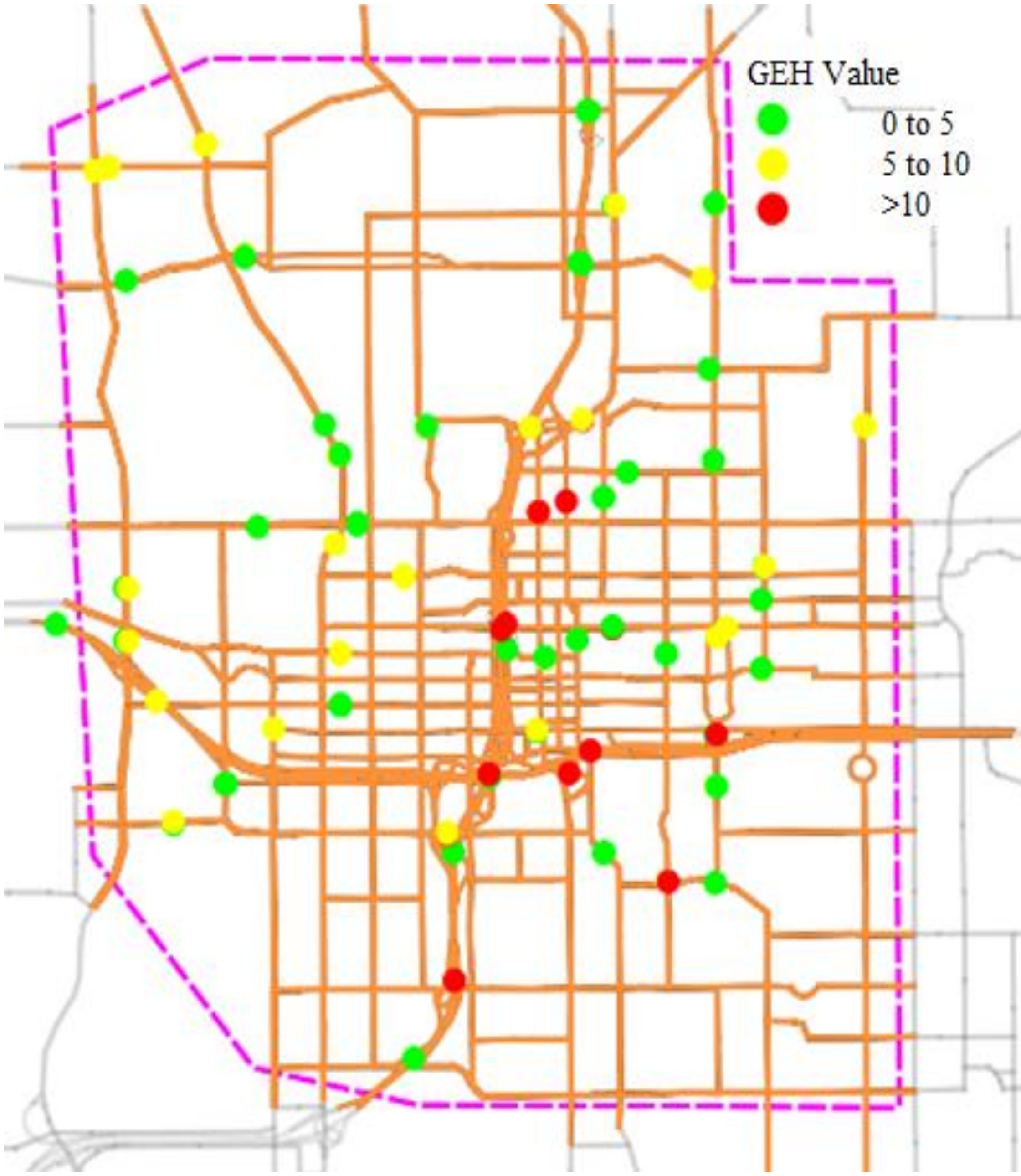
Figure 154. Locations of travel time detectors in the microsimulation area

Like mesoscopic calibration, there are two main parts to calibrate the parameters in order to achieve the good validation criteria: (1) dynamic traffic assignment or route choice and (2) microscopic parameters. The microscopic model includes a much larger number of parameters that should be calibrated which are not included in the mesoscopic model. Hence, a sensitivity analysis was also conducted to calibrate both traffic assignment and microscopic parameters to achieve the good validation of the microscopic model. The calibrated values of both traffic assignment parameters and the microscopic parameters are presented in Table 64.

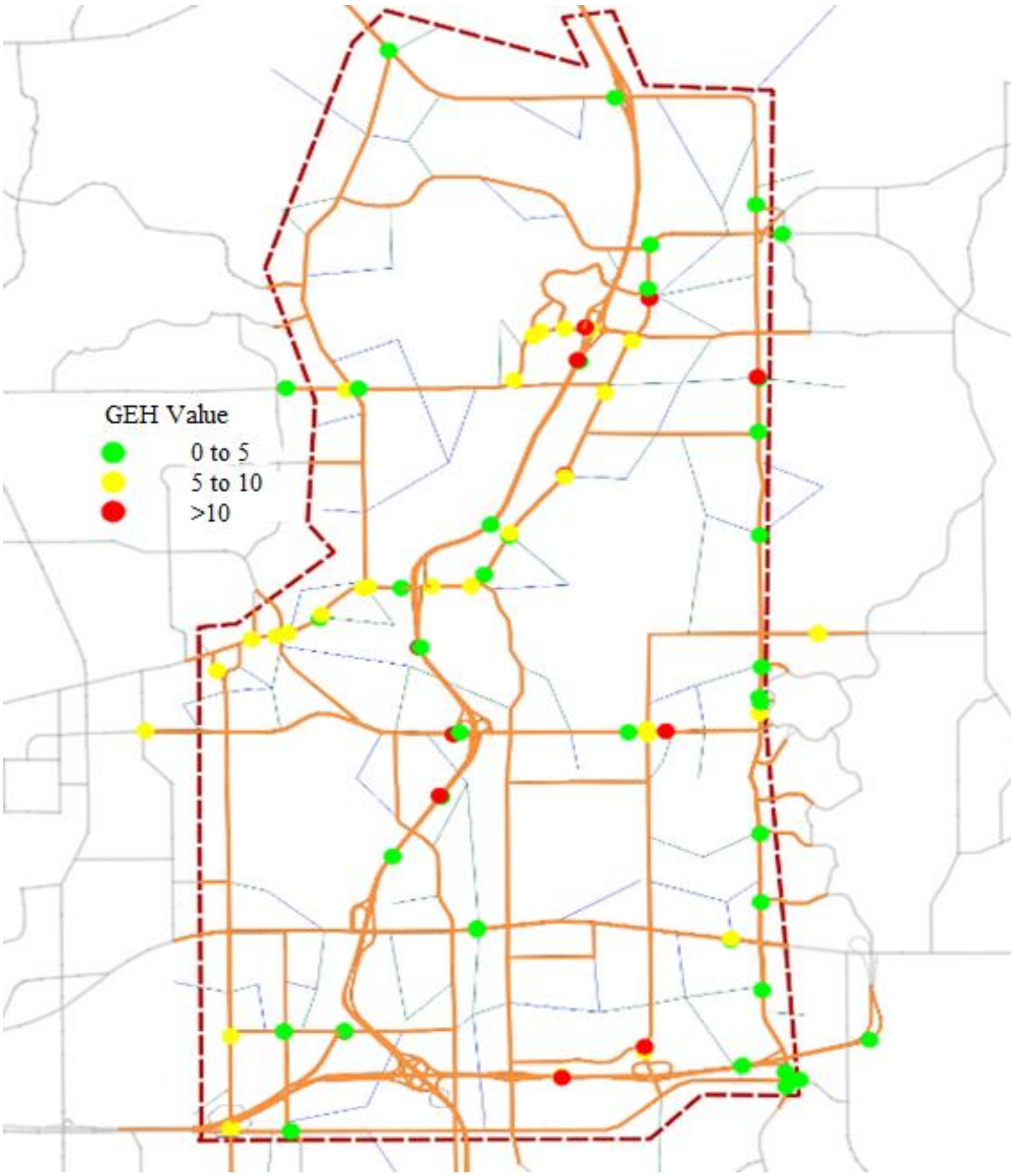
Table 64. Aimsun Next calibration parameters for microscopic simulation areas

Parameters	Unit	Default value	Calibrated value based on Travel Time
Microscopic Calibration Parameters (Downtown Orlando Area)			
Traffic assignment parameter			
Model selection	N/A	uniform	C-logit
Attractiveness weight	N/A	0	5
Maximum number of initial paths to consider	N/A	All	3
Maximum Paths per interval	N/A	3	5
Mesoscopic parameters			
Reaction time	s	1.2	0.8
Reaction time at traffic light	s	1.6	1.2
Look ahead distance variability	%	40	50
Speed acceptance for Car	N/A	1.1	1.5
Speed acceptance for Truck	N/A	1.0	1.4
Microscopic Calibration Parameters (East Orlando Area)			
Traffic assignment parameter			
Model selection	N/A	uniform	C-logit
Attractiveness weight	N/A	0	5
Maximum number of initial paths to consider	N/A	All	3
Maximum Paths per interval	N/A	3	5
Microscopic parameters			
Reaction time	s	1.1	0.90
Reaction time at traffic light	s	1.6	1.2
Look ahead distance variability	%	40	50
Speed acceptance for Car	N/A	1.1	1.5
Speed acceptance for Truck	N/A	1.0	1.4

To represent the driver's behavior in the lane-changing decision process, two different zones (1) distance zone 1 and (2) distance zone 2 are considered as microscopic calibration parameters on that decision process (Aimsun, 2018). In microscopic behavioral calibration, distance zone 1 and 2 are considered significant calibration parameters to represent the driver behavior in the lane changing decisions. Distance zone 1 is essential for overtaking maneuver model. The lane-changing decisions are mainly governed by the traffic conditions of the lanes involved. In this zone, several parameters should be considered in order to measure the improvement that the driver will get from changing lanes: the desired speed of the driver, the speed and distance of current preceding vehicle, and the speed and distance of the future preceding vehicle in the destination lane. Distance zone 2 is the zone in which vehicle will try to stay in the correct lane of the roadway. Vehicles driving in the "wrong" lane (i.e. lanes where the desired turn movement cannot be made) tend to get closer to the correct side of the road from which the turn is allowed. Vehicles looking for a gap try to adapt the speed to find the gaps located at either the downstream or adjacent locations to them (Aimsun, 2018). Distance zones 1 and 2 were iteratively adjusted in various turning movements (turning left or right at arterial signals or takin freeway off-ramps) by looking at the unrealistic behaviors of traffic, missed turns, etc. Moreover, cooperation and aggressiveness parameters in the section were adjusted to match the calibration and validation criteria. After calibrating the parameters, the GEH values were calculated for both microsimulation areas. From the microscopic calibration results, both the Downtown Orlando area and the East Orlando area achieved 86% of GEH less than 10, which represents good calibration for both microscopic areas based on simulation guidelines. Figure 155 shows the GEH value representation from Aimsun Next, including both microscopic simulation areas, highlighting the maps of microscopic areas with different colors.



(a) Downtown Orlando (I4, SR 408 etc.)



(b) East Orlando Area (SR417, SR434 etc.)

Figure 155. GEH value representation for both microscopic areas

Validation of the calibrated two microscopic DTA model has been also carried out. The combination of those calibrated parameters with behavioral modifications in Downtown Orlando and East Orlando areas provide 87% and 86% locations which are within ±1 minute and ±15%

for routes with observed travel times less than seven minutes and more than seven minutes, respectively. Hence, within the DTA framework, the microscopic area is well calibrated and validated based on accepted guidelines. Finally, the mesoscopic and microscopic DTA simulation model are calibrated and validated separately in order to test the active traffic management strategies and decision support system.

8.6. Summary

This chapter described the process of building the large-scale dynamic traffic assignment-based mesoscopic and microscopic simulation models with full Multi-Resolution Modelling (MRM) framework in Orlando, Florida using Aimsun Next interfacing with the Cube based regional traffic demand model (RTDM). Such models were shown to allow the investigation of active traffic management and decision support system in an integrated environment beyond the scope of existing regional traffic models. The Orlando Urban Area Transportation Study (OUATS) with base year 2009 was selected as the regional traffic demand model extracted from Cube Voyager. To develop DTA simulation model, Orange and Seminole Counties were extracted from OUATS for mesoscopic simulation, while small subarea network including Downtown Orlando and East Orlando were utilized as microsimulation areas.

Numerous data sources were acquired and processed. That include the RTDM model from Cube, traffic counts, and travel times from multiple detector systems available at all corridors in the studied area. The deployment of data intensive calibration and validation techniques are presented for both the mesoscopic and microscopic areas within the DTA simulation network. The results showed that both mesoscopic and microscopic areas were calibrated and validated within an acceptable bound of error. In terms of mesoscopic area calibration, 95% of the 689 calibration points (traffic counts) and the 86% of the 410 validation locations (travel time) with eight time-intervals spread across the network within an acceptable bound of error. For the microscopic areas, this study also achieved calibration and validation criteria with lower margin of error based on widely accepted calibration and validation guidelines.

The calibration and the validation of any DTA based simulation model is required for reliable investigation of traffic impact studies. This calibrated and validated DTA model could be used for applications such as active traffic management and decision support system. Further, this calibrated and validate DTA model can be a good platform of hybrid simulation to test the active traffic management strategies in the microscopic model in selected areas and the mesoscopic in the remainder of the large network. The presented modelling framework of developing a calibrated and validated DTA model is generic and thus can be applied to other large-scale networks. In the following chapter, the benefits of IATM strategies were tested and evaluated for the two selected corridors based on the developed simulation platform.

CHAPTER 9. EVALUATION OF IATM BENEFITS

9.1. Overview

In Chapter 7, it was recommended IATM control strategies for the critical corridors to mitigate traffic congestion, address travel time unreliability, and safety problems. Potential benefits of the strategies were also presented. In Chapter 8, the Aimsun simulation platform was developed for the Greater Orlando metropolitan area. The calibrated and validated large scale DTA model provides an effective tool to replicate traffic patterns in the greater Orlando metropolitan region.

In this chapter, it was evaluated the benefits of the IATM control strategies, i.e., variable speed limit (VSL), ramp metering (RM), queue warning (QW), and dynamic routing (DR), by using the developed simulation model. The I-4 corridor, which is one of the most congested roads in the Orlando metropolitan area, was used as a testbed to evaluate the effectiveness of the IATM strategies. Each strategy was separately implemented to investigate the potential benefit on I-4 and the impact on the adjacent arterials and network. Based on the evaluation results, the research team provided insights for integration of the strategies and network.

Section 9.2 presents an overview of the evaluation measures of the strategies. The benefits of the strategies were analyzed in terms of traffic efficiency, travel time reliability, and traffic safety. To evaluate traffic efficiency, measures including travel time and travel time rate were used. In addition, standard deviation (SD) of travel time rate (TTR) was used for evaluating travel time reliability. Meanwhile, real-time crash risk was estimated based on pre-developed models of safety to make sure any strategy to improve traffic efficiency and reliability would not negatively impact traffic safety.

Sections 9.3-9.6 investigated the effects of VSL, QW, and RM extensively. The control methods and deployment locations of strategies were proposed based on our work, the existing systems and previous studies. Then, the strategies were set up in the developed simulation model and different measures were computed. Based on the measures, the benefits of each strategy were evaluated and the scenarios which could benefit from each IATM control strategy were discussed.

Finally, the evaluation of the benefits of the IATM control strategies was summarized and it was suggested guidelines if there is a need to integrate multiple strategies. The impact and opportunities for the corridor integration and improvement were also addressed.

9.2. Evaluation Measures

Most of the previous studies have only shown the benefits of active traffic management strategies for freeways or expressways. In this study, the research team provides the effects of ATM on freeways/expressways as well as arterials/collectors. Specifically, the effects of four strategies implemented on I-4 were analyzed in terms of traffic efficiency, travel time reliability, and traffic safety. The results were presented as freeways/expressways, i.e., eastbound and westbound of I-4 mainline, arterials/collectors, and whole corridor/network in the study.

For evaluation of the traffic efficiency, travel time and travel time rate were used. These measures could be directly obtained from the well calibrated and validated simulation model. On the other hand, it is difficult to produce performance values related to travel time reliability and real-time crash risk. Hence, the research team developed models to estimate the standard deviation (SD) of travel time rate (TTR) as a travel time reliability measure for both freeways/expressways and arterials/collectors. Meanwhile, real-time crash risk models based on the previous work from the research team were used to evaluate the safety performance to make sure that any strategy to improve reliability and efficiency would not negatively impact safety.

9.2.1. Traffic Efficiency

In the study, travel time is defined as the travel time of actual trips, which means only the travel time of vehicles that traveled along the whole section of the freeway was collected. The travel time of the whole I-4 stretch within the microscopic simulation area was gathered directly.

For more detailed analysis, the effect of the strategies was analyzed according to spatial relation and traffic states. Considering the spatial relation, I-4 was divided into several sections considering the locations of interchanges and number of lanes (see Figure 156). Then, the benefit in each section was estimated. These results could provide insights about the roadway condition which could benefit from each control strategy.

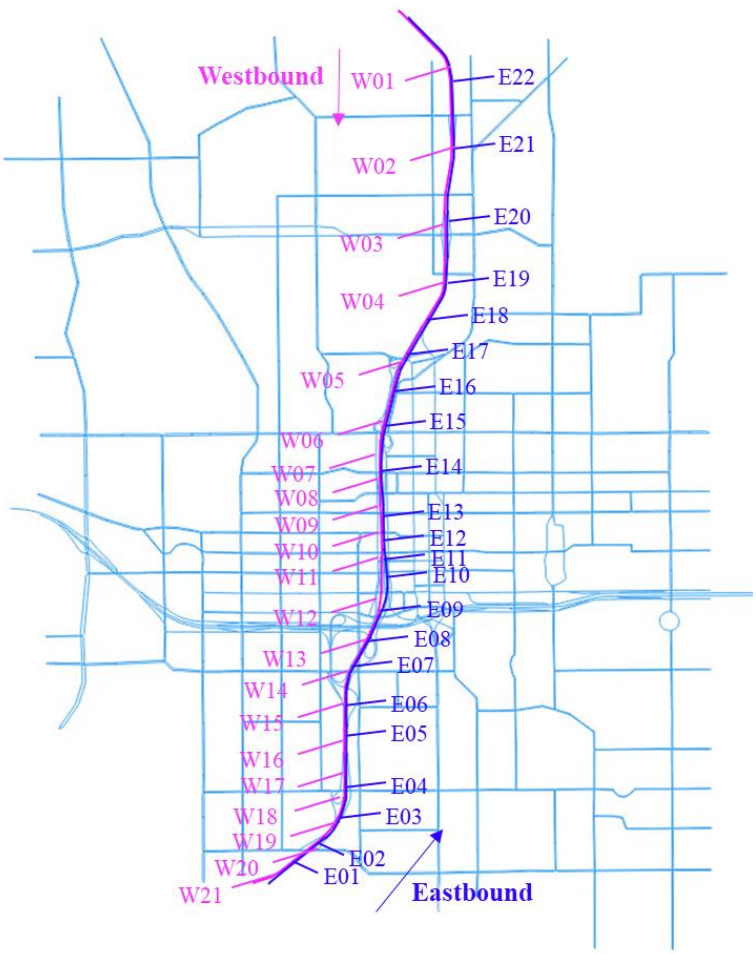


Figure 156. Layout of sections in I-4

We also analyzed the benefits of the IATM strategies according to traffic states. The traffic on freeways could be classified into three states, free-flow, transitional, and congested traffic states based on speed-flow fundamental diagrams (May, 1990). By using the traffic data on the eastbound and westbound of I-4 mainline, the speed thresholds for the classification were set at 30 mph and 45 mph (see Figure 157). Hence, traffic states on I-4 could be determined accordingly, which could be used to determine how strategies should be activated given the traffic states.

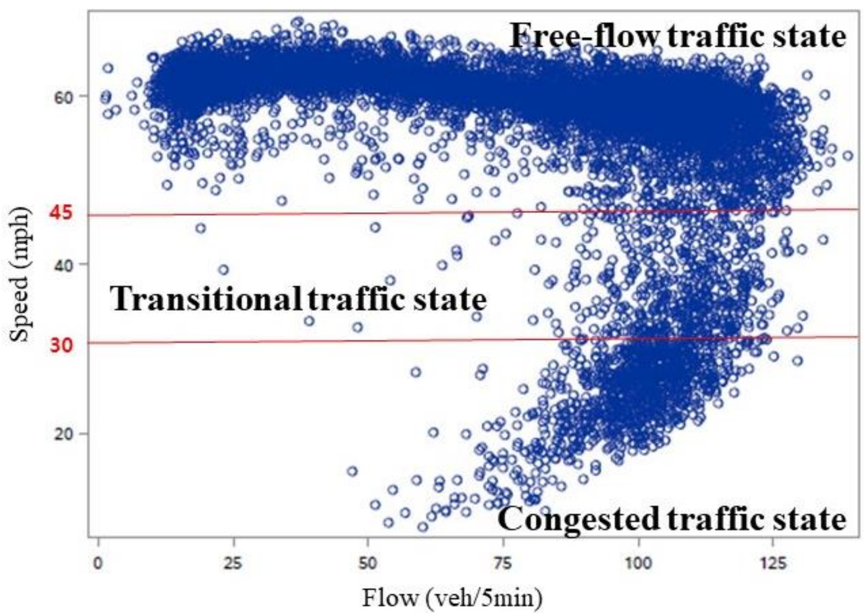


Figure 157. Speed-Flow fundamental diagram and traffic state classification in I-4

The research team conducted statistical tests to verify whether each strategy could significantly improve the traffic efficiency. The average travel time for each five-minute interval was collected to be used as paired data points (24 pairs in two hours). Since the sample size is relatively small (less than 30), Wilcoxon signed-rank tests were conducted to examine whether the travel times were significantly different in the base condition and the conditions where an IATM strategy has been implemented.

9.2.2. Travel Time Reliability

For the evaluation of travel time reliability through simulation results, it is required to develop a model to convert the results to travel time reliability measures based on historical data. However, it is practically impossible to reproduce all kinds of real-world traffic conditions related to traffic demand, incidents, events and weather conditions through traffic simulation. Instead, the travel time reliability can be estimated through models estimating measures related to travel time reliability. Among various measures for the travel time reliability, standard deviation (SD) of travel time rate regarding travel time variability was selected in this project. Because it was proved and well-known that there is a linear relationship between travel time rate and its standard deviation (Mahmassani et al., 2013).

Based on the previous research, there is a linear relationship between the TTR and its SD (Jones, 1988; Mahmassani et al., 2012). To develop the model, additional impact factors such as speed limit and weather condition were considered. A model to estimate the SD of mean travel time was developed using the Tobit modeling method with censored data. The censoring concept can be used when data on the dependent variable is limited but not data on the independent variables (Breen, 1996). In the case of the SD, which is the dependent variable in this study, the value cannot become less than zero. Therefore, it should be proper to use the Tobit model as a censored regression model:

$$y_i^* = \boldsymbol{\beta X}_i + \varepsilon_i, i = 1, 2, \dots, N$$

$$y_i = \begin{cases} y_i^* & if\ y_i^* > 0 \\ 0 & if\ y_i^* \leq 0 \end{cases}$$

where y_i^* is a latent variable, N is the number of observations, $\boldsymbol{X}_i$ indicates a vector of independent variables: travel time, volume, speed, etc., $\boldsymbol{\beta}$ is a vector of estimated parameters, and $\varepsilon_i \sim N(0, \sigma^2)$.

Regarding the data preparation, traffic data, crash data, weather data, and geometry data were collected to develop a model between the SD of TTR and other impact factors: mean travel time, traffic volume, precipitation, crash, etc. The traffic data were obtained from the AVI system of CFX for individual travel times, NPMRDS for mean travel time, and MVDS of RITIS for traffic volume, speed, and occupancy at each location of MVDS (CATT, 2008; FHWA, 2018). The precipitation data were collected from the Quality Controlled Local Climatological Data (QCLCD) (NCEI, 2017), and the crash data were gathered from the Signal Four Analytics (S4A) system. Finally, speed limits and the number of lanes of each link were collected from the Roadway Characteristics Inventory (RCI) database of FDOT.

The collected travel times were converted into travel time rate (TTR) by the length of each link as follows:

$$Travel\ Time\ Rate\ (TTR;\ minute/mile) = \frac{Travel\ Time\ (minute)}{Distance\ of\ each\ Link\ (mile)}$$

After link-mean TTR and its SD were aggregated at five-minute intervals, the SD estimation model was developed. Tables 64 and 65 show the results for the Tobit model to calculate the SD of TTR for freeways/expressways and arterials/collectors, respectively. Based on the model, travel time reliability could be evaluated considering the impacts of roadway characteristics, weather, crash, and other events. According to the exploration and modeling results, TTR and its SD have a statistical positive significant relationship at the link level. In case of the model for arterials, statistically insignificant variables such as weekend and holiday indicators were removed in the table. The rainfall amount with unreasonable trend was removed as well.

Table 65. Results of the Tobit model to calculate the SD of TTR for freeways/expressways

Parameter	Estimated results of the model	
	Estimates	Pr>|t|
Intercept	-0.8144	<.0001
Mean TTR	0.7400	<.0001
Length of Link	-0.0013	<.0001
Number of Lanes	0.0120	<.0001
Speed Limits	0.0033	<.0001
Amount of Rainfall	0.0125	<.0001
Crash Indicator	0.0104	<.0001
Weekend indicator	-0.0104	<.0001
Holiday Indicator	-0.0221	<.0001
Observations	335,124	

Table 66. Results of the Tobit model to calculate the SD of TTR for arterials/collectors

Parameter	Estimated results of the model	
	Estimates	Pr>|t|
Intercept	-0.563831	<.0001
Mean TTR	0.753237	<.0001
Length of Link	-0.007830	<.0001
Number of Lanes	0.054012	<.0001
Observations	192,290	

Finally, SDs of TTR were aggregated for the selected routes or network. Usually, VMT-weighted mean values were computed to get the aggregated evaluation measures for freeways and arterials/collectors. The formula is as follows:

$$\overline{SD}_{network}(t) = \frac{\sum_{i=1}^{n} VMT_i(t) \times SD_i(t)}{\sum_{i=1}^{n} VMT_i(t)}$$

where, $\overline{SD}_{network}(t)$ = Network-level VMT-weighted Mean SD of TTR at time interval "t",

$VMT_i(t)$ = Vehicle Miles Traveled of link "i" at time interval "t",

$TTR_i(t)$ = Mean TTR of vehicles passing link "i" at time interval "t",

$SD_i(t)$ = Standard Deviation between vehicles of link "i" at time interval "t".

9.2.3. Traffic Safety

For the evaluation of traffic safety, real-time crash risk models were selected to evaluate the safety performance for freeways and arterials/collectors. It should be noted that while this effort does not include safety as a measure of effectiveness, it is still used to guarantee that any ATM strategy would not produce negative safety implications. Safety is also an important component in improving travel time reliability and reducing incident related congestion.

9.2.3.1. Freeways

For total crash risk prediction, the logistic model was selected from previous studies of the research team (Wang et al., 2015; Ahmed et al., 2012). The probability of total crash occurrence could be calculated as:

$$crash\ probability_i = \frac{exp[(-5.037) - 0.111X_1 + 0.064X_2]}{1 + exp[(-5.037) - 0.111X_1 + 0.064X_2]}$$

Where $\text{crash probability}_i$ is the predicted probability of total crash occurrence of the ith observation; X_1 is the average speed of the segment; X_2 is the average absolute difference in speed between upstream and downstream stations.

9.2.3.2. Arterials

In terms of urban arterials and collectors, the random parameter conditional logistic model developed by Yuan et al. (2018) was chosen to evaluate the crash risk of arterial segments. The odds ratio of crash occurrence of the i^{th} observation could be expressed as:

$$odd\ ratio_i = exp[(-0.027)(X_1 - \bar{X}_1)]$$

Where $odd\ ratio_i$ is the predicted odd ratio of the ith observation is a crash relative to the other non-crash events; X_1 is the average speed of the current segment; $\bar{X}_1$ is the mean value of the average speed of the current segment during non-crash events. Since the predicted odds ratio may larger than 1. In order to be consistent with the probability of crash occurrence, all the odds ratios predicted by the conditional logistic model were normalized by using min-max normalization.

9.3. Variable Speed Limits (VSL)

Variable Speed Limits (VSL), which is sometimes referred to as Dynamic Speed Limits (DSpL) or speed harmonization, is a vital active traffic management system (ATM) strategy. It is used to provide appropriate speed limits to drivers, who are required to respond to the change in traffic conditions due to bottlenecks, low visibility, slippery pavement, etc. Specifically, it is known that the VSL has been applied to defer or prevent the onset of traffic congestion, decrease speed variation, mitigate shockwaves, increase throughput, and smoothen traffic flow. In order to find the appropriate speed limits, real-time or predicted traffic conditions should be used on the basis of the goals/objectives of traffic management. So far, many algorithms have been developed to select the appropriate speed limits. The VSL can be regulatory or advisory according to the local traffic control policies. Usually, it is recommended to use regulatory speed limits to get a high compliance rate to maximize the benefits of the VSL.

According to the previous research results, most of VSL strategies improved traffic safety through speed harmonization (Abdel-Aty et al., 2008; Abdel-Aty et al., 2006a; Abdel-Aty et al., 2006b; Shi and Abdel-Aty, 2015). However, it is controversial whether the VSL strategy can improve traffic efficiency. Therefore, this research concentrated on the effectiveness of VSL strategy on traffic efficiency and travel time reliability. For confirmation of traffic safety improvement real-time crash risk was analyzed. Furthermore, in terms of the integrated operation of the corridor network, the impact of the VSL strategy on the adjacent arterials/collectors and the whole network were explored.

9.3.1. Literature Review

European nations introducing the VSL system earlier reported many evaluation results based on empirical studies. Smulders (1990) and Van Toorenburg (1983) concluded that speed harmonization using VSL can increase safety and reduce the probability of congestion based on the experiment results with the Dutch Motorway Control and Signaling System in 1983. Van den Hoogen and Smulders (1994) concluded that VSL applications in the Netherlands was not a proper strategy to mitigate traffic congestion at bottlenecks according to the pilot experiment results on the motorway. Harbord (1998) reported that VSL with enforcement systems of speed limits on M25 in the UK made traffic flow smoother based on the lane utilization improvement and uniform headways, and also reduced crashes. Borrough (1997) confirmed that the VSL system could reduce crashes and increased travel times through the smoother traffic flow during the 18 months of operation with speed camera to enforce the speed limits. Papageorgiou et al. (2008) investigated the change of flow-occupancy diagrams between VSL and no-VSL conditions to analyze traffic efficiency of VSL through traffic data on VSL-equipped motorway of over 800 km in the UK. It was obvious that the controlled speed limits will not improve traffic efficiency when it applied at under critical occupancies. Finally, it was recommended that real-time estimated slopes of the flow-occupancy diagram should be considered regarding the decision of VSL activation. MacDonald (2008) reported the evaluation results of 4-lane variable mandatory speed limits (4L-VMSL) in an Active Traffic Management (ATM) system on the M42 in the UK. Comparing 4L-VMSL with no-VSL, the observed capacity increased, the traffic demand grew up, the average journey times increased, the variability of journey times reduced, and the average number of Personal Injury Accident (PIA) dropped. Mirshahi et al. (2007b) reported that there was a crash reduction on the A5 motorway in German.

On a few evaluation studies of VSL have been conducted in the USA. Bham et al. (2010) reported that a VSL system resulted in the discernible reduction of crashes along the I-270/I-255 corridor in St. Louis, but the system didn't improve travel times and travel time reliability at all segments in the corridor. Kwon and Park (2015) reported that the VSL system on the Interstate 35W corridor in Minnesota improved substantially travel time reliability. Riffkin et al. (2008) evaluated the effectiveness of VSL at work zones by using the average speed and the speed variation. The provided speed limits were two values: 55 mph during the day and 65 mph during the night. The VSL at work zones resulted in the reduction of both measures. Kwon et al. (2007) also evaluated VSL for work zones and found the reduction of speed difference and the increase of throughput. Ulfarsson et al. (2005) evaluated the effectiveness of VSL under adverse weather conditions. The VSL was provided through Variable Message Signs (VMSs) and was installed on Interstate 90 (I-90) in Washington State. Based on weather data and pavement status, speed limits were determined in the range from 65 mph to 35 mph in a 10-mph diminution. It was found that VSL resulted in a statistically significant reduction of average speed, but speed deviation either decreased or increased significantly.

On the other hand, in order to figure out various features regarding the effectiveness of VSL, traffic simulation can be utilized although it has limitations to model human behavior. Lee et al. (2004) evaluated safety benefits of VSL by using the crash risk and indicated that the total crash potential was reduced over all freeway segments. Speed limits were determined in 80 km/h, 70 km/h, 60 km/h, and 50 km/h based on the average speed of segments. In detail, Abdel-Aty et al. (2006a) conducted the analysis of traffic safety benefits of the VSL on Interstate 4 in Orlando, Florida. The results showed that traffic safety was improved in medium-to-high-speed conditions, but not in low-speed conditions. Additionally, it was confirmed that travel time was saved. Allaby et al. (2007) introduced a decision tree as a practical algorithm to determine the new posted speed limit in the predefined values (i.e., 100 km/h, 80 km/h, and 60 km/h) based on traffic volume, occupancy, and average speed. The study also provided a method to optimize the algorithm thresholds considering both the improvement of traffic safety and the reduction of travel times. Mazzenga and Demetsky (2009) evaluated the ATM including VSL and hard shoulders running to solve the recurring congestion on freeways through traffic simulation. The effectiveness analysis for the only VSL on I-66 in Northern Virginia indicated that VSL systems postponed the onset of congestion and smoothed vehicle speeds through bottlenecks. However, the VSL systems were not effective under heavy traffic congestion. By using traffic simulation with a simple online VSL algorithm, Waller et al. (2009) confirmed that only VSL strategy for urban freeway congestion in Texas could not increase the capacity of the freeway or reduce total system travel time. However, the VSL could reduce speed variability. Speed limits were selected in 65 mph, 50 mph, and 40 mph based on the average speed of each segment when traffic volume was more than 1600 vehicles per hour per lane or occupancy is more than 15%. Habtemichael and de Picado Santos (2013) confirmed that VSL has the potential to improve traffic safety and efficiency on motorway through traffic simulation. The operational benefit of the VSL was highest for slightly congested traffic conditions, which meant VSL should be provided in advance before the peak hours. Speed limits were determined in 120 km/h, 100 km/h, 80 km/h, and 60 km/h (75 mph, 62.5 mph, 50 mph, and 37.5 mph) based on the flow rate per lane per hour.

Many evaluation studies of VSL applications have been attempted to find out VSL's benefits particularly in terms of traffic safety, efficiency, and travel time reliability. The effectiveness analysis of the VSL applications has been conducted through both empirical studies and simulation-based studies. According to the empirical and simulation-based studies of the VSL, it is obvious that traffic safety and environment were improved, but traffic efficiency is mixed with improvement and degradation. Overall, it is obvious that VSL applications are expected to provide the following potential benefits (Mirshahi et al., 2007b):

- Increase trip reliability
- Increase in throughput
- More uniform speeds
- Decrease in headways
- Delay onset of freeway breakdown

9.3.2. Selection of Deployment Locations

Although there were numerous studies regarding the effectiveness and algorithm developments of VSL, a few studies discussed how to decide on the location selection of VSL. Harbord (1998) recommended that standard gantries displaying VSL should not be located more than 1 km in order to help drivers see the next VSL signs. In addition, Abdel-Aty et al. (2006a) suggested that speed limits should be displayed within a short distance (2 miles) for traffic safety improvement. According to the deployment guideline of VSL harmonizing European ITS services, speed limits should be showed repeatedly and also the spacing of the VSL should not be exceeded more than 10 km (6 miles) (EasyWay, 2015). FHWA (Federal Highway Administration) suggested that VSL should be installed at regular intervals and the reduced speed limits should not be displayed more than 1 mile at the upstream from the critical sections related to wet weather (Katz et al., 2012). In conclusion, VSL should be located at a certain distance so that drivers can recognize and react to it.

To evaluate the effectiveness of VSL, segments on I-4 in the Orlando CBD area were selected. Considering the general guide deploying VSL, the VSL locations were placed at major ramps. Totally 12 locations were selected at 6 ramps for eastbound and westbound, respectively. The average installation spacing is about 1 mile. Table 67 is the summary of geometric and operational features based on the segments defined by the VSL locations, Figure 158 shows the exact locations and segments of VSL.

Table 67. Geometric and operational features of the VSL segments

Segment ID	Direction	Length [miles]	Lane Count		Static Speed Limit [mph]
			Min	Max	
SE-1	Eastbound	1.21	4	4	55
SE-2	Eastbound	0.60	4	4	55
SE-3	Eastbound	0.58	3	4	55
SE-4	Eastbound	1.27	3	4	55
SE-5	Eastbound	0.67	3	4	55
SE-6	Eastbound	1.62	4	4	55
SW-1	Westbound	0.94	4	4	55
SW-2	Westbound	0.46	4	4	55
SW-3	Westbound	1.50	4	4	55
SW-4	Westbound	0.78	4	4	55
SW-5	Westbound	1.14	4	4	55
SW-6	Westbound	1.25	4	4	55

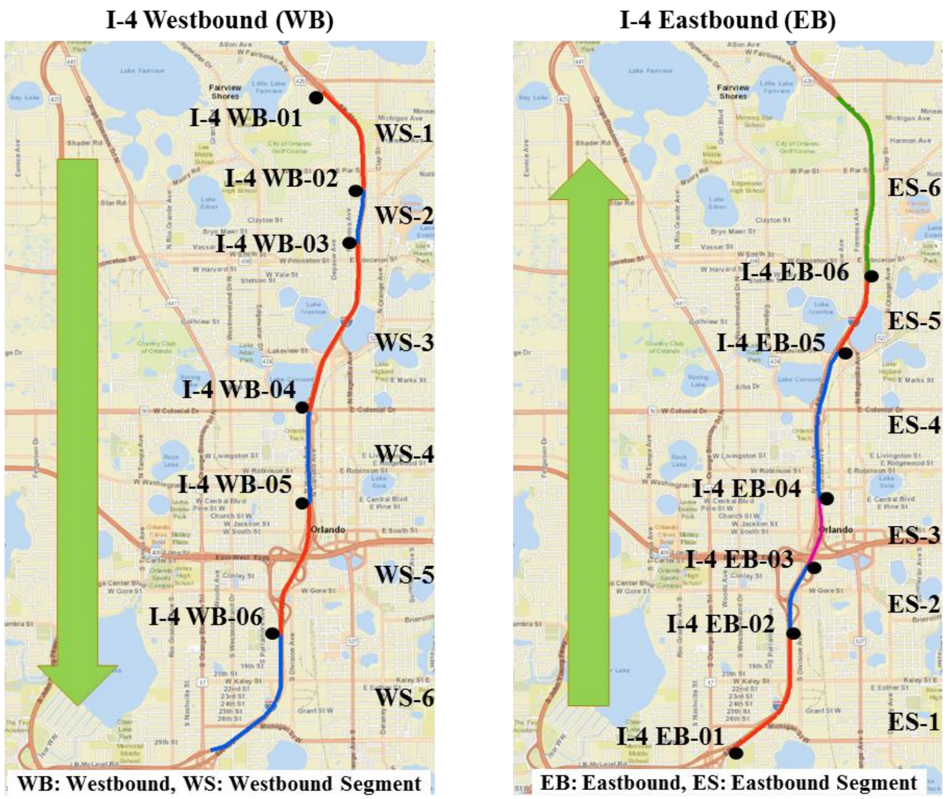


Figure 158. VSL locations and segments on I-4 in the Orlando CBD area

9.3.3. VSL Control Method

Usually, VSL control algorithms can be categorized into two classes: reactive rule-based approaches and proactive approaches (Khondaker and Kattan, 2015; Yu and Abdel-Aty, 2014). The reactive rule-based approaches change speed limits when real-time traffic data exceed predefined criteria of traffic volume, density, or speed. Whereas, the proactive approaches determine the speed limits based on the predicted traffic data. It is expected to reduce errors between current real-time measurements and near-future traffic measurements due to the time lag. Most of the proactive approaches are based on model predictive control (MPC) using extensions of Payne's second-order model with different drivers' desired speed based on the speed limit or free flow speed.

Although numerous advanced proactive VSL algorithms were developed, still many agencies are using simple reactive rule-based algorithms and showed various benefits of traffic efficiency and safety in previous research. Considering applicability in the field and scalability in the traffic simulation, a representative online VSL algorithm was provided and developed (see Figure 159). The basic logic is that speed limits are changed toward the 85-percentile speed if there is a difference between the posted speed limit and the 85-percentile speed. This logic was applied in Florida, Oregon, and Washington states (Katz et al., 2017).

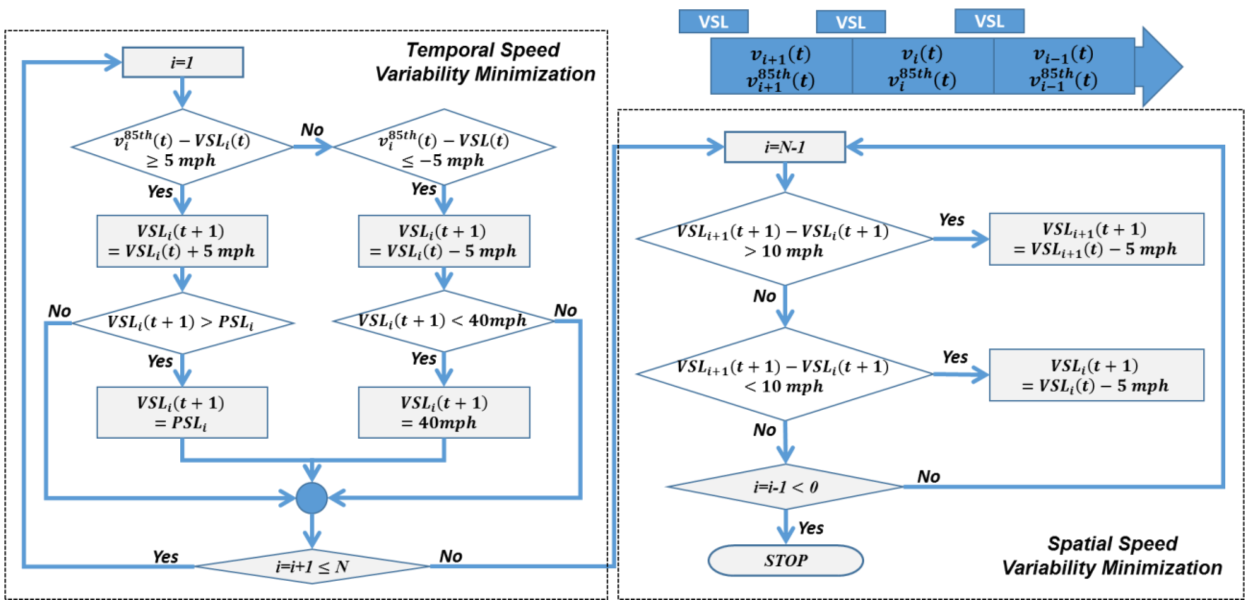


Figure 159. Major structure of the applied VSL logic

Additionally, operational constraints proved in the previous studies of the research team were considered to make sure that the implemented VSL would not introduce any negative safety impacts. The constraints are as follows:

- The maximum difference between two neighboring posted speed limits should be 10 mph (spatial constraint) (Yu and Abdel-Aty, 2014).
- The maximum difference between two consecutive VSL control time steps should be 10 mph (temporal constraint) (Abdel-Aty et al., 2008; Yu and Abdel-Aty, 2014).

- An increment of VSL should be 5 mph (Abdel-Aty et al., 2006b).
- Variable Speed Limit should be updated by 5 minutes (Yu and Abdel-Aty, 2014).
- The minimum variable speed limit should be 40 mph (Abdel-Aty et al., 2008).
- The posted speed limit should never exceed the design speed on the freeway.

9.3.4. Evaluation of VSL effect

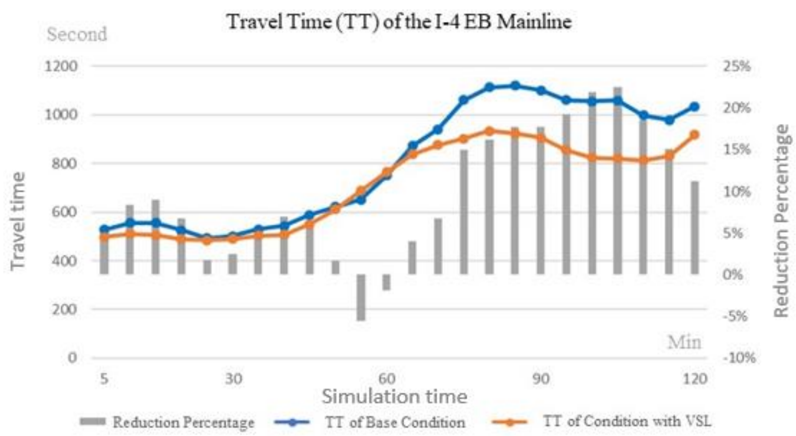
The VSL control logic, mentioned in the previous section, was written in python script which controls the simulation in real-time through the application programming interface (API) of Aimsun. The simulation network has been well calibrated and validated based on real-world data. In order to capture the randomness effect of the simulation, each scenario (e.g., base condition, VSL condition) was run repeatedly 30 times for different random seeds and the average result was reported for the final evaluation. The total time to run one scenario was around ten hours because of the large network.

9.3.4.1. Traffic efficiency

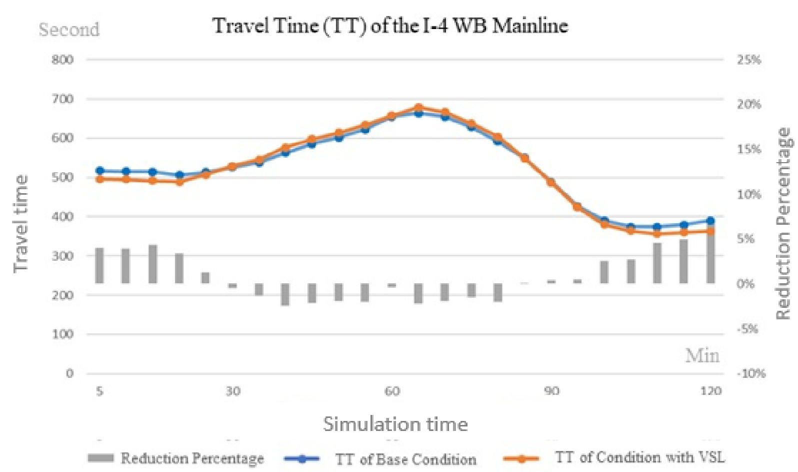
A. Effects of traffic efficiency on freeways

The effects of VSL on I-4 mainline are presented by dividing into eastbound and westbound. Figure 160 shows the result of the travel time on the whole I-4 mainline with and without the VSL (base condition). The reduction percentage was calculated by comparing the scenarios with and without the VSL. The positive percentage value indicates that the VSL could reduce travel time on the freeway and vice versa. Figure 160 (a) indicates that the reduction percentage ranged from -5% to 23% for 5-minute aggregation intervals. In most time, the implementation of VSL could significantly reduce the travel time along the EB mainline of I-4. However, as shown in Figure 160 (b), the reduction percentage of the travel time along the WB mainline of I-4 at every time interval was less than 7% while travel time got a slight increase at some time intervals. It was shown that the effectiveness of VSL on the I-4 WB freeway was lower than the I-4 EB freeway.

Comparing the I-4 WB freeway with the I-4 EB freeway, the I-4 WB freeway had lower travel time than the I-4 EB freeway, which means that the I-4 EB freeway was more congested than the I-4 WB freeway. In fact, the I-4 EB freeway has high traffic turbulence due to lane drops at ramps. A detailed explanation will be given in the following analysis of speed standard deviation.



(a) Travel Time of Base Condition and Condition with VSL on the I-4 EB Mainline



(b) Travel Time of Base Condition and Condition with VSL on the I-4 WB Mainline

Figure 160. Travel time of base condition and condition with VSL on the I-4 freeway

Table 68 shows the average travel time per vehicle and the p-values of the tests for the I-4 freeway in the base condition and the condition with VSL. The travel time of each vehicle passing through the VSL implementation section (6 miles) was reduced by over 70 seconds on average on the I-4 EB. The p-value for the EB shows that the difference of travel time in the scenarios with and without the VSL was statistically significant, while the value for the WB was not. It means that the VSL could reduce the travel time on the EB of I-4 mainline, which is more congested.

Table 68. Statistical test of benefit of the VSL

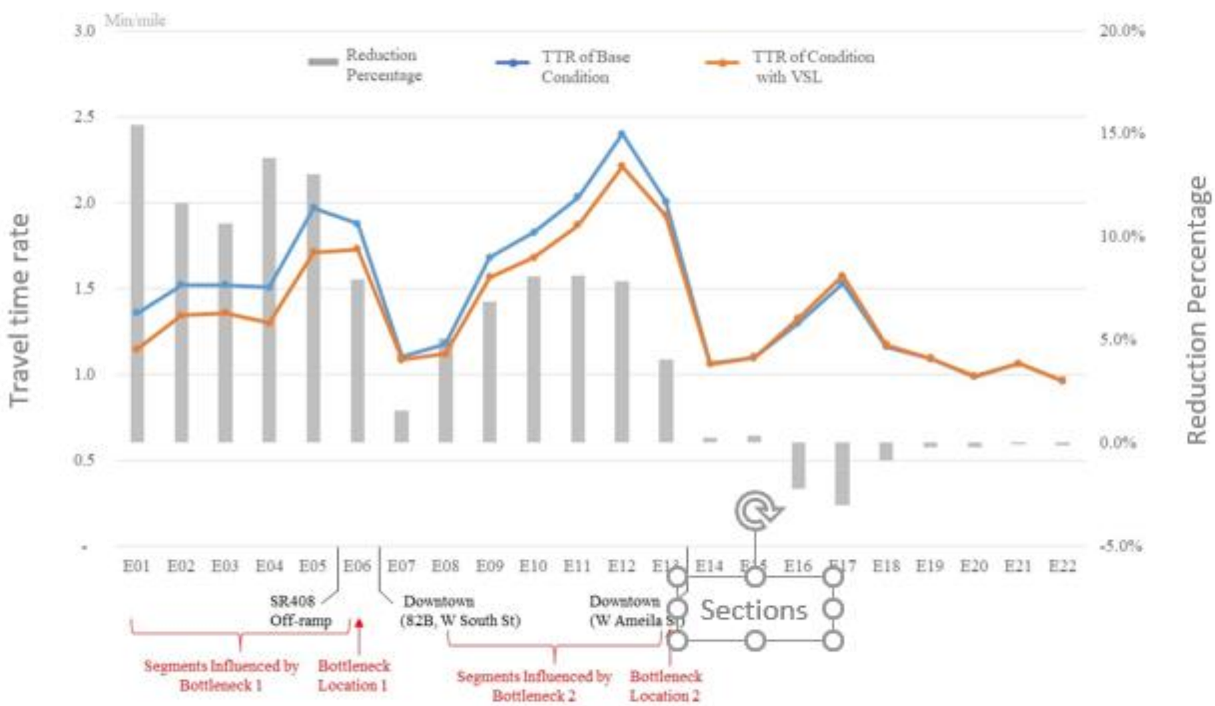
I-4 mainline direction	Average TT per vehicle (sec)		P-value
	Base condition	Condition with VSL	
EB	742	666	<.0001
WB	532	529	0.3002

Total saving hours by the VSL were summarized in Table 69 to confirm the benefit of the VSL. On the I-4 EB freeway, the VSL implementation could save 8.0% of total travel time, which is about 163 hours over the peak period. On the I-4 WB freeway, the VSL implementation could only save 0.8% of total travel time, which is about 13 hours.

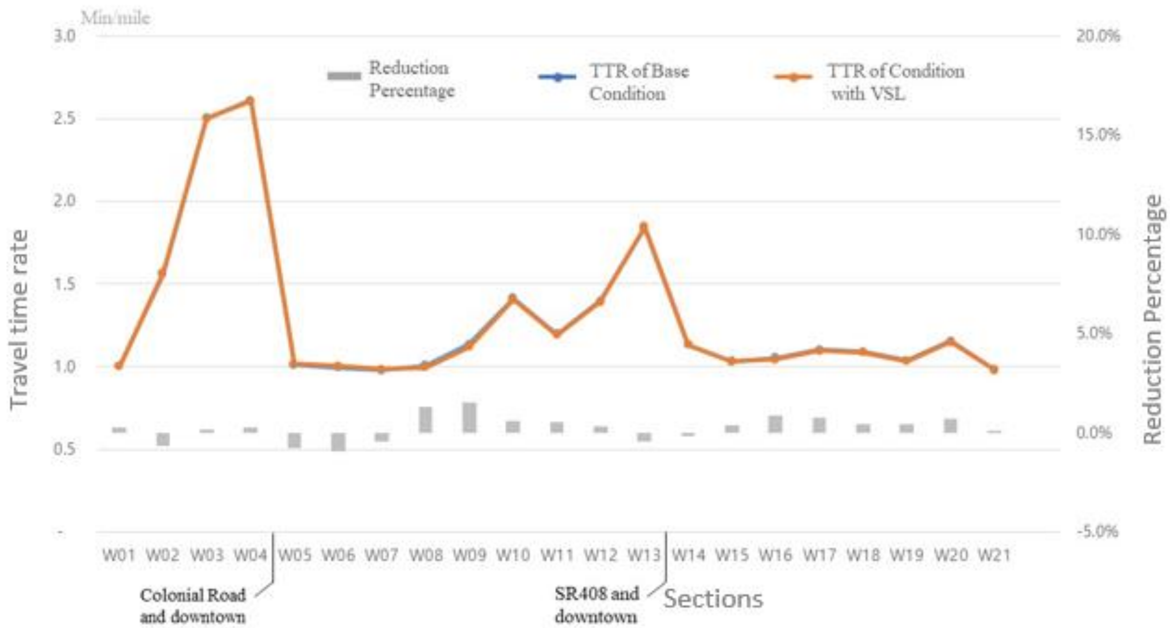
Table 69. Total saving hours by the VSL (for 2 Hours at Peak Time)

I-4 mainline direction	Total travel time (h)		Total saving hours (h)	Percentage of the saving
	Base condition	Condition with VSL		
EB	2,032	1,870	163	8.0%
WB	1,729	1,716	13	0.8%

For more detailed analysis, the changes in travel time rate (TTR) were analyzed along the sections on the I-4 freeway. As shown in the TTR of the base condition in Figure 161 (a), it is confirmed that the I-4 EB freeway had two bottlenecks segments (E01-E06 and E08-E13) at the upstream of two off-ramps for W. South Street and W. Amelia Street. The bottlenecks were caused by the lane reduction (i.e., from 4 to 3 lanes) (see Table 67). In addition, Figure 161 (a) shows the improvement of travel time rate at each section between the scenarios before and after VSL controls. This result shows that the VSL has a benefit on significantly the upstream of bottlenecks. After the bottlenecks, the effectiveness of the VSL was relatively small. As for the I-4 WB, there were congestion at the upstream of the interchange with Colonial Road and SR 408. However, the congested sections didn’t form a bottleneck. As shown in Figure 164 (b), the effectiveness of VSL on the TTR of the I-4 WB freeway was very small in all sections.



(a) Improvement of Travel Time Rate by VSL according to Sections (the I-4 EB Mainline)



(b) Improvement of Travel Time Rate by VSL according to Sections (I-4 WB Mainline)

Figure 161. Improvement of travel time rate by vsl according to sections on the I-4 freeway

Meanwhile, the effectiveness of VSL control for the three different traffic states (i.e., free-flow traffic, transitional traffic, and congested traffic) was investigated, separately. For the I-4 EB freeway which observed significant TTR reduction, the average TTR of sections was calculated for the three traffic states and presented in Figure 162. It is shown that VSL is effective for both transitional and congested traffic states. Similar to previous studies, VSL could have a benefit in transitional traffic state and slightly congested traffic state by harmonizing vehicle speed (Habtemichael and de Picado Santos, 2013).

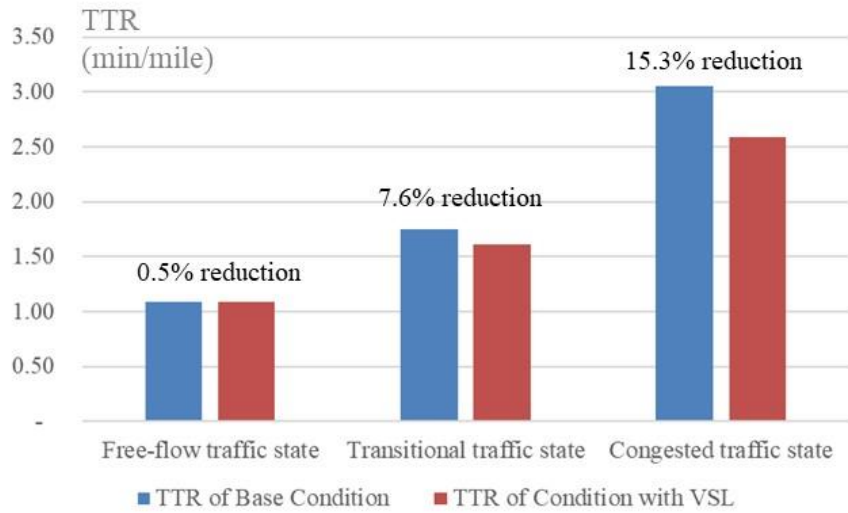
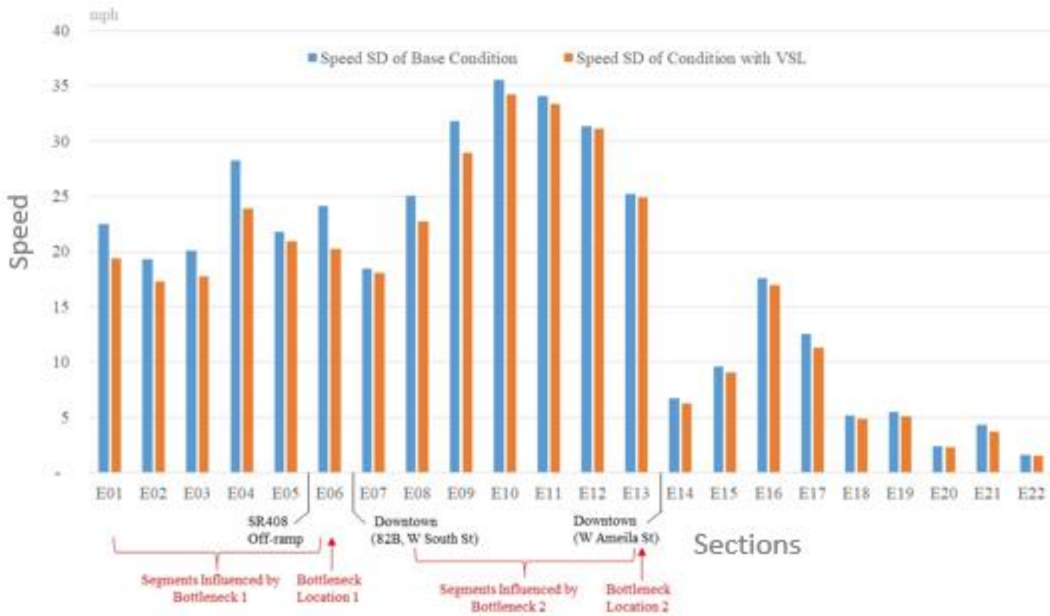
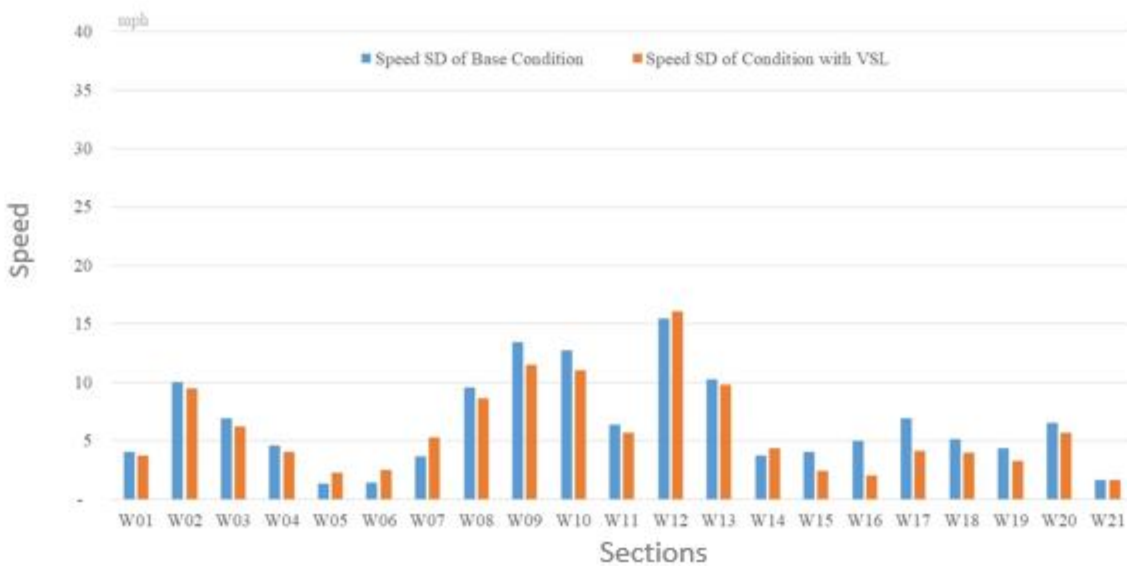


Figure 162. Improvement of travel time rate by VSL according to traffic states on the I-4 EB freeway

Figure 163 (a) shows the standard deviation (SD) of speeds with and without applying VSL on the I-4 EB mainline. As expected, it is obvious that the higher speed harmonization was achieved at two bottleneck segments. Based on Figures 163 (a) and 163 (b), it can be shown that TTR got reduced in the section with a high SD of speeds in base condition (E01-E13). It means that VSL is effective in sections with a high SD of speeds. Especially, the SD of speeds on I-4 EB can be further increased by the geometric changes such as lane reduction. As shown in Table 67, on the EB, the number of lanes changes depending on sections (E07-E13). The change in the number of lanes enforced mandatory lane changing, which could lead to congestion and also increase the SD of speeds. According to the results of the I-4 EB, the VSL could mitigate the adverse effects on traffic flow turbulence caused by lane reduction due to lane drops, roadworks, and crashes. Figure 163 (b) shows similar speed SDs on the I-4 WB before and after implementing the VSL control.



(a) Speed SD of Base Condition and Condition with VSL (the I-4 EB Mainline)

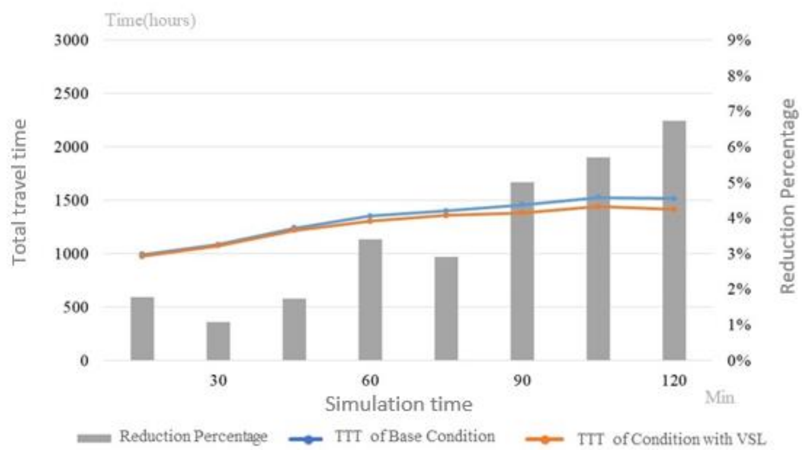


(b) Speed SD of Base Condition and Condition with VSL (the I-4 WB Mainline)

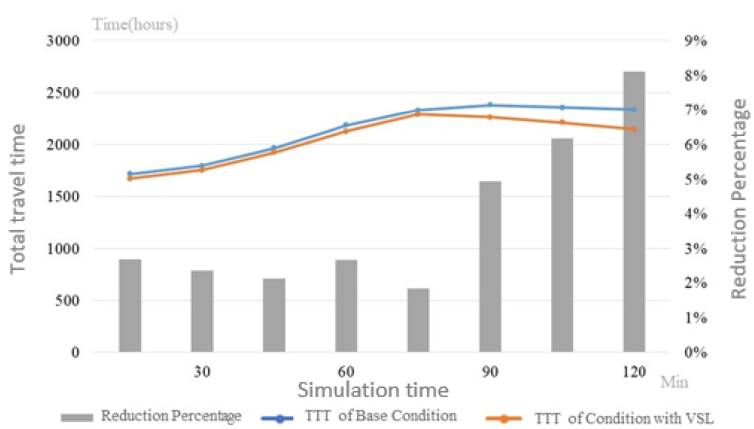
Figure 163. Speed SD of base condition and condition with VSL on the I-4 EB mainline

B. Impact of traffic efficiency on arterials/collectors and whole corridor network

In order to verify the impact of VSL strategy on arterials/collectors and the whole corridor network, the total travel time of all arterials/collectors and the whole network was calculated (Figure 164). The result indicated that the VSL could improve total travel time of arterials/collectors as well as the whole network and the improvement percentage ranged from 1% to 8%. This effect was greater when congestion in the freeway was severe. It is considered that the effect of speed improvement on the freeway by the VSL is exerted on the whole network. The total travel time was reduced by 683 hours with the VSL on the whole network.



Total travel time of arterials/collectors



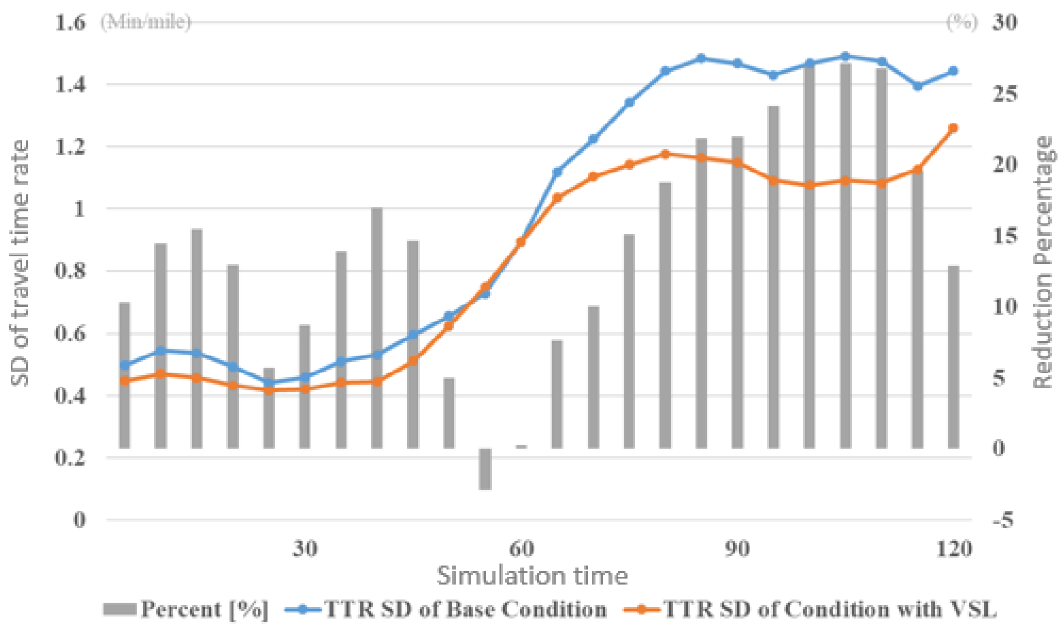
Total travel time of the whole roadway network

Figure 164. Total travel time of arterials/collectors, and whole network

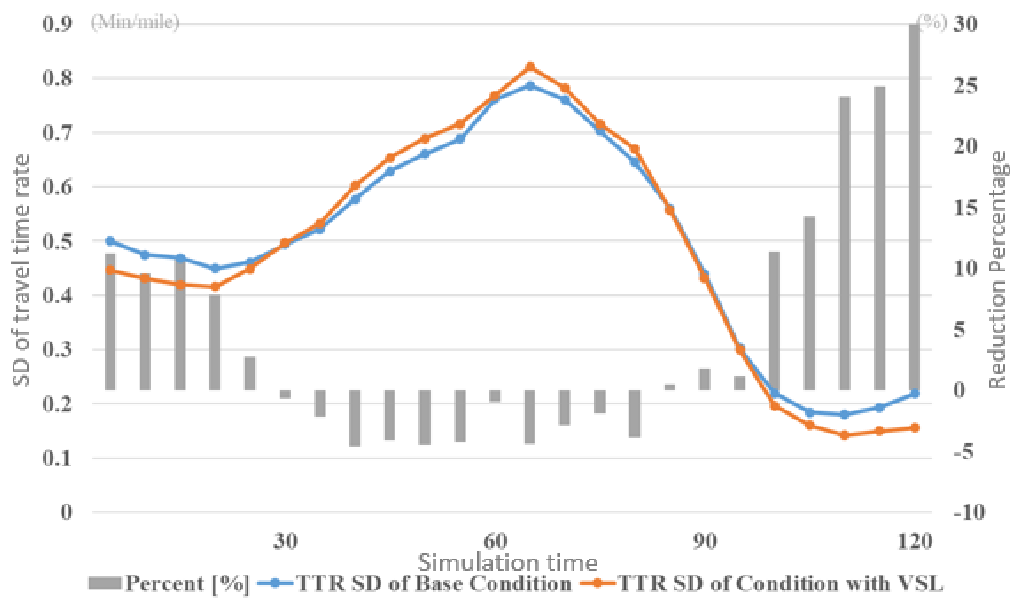
9.3.4.2. Travel time reliability

A. Effects of travel time reliability on freeways

Figure 165 shows the SD of TTR on the I-4 mainline with and without the VSL (base condition). It shows that the relatively larger SD of TTR could be found on I-4 EB, indicating that travel time on I-4 EB is less reliable. Figure 168 (a) shows that the SD of TTR was generally reduced by the VSL control on the I-4 EB, and the percentage of change is over 15% for most time. It means the significant improvement of travel time reliability on I-4 EB. On the other hand, no significant change could be found before and after implementing the VSL control on the I-4 WB freeway for most time. Although some improvements could be found at the end of the simulation, the absolute difference between the scenarios before and after applying the VSL is not large. Hence, more benefits of VSL are expected on freeways with lower reliability.



(a) SD of TTR of Base Condition and Condition with VSL on the I-4 EB Mainline



(b) SD of TTR of Base Condition and Condition with VSL on the I-4 WB Mainline

Figure 165. SD of TTR of base condition and condition with VSL on the I-4 mainline

B. Impact of travel time reliability on arterials/collectors and whole corridor network

Figures 166 and 167 show SD of TTR on arterials/collectors and the whole network. Compared to the freeways, larger SD of TTR (lower reliability) could be found on arterials/collectors. It is indicated that the reliability got improved and the improvement percentage was up to 17% on arterials/collectors. The similar trend was found for the whole network. It seems that the effect of reliability improvement on the freeway by the VSL was exerted on the whole network. As VSL could improve the reliability of freeways, more traffic could be attracted to the freeways. Hence, it is as expected that the unreliability of arterials/collectors could be mitigated.

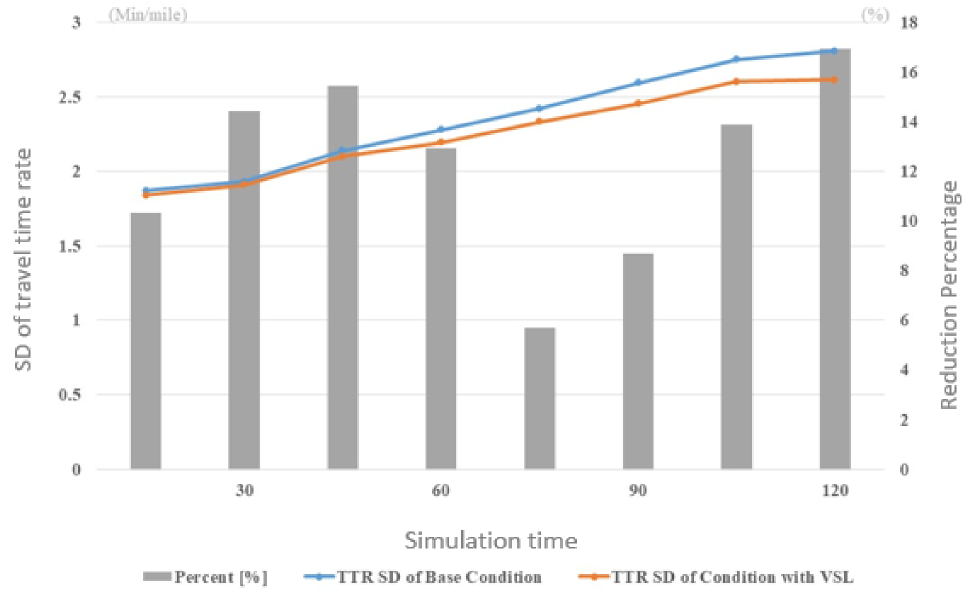


Figure 166. SD of TTR of base condition and condition with VSL on arterials/collectors

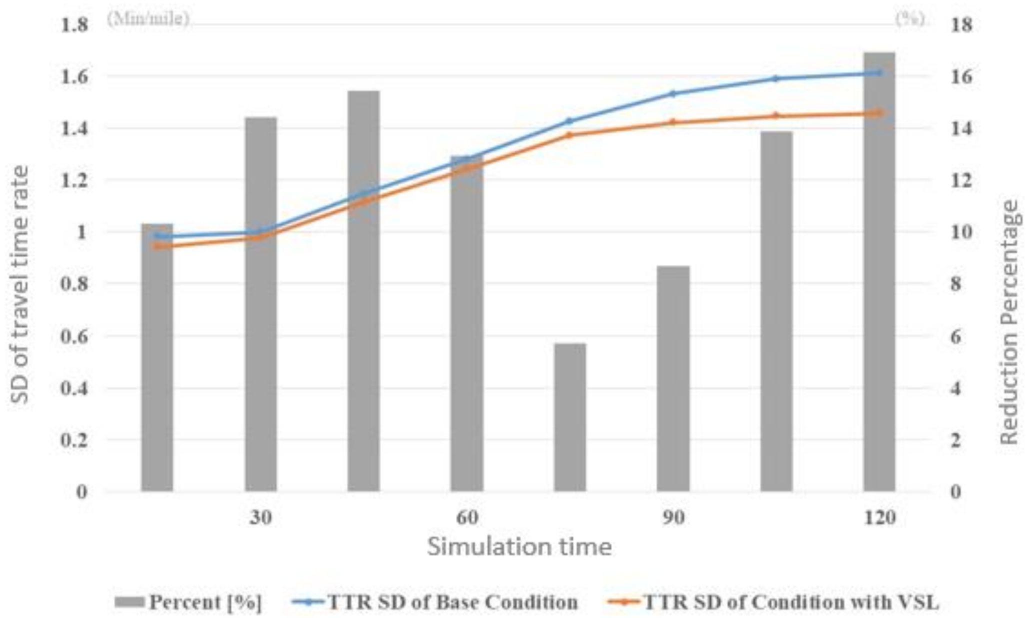
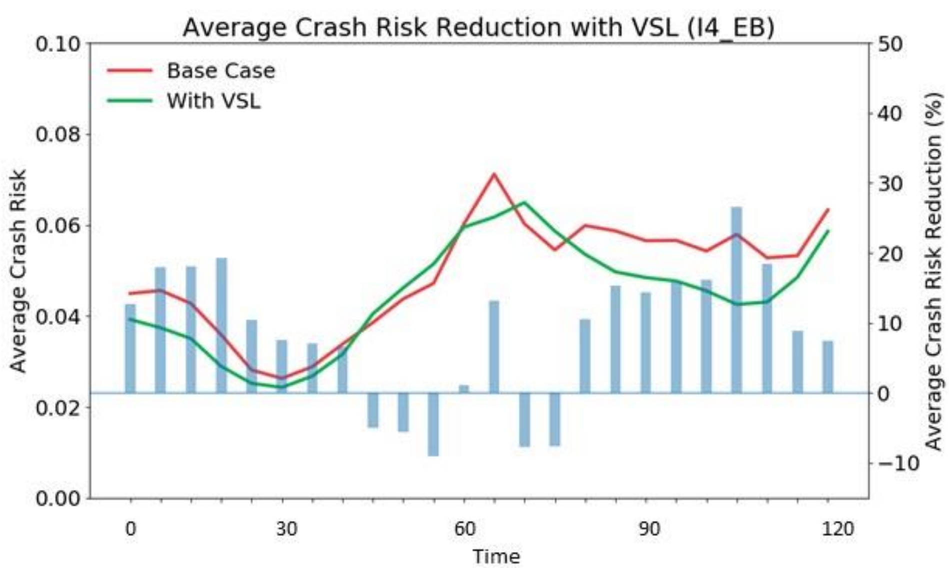


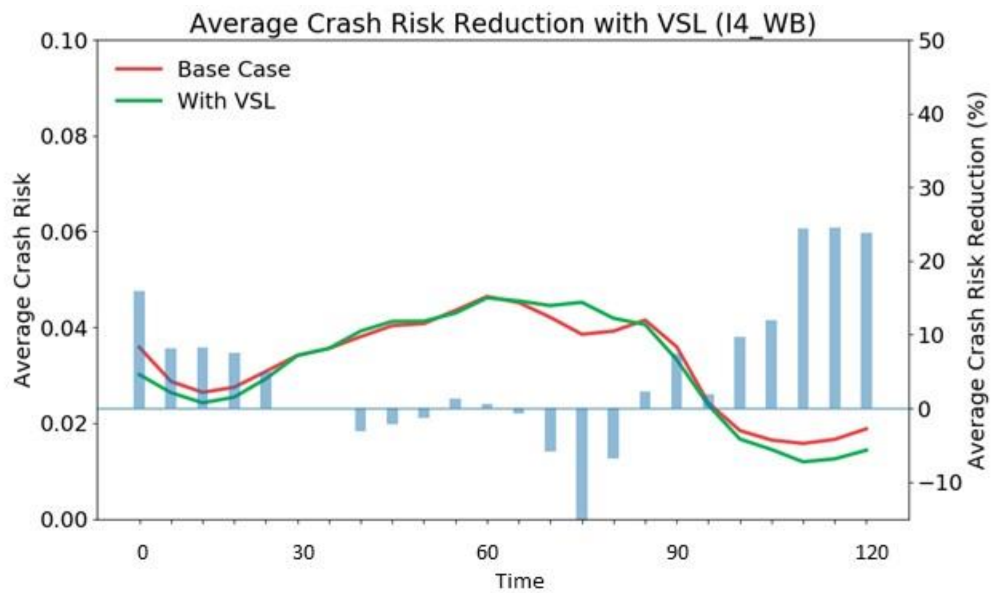
Figure 167. SD of TTR of base condition and condition with VSL on whole network

9.3.4.3. Traffic safety

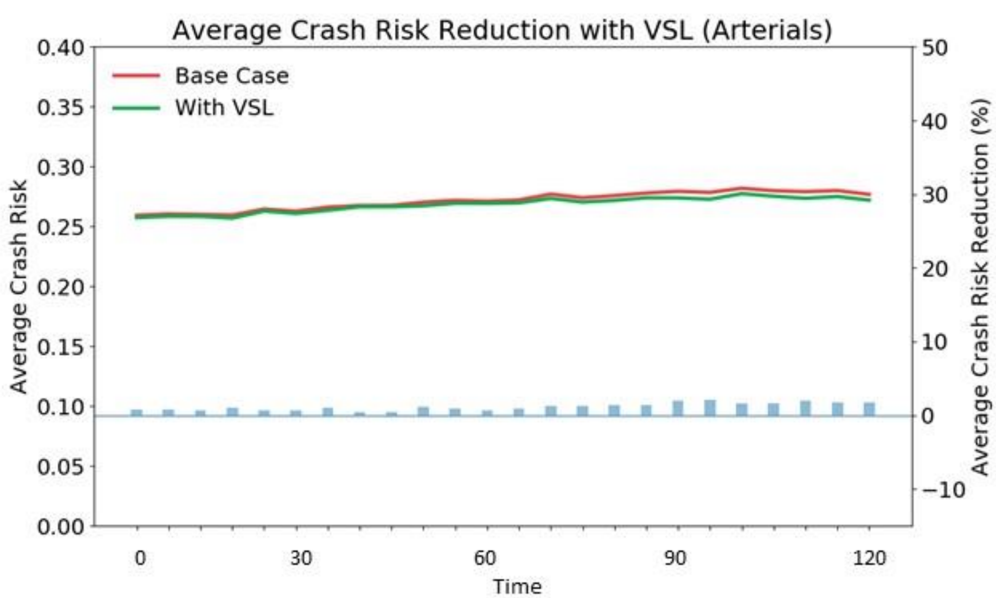
Figure 168 shows the average crash risk on I-4 EB freeway, I-4 WB freeway, and arterials/collectors in the scenarios with and without VSL (base condition) for every 5 minutes during the simulation. Figure 168 (a) illustrates that the implementation of VSL could generally reduce the crash risk on the I-4 EB freeway. Overall, the average reduction of crash risk on I-4 EB is 9.04 %. As for the I-4 WB freeway (See Figure 168 (b)), the safety effect of VSL is mixed and the change is not significant. Figure 168 (c) shows the average crash risk on all arterials and collectors. The figure implies that the implementation of VSL reduced the crash risk on arterials and collectors, but the change is very small and the average reduction in crash risk is only 1.18%. Hence, it could be concluded that the implementation of VSL could help improve traffic safety on freeways with congestion while no adverse safety impact was found on arterials and collectors.



(a) Average Crash Risk on I-4 EB under Base Condition and VSL Condition



(b) Average Crash Risk on I-4 WB under Base Condition and VSL Condition



(c) Average Crash Risk on Arterials/Collectors under Base Condition and VSL Condition

Figure 168. Average crash risk on I-4 freeway and arterials/collectors

9.4. Queue Warning (QW)

In general, queues occur due to three major causes: recurring traffic congestion, work zones, and incidents (Wiles et al., 2003). Basically, a queue warning (QW) strategy has been used to alert drivers to the existence of the queue in downstream or guide them to choose proper lanes. So, it was deployed to reduce rear-end crashes and improve traffic safety, and also improve the roadway capacity. The alerts and guidance can be provided through various methods: static signing, variable message sign (VMS), lane control signals (LCSs), incident response vehicles, and in-vehicle devices (in a connected V2X environment). In terms of active traffic management (ATM) strategies, static signs are not included in the QW strategy. Especially, the QW strategy in this research considered LCS and VMS.

Recently, QW systems in ATM can be regarded as an extension of VSL systems (Fuhs and Brinckerhoff, 2010; Mirshahi et al., 2007b; Strömgren and Lind, 2016; Tignor et al., 1999). It is because the queue warning signs can be displayed as warning messages with either recommended speeds or lane control signs. In Europe, most of queue warning is integrated as one of components in the speed harmonization system (see Figure 169). Thus, it is not easy to quantify separate benefits of only queue warning strategy in the field operational results (Fuhs and Brinckerhoff, 2010).

Figure 169. QW sign with VSL on the M25 in UK **(Source: https://www.geograph.org.uk/photo/3731569)**

Figure 170 shows how lane control signals and variable speed limits can be integrated to announce a queue due to an incident. In any case, it is obvious that QW applications can provide the following potential benefits (Mirshahi et al., 2007b):

- More uniform speeds
- Increase trip reliability
- Decrease headways
- More uniform driver behavior
- Decrease in primary incidents, especially rear-end crashes

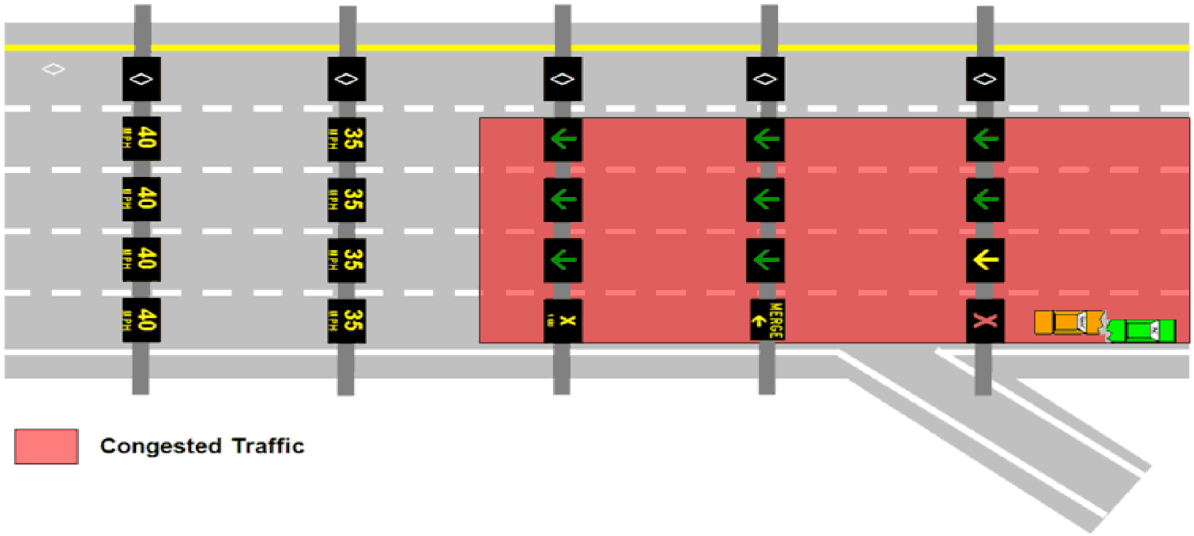


Figure 170. Example of display of intelligent lane control signals during an incident (Murphy et al., 2012)

9.4.1. Literature Review

Basic QW systems just provided alert sign for drivers to reduce their driving speeds safely. For instance, traffic authorities in Belgium deployed QW systems using portable VMS with video detectors on E313 as a Flemish project, which was motivated to enhance the road safety related to queue due to the road works (Versavel, 1999). In the project, queue state was determined when speed was less than 50 km/h (31 mph) in one or more lanes and occupancy was more than 50 %. The portable VMSs were placed every 500 meters. When a video detector on the potable VMS detected queue, the corresponding VMS displayed queue warning. Furthermore, the Ministry of Transportation Ontario (MTO) in Canada deployed several QW systems in the Toronto metropolitan area, on the St. Catharine's Queen Elizabeth Way, and near a United States border crossing (Versavel, 1999). The QW systems used to alert the queues through various devices: large VMSs, arterial advisory sign with VMS panel, arterial advisory sign with indicator beacons, and flashing lights. The California Department of Transportation (Caltrans) is operating QW systems for exit ramp spillback, locations with limited sight distance, and inclement weather such as rain and heavy fog. The QW displayed through VMS with incident response vehicles. In case of a weather-related warning system, five kinds of warning messages were displayed: slow traffic ahead, stopped traffic ahead, foggy conditions ahead, dense fog ahead, and high wind warning. "Slow Traffic Ahead" message was selected when the average speed was between 11 and 35 mph, and "Stopped Traffic Ahead" was displayed when the average speed was less than 11 mph (Murphy et al., 2012).

Regarding benefits of the basic QW systems, there were several evaluation studies. The effectiveness of a QW system on the Helsinki western artery in Finland was evaluated (Finnish National Road Administration, 1998). The QW system consisted with speed limits and queue warning symbol for traffic safety and efficiency. When the 60 km/h speed limit and queue warning were displayed, speed and its standard deviation were reduced at the beginning of congestion. However, the speed and the standard deviation got increased during long congestion. The QW system reduced the average speed, and also improved traffic safety. Japan has their own QW system, which is called as a congestion tail display (CTD) (Ikeda and Matano, 1999). After the introduction of the CTD system, the total number of rear-end collisions slightly decreased by 3.6% in 1996. In Norway, an automatic QW system using VMS, camera, and video detectors were installed on the E18 highway in Oslo (Engen and Haugen, 2001). The queue was detected under the situation: the speed was less than 30 km/h (19 mph), the zone occupancy was more than 30 %, and both states should be sustained over 15 seconds. The evaluation results showed that QW reduced speeds and increased the brakes. MnDOT (Minnesota Department of Transportation) introduced the QW system in the existing ATM on I-35W and I-94 (Hourdos et al., 2017). An infrastructure-based queue warning system (QWARN) and the Michigan Queue Warning Algorithm (MQWA) were applied for I-94 and I-35W, respectively. According to the evaluation results (Hourdos et al., 2017), QWARN reduced crashes and near-crash events on I-94. Additionally, MQWA on I-35W showed that the speed variance at downstream locations was reduced and the speed difference between upstream and downstream locations was decreased. On the other hand, there was a study to analyze design parameters of a dynamic queue warning system at a freeway work zone with lane closure by using microscopic traffic simulations (Pesti et al., 2013). Table 70 shows the recommended thresholds of each design parameter.

Table 70. Recommended values for the design parameters of a queue warning system

Design Parameter	Recommended Value
Speed threshold for "STOPPED TRAFFIC"	35 mph
Speed threshold for "SLOW TRAFFIC"	55 mph
Detector spacing	½ mile
Speed aggregation interval	5 minutes
PCMS message update interval	1 or 5 minutes
PCMS distance upstream of lane closure	1-2 miles upstream of the longest expected queue

Some systems provided QWs as recommended speeds, which could be considered as an extension of VSL systems. A queue warning system on a motorway in Denmark was activated when speed is less than 50 km/h (31 mph) (Wiles et al., 2003). The queue warning was displayed as speed limits and drivers could see successive VMS with predefined speed limits of 90, 70, and 50 km/h (56, 44, and 31 mph) until they met the end of queue. In Sweden, motorway control systems on the E4 employed QW system (recommended speed without a red ring) and dynamic speed limits (with a red ring). In the system, the QW was activated and a speed of 70 km/h (44 mph) was recommended when the automatic accident detection algorithm detected that the speed was lower than 45 km/h (28 mph). Otherwise, speed harmonization can be activated in the dense traffic condition and then the advisory speed limits were displayed as 80 km/h (50 mph). In order to evaluate the effects of QW systems on freeway work zones though traffic simulation, variable speed limits among the pre-defined six schemes were determined for two or four portable changeable message signs (Ramirez, 2017). The speed limits were selected in the range from 30 mph to 65 mph at a 5-mph increment. The six schemes were defined depending on the type of spatial speed reduction and the impact range of work zones. The maximum impact range of work zones was 3.5 miles. Figure 171 shows one scheme for drastic decrease in speeds with moderate speed reductions using 4 PCMS with advancing warning.

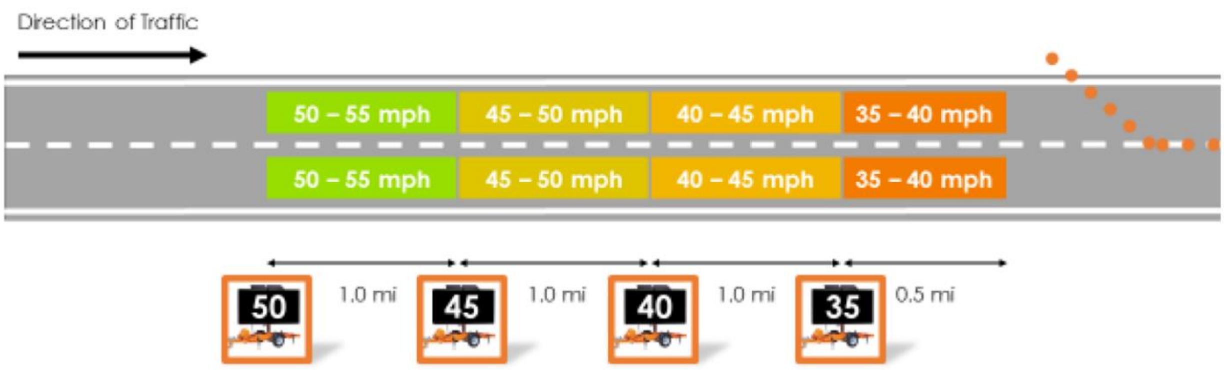


Figure 171. Scheme “F” among six schemes (Ramirez, 2017)

In summary, according to the previous research, most of QW applications using alert signs reduced speed and its standard deviation. One research confirmed the reduction in the number of crashes. However, there is no research to analyze the benefits of the only QW systems as an extension of VSL systems. Furthermore, travel time and travel time reliability were not explored.

9.4.2. Selection of Deployment Location

In this project, a composite gantry was suggested for IATM. The composite gantry can include QW and VSL. Figure 172 shows an example image of the composite gantry to use QW and VSL. Thus, the QW strategy for the IATM can be implemented as an extension of VSL. QW signs are located at the same locations of VSL in Chapter 3 so that each QW sign are linked to the downstream segments. Six QW signboards are operated in each direction of WB and EB. When the queue is detected in the downstream segments, QW signs and advisory speeds will be provided concurrently according to the QW control method.

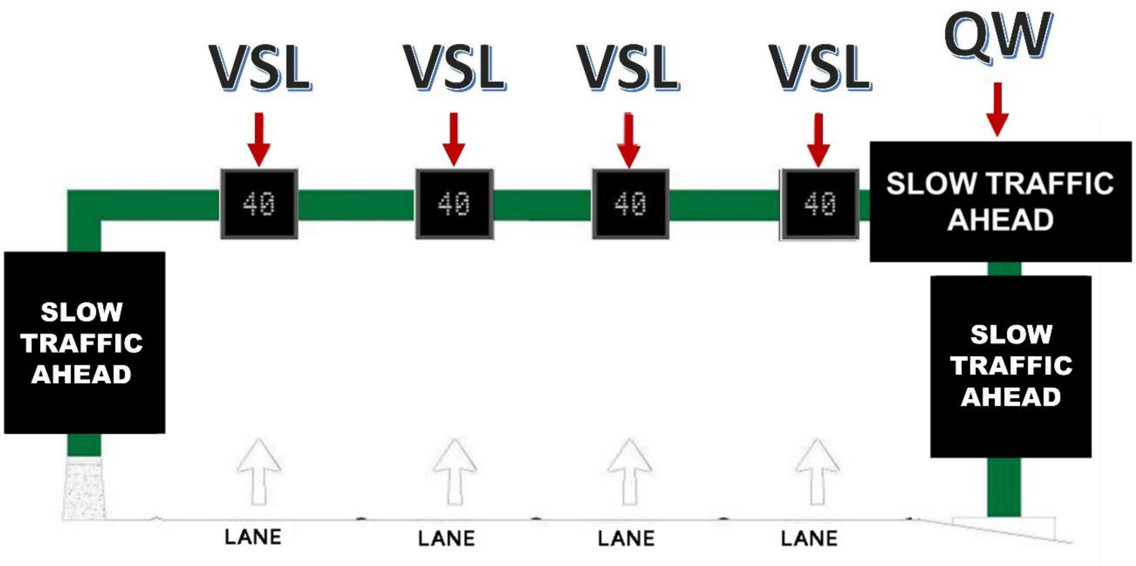


Figure 172. Suggested composite gantry for IATM

9.4.3. QW Control Method

Usually, QW can be provided by alert messages (e.g., "STOPPED VEHICLE AHEAD", and "SLOW VEHICLE AHEAD") or recommended speeds. In this study, the recommended speed was used for precise traffic control. The QW strategy using recommended speeds can be implemented in the simulation for the effectiveness analysis.

In order to implement a QW algorithm with recommended speeds, three aspects were considered:

- Detecting segments in which queues exist
- Deciding recommended speeds in segments with queues
- Guiding speed reduction gradually

For the QW activation, segments with queues should be detected. The queue existence of a segment was determined when the average speed of the segment is less than 40 mph. Thus, VSL and QW could be activated and separated at different speed ranges consistently. When the average speed of segments is more than 40 mph, speed limits will be determined through a VSL algorithm. On the contrary, the QW algorithm will work in case of less than 40 mph.

Additionally, recommended speeds in segments with queues were more specified in this project as follows:

- The recommended speed is 40 mph, if the average speed of a segment is between 35 and 40 mph
- The recommended speed is 35 mph, if the average speed of a segment is between 30 and 35 mph
- The recommended speed is 30 mph, if the average speed of a segment is between 25 and 30 mph
- The recommended speed is 25 mph, if the average speed of a segment is between 20 and 25 mph
- The recommended speed is 20 mph, if the average speed of a segment is less than 20 mph

For the gradual speed reduction of upstream from a segment under queue state, the size of the gradual speed reduction was determined as a constant value of 5 mph. Maximum 2 upstream segments from the segment under queue state were controlled for the gradual speed reduction. Depending on the recommended speed of segments with queues, if the upstream segments are not under queue state, the upstream segments' recommended speeds can be determined as follows:

- When the recommended speed for the queue segment is 40 mph, the first upstream segment is 45 mph and the second upstream segment is 50 mph.

- When the recommended speed for the queue segment is 35 mph, the first upstream segment is 40 mph and the second upstream segment is 45 mph.

- When the recommended speed for the queue segment is 30 mph, the first upstream segment is 35 mph and the second upstream segment is 40 mph.

- When the recommended speed for the queue segment is 25 mph, the first upstream segment is 30 mph and the second upstream segment is 35 mph.

- When the recommended speed for the queue segment is 20 mph, the first upstream segment is 25 mph and the second upstream segment is 30 mph.

Figure 173 shows an example of the gradual speed reduction of upstream segments when the average speed of the segment with a queue state is 30 mph.

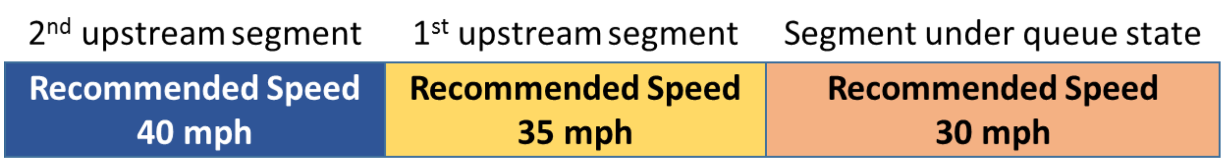


Figure 173. An example of the gradual speed reduction of upstream segments

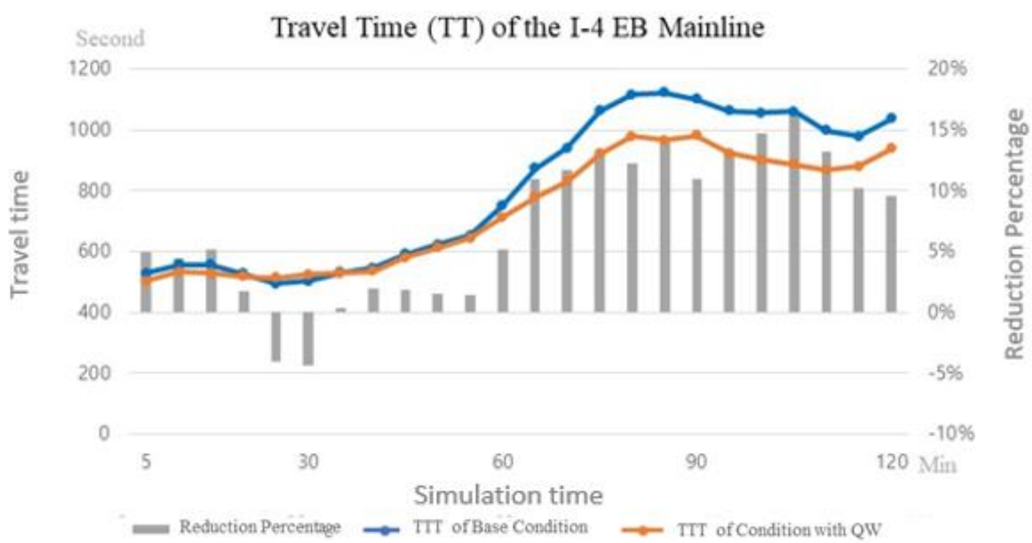
9.4.4. Evaluation of QW Effect

The effect of the QW was evaluated by a microscopic traffic simulation. As mentioned in Chapter 9.2, evaluation measures were collected during the simulation in several levels: freeway mainlines, arterials and collectors, and global network. The QW was implemented on both eastbound and westbound of I-4 mainline.

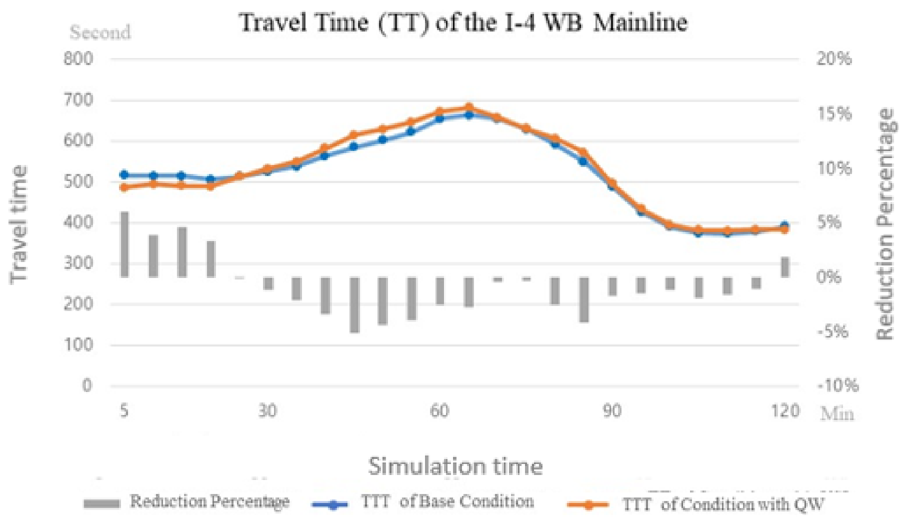
9.4.4.1. Traffic efficiency

A. Effects of traffic efficiency on freeways

Figure 174 shows the results of the travel time on the whole I-4 freeway with and without the QW (base condition). Figure 174(a) shows that the travel time of the I-4 EB freeway got reduced by the percentages from -4% to 16%. The effect of QW was not significant before the severe congestion (before 60 minutes) of the EB of the I-4 freeway, but the QW had a great benefit when there is severe congestion. It indicated that QW could have a benefit in terms of traffic efficiency. On the other hand, as shown in Figure 174(b), the effect of QW on the I-4 WB freeway is mixed and no significant difference could be observed. Compared to the I-4 EB freeway, the effect of QW was smaller on the I-4 WB freeway, which may be because the I-4 WB freeway had rare queue sections.



(a) Travel Time of Base Condition and Condition with QW on the WB of I-4 Mainline



(b) Travel Time of Base Condition and Condition with QW on the WB of I-4 Mainline

Figure 174. Travel time of base condition and condition with QW on the I-4 freeway

Table 71 shows the average travel time per vehicle and the p-values of the tests for the I-4 freeway in the base condition and the condition with QW. The p-value for the EB shows that the difference in travel time with and without the QW was statistically significant. The travel time of each vehicle passing through the QW implementation section (6 miles) was reduced by over one minute on the EB. However, the travel time on the I-4 WB got increased with the QW while the difference was not significant. The results mean that the QW could reduce the travel time on the EB of I-4 mainline.

Table 71. Statistical test of benefit of the QW

I-4 mainline direction	Average TT per vehicle (sec)		P-value
	Base condition	Condition with QW	
EB	742	677	<0.001
WB	532	538	0.0534

As shown in Table 72, total saving hours by the QW were presented for two hours at peak time to confirm the benefit of the QW. On the I-4 EB freeway, the QW implementation could save 5.6% of total travel time, which is about 114 hours. On the I-4 WB freeway, however, no significant change could be observed.

Table 72. Total saving hours by the QW (for 2 Hours at Peak Time)

I-4 mainline direction	Total travel time (h)		Total saving hours (h)	Percentage of the saving
	Base condition	Condition with QW		
EB	2,032	1,918	114	5.6%
WB	1,729	1,734	-5	-0.3%

For more detailed analysis, the benefit of the QW was analyzed according to sections on the I-4 EB freeway where significant efficiency improvement was found. Figure 175 shows the improvement of travel time rate by QW according to the sections. As shown in the figure, the speed improvement effect of the QW was significant in congested sections (E05 and E12). It means that the QW has a great benefit in severely congested sections (queue section) by harmonizing and stabilizing the traffic flow. On the other hand, in less congested sections, the effect of the QW was not significant.

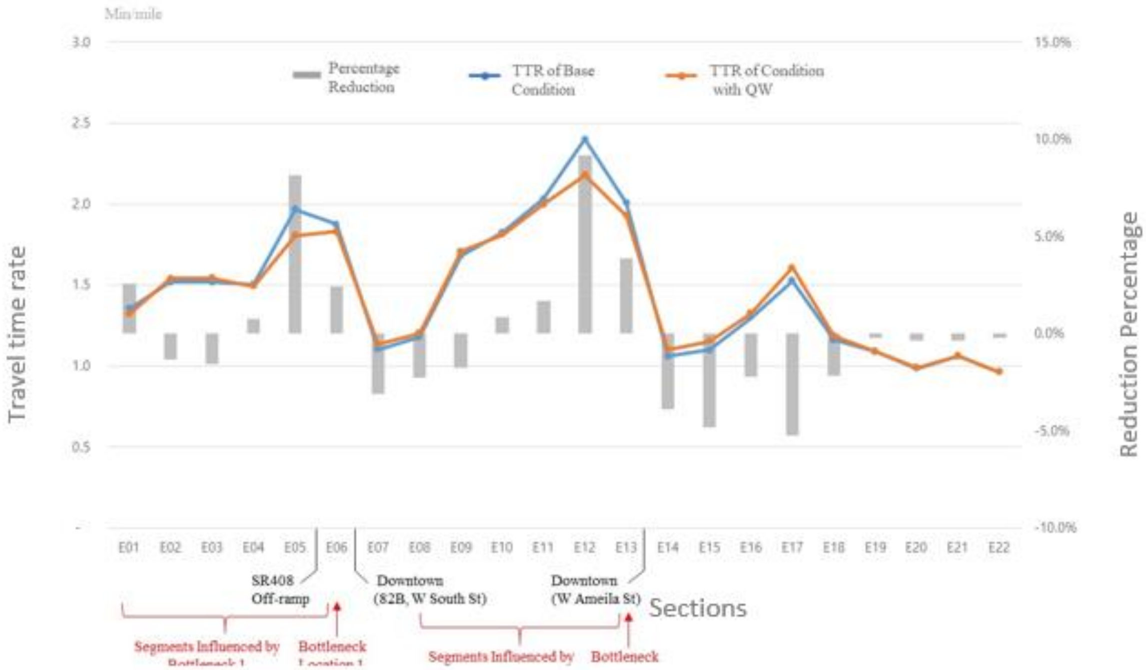


Figure 175. Improvement of travel time rate by QW according to sections (the I-4 EB Mainline)

In terms of traffic efficiency, Figure 176 shows the improvement of TTR by QW according to traffic states on the EB. In the figure, the QW could reduce the TTR by 8.6% in congested traffic states, but it has an adverse effect in free-flow and transitional traffic states. It indicates that the QW activated by the queue at the bottleneck could increase the travel time rate of the upstream in free-flow or transitional traffic states. The relatively lower recommended speed for safety by the QW may lower the efficiency of the upstream where traffic is not congested while it could improve traffic efficiency in the congested area.

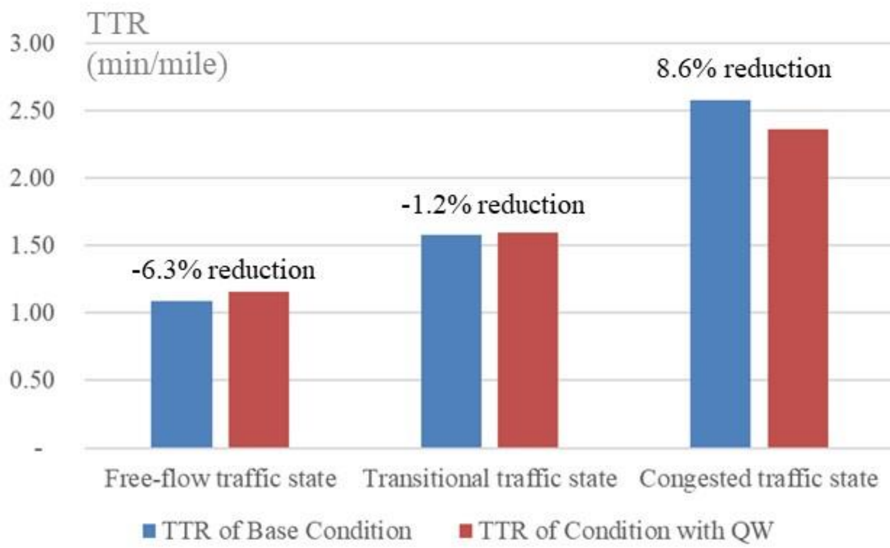
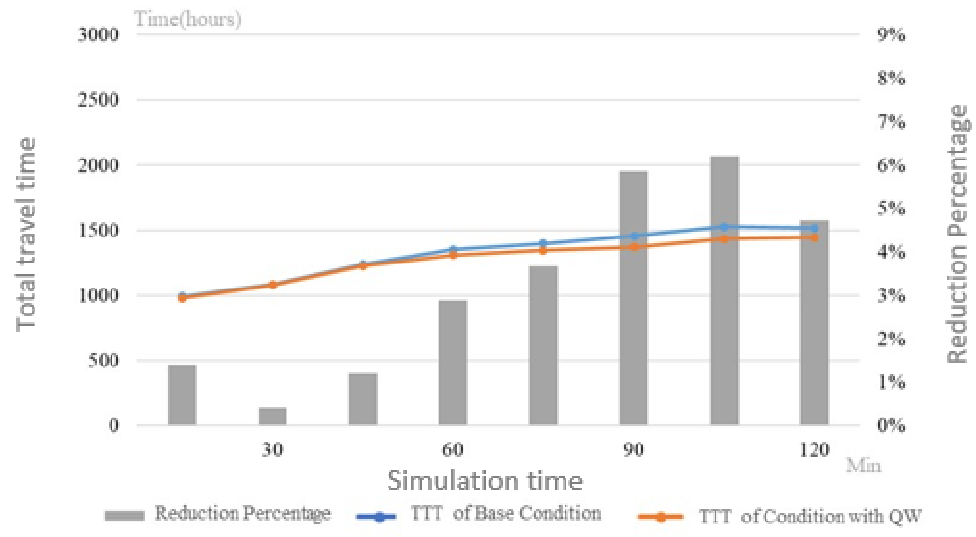


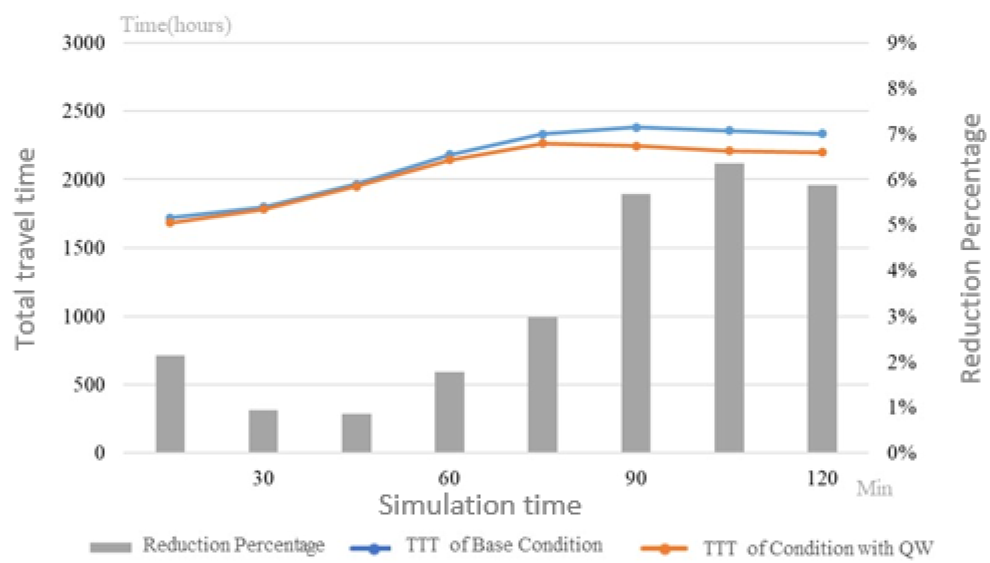
Figure 176. Improvement of travel time rate by QW according to traffic states (the I-4 EB mainline)

B. Impact of traffic efficiency on arterials/collectors and whole corridor network

In this part, the effect of QW implementation on the arterials/collectors and the whole network was analyzed. The total travel time was calculated and presented in Figure 177. As a result, the QW had a benefit on the arterials and collectors when recurring congestion begun on the freeway (after 60-minutes). It is considered that the effect of speed improvement on the freeway by the QW is extended to the whole network. The total travel time of 601 hours was saved by the QW on the whole network.



(a) Total travel time of arterials/collectors



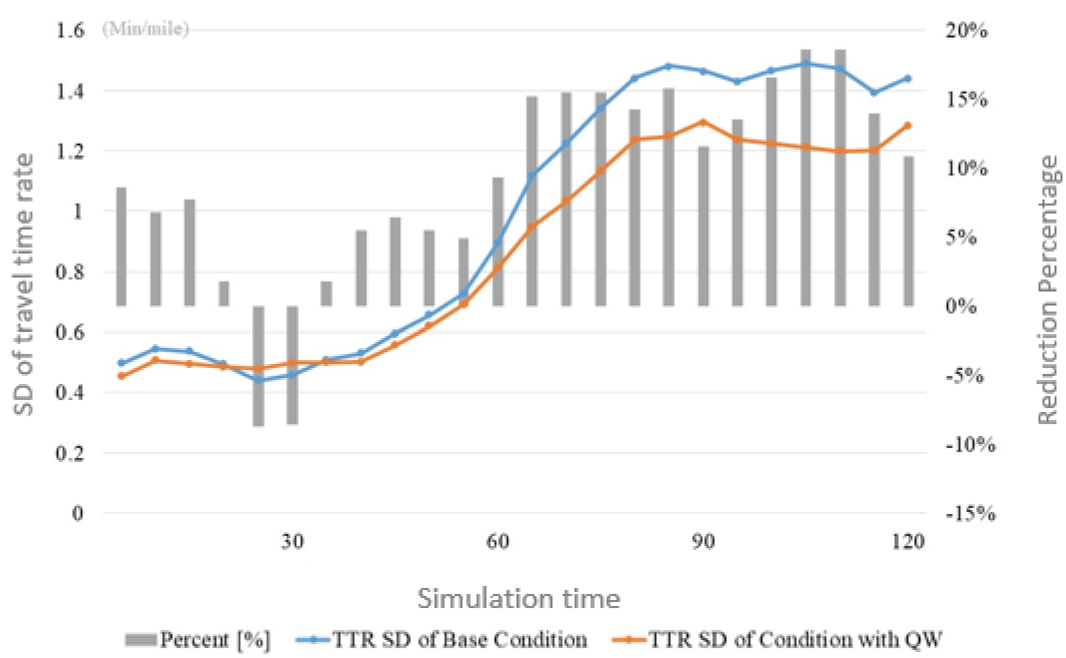
(b) Total travel time of the whole network

Figure 177 Total travel time of arterials/collectors, and whole network

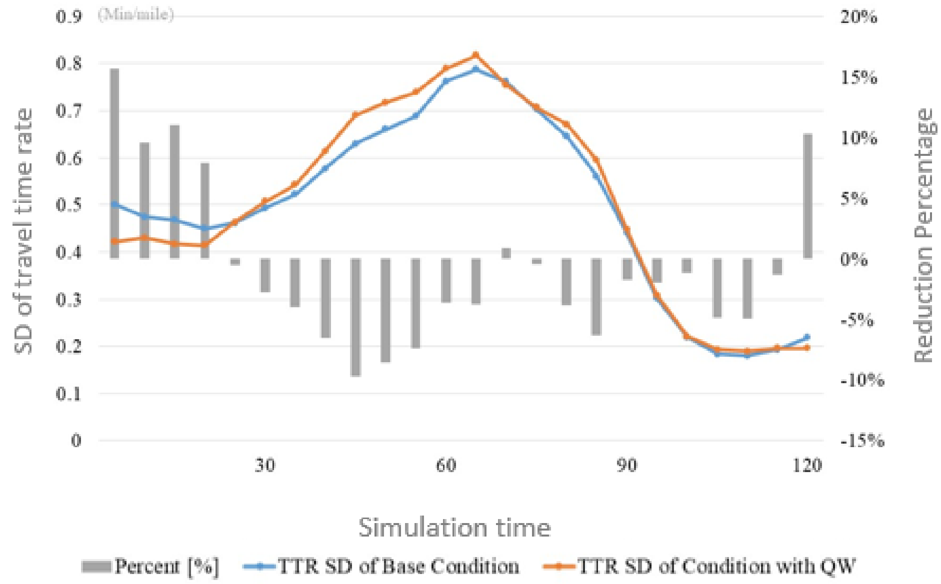
9.4.4.2. Travel time reliability

A. Effects of travel time reliability on Freeways

Figure 178 shows the SD of TTR on the whole I-4 freeway with and without the QW (base condition). It is shown that the reliability on the I-4 EB was lower than the I-4 WB. The SD of TTR was larger than 1 for the last one hour on the I-4 EB while the SD of TTR was always lower than 1 on the I-4 WB. Figure 178 (a) shows that the SD of TTR was slightly reduced by the QW on the I-4 EB freeway except for 10 minutes. The reduction percentage was over 10% when the SD of TTR was over 1 (unreliable condition). This means that the implementation of QW could improve the travel time reliability of I-4 EB mainline, especially for the unreliable condition. On the WB, as shown in Figure 178 (b), no significant change could be found before and after implementing the QW control on the I-4 WB freeway for most time.



(a) SD of TTR of base condition and condition with QW on the I-4 EB freeway



(b) SD of TTR of base condition and condition with QW on the I-4 WB freeway

Figure 178 SD of TTR of base condition and condition with QW on the I-4 freeway

B. Impact of travel time reliability on arterials/collectors and whole corridor network

Figures 179 and 180 show SD of TTR on the arterials/collectors and the whole network. The improvement of reliability (SD of TTR) was up to 7% on arterials/collectors and 8% on the whole network. It is considered that the effect of reliability improvement on the freeway by the QW could also help improve the traffic reliability of arterials/collectors and the whole corridor network.

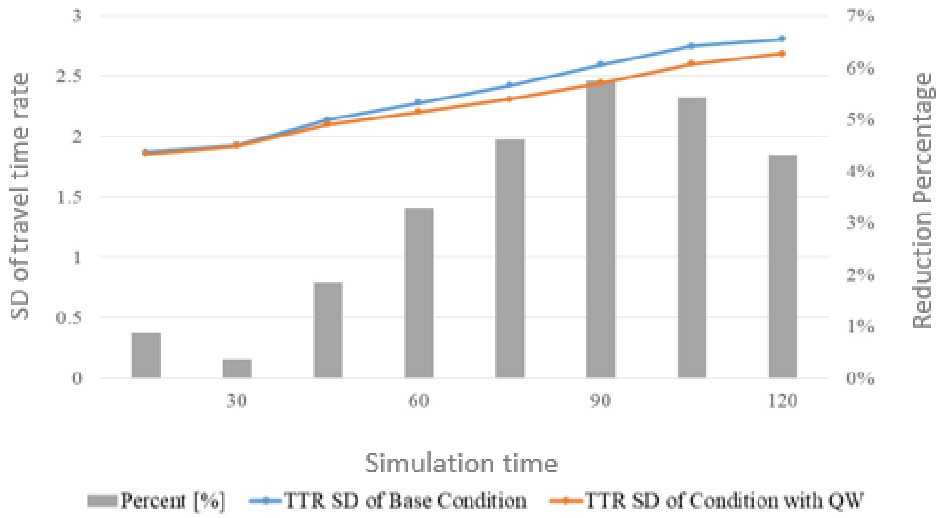


Figure 179. SD of TTR of base condition and condition with QW on arterials/collectors

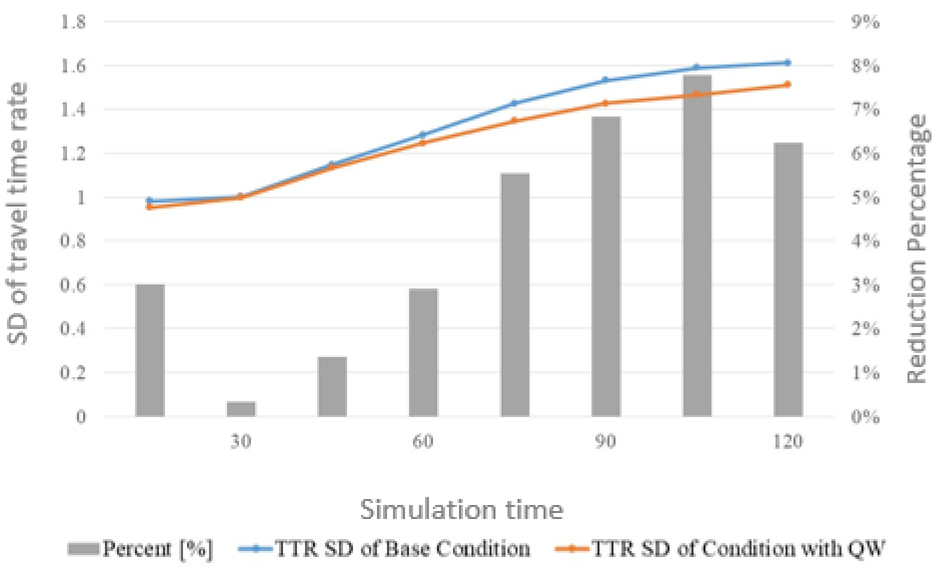
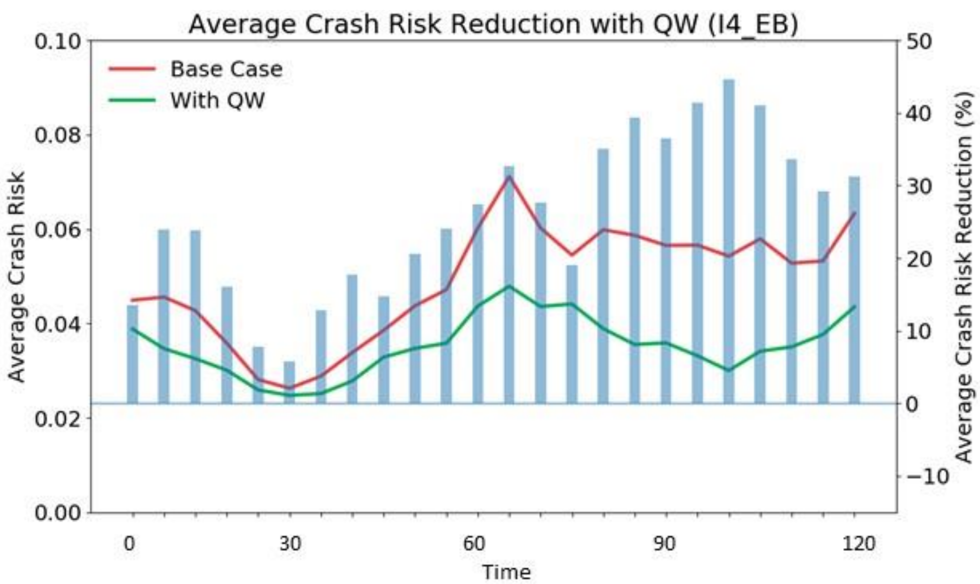


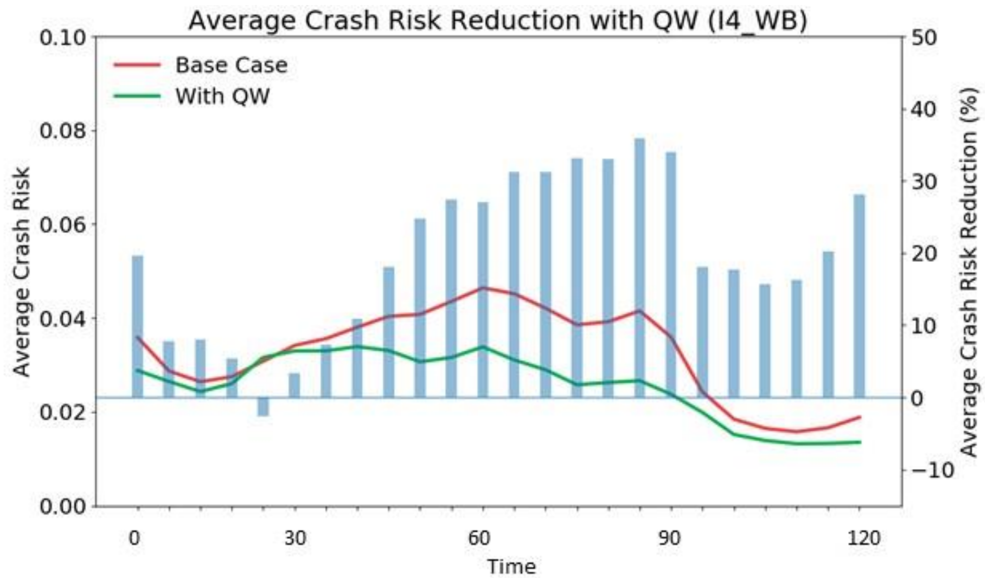
Figure 180. SD of TTR of base condition and condition with QW on the whole network

9.4.4.3. Traffic safety

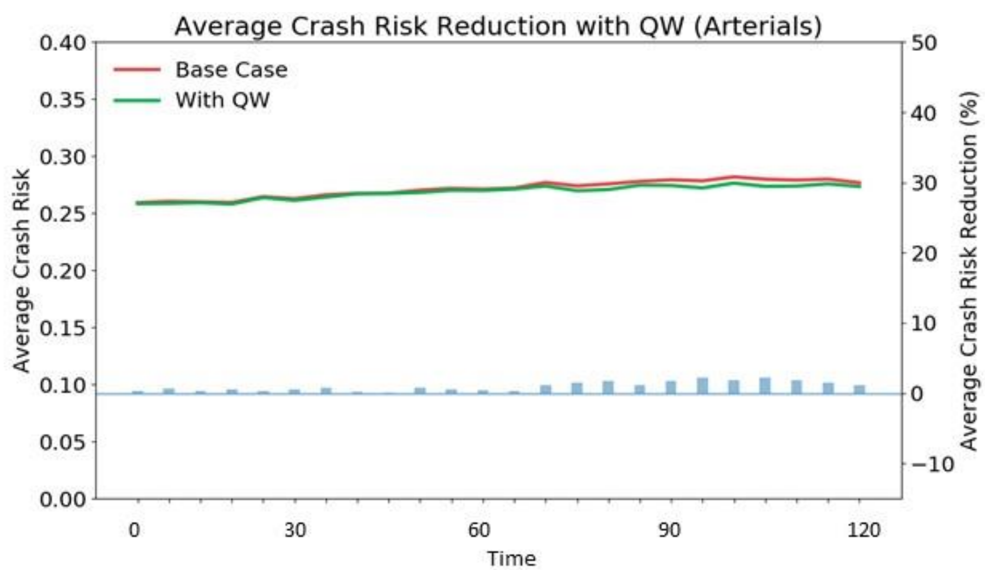
Figure 181 shows the average crash risk on I-4 EB freeway, I-4 WB freeway, and arterials/collectors in the scenarios with and without QW for every 5 minutes during the simulation. Figure 181 (a) reveals that the implementation of QW can significantly reduce the crash risk on the I-4 EB. Overall, the average reduction of crash risk on I-4 EB is 27.96%. More safety improvement could be observed at the last 1 hour, when heavy congestion occurred. Figure 181 (b) indicates that the implementation of QW can also significantly reduce the crash risk on the I-4 WB. In average, the reduction of crash risk on I-4 WB is 20.91%. The impacts of QW are much more effective during high-risk periods. The average crash risk on all arterials and collectors without and with the QW was presented in Figure 181 (c). The figure implies that the implementation of QW on the freeway would not affect the traffic safety on the arterials and collectors significantly.



(a) Average crash risk on I-4 EB under base condition and QW condition



(b) Average crash risk on I-4 WB under base condition and QW condition



(c) Average crash risk on arterials/collectors under base condition and QW condition

Figure 181. Average crash risk on I-4 freeway and arterials/collectors under base condition and QW condition

9.4.5. Discussions

The QW system in ATM can be regarded as an extension of VSL systems. Thus, QW signs were located at the same locations of VSL in Section 7.3. Also, the QW strategy with recommended speeds was implemented in this study. The results suggested that the QW improved travel time on severe congested traffic state in freeway mainlines. In particular, it was found that the QW could improve not only travel time but also its reliability. Also, it was found that the QW had a significant benefit in terms of safety, which was expected since QW has been usually used to improve traffic safety. No negative impact of QW was found on the arterials/collectors with the aspects of travel time, travel time reliability, and traffic safety.

Based on the evaluation results, the research team can provide insights on the implementation of QW. In order to have a benefit in terms of efficiency and reliability, the QW should be implemented in severe congestion where a queue is constantly forming. Meanwhile, QW is expected to bring the safety benefits on freeways. It is also necessary to integrate with VSL to improve efficiency reduction on bottleneck upstream caused by the QW.

9.5. Ramp Metering (RM)

Ramp meters are traffic signals installed on the on-ramps of limit-accessed freeways/expressways to control vehicles entering the freeways/expressways mainlines. Ramp Metering (RM) allows efficient use of freeways/expressways mainline capacity by managing the inflows from the arterials/collectors and reduces the crash risk of freeway merging area by breaking up platoons of merging vehicles considering the limited gaps. RM controls the volume of in-flow (metering rate) by adaptive algorithms based on real-time and/or anticipated traffic conditions.

While RM has a lot of benefits, it might not be applicable for every freeway on-ramp. For example, ramp meters stop the vehicles entering the freeway mainline if the downstream freeway mainline section is congested, which could cause queues on on-ramps. If the metered failed to provide enough space to accommodate the queued vehicles, the queue would spill over to connected arterials/collectors, and cause excessive delay. Therefore, inappropriate RM might be detrimental to the performance of arterials and the roadway network as a whole.

This chapter demonstrates the whole process to evaluate the effectiveness deployed in our study area. Throughout the process, a rigorous selection of the potential locations of RM deployment was conducted to ensure the proposed RM deployment could potentially enhance the traffic operation of freeway mainline while not impact that of arterials and whole roadway network negatively. Then, the proposed RM strategies were deployed on the selected on-ramps in the microscopic traffic simulations. Finally, a before-after study of the RM deployment in the simulation is utilized to evaluate the effectiveness, including traffic efficiency and travel time reliability of freeway mainline, arterials/collectors, and the whole roadway network.

9.5.1. Warrants of Ramp Metering

There are two major steps in the selection of deployment locations: (1) Critical segment identification, which aims at identifying the locations suffering congestion and unreliable travel time and (2) Ramp metering warrant check, which mainly plays a role in avoiding side effects.

Critical segments were identified in Chapter 5. According to the results, all the segments of I-4 in Downtown Orlando Area were identified as critical segments with either high or medium congestion and unreliability problems. Therefore, all the critical segments and their connected on-ramps were considered.

Before the ramp metering deployment, some ramp metering warrants were referred to select the ramps which were appropriate to deploy RM. Seven ramp metering warrants developed in 2011 for State of Florida (Gan et al., 2011) were utilized:

- Warrant 1- Mainline Volume: Ramp signaling is warranted at a location where the overall average mainline volume during the peak hour is greater than 1,200 vehicles per hour (vph) for each lane.

- Warrant 2- Mainline Speed: Ramp signaling is warranted at a location where the average mainline speed during the peak hour is less than 50 mph.
- Warrant 3- Ramp Volume: Ramp signaling is warranted at a location if the following conditions are met:
  - For a ramp with a single lane, ramp signaling is considered when the peak hour onramp volume is between 240 and 1,200 vph.
  - For a ramp with multiple lanes, ramp signaling is considered when the peak hour onramp volume is between 400 and 1,700 vph.
- Warrant 4- Total Mainline and Ramp Volume: Ramp signaling is warranted when any of the following conditions is met:

  Condition 1: The summation of peak hour mainline volume and ramp volume exceeds the following threshold values:

  - If there are two lanes, warrant is met when total volume is greater than 2,650 vph
  - If there are three lanes, warrant is met when total volume is greater than 4,250 vph
  - If there are four lanes, warrant is met when total volume is greater than 5,850 vph
  - If there are five lanes, warrant is met when total volume is greater than 7,450 vph
  - If there are six lanes, warrant is met when total volume is greater than 9,050 vph
  - If there are more than six lanes, warrant is met when total volume is greater than 10,650 vph

The summation of peak hour mainline volume and ramp volume exceeds the following threshold values

Condition 2: Peak hour volume of the rightmost lane exceeds 2,050 vph.

- Warrant 5- Ramp Storage: Ramp signaling is warranted at a location where the ramp storage distance is longer than the queue length estimated by the following equation:

$$L = 0.25V - 0.00007422V^2$$

where, L: required single-lane storage distance (meter)

V: peak hour ramp demand (vph)

- Warrant 6- Acceleration Distance: Ramp signaling is warranted at a location where the acceleration distance after the stop bar is longer than the required safe merging distance estimated by the following equation:

$$L = 0.14V^2 + 3.00V + 9.21$$

where, L: required minimum acceleration distance (feet)

V: freeway mainline prevailing speed (mph)

- Warrant 7- Crash Rate: Ramp signaling is warranted at a location where the facility or roadway segment has a crash rate of over 80 crashes per hundred million vehicle miles (HMVM). RHMVM is calculated using the following formula:

$$RHMVM = \frac{Number\ of\ Crashes\ per\ year \times 100000000}{AADT \times 365 \times Distance}$$

where, $RHMVM$: crash rate per hundred million vehicle-miles

AADT: Average Annual Daily Traffic on the facility (vpd)

Distance: length of roadway segment (mile)

9.5.2. Selection of Deployment Location

The aforementioned seven warrants could be classified as three categories: traffic (Warrants 1 to 4), geometric (Warrants 5 and 6), and safety (Warrant 7). Since this project focuses not only congestion but also travel time reliability, Warrants 1 and 4 which focus on the mainline traffic volume and Warrant 7 which focuses on the safety might not be sufficient. In addition, the first step of selection process has already identified the critical segments in Chapter. Those warrants are not used although the mainline volumes are gathered as only references.

Warrant 2 was designed to determine the location of bottlenecks (Gan et al., 2011). It might be unrealistic to ensure peak hour speed to be the post speed limit. Thus, the speed threshold of the bottleneck was set as 30 mph. In addition, since the data is available at a 5-minute aggregation level, it is able to get more reasonable classification of the bottleneck.

While the actual volumes of freeway mainline is continually monitored in the study area, the traffic volumes of on-ramps are not accessible. Therefore, to apply Warrant 3, all the traffic data including referenced mainline were acquired from the simulation.

Warrant 5 aims at avoiding the queue spillover on arterials, which guarantees that the RM would not impact the traffic operation of arterials negatively. It requires either acquiring the demand by survey or estimation. However, the survey conducted in this project is insufficient to estimate the demand. Therefore, Warrant 5 is not used in this study. Instead, the average queue length of the on-ramps was monitored during the simulation of the before (base) condition.

Warrant 6 about acceleration lane length is designed to ensure the safety. However, a statistic of the acceleration lane lengths of ramp meters implemented in 6 cities concluded that none of them met the required minimum length for trucks (Hadi et al., 2017). Thus, in this project, only the minimum acceleration length for passenger cars was considered. In addition, according to a study (Tian et al., 2016), the calculated acceleration lane length in Warrant 6 is too conservative. The value used in this project was recommended by the aforementioned study, which was 500 feet given the posted speed limit of I-4 was 50 mph and merge speed was assumed as 40 mph.

As mentioned earlier, the maximum queue length during the simulation is used for Warrants 5 and 6. The maximum storage in number of vehicles is estimated by:

$$S = \frac{L_{ramp} - L_{acclane}}{L_{vehicle} + L_{headway}}$$

where, S: maximum storage in number of vehicles

L_{ramp}: length of the ramp

$L_{acclane}$: length of acceleration lane, which is 500 feet

$L_{vehicle} + L_{headway}$: summation of the average vehicle length and the special headway, which is assumed as 20 feet.

Table 73 illustrated the traffic and geometric information of critical segments on I-4 and their associated on-ramps. The traffic data were gathered from the base-case simulations which will be elaborated in next section.

According to Table 73, only four ramps, which are the on-ramp connecting Kaley St with the I-4 EB, the on-ramp connecting Anderson St with the I-4 EB, the on-ramp connecting South St with the I-4 EB and the on-ramp connecting Princeton St with the I-4 WB, meet Warrant 2. Since all four ramps have only one lane and their volumes were greater than 240 vehicles per hour, all four ramps met Warrant 3. Warrant 6 were also met as the lengths of all four on-ramps were longer than 500 feet.

During the simulation, the maximum queue length on the on-ramp connecting Princeton St with I-4 Westbound and that connecting Michigan St with I-4 Eastbound might exceed the maximum storage. That means the queue might spill over to the connected arterial which could negatively affect the traffic operation on the arterial if a RM is deployed on the ramp. Therefore, the RM was not implemented on the specific on-ramp due to the side-effect.

Table 73. Traffic and geometric information of critical segments from traffic simulation

Corridor	Ramp Name	Warrant 2	Warrant 3		Warrant 5	Warrant 6		References			
		Bottleneck	Ramp Lanes	Ramp Volume	Ramp Length	Storage	Queue	Lanes	Ave Volume	Right -most	Total
I-4 EB	Michigan St	Yes	1	885	620	6	20	4	1,259	1,376	5914
	Kaley St	Yes	1	1,145	1,020	26	19	4	1,346	1,439	6,817
	Anderson St	Yes	1	464	1,460	48	5	3	1,192	1,458	4,040
	South St	Yes	1	637	1,750	65	21	4	1,242	1,539	6,506
	SR-50	No	1	503	914	21	21	4	1,353	1,671	5,915
	Magnolia Ave	No	1	920	1,276	39	1	4	1,588	926	7,270
	Princeton St	No	1	590	1,150	33	1	4	1,548	15,75	6,781
I-4 WB	E Par St	No	1	598	833.3	17	6	4	1,728	17,15	7,511
	Princeton St	Yes	1	533	1,130	32	36	4	1,654	13,59	7,150
	SR 50	No	1	648	757	13	1	5	1,325	754	7,274
	Amelia St	No	1	608	1,370	44	1	5	1,810	1,518	9,661
	South St	No	1	681	1,540	52	39	4	1,615	1,296	7,142
	Kaley St	No	1	562	1,200	35	1	5	1,302	570	7,069

* The highlighted ramps meet the warrants.

In conclusion, RM was implemented on three on-ramps (Kaley Street to I-4 EB, Anderson St to I-4 EB, and South Street to I-4 EB) connected the I-4 EB freeway. Figure 182 shows the locations where the ramp meters were deployed.

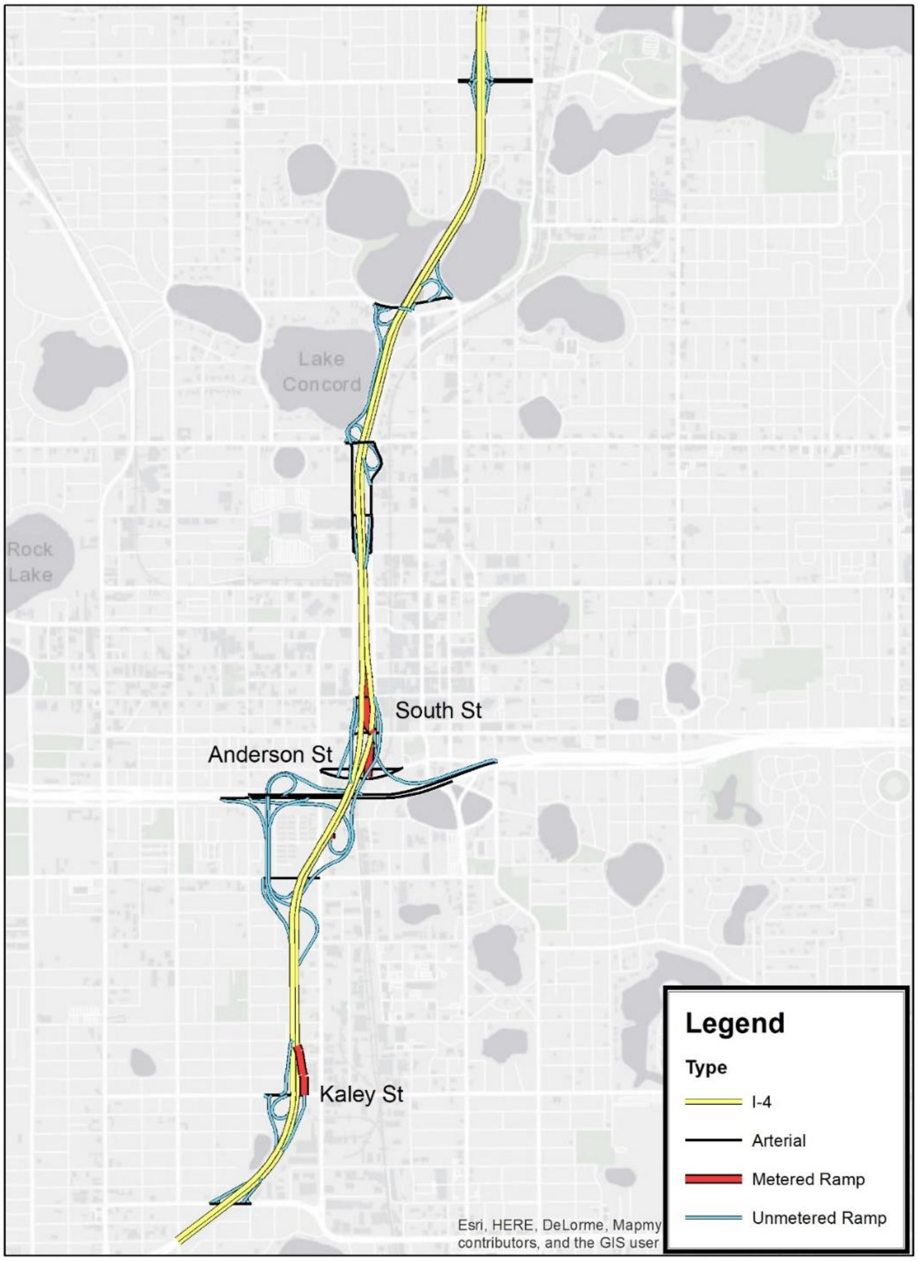


Figure 182. The location of metered ramps

9.5.3. RM Control Method

Ramp meters using ALINEA algorithm were implement on the selected three on-ramps (Papageorgiou et al., 1991). ALINEA (Asservissement Linéaire d'Entrée Autoroutière) is a simple, robust, flexible, and effective local strategy for ramp metering. Throughout the years, it has been implemented in several European cities such as Paris, Amsterdam, and Munich (Hadi et al., 2017). The basic idea of ALINEA is keeping the mainline occupancy under a pre-defined threshold (critical occupancy) to avoid the formation of bottleneck. The real-time metering rate is calculated by:

$$r(k) = r(k-1) + K_R(\hat{o} - o_{k-1})$$

where, $r(k)$: the metering rate (vph) at time step k (current time step), the length of control time step is set as the default value one minute

$r(k-1)$: the metering rate (vph) at time step k-1 (previous time step)

K_R: the occupancy regulator parameter (vph). The previous study shows that the metering rate is insensitive to this regulator parameter (Papageorgiou et al., 1991) and 70 vph was recommended.

$\hat{o}$: critical occupancy (%). The critical occupancy is set as 23% in accordance with the previous studies (Abdel-Aty and Gayah, 2010; Wang et al., 2017) to provide better safety benefits.

o_{k-1}: the occupancy (%) at time step k-1

The stop line of ramp metering was set at the location where the length of acceleration lane was ensured. The set of occupancy detectors was “installed” at the downstream of metered on-ramp (Figure 183). It is noted that no more occupancy detectors are needed if there are MVDS detectors.

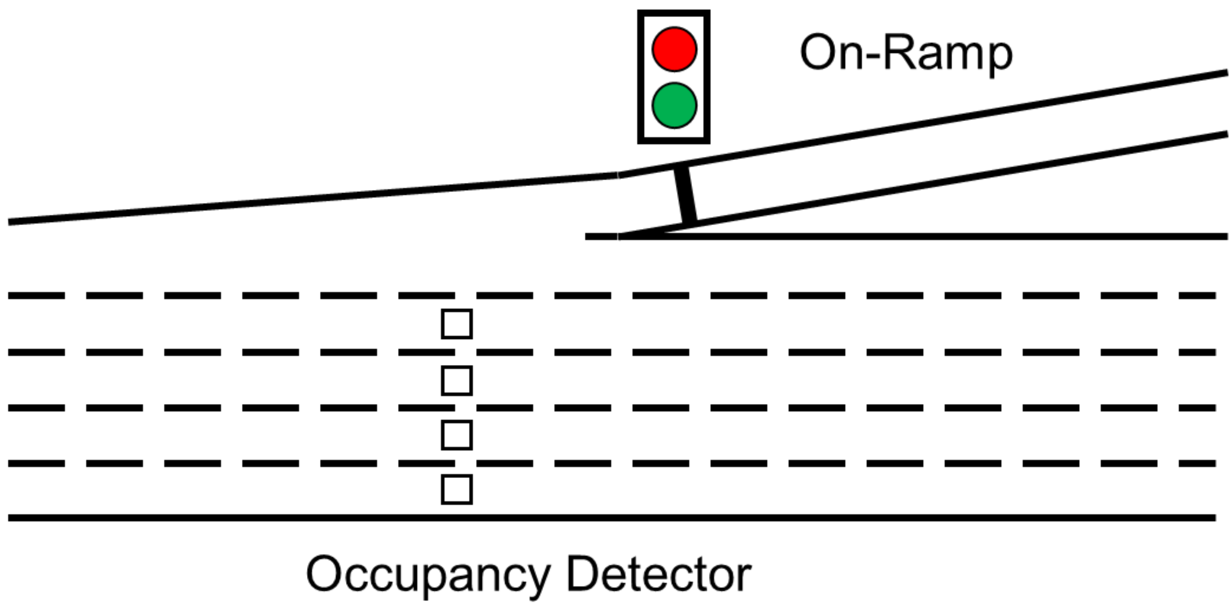


Figure 183. The location of ramp meters and occupancy detectors

Additionally, the ramp meters were configured with a simple queue control scheme since it is important to avoid the queue spillover to the adjacent arterials. In this evaluation study, a minimum allowed ramp-inflow of 240 vph was used. It means that the ramp meters could discharge the queues on the on-ramp regardless of the currant occupancy of freeway mainline to prevent excessive queue accumulation.

9.5.4. Evaluation of RM effect

The research team evaluated the effect of RM in Aimsun traffic simulation. The used simulation network has been pre-calibrated and validated in Chapter 9. The well-calibrated and validated simulated traffic network is able to represent the traffic dynamics in the real world without any IATM strategies implemented. Therefore, it was used as the base scenario.

Several different Measures of Effectiveness (MOEs) were collected during the simulation in several locations: freeway mainlines, arterials and collectors, and the whole network. As RM was only implemented on the I-4 EB, the effects of RM on the freeway were only evaluated for the I-4 EB. It is also important to investigate adverse effects on metered ramps and roads connected to the ramps. Therefore, this evaluation examined the adverse effects of the RM in detail by analyzing the queue length and delay of the ramps and arterials. Also, the duration of the bottleneck and the throughput of downstream freeway segments were presented.

9.5.4.1. Traffic efficiency

A. Effects of traffic efficiency on freeways

The travel time was used to evaluate the traffic efficiency before and after the deployment of RM. Figures 184 shows the travel time on the whole I-4 EB section with and without RM (base condition) for every 5 minutes during the simulation. The figure illustrates that RM is generally able to improve both efficiency except for short time period (simulation time 50 minutes to 70 minutes).

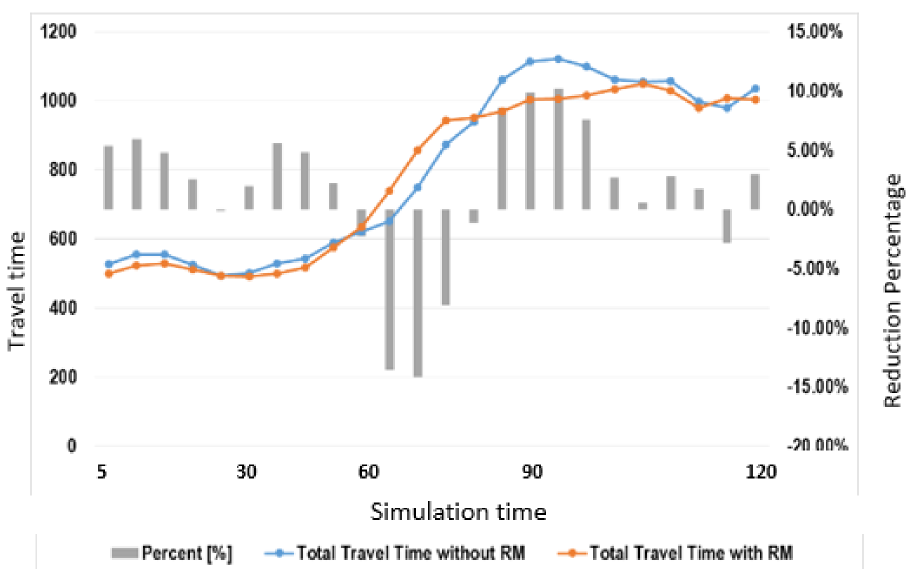


Figure 184. Travel time of base condition and condition with RM on the I-4 EB mainline

In order to verify the benefit of the RM, the research team conducted a statistical test to verify whether the travel time was significantly different in the base condition and the condition with RM. As shown in Table 74, the p-values show that the differences in travel time with and without the RM were statistically significant on the EB of I-4 mainline. It means that the RM could reduce the travel time on the freeway mainline by controlling vehicles entering the freeway mainlines.

Table 74. Statistical Test of Benefit of the RM

I-4 mainline direction	Average TT per vehicle (sec)		P-value
	Base condition	Condition with RM	
EB	742	723	0.0071

We presented total saving hours by the RM for two hours at the peak time to confirm the benefit of the RM (Table 75). On the EB, the RM implementation could save 2.4% of total travel time, which was about 49 hours.

Table 75. Total Saving Hours by the RM (for 2 Hours at Peak Time)

I-4 mainline direction	Total travel time (h)		Total saving hours (h)	Percentage of the saving
	Base condition	Condition with RM		
EB	2,032.4	1,983.7	48.7	2.4%

In the result of travel time on I-4 EB mainline, it was shown that RM could increase the travel time on the freeway mainline for certain time periods, which could be due to the queue control scheme of the proposed RM algorithm. Figure 185 overlays the percentage difference after the implementation of RM with the total inflow from the three metered on-ramps. It clearly shows that the travel time of mainline increased when the inflow was high. It is expected since the queue control scheme would be activated (i.e., the meters would be deactivated) when on-ramp inflows were high. Due to the surge of inflow caused by such queue control scheme, the mainline travel time increased. This finding suggests that the simple queue control by setting the minimum allowed inflow might not be enough especially when the on-ramp demand is high. The queue status of the ramps also needs to be considered.

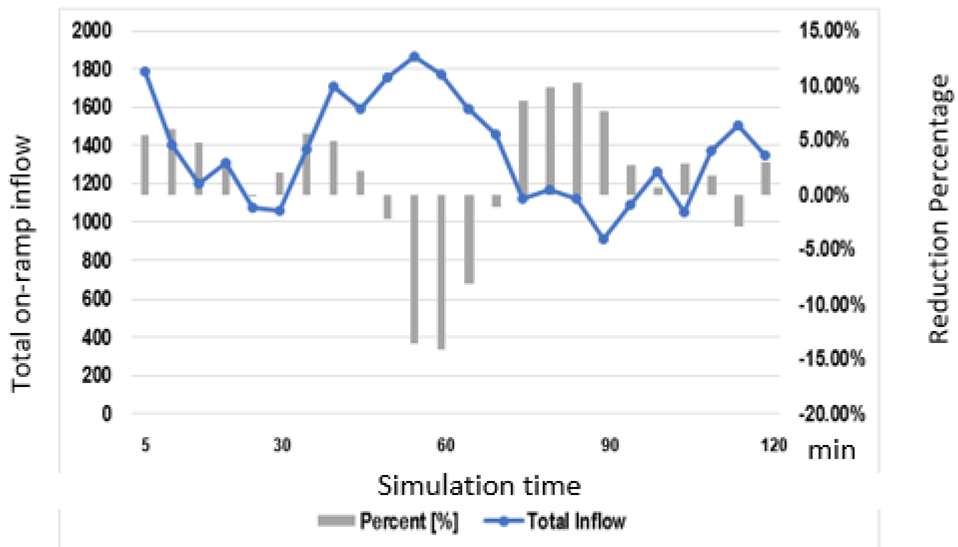


Figure 185. Total on-ramp inflow versus percentage change of travel time with RM

For more detailed analysis, the improvement of travel time rate for different traffic states and for different freeway sections are presented. Figure 186 shows the improvement for different categories of traffic states defined in Section 7.2: free-flow, transitional and congested. Generally, the improvement of travel time rate increased as the congestion level went up. For the free-flow condition, the benefit of the RM was negligible. On the other hand, RM is able to reduce 2.5% of travel time averagely for transitional traffic state and 13.2% of that for congested situation respectfully. For the spatial effect, as shown in Figure 187, the RM enhances the operation of both upstream and downstream sections by reducing the turbulence incur by inflows. However, the effect could not spread to freeway downstream sections far away from the metered ramp.

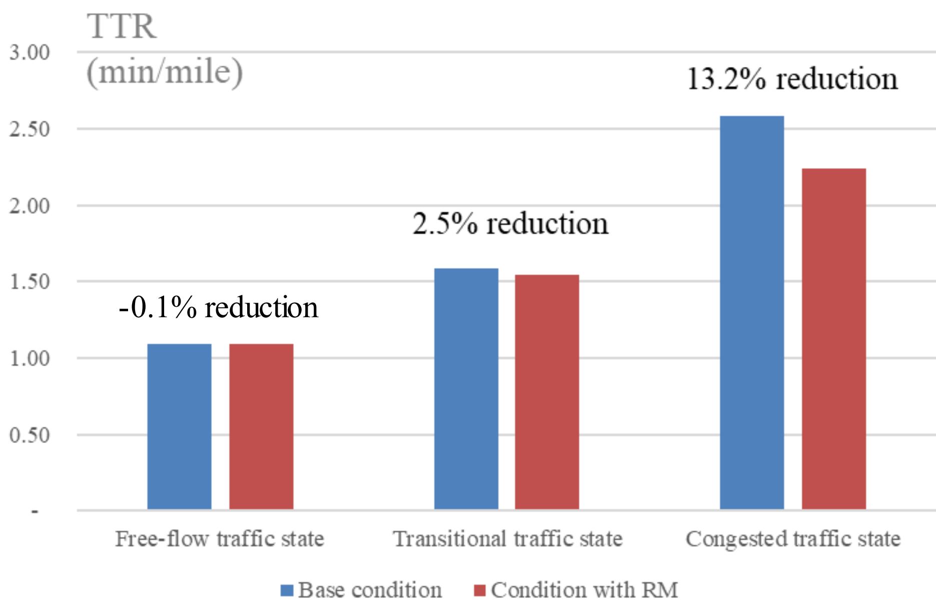


Figure 186. Improvement of travel time rate by RM according to traffic states

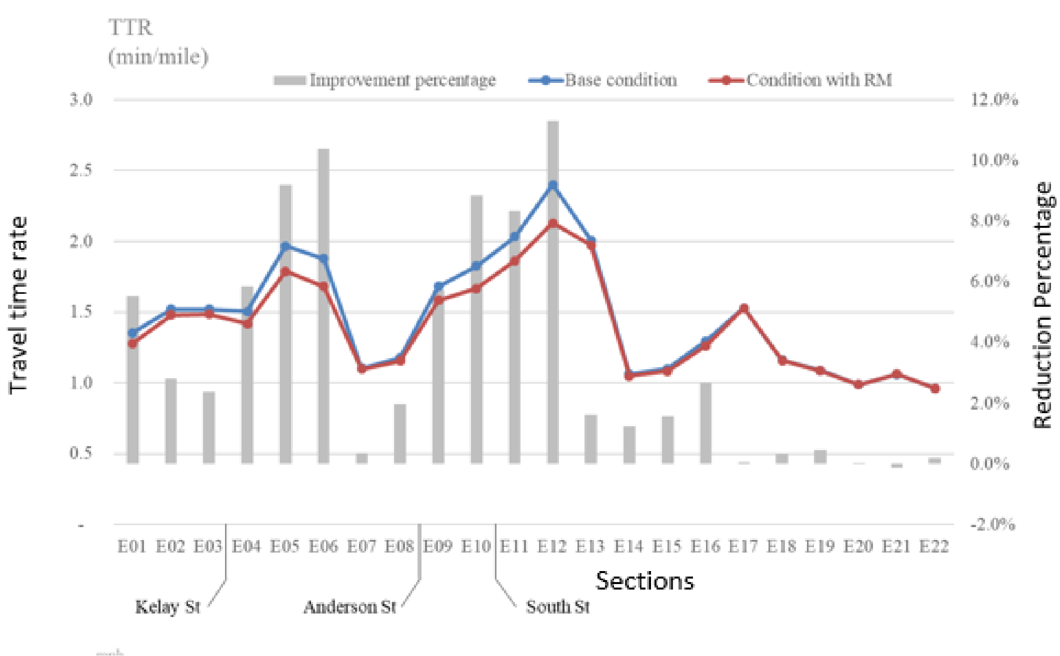


Figure 187. Improvement of travel time rate by RM according to sections

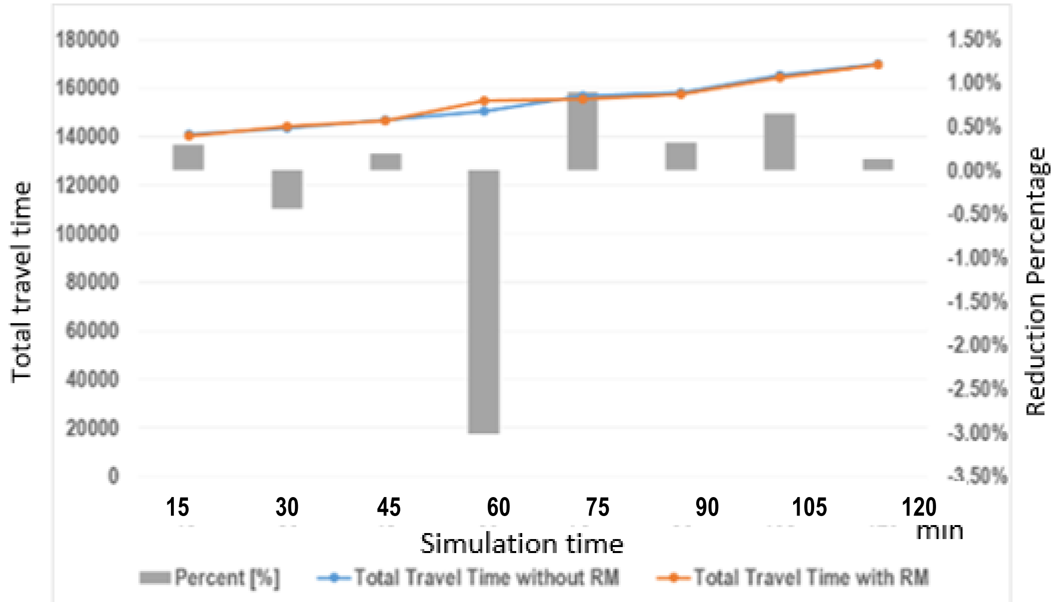
The ramp metering could also help eliminate the bottlenecks of freeway and increase the freeway throughput. The freeway bottleneck here is defined if the speed of a specific freeway segments is lower than 30 mph. In this evaluation study, the temporal duration of bottleneck and the throughput of downstream freeway segment of metered on-ramps were collected to evaluate the effectiveness of RM. Table 82 shows the duration of bottleneck and the throughput of downstream freeway segments of base condition and the condition with the RM. As shown in the table, the duration of bottlenecks was reduced. Especially for the downstream segment of on-ramp connecting Kaley Street, the duration is reduced by 88.89%. The proposed RM could also increase the throughput of downstream freeway section.

Table 76. The duration of bottleneck and the throughput of downstream freeway segments

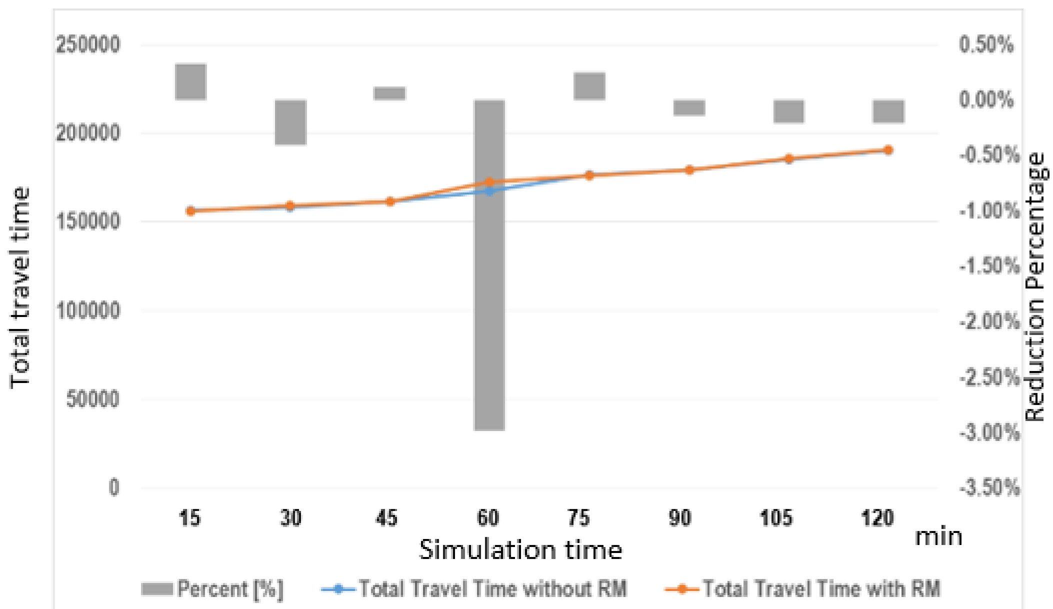
Ramp Names	Bottleneck Duration (min)			Throughput (vehicles)		
	Before	After	Difference	Before	After	Difference
Kaley St	45	5	-88.89%	11,880	12,347	3.93%
Anderson St	35	30	-14.29%	7,524	7,975	5.99%
South St	45	40	-11.11%	9,651	9,705	0.56%

B. Impact of traffic efficiency on arterials/collectors and whole corridor network

In order to examine whether the proposed RM affected the performance of arterials/collectors, the total travel time of all arterials/collectors and the whole network was collected and presented in Figure 188. There was not any significant impact on the performance of arterials/collectors except for a short time period (simulation time 45 minutes to 60 minutes), which was exactly when the queue control scheme was activated. It also confirmed the necessity of the queue control scheme. Similar trend of travel time could be found on the whole network.



(a) Total travel time of all arterials/collectors



(b) Total travel time of the whole network

Figure 188. Total travel time of all arterials/collectors, and whole network

9.5.4.2. Travel time reliability

A. Effects of travel time reliability on freeways

Figure 189 shows the SD of TTR on the I-4 EB mainline with and without the RM. The figure suggests that RM could reduce the SD of TTR (improve the travel time reliability) for most time. The trend was similar to the effect of RM on the travel time. The reduction percentage could be up to 15%. At the last one hour, when the travel time reliability was low, more significant improvement could be found.

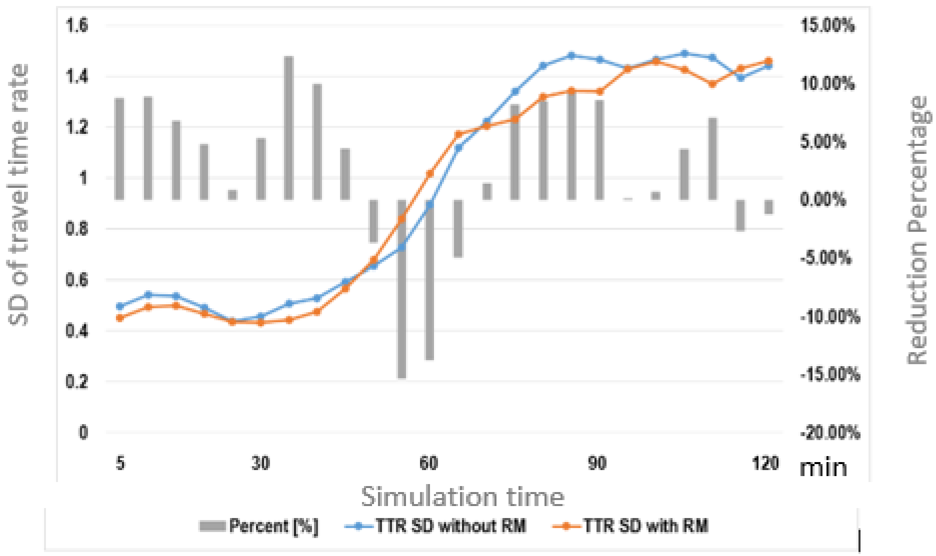


Figure 189. SD of TTR of base condition and condition with RM on the I-4 EB mainline

B. Impact of travel time reliability on arterials/collectors and whole corridor network

Figures 190 and 191 show SD of TTR on arterials/collectors and the whole network. The two figures show that no significant impact could be found on arterials/collectors and the whole network. It indicates that RM could improve the travel time reliability on freeways without bringing negative impacts on arterials/collectors.

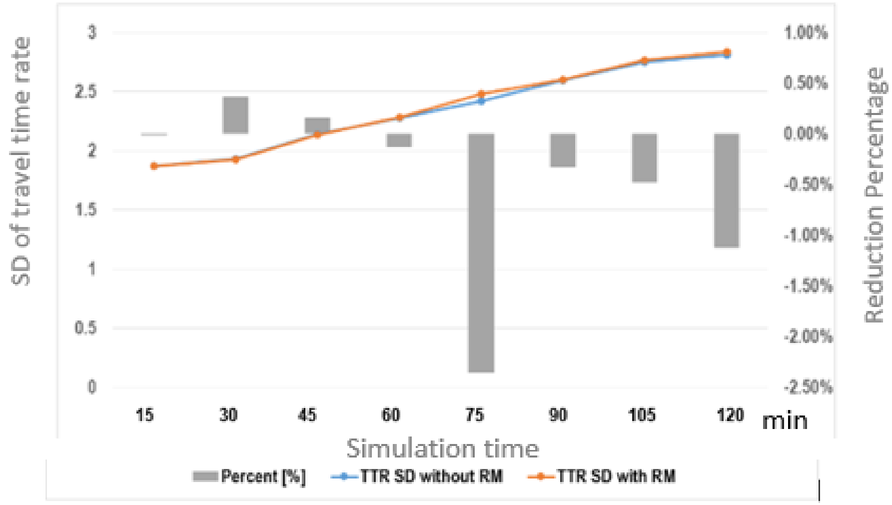


Figure 190. SD of TTR of base condition and condition with RM of arterials/collectors

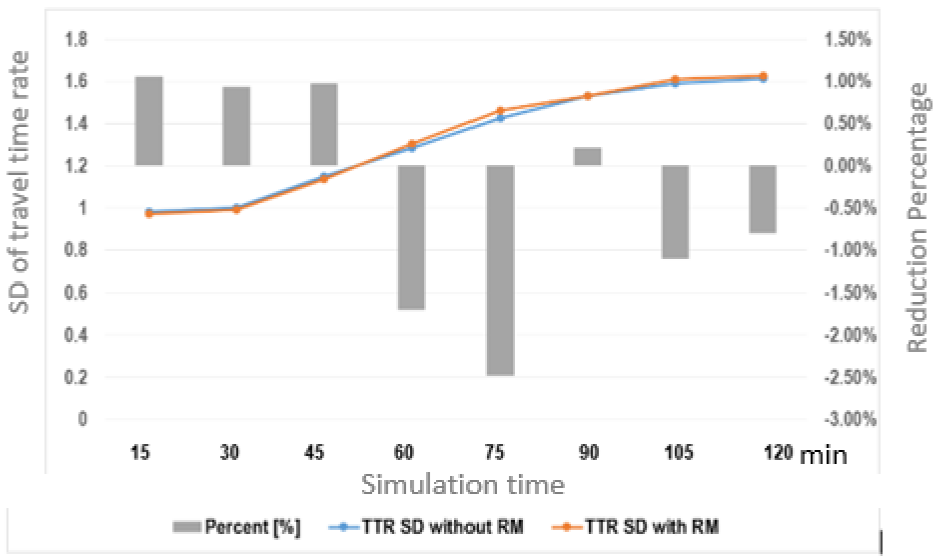


Figure 191. SD of TTR of base condition and condition with RM of the whole network

9.5.4.3. Traffic safety

The average predicted crash risk was utilized as MOEs to evaluate the safety effectiveness of RM. Figure 192 shows the average predicted crash risk on the whole I-4 EB section with and without RM (base condition) for every 5 minutes during the simulation. This figure clearly shows that the implementation of RMs could reduce the crash risk on the I-4 EB, especially for the high-risk situation. The percentage of average crash risk reduction could be up to 22.73%. Overall, the average reduction of crash risk on I-4 EB is 5.75%. Figure 193 shows the average crash risk on all arterials and collectors. No significant change could be found on arterials and collectors.

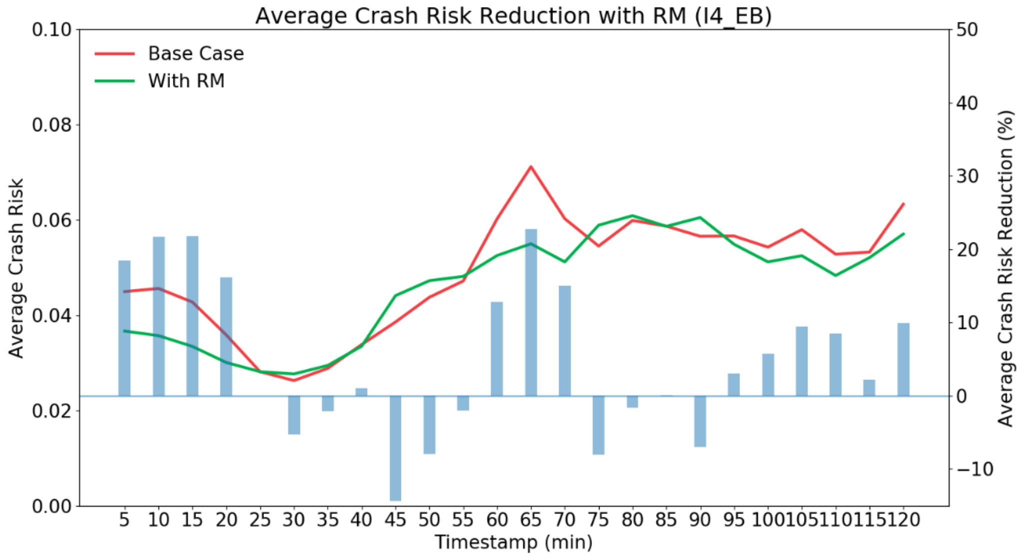


Figure 192. Average crash risk on I-4 EB under base condition and RM condition

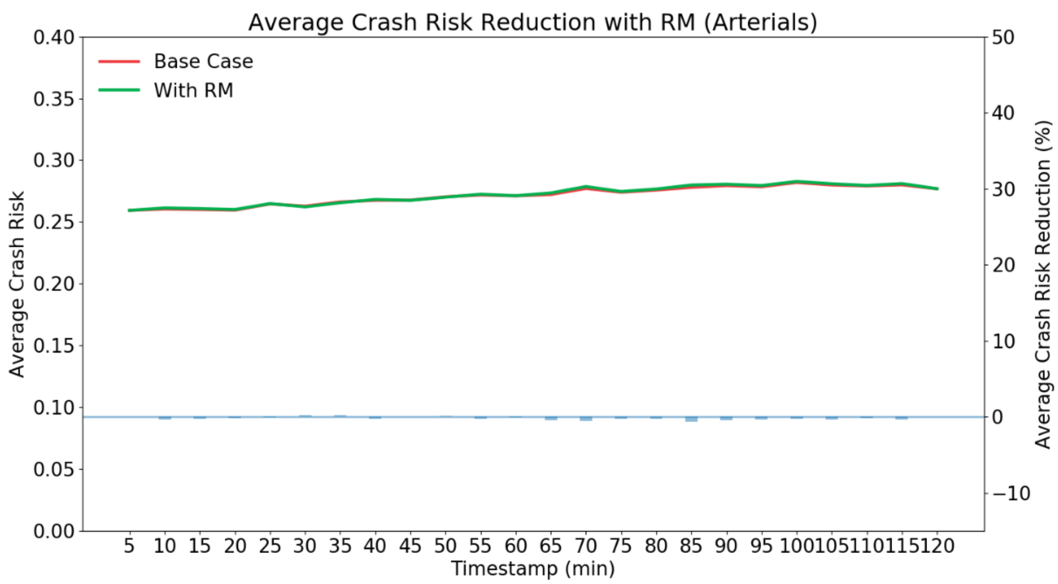


Figure 193. Average crash risk on arterials/collectors under base condition and RM condition

9.5.4.4. Discussions

This section aims at assessing the effectiveness of ramp metering in the study area. A rigorous selection was firstly conducted based on the critical segments and Ramp Metering Warrants from literatures to identify locations which might benefit from the metering. Three on-ramps on I-4 eastbound were carefully selected. Then, ramp meters based on ALINEA algorithm with queue control were implemented on the selected on-ramps in the simulation. The results showed that the proposed RM could reduce the travel time, increase the travel time reliability, increase the throughput of freeway mainlines, and reduce the crash risk while no significantly adverse impact could be found on arterials/collectors. However, the proposed RM is not perfect. The queue control scheme of proposed RM should be improved by refining algorithm, implementing more detectors or coordinating with ramp signals. Also, the coordination of ramp meters with other IATM strategies such as detour routing, is needed to eliminate the side effects of RM.

9.6. Summary

In this task, four IATM strategies (i.e., variable speed limit, queue warning, ramp metering, detour routing) were evaluated through the microscopic simulation. The I-4 corridor network in the Orlando city, which was among the critical corridors in Chapter 7, was selected for the effectiveness evaluation. The selected corridor network included both freeways and arterials/collectors. Also, multiple on ramps and off ramps which connect freeways and arterials/collectors were included.

The effectiveness of each strategy for IATM was analyzed in terms of traffic efficiency, travel time reliability, and traffic safety. This analysis included both arterials/collectors as well as mainlines and ramps of I-4 to confirm the impact of the strategies on the whole network. As measures of the traffic efficiency, travel time and travel time rate were used. The measures of the traffic efficiency were analyzed in the three traffic states and in the spatial along the stretch of the I-4. For the travel time reliability, standard deviation of travel time rate was used. Models to estimate the standard deviation of travel time rate were developed for both freeways and arterials/collectors by using real traffic data, as this measure could not be obtained directly from the simulation. In addition, by using real-time crash risk models developed by the previous studies of the research team, the traffic safety was assessed to verify whether each control strategy affect traffic safety negatively. Finally, the impact of each strategy on arterials/collectors was evaluated.

According to the evaluation results, VSL at segments with traffic turbulence due to on/off ramps, incidents, and roadworks can reduce travel time and improve travel time reliability and safety. To be specific, the benefits of the VSL could be obtained during transitional and congested traffic state. Thus, in order to achieve the maximum effectiveness of VSL, VSL strategy should be activated in advance before the congested traffic state and implemented on upstream sections of a bottleneck. Similarly, QW in the congested traffic state with queues could reduce travel time and improve travel time reliability and traffic safety. Furthermore, RM strategy controlling traffic demand of on-ramps on the stretch of freeways was able to diminish travel time and ameliorate travel time reliability and traffic safety. The benefits of the RM can also be achieved in the transitional state and congested state. Finally, DR strategy could have a benefit in terms of efficiency when a freeway mainline at the downstream is heavily congested. However, it is required to consider a proper detour rate according to traffic conditions of the whole network, and adjustment for traffic signal control.

For the impacts of the four strategies on arterials/collectors, VSL and QW would not negatively affect the arterials. In addition, RM would not have an adverse impact on the adjacent arterials when the installation of ramp meters follows the warrants. However, the DR strategy could have a direct adverse impact on arterials/collectors, especially for the detour arterials/collectors. Therefore, the DR strategy should be applied deliberately. During the recurring congestion, travel times of several competitive routes should be provided because there might not be enough capacity at the surrounding arterials/collectors. Whereas, for the non-recurring congestion, it is necessary to adjust the available capacity of arterials/collectors on the detour route according to the amount of traffic demand following the detour guidance.

The evaluation results suggested that the four test strategies could generally improve traffic efficiency and travel time reliability without bringing significantly negative safety impacts. Based on the various real-time traffic conditions, it is obvious that each strategy would have different activation conditions and have different effectiveness. At the corridor level, it is important to conduct integrated analysis of the effects by each strategy to make sure the strategy would not cause serious negative impact on either freeways or arterials/collectors. Hence, it is necessary to combine different strategies by integrating the traffic on both freeways and arterials/collectors. In the following task, a decision support system will be developed to find the proper strategies and their control parameters through the predefined control sets through an integrated approach. Also, the side effects of the control strategies on other roads beyond the study corridor will be analyzed by using the calibrated hybrid simulation.

CHAPTER 10. DEVELOPMENT OF DECISION SUPPORT SYSTEM FOR IATM

10.1. Overview

As effective traffic congestion management strategies including recurring and non-recurring traffic congestion, active traffic management (ATM) and integrated corridor management (ICM) are typical cases integrating traffic management strategies such as Variable Speed Limits (VSL), Queue Warning (QW), Ramp Metering (RM), and so on. ATM aims to maximize the effectiveness of ATM strategies by using the synergistic relationships between traffic management strategies through the integration of conventional systems, which are usually independently operated. Additionally, the purpose of ICM is to exert synergy among networks by maximizing the utilization of the existing infrastructure assets such as freeways and arterials. A representative strategic area is balancing traffic demand in the corridor or network. The load balancing can be performed by implementing ramp metering, reversible lanes, hard shoulder running lanes and so on. Therefore, Decision Support System (DSS) for an Integrated Active Traffic Management (IATM) is developed to achieve the synergistic relationships among traffic management strategies (VSL, QW, and RM) and also the synergy effect between freeways and arterials through the load balancing by ramp metering.

As the travel time reliability has been considered as a traffic network performance measure in the objectives of the current programs such as ATDM, ICM, and TSM&O, it is required that DSS should contribute to improving travel time reliability. Among various measures to quantify the travel time reliability, standard deviation (SD) of travel time rate (TTR; minute per mile) as a statistical range measure was adopted in this research. Although there are many approaches of ATM strategies, representative three strategies including variable speed limits

(VSL), queue warning (QW), and ramp metering (RM) were selected in order to develop the DSS considering travel time reliability during traffic congestion. Although detour routing and adaptive signal control strategies should be applied in DSS to maximize the effectiveness of IATM, the two strategies are not included in DSS because the two strategies should be coordinated with signal control and are out of the scope of this project.

Section 10.2 summarizes the previous research related to DSS. Section 10.3 describes major components of the DSS developed to achieve the synergy effect among traffic management strategies and load balancing between freeways and arterials. Section 10.4 presents two study sites, the downtown I-4 corridor network and the northern SR4- 417 corridor network, for the effectiveness analysis of the developed DSS. Section 10.5 accounts for possible operational combinations among VSL, QW, and RM under the different traffic congestion. Section 10.6 analyzes the synergetic relations between traffic management strategies (VSL, QW, and RM) through their combinations, which is used to derive static generic decision rule. Section 10.7 describes the effectiveness of the developed DSS in the dynamically changed traffic congestion. Finally, Section 10.8 recommends generic rules to select a proper ATM strategy and concludes the effectiveness of the developed DSS. For this research, 420 simulation runs were undertaken.

10.2. Literature Review

Decision Support Systems have been developed and used to assist operators' decision-making in various traffic circumstances. Casas et al. (2014) presented today's generic architecture of decision support systems for traffic management systems, which consist of several components: real-time data, historical data, monitoring, predictive system, and strategy analysis (see Figure 194). The real-time data include all kinds of data such as traffic data, weather data, incidents, special events. The historical data is to be accumulated from the real-time data. The monitoring identifies and classifies the state of the traffic network in real time. The predictive system is intended to predict the state of traffic networks through analytical models and simulation-based models using real time and historical data. Finally, strategy analysis is designed to determine a set of strategies and recommend a best strategy through a set of performance measures for the strategy evaluation. Selecting a set of strategies depends on the operators' knowledge, and indicators evaluating the strategies can be determined in various aspects.

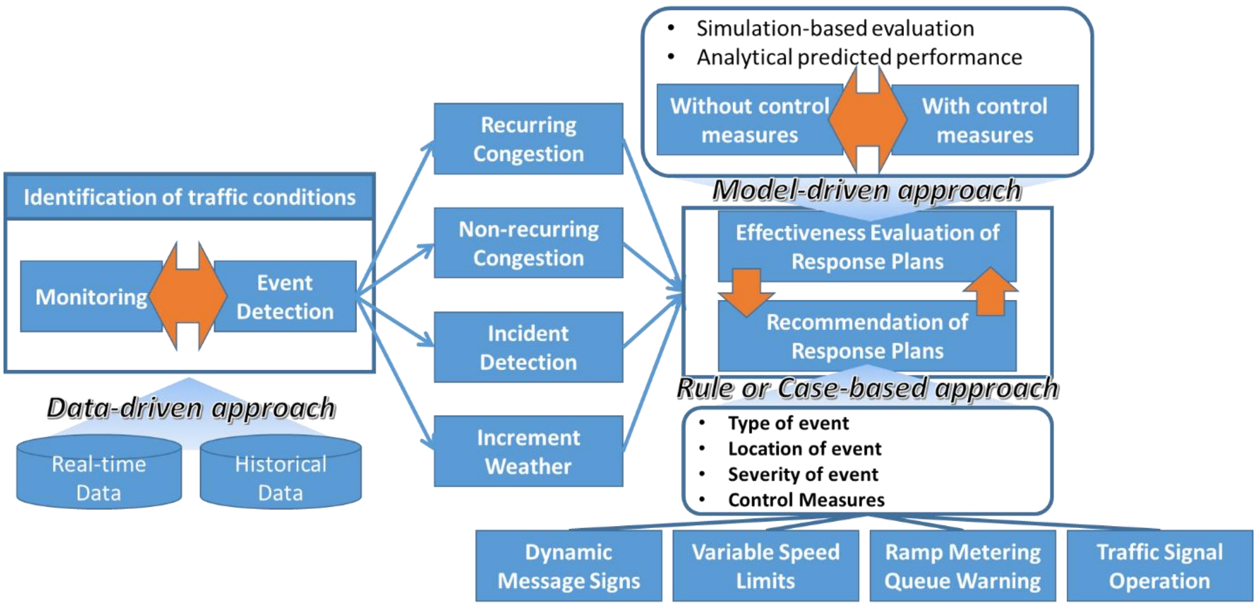


Figure 194. Generic overview of DSS

10.2.1. Knowledge (Rule)-based DSS

The first decision support system based on expert system approach was introduced to aid traffic signal control operation for urban traffic control in 1987 (Foraste & Scemama, 1987). The initial expert system approach made the knowledge base using the facts to contain objects representing the network (i.e., links, intersections, routes, zones, and subzones), and the rules to make the expert lines of reasoning. Cuena (1989) presented the AURA (Accessor Urbanos Regulados Automaticamente) expert system for traffic control in urban motorways. AURA's knowledge representation includes a prediction knowledge, an interpretation knowledge to identify traffic incidents, and a knowledge base to recommend traffic control decisions. These were formulated in a role form. Cuena et al. (1992) showed KITS (Knowledge-based Intelligent Traffic Control Systems) architecture to model and apply traffic control knowledge. KITS' functionalities, roles, and modeling approach were presented (Boero, 1993; Boero et al, 1994; Cuena et al., 1992; J Cuena, Hernández, & Molina, 1994). For adaptive traffic management systems, Cuena et al. (1995) proposed a general structure for real-time traffic management support using knowledge-based models. The decision support model for real-time traffic management was based on agent models and used traffic signal operations and VMS (Variable Message Signs) as treatments for traffic management. Especially, a traffic simulator was used to build traffic models in the offline mode. To enhance agent-based models, Hernandez et al. (2002) proposed a multi-agent architecture for intelligent traffic management systems including congestion warning, weather information, incident notification with diversion of traffic, speed control and so on. Ossowski et al. (2005) presented an abstract architecture for multi-agent DSS and showed examples to deal with real-world problems. Considering a new conceptual architecture, Dunkel et al. (2011) proposed a reference architecture for event-driven traffic management systems.

To provide decision supports for traffic management center operators in integrated freeway and arterial traffic management systems, Ritchie (1990) suggested a knowledge-based decision support architecture, using a new artificial intelligence-based solution approach, for advanced traffic management. Main functions of the knowledge-based DSS are incident detection by algorithmic methods, incident verification by CCTV, identification and evaluation of predefined alternative responses and actions, implementation of selected response(s), and monitoring recovery through the selected measures of effectiveness (MOE's). Representative possible responses are as follows:

- Modifying surface street signal timing plans
- Initiating ramp metering changes
- Coordination of ramp meters and surface street traffic signal timing
- Activating freeway major incident traffic management teams
- Locating and activating freeway mobile and ground-mounted changeable message signs (including composition of messages)
- Activating changeable message signs on surface streets and approaches to freeway access ramps (including composition of messages)
- Selecting and implementing signed traffic detours and so on

10.2.2. DSS Using Real-Time Traffic Simulation

Some experts concentrated on research of decision support systems for effective traffic incident management. Hu et al. (2003) proposed a real-time evaluation and decision support system for incident management, which is composed of preprocess module, decision support module and monitoring module (see Figure 195). The preprocess module has three functions: data screening, data fusion, and incident detection. The decision support module includes neural-network-based expert system, which can overcome the fuzziness of decision-making in rule-based expert systems, data mining, real-time microscopic traffic simulation (PARAMICS; PARAllel MICroscopic Simulator) to estimate the impact of the incident (e.g. delay and queue length), and comprehensive evaluation. The monitoring module has functions of traffic monitoring and before/after evaluation. The neural networks have self-study abilities in adjusting their own parameters to changing situations.

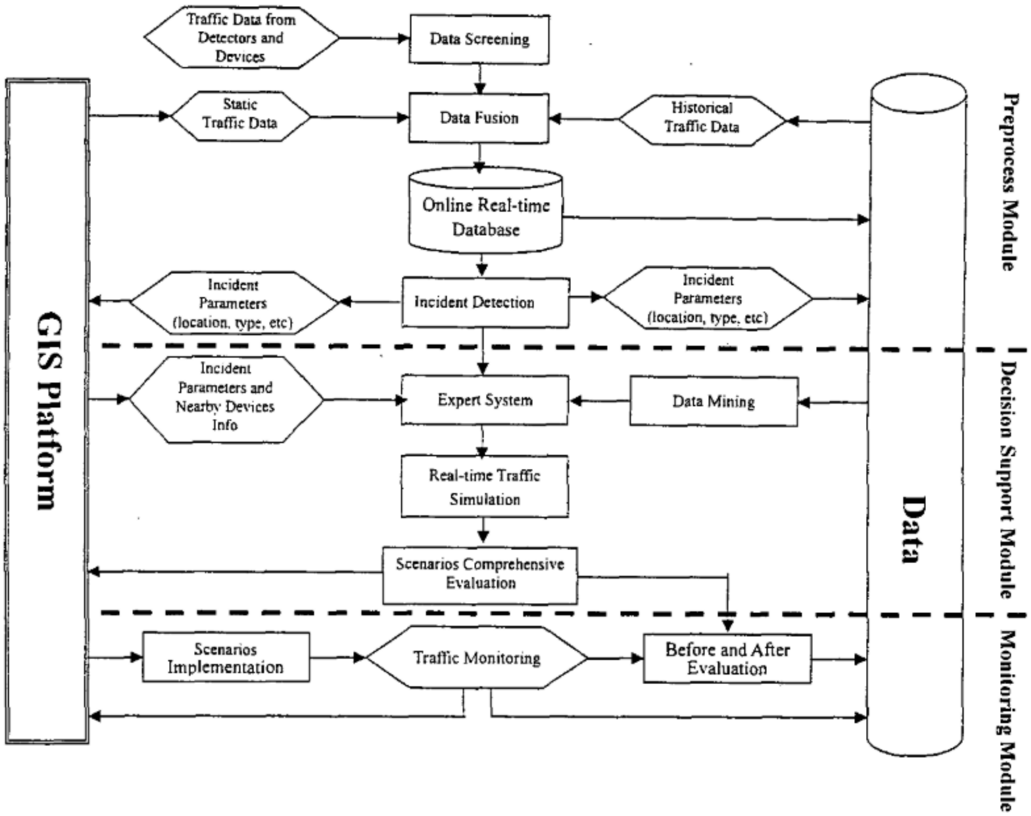


Figure 195. Working process of the real-time evaluation and decision support system (Hu et al., 2003)

Similarly, Chen et al. (2005) suggested a self-learning-process based decision support system, which contains expert knowledge-based choice, case-based reasoning, and real-time simulation, for Beijing traffic management. A mesoscopic large-scale network dynamic simulation was used to identify problems and evaluation was performed by indicators. The simulation is based on Dynamic Traffic Assignment (DTA).

Shah et al. (2008) proposed a system architecture of a decision support system for freeway incident management in the Republic of Korea, which is based on traffic simulation. The main function of the decision support system is to predict impacts of traffic incidents by using traffic volume and speed. There was no explanation of decision support algorithms or techniques.

For weather responsive traffic signal operations, Kim et al. (2014) developed real-time simulation-based decision support system to reduce the impact of weather and keep the target network service level (see Figure 196). The decision support system consists of real-time traffic estimation and prediction system (TrEPS), scenario manager, and scenario library. The TrEPS, which has two prototypes: DYNASMART-X (H. S. Mahmassani, 1998) and DynaMIT-R (Ben-Akiva et al., 1998), estimates current traffic conditions and predicts the future traffic conditions with/without an alternative control strategy. The scenario manager provides functions to identify and assess alternative signal control strategies based on TrEPS-predicted network states. The scenario library stores predetermined weather-responsive signal timing plans, which the scenario manager uses in real time. Performance measures including mean travel time, total travel time, mean stopped time, and standard deviation of travel time were used decide an alternative traffic signal control.

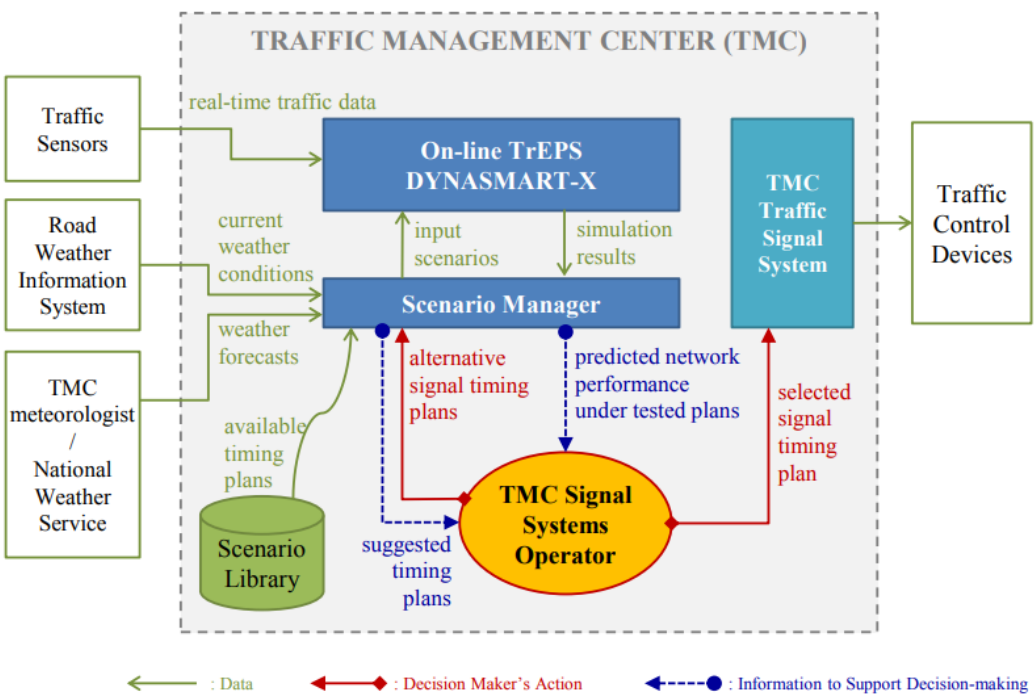


Figure 196. Framework of TrEPS-based decision support system for weather-responsive traffic signal operations (Kim et al., 2014)

Still, real-time traffic simulation has a limitation, which is to analyze many strategies in real time within allowable computational budgets. Osorio and Bidkhori (2012) proposed a simulation-based optimization (SO) algorithm to execute on-line traffic simulation under few runs. The simulation-based optimization algorithm uses a Metamodel approach combining information from the simulation model with information from an analytical probabilistic traffic model, which is a network model based on finite capacity queueing theory.

10.3. Decision Support System for IATM

In this project, the developed decision support system consists of several components: collection of real-time traffic data, recommendation of response plans, effectiveness evaluation of response plans, and selection of a response plan (see Figure 197). Since the current DSS cannot be linked to the real traffic operation system, AIMSUN traffic simulation was used instead. Possible response plans were created on the basis of the control rules of VSL, QW, and RM strategies. In the practical aspect, the logic of each strategy was selected and adjusted for this study.

As a core part of the DSS, the effective evaluation of response plans uses two models: METANET to predict the near-future traffic status depending on control values of three strategies and travel time variability estimation model using the standard deviation of travel time rate.

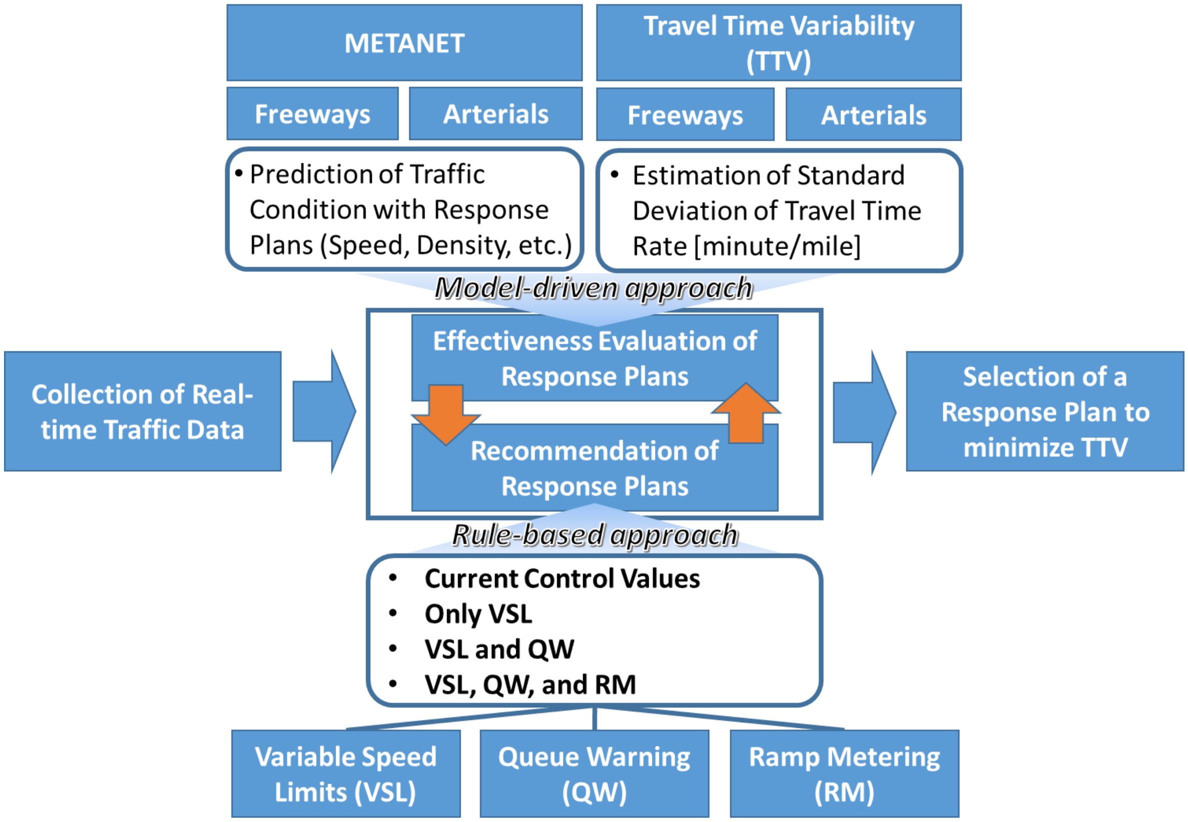


Figure 197. Decision support system configuration

10.3.1. Rules of Active Traffic Management Strategies

10.3.1.1. VSL (Variable Speed Limits) Control Rule

Variable Speed Limits (VSL), which is sometimes referred to as Dynamic Speed Limits (DSpL) or speed harmonization, is a vital active traffic management system (ATM) strategy. It is used to provide appropriate speed limits to drivers, who are required to respond to the change in traffic conditions due to bottlenecks, low visibility, slippery pavement, etc. Specifically, it is known that the VSL has been applied to defer or prevent the onset of traffic congestion, decrease speed variation, mitigate shockwaves, increase throughput, and smoothen traffic flow. In order to find the appropriate speed limits, real-time or predicted traffic conditions should be used on the basis of the goals/objectives of traffic management. So far, many algorithms have been developed to select the appropriate speed limits. Regarding the drivers' acceptance of VSL, the VSL can be regulatory or advisory, depending on local traffic control policies. Usually, it is recommended to use regulatory speed limits to achieve high compliance rate to maximize the benefits of the VSL.

Although numerous advanced VSL algorithms were developed, still many agencies are using simple reactive rule-based algorithms and showed various benefits to traffic safety or efficiency in previous research (Abdel-Aty et al., 2008; Abdel-Aty et al., 2006; Bham et al., 2010; Khondaker and Kattan, 2015). Considering applicability in the field and also scalability in the traffic simulation, a simple, but representative and practical, online VSL algorithm was provided and developed in this study (see Figure 198). The basic logic is that speed limits are changed toward the 85-percentile speed if there is a difference between the posted speed limit and the 85-percentile speed. This type of logic has been applied in Florida, Oregon, and Washington states (Katz et al., 2017). In Figure 5, N is the number of VSL control considered. At each time step t, the temporal speed variability minimization first from the downstream to the upstream. Once the temporal speed variability minimization is done (i.e., i>N), the VSL values at different locations would be determined based on the spatial speed variability minimization from the upstream to the downstream. Noteworthy, at the beginning of the VSL control, the default VSL value is the speed limit for the segment.

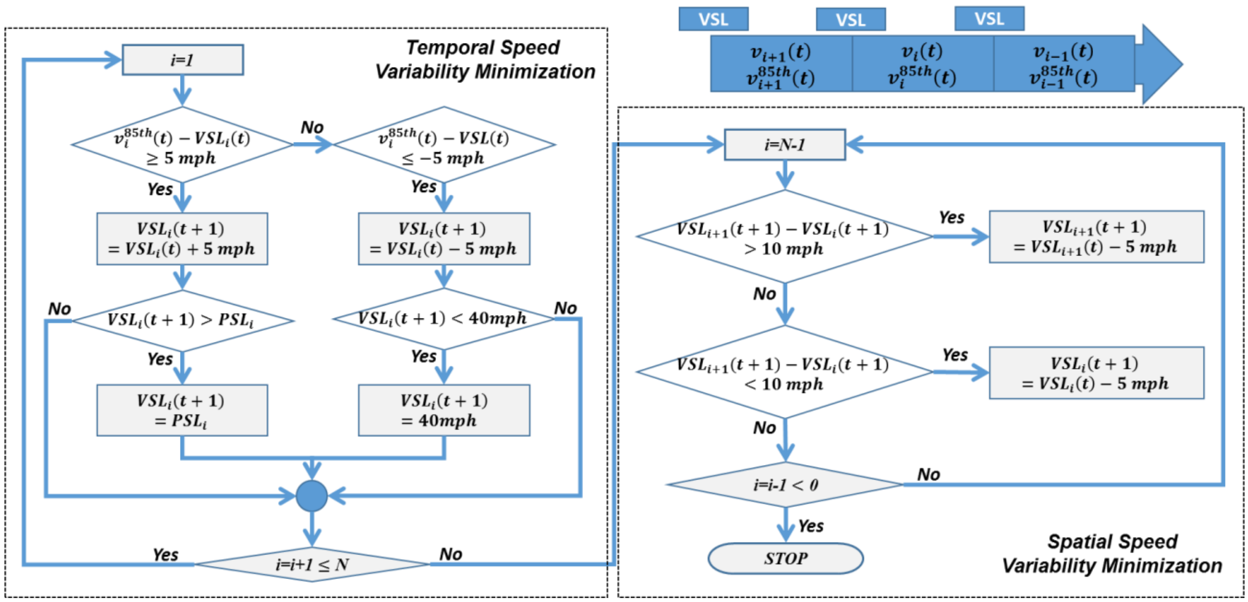


Figure 198. VSL control logic

Additionally, operational constraints proved in the previous research were considered to make sure that the implemented VSL would not introduce any negative safety impacts. The constraints are as follows:

- The maximum difference between two neighboring posted speed limits should be 10 mph (spatial constraint) (Yu and Abdel-Aty, 2014).
- The maximum difference of posted speed limits between two consecutive VSL control time steps should be 10 mph (temporal constraint) (Abdel-Aty et al., 2008; Yu and Abdel-Aty, 2014).
- An increment of VSL at the same VSL control location should be 5 mph (i.e., gradually change) (Abdel-Aty et al., 2006).
- Variable Speed Limit should be updated by 5 minutes (Yu and Abdel-Aty, 2014).
- The minimum variable speed limit should be 40 mph (Abdel-Aty et al., 2008).
- The posted speed limit should never exceed the design speed on the freeway.

10.3.1.2. QW (Queue Warning) Control Rule

Queues occur due to three major causes: recurring traffic congestion, work zones, and incidents (Wiles et al., 2003). Basically, the queue warning (QW) strategy has been used to alert drivers to the existence of the queue in downstream or guide them to choose proper lanes. So, it was deployed with the intention of reducing rear-end crashes and improving traffic safety, and also improving the available roadway capacity. The alerts and guidance can be provided through various methods: static signing, variable message sign (VMS), lane control signals (LCSs), incident response vehicles, and in-vehicle devices. In terms of active traffic management (ATM) strategies, static signs are not included in the QW strategy. Especially, the QW strategy in this research considered LCS and VMS.

Recently, QW systems in ATM can be regarded as an extension of VSL systems (Fuhs, 2010; HNTB, 2013; Mirshahi et al., 2007a; Strömgren & Lind, 2016; Tignor et al., 1999). It is because that the queue warning signs can be displayed as warning messages with either recommended speeds or lane control signs. In Europe, most of the queue warning is integrated as one of the components in a speed harmonization system. A queue warning system on a motorway in Denmark is activated when speed is less than 50 km/h (31 mph) (Wiles et al., 2003). The queue warning is displayed as speed limits and drivers see successive VMS with predefined speed limits of 90, 70, and 50 km/h (56, 44, and 31 mph) until they meet the end of queue. In Sweden, motorway control systems on the E4 employed QW system (recommended speed without a red ring) and dynamic speed limits (with a red ring) (Strömgren & Lind, 2016). The signs with/without a red circle are intended to improve the perception of drivers. For instance, in the UK, a red ring was used to indicate that the speed limits were regulatory and utilized to enforce speed violation. When drivers will see the speed in a red ring, they will think the sign is the speed limit. On the contrary, when drivers see the speed without a red ring, they will consider that the speed sign is the advisory speed, not the speed limits. In the system, the QW is activated and a speed of 70 km/h (44 mph) is recommended when the automatic accident detection algorithm detects that the speed is lower than 45 km/h (28 mph). Otherwise, speed harmonization can be activated in the dense traffic condition and then the advisory speed limits are displayed as 80 km/h (50 mph).

QW can be provided by alert messages (e.g., “STOPPED VEHICLE AHEAD”, and “SLOW VEHICLE AHEAD”) or recommended speeds. In this study, the recommended speed was used for precise traffic control. The QW strategy using recommended speeds can be implemented in the simulation for the effectiveness analysis.

In order to implement a QW algorithm with recommended speeds, three aspects are considered:

- Detecting segments in which queues exist
- Deciding recommended speeds in segments with queues
- Guiding speed reduction gradually

For the QW activation, segments with queues should be detected. The queue existence of a segment was determined when the average speed of the segment is less than 40 mph. Thus, VSL and QW could be activated and separated at different speed ranges consistently. When the average speed of segments is more than 40 mph, speed limits would be determined through a VSL algorithm. On the contrary, the QW algorithm would work in case of less than 40 mph.

Additionally, recommended speeds in segments with queues were more specified in this project as follows:

- The recommended speed is 40 mph, if the average speed of a segment is between 35 and 40 mph
- The recommended speed is 35 mph, if the average speed of a segment is between 30 and 35 mph
- The recommended speed is 30 mph, if the average speed of a segment is between 25 and 30 mph
- The recommended speed is 25 mph, if the average speed of a segment is between 20 and 25 mph
- The recommended speed is 20 mph, if the average speed of a segment is less than 20 mph

For the gradual speed reduction of upstream traffic from a segment under queue state, the size of the gradual speed reduction was determined as a constant value of 5 mph. Maximum 2 upstream segments from the segment under queue state were controlled for the gradual speed reduction. Depending on the recommended speed of segments with queues, if the upstream segments are not under queue state, the upstream segments' recommended speeds can be determined as follows:

- When the recommended speed for the queue segment is 40 mph, the first upstream segment is 45 mph and the second upstream segment is 50 mph.
- When the recommended speed for the queue segment is 35 mph, the first upstream segment is 40 mph and the second upstream segment is 45 mph.
- When the recommended speed for the queue segment is 30 mph, the first upstream segment is 35 mph and the second upstream segment is 40 mph.

- When the recommended speed for the queue segment is 25 mph, the first upstream segment is 30 mph and the second upstream segment is 35 mph.
- When the recommended speed for the queue segment is 20 mph, the first upstream segment is 25 mph and the second upstream segment is 30 mph.

Figure 199 shows an example of the gradual speed reduction of upstream segments when the average speed of the segment with a queue state is 30 mph.

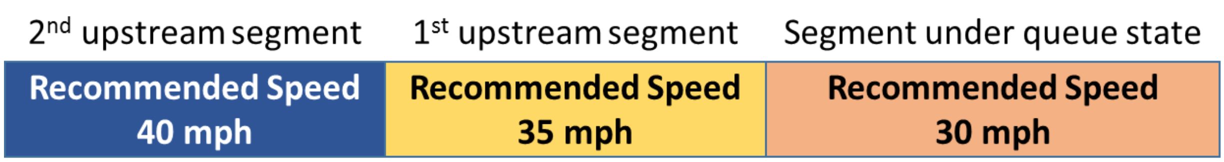


Figure 199. An example of the gradual speed reduction of upstream segments

10.3.1.3. RM (Ramp Metering) Control Rule

Ramp meters are traffic signals installed on the on-ramps of limited-access freeways/expressways to control vehicles entering the freeway/expressway mainline. It is well-accepted that ramp metering allows efficient use of freeways/expressways mainline capacity by managing the inflows and reduces the crash risk of freeway merging area by breaking up platoons of merging vehicles considering the limited gaps (Papageorgiou & Kotsialos, 2002).

The ramp metering algorithms can be divided into pre-planned metering algorithms and traffic responsive metering algorithms. The pre-planned metering algorithms recommend a fixed metering rate that is not related to the current traffic state on mainline. In contrast, the traffic responsive metering is directly affected by the current traffic state on mainline and ramp. The metering rate is selected based on the real-time traffic variables (e.g., occupancy). In the traffic responsive metering, the control logic also can be divided into closed loop and open loop control.

The closed loop control is a feedback control to incorporate updated measurements in addition to the initial state (e.g., ALINEA). In the open loop control, one of many predefined metering rates is selected based on the current measurement and, which can be easily integrated with other strategies.

In this study, an open loop control method was selected, which can provide predefined metering rates based on traffic variables such as occupancy and volume. With reference to the previous studies (Blumentritt et al., 1981; McDermott, Kolenko, & Wojcik, 1979), local actuated metering rates were applied. Table 77 shows that the actuated metering rates can be selected according to the mainline occupancy. The cycle length and green time were tested and adjusted to generate the pre-defined metering rate in the microscopic traffic simulation.

Table 77. Local actuated metering rates as a function of mainline occupancy

Occupancy (%)	Metering Rate (Vehicle/Minute)	Metering Rate (Vehicle/Hour)	Cycle Length	Green Time
≤ 10	12	720	10	6
11 – 16	10	600	10	5
17 – 22	8	480	10	4
23 – 28	6	360	15	6
29 – 34	4	240	15	4
> 34	3	180	20	4

10.3.2. A Macroscopic Traffic Flow Model for the Freeway and Arterial Network

This research uses a model predictive control (MPC) approach, which has been applied to various ATM strategies of freeway networks (Hegyi, 2004). Usually, model predictive control uses a model to anticipate the near-future change of the traffic flow when a control is applied to the existing traffic flow status. The most important part of the MPC approach is to select a model to well represent the change of traffic flow according to the control values of traffic strategies. Considering the applicability of various ATM strategies and the integration of freeways/expressways and arterials/collectors, the well-known METANET model was utilized, a deterministic macroscopic modeling tool using a second-order traffic flow model. The METANET model is able to simulate all types of traffic statuses, incidents reducing capacity, and also traffic control actions such as ramp metering, variable speed limits, and queue warning. It should be noted the Cell Transmission Model (CTM) could also be used for the traffic flow prediction. The research team decided to use METANET since previous studies found that the METANET model could offer more accurate representation of the prevailing traffic conditions (Spiliopoulou et al., 2014).

10.3.2.1. Freeway Traffic Model

In the METANET model, the macroscopic traffic flow is described through the definition of adequate variables representing the average behavior of the vehicles at certain freeway segments "i" and times "t" (Papageorgiou et al., 1989, 1990). Freeway stretches are split into segments with length of L_i and λ_i lanes, which have traffic density, mean speed, and traffic volume. By using the discretized time and space, traffic density $\rho_i(k)$ [vehicle/lane/mile] is defined as the number of vehicles in the segment at time $t = kT$ divided by the segment length L_i where $k = 0, 1, 2, \ldots$ is the discrete time index, and T indicates the simulation time interval. In the same way, $v_i(k)$ denotes the mean speed [mph] of vehicles in the segment at time $t = kT$. Finally, traffic volume $q_i(k)$ [vehicle/hour] is the number of vehicles leaving the segment during $kT < t < (k+1)T$, divided by T. T is the time step used for traffic flow prediction, chosen T=(1/60) hour in this study. The macroscopic traffic flow model for each segment i is composed of the following equations:

$$\rho_i(k+1) = \rho_i(k) + \frac{T}{L_i \lambda_i}[q_{i-1}(k) - q_i(k) + r_i(k) - s_i(k)]$$

$$q_i(k) = \rho_i(k) \cdot v_i(k) \cdot \lambda_i$$

$$v_i(k+1) = v_i(k) + \frac{T}{\tau}[V[\rho_i(k)] - v_i(k)] + \frac{T}{L_i} v_i(k)[v_{i-1}(k) - v_i(k)]$$

$$- \frac{\nu * T}{\tau * L_i} \frac{\rho_{i+1}(k) - \rho_i(k)}{\rho_i(k) + \kappa} - \frac{\delta * T}{L_i \lambda_i} \frac{q_\mu(k) * v_{m,1}(k)}{\rho_i(k) + \kappa}$$

$$- \frac{\phi * T * \Delta\lambda}{L_i \lambda_i} \frac{\rho_{i,N_i}(k) * v_{i,N_i}(k)^2}{\rho_{cr,i}}$$

$$V[\rho_i(k)] = v_f * exp\,[-\frac{1}{a}(\frac{\rho_i(k)}{\rho_{cr}})^a]$$

where v_f, ρ_{cr} denotes the free-flow speed and the critical density of freeways/expressways, respectively. $a, \tau, \nu, \kappa, \delta$ and ϕ are constant parameters to be estimated.

To illustrate flow-density diagram regarding speed limit, a quantified model was used, which was developed by Papageorgiou et al. (1989). The impact of the control of speed limits on the flow-density diagram is quantified as follows:

$$v_f' = v_f \cdot b(k)$$

$$\rho_{cr}' = \rho_{cr} \cdot [1 + A \cdot (1 - b_i(k))]$$

$$a' = a \cdot [E - (E - 1) \cdot b_i(k)]$$

where v_f, ρ_{cr}, and a represent the condition under the posted speed limits; A and E are constant parameters that represent the impact of the changed speed limit on the fundamental diagram. The value of A and E was chosen as 0.69 and 1.76 estimated by the previous study (Yu and Abdel-Aty, 2014). $b_i(k)$ denotes the optimal VSL rates that should be implemented for segment i at time step k, where $b_i(k) \in [b_{min}, 1]$ as $b_{min} \in (0,1)$ is the lowest admissible bound for the VSL rates.

By using traffic data collected from AIMSUN simulation, constant parameters of METANET were calibrated through the deterministic Nelder-Mead algorithm, which can provide converged robust model parameter sets and also reduce computation time (Spiliopoulou et al., 2017). The calibrated parameters are $v_f = 61$ mph, $\rho_{cr} = 51$ veh/lane/mile, $a = 3.315$, $\tau = 0.019$, $\kappa = 33.52$, $\delta = 0.838$ and $\phi = 0.784$.

10.3.2.2. Arterial Traffic Model

In this study, it is necessary to consider not only freeways/expressways but also arterials/collectors to develop the decision support system. Therefore, a METANET for arterials/collectors should also be developed and integrated with a METANET for freeways/expressways. The METANET for arterials/collectors should describe traffic congestion realistically and reflect the effect of strategies on arterials/collectors. For example, when a ramp metering is being implemented on a freeway, it should reflect the effect of the queue on the arterial. However, a complicated model for arterials/collectors could cause computational inefficiency, so a simple model with low computation cost is needed.

This study presented a simple model to estimate travel time in a link based on density. This method is similar to volume-delay function (VDF) or link-congestion function that reproduces traffic speed or travel time in a link based on traffic volume. The VDF can reproduce congestion effects in macroscopic models and can be applied for various purposes. However, there was a limitation in the application to the operational level (i.e., controlled by vehicle unit) due to the assumption that the volume can exceed capacity (Kucharski & Drabicki, 2017). This assumption could lead to unrealistic results in congested traffic in terms of traffic operations

(Kucharski & Drabicki, 2017). To overcome this issue, we presented the METANET for arterials/collectors by using density instead of volume.

This model considered the traffic flows of adjacent arterials/collectors and ramps entering and leaving a target link. As shown in Figure 200, in the target link *i*, the inflow, f_{in}, is the sum of the entering flows from arterials/collectors ($f_{in,j}$) and off-ramp (r_{off}), and the outflow, f_{out}, is the sum of the leaving flows to arterials/collectors ($f_{out,j}$) and on-ramp (r_{on}). The density of link i is calculated as follows:

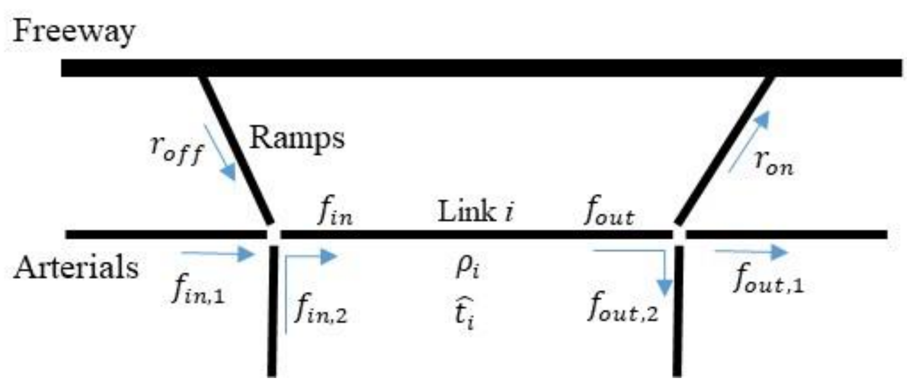


Figure 200. METANET for arterial

$$\rho_i(k+1) = \rho_i(k) + f_{in}(k) - f_{out}(k)$$

$$f_{in}(k) = \sum_j f_{in,j}(k) + r_{off}$$

$$f_{out}(k) = \sum_j f_{out,j}(k) + r_{on}$$

where, ρ is density and k is time step. Based on the density, the travel time in the link i is estimated as follows, and this equation is called as density-based delay function (Kucharski & Drabicki, 2017; Olszewski et al., 1995):

$$\widehat{t_i(k)} = L \times t_0 \left(1 + a \left(\frac{\rho_i(k)}{\rho_c}\right)^b\right)$$

where, $\hat{t}$, and t_0 are estimated travel time and free-flow travel time. L is link length, ρ_c is critical density, and a and b are calibrated parameters. The parameters were calibrated in this project by the deterministic Nelder-Mead algorithm: t_0= 104.189768 (sec), $\rho_c = 51.066247$ (veh/km), $a = 2.540349$, and $b = 0.991533$.

10.3.3. Travel Time Reliability Model

For the evaluation of travel time reliability (TTR) through simulation results, it is required to develop a model to convert the results to travel time reliability measures based on historical data. However, it is practically impossible to reproduce all kinds of real-world traffic conditions related to traffic demand, incidents, events and weather conditions through traffic simulation. Instead, the travel time reliability can be estimated through models, which could estimate measures related to travel time reliability. Among various measures for the travel time reliability, standard deviation (SD) of travel time rate regarding travel time variability was selected in this project. Because it was proved and well-known that there is a linear relationship between travel time rate and its standard deviation (Mahmassani et al., 2013). The SD of TTR models for freeways/expressways and arterials have been developed in Section 9.2.2. SDs of TTR were aggregated for the selected routes or network. Usually, VMT-weighted or distance-weighted mean values were computed to get the aggregated evaluation measures for freeways/expressways and arterials/collectors. In this study, the VMT-weighted mean method at each time slot was used as follows:

$$\overline{TTR}_{network}(t) = \frac{\sum_{i=1}^{n} VMT_i(t) \times TTR_i(t)}{\sum_{i=1}^{n} VMT_i(t)}$$

$$\overline{SD}_{network}(t) = \frac{\sum_{i=1}^{n} VMT_i(t) \times SD_i(t)}{\sum_{i=1}^{n} VMT_i(t)}$$

where, $\overline{TTR}_{network}(t)$ = Network-level VMT-weighted Mean TTR at time slot "t",

$\overline{SD}_{network}(t)$ = Network-level VMT-weighted Mean SD of TTR at time slot "t",

$VMT_i(t)$ = Vehicle Miles Traveled of link "i" at time slot "t",

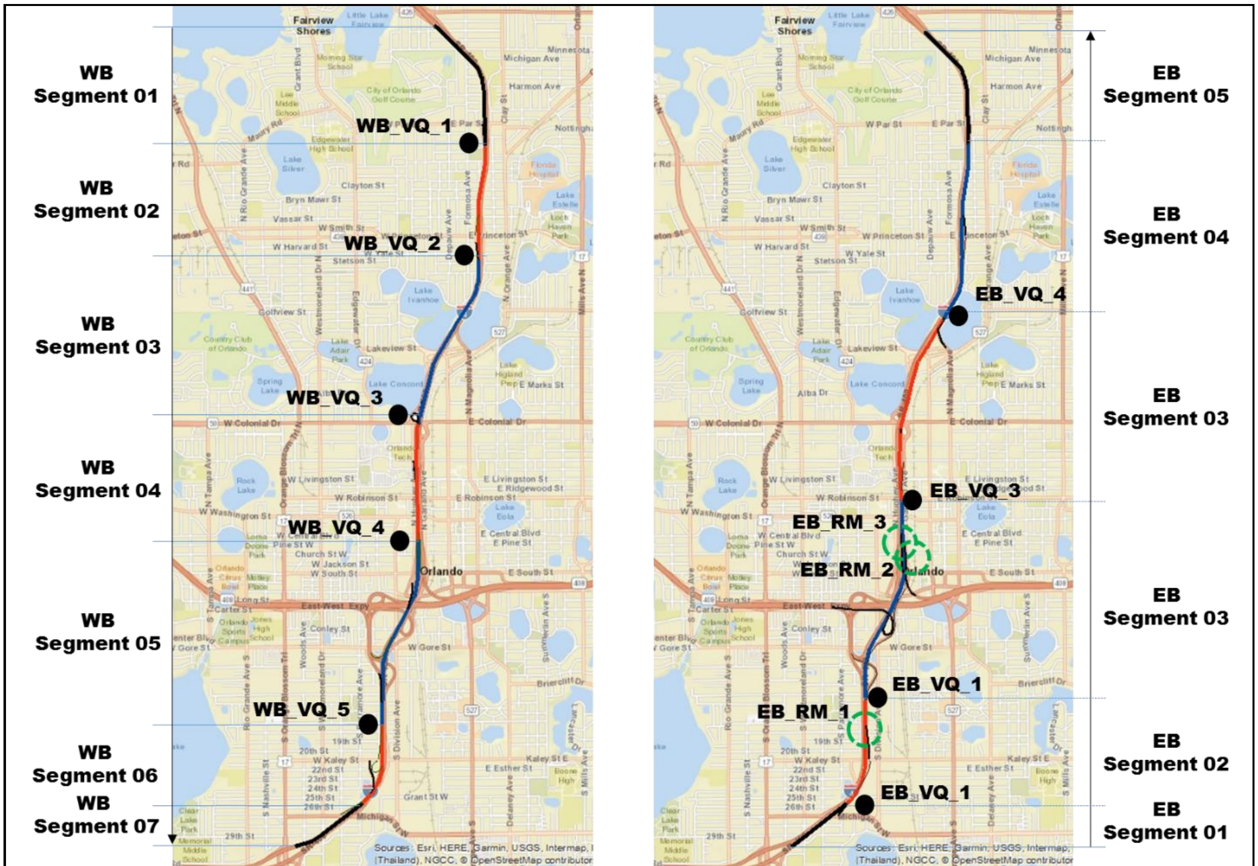
$TTR_i(t)$ = Mean TTR of vehicles passing link "i" at time slot "t",

$SD_i(t)$ = Standard Deviation between vehicles of link "i" at time slot "t".

10.4. Study Sites for the Evaluation of DSS

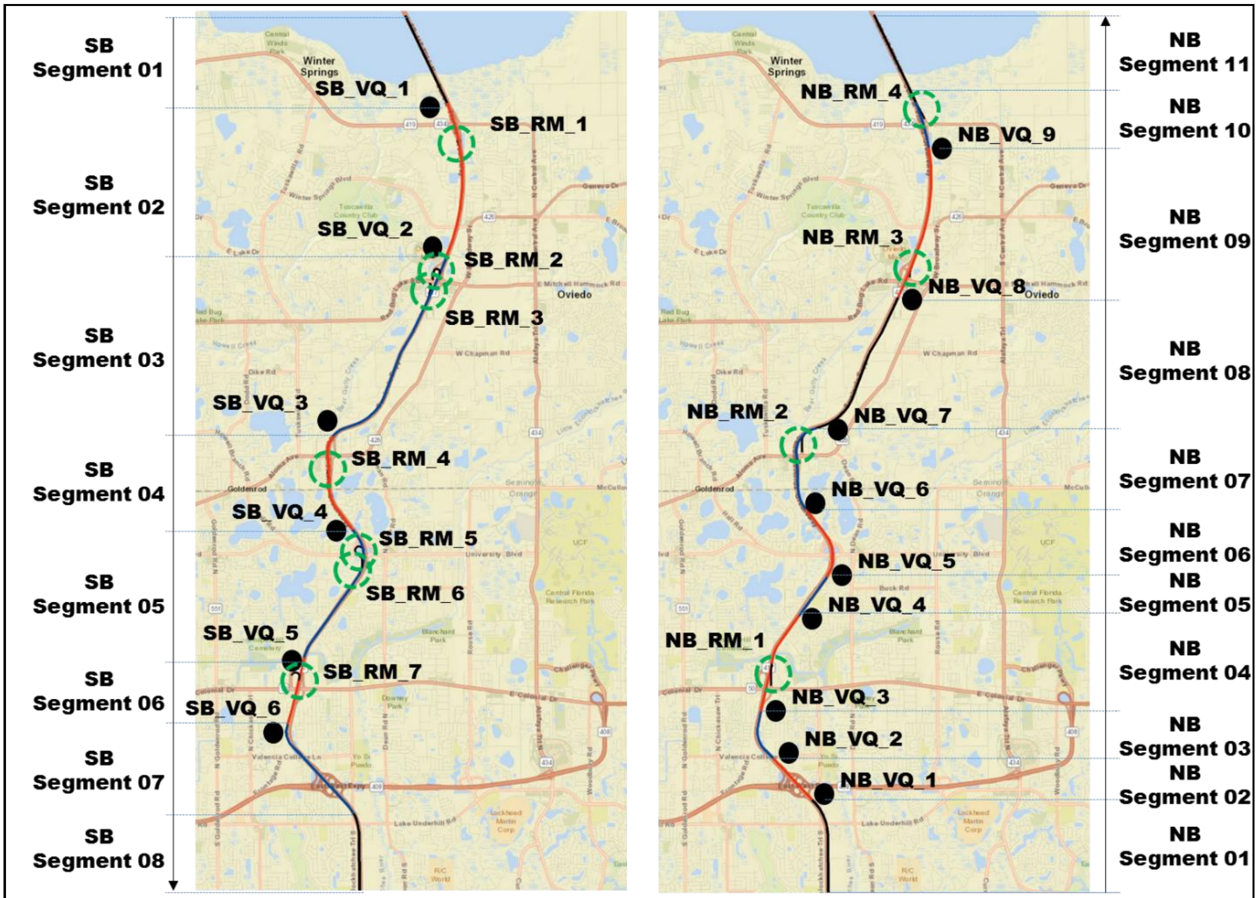
10.4.1. Two Corridor Networks

An Interstate 4 (I-4) corridor network in the Orlando downtown area between West Michigan Street and East Par Street was chosen, which has the most congested bottlenecks in the Orlando Metropolitan area (see Figure 201). In addition, a northern SR4- 417 corridor network between SR 408 and Lake Jesup was chosen (see Figure 202). The posted speed limit on the about 6-mile freeway of I-4 is 55 mph, and SR4- 417 with approximately 15 miles is 70 mph. There are 9 and 8 on-ramps on the eastbound and westbound of I-4, respectively. The northbound and southbound of SR4- 417 have 4 and 7 on-ramps, respectively.



Note:
- VQ: VSL and QW, WB: Westbound, and EB: Eastbound
- Different colors are given to the segments and on-ramps to identify them.

Figure 201. Study site of the downtown I-4 corridor network



Note:

- VQ: VSL and QW, WB: Westbound, and EB: Eastbound
- Different colors are given to the segments and on-ramps to identify them.

Figure 202. Study site of the northern SR4- 417 corridor

10.4.2. Selection of VSL and QW Deployment Location

Harbord (Harbord, 1998) recommended that standard gantries displaying VSL should not be located more than 1 km apart in order to help drivers see the next VSL signs. In addition, Abdel-Aty et al. (Abdel-Aty et al., 2006) suggested that speed limits should be displayed within a short distance (2 miles) for traffic safety improvement. According to the deployment guideline of VSL harmonizing European ITS services, speed limits should be showed repeatedly and also the spacing between the VSL gantries should not be exceeded more than 10 km (6 miles) (EasyWay, 2015). FHWA (Federal Highway Administration) guidelines state that VSL should be installed at regular intervals and the reduced speed limits should not be displayed more than 1 mile upstream from the critical sections related to wet weather (Katz et al., 2012). In conclusion, VSL should be located at a certain distance so that drivers can recognize and react to it.

Considering the general guidelines of VSL deployment, the VSL locations were placed before the start of the interchange. The average installation spacing is about 1 mile. Figures 8 and 9 show the exact locations and segments of VSL. In addition, QW signs are located in the same location of VSL because VSL and QW would usually be integrated in a composite gantry and also the QW strategy could be implemented as an extension of VSL. When the queue is detected in the downstream segments, QW signs and advisory speeds would be provided concurrently according to the QW control method.

10.4.3. Selection of RM Deployment Location

While RM has many benefits, it might not be applicable for every freeway on-ramp. It is required that a rigorous selection of the potential locations of RM deployment to be conducted. Then, the proposed RM strategies are deployed on the selected on-ramps in the microscopic traffic simulation. The following ramp metering warrants developed in 2011 for the State of Florida (Gan et al., 2011) were considered:

- **Mainline Speed**: Ramp signaling is warranted at a location where the average mainline speed during the peak hour is less than 50 mph.
- **Ramp Volume**: Ramp signaling is warranted at a location if the following conditions are met:
  - For a ramp with a single lane, ramp signaling is considered when the peak hour on ramp volume is between 240 and 1,200 vph.

- For a ramp with multiple lanes, ramp signaling is considered when the peak hour onramp volume is between 400 and 1,700 vph.

- **Ramp Storage**: Ramp signaling is warranted at a location where the ramp storage distance is longer than the queuing length estimated by the following equation:

$$L = 0.25V - 0.00007422V^2$$

where, L: required single-lane storage distance (meter)
V: peak hour ramp demand (vph)

- **Total Mainline and Ramp Volume**: Based on the previous study which developed ramp metering warrants in 2011 for the State of Florida (Gan et al., 2011), ramp signaling is warranted when any of the following conditions is met:

  Condition 1: The summation of peak hour mainline volume and ramp volume exceeds the following threshold values depending on the total number of mainline lanes including auxiliary lanes:

  - If there are two lanes, warrant is met when total volume is greater than 2,650 vph
  - If there are three lanes, warrant is met when total volume is greater than 4,250 vph
  - If there are four lanes, warrant is met when total volume is greater than 5,850 vph
  - If there are five lanes, warrant is met when total volume is greater than 7,450 vph
  - If there are six lanes, warrant is met when total volume is greater than 9,050 vph
  - If there are more than six lanes, warrant is met when total volume is greater than 10,650 vph

  The summation of peak hour mainline volume and ramp volume exceeds the following threshold values

  Condition 2: Peak hour volume of the rightmost lane exceeds 2,050 vph.

According to the ramp metering warrants, three ramps for the downtown I-4 corridor and eleven on-ramps for the northern SR4- 417 corridor were selected. Although the actual peak hour volume of SR4- 417 does not meet the warrants, the adjusted traffic volume for the traffic congestion of SR4- 417 meet the above warrants. Figure 8 and 9 show the locations of the selected on-ramps for the ramp metering strategy.

10.5. Evaluation Environment and Indicators for Possible IATM Strategies

10.5.1. Generation of Different Traffic Conditions

In order to create reasonable simulation scenarios representing real-world traffic flow in the Orlando area, possible scenarios related to IATM can be created on the basis of traffic condition and possible operational strategies of IATM. In this research, IATM is an integrated system of ATM strategies that not only evaluated in real-time the traffic operation performance of both freeways/expressways and arterials/collectors, but also integrate them.

The effectiveness of IATM system on a corridor network linking freeways/expressways and arterials/collectors was analyzed according to different traffic conditions. Especially, the effect of IATM system was evaluated under traffic congestion. The traffic congestion of freeway/expressway in corridor networks was categorized into three classes:

- Extreme Traffic Congestion: Average vehicle speed less than 25 mph
- Heavy Traffic Congestion: Average vehicle speed between 25 mph and 35 mph
- Moderate Traffic Congestion: Average vehicle speed between 35 mph and 45 mph

If the speed is over 45 mph, the network is categorized as non-congested. According to the calibrated and validated traffic condition (see Table 78), the eastbound and westbound of I-4 experience extreme and moderate traffic conditions. Both directions of SR417 are non-congested. In order to generate different traffic conditions, the traffic demand of I-4 and SR417 were adjusted. The traffic demand of I-4 was also reduced by 80% and 90% of the original traffic demand to generate different levels of congestion. The traffic demand of SR417 was increased by 150% and

170% to generate traffic congestion to examine the IATM strategies and the Decision Support System (DSS), and to reach generic DSS rules that are implementable in Florida. Table 79 shows the traffic conditions created from the adjusted traffic demand. Cases (Case-3, Case-4, Case-6 and Case-8) related to the non-congested traffic conditions were not used for the analysis of effectiveness of IATM strategies. In addition, the westbound of I-4 corresponding to Case-2, Case-6, and Case-8 was excluded from the final analysis because there is no on-ramp metering system that meet the warrants and could be implemented.

Table 78. Traffic condition of the calibrated and validated I-4 and SR-417

Roadway	Traffic Demand	Direction	Mean Speed [mph]	Mean Travel Time Rate [minute/mile]	Traffic Condition	Case
I4	Two peak hours	Eastbound	24.0	2.534	Extreme	Case-1
		Westbound	38.5	1.558	Moderate	Case-2
SR417	Two peak hours	Northbound	61.0	0.984	Non-congestion	Case-3
		Southbound	57.3	1.048	Non-congestion	Case-4

Table 79. Traffic condition of I-4 and SR-417 based on the adjusted traffic demand

Roadway	Traffic Demand	Direction	Mean Speed [mph]	Mean Travel Time Rate [minute/mile]	Traffic Condition	Case
I-4	90% of two peak hours	Eastbound	29.8	2.015	Heavy	Case-5
		Westbound	53.5	1.122	Non-congestion	Case-6
I-4	80% of two peak hours	Eastbound	40.6	1.479	Moderate	Case-7
		Westbound	59.6	1.007	Non-congestion	Case-8
SR417	145% of two peak hours	Northbound	39.3	1.525	Moderate	Case-9
		Southbound	38.7	1552	Moderate	Case-10
SR417	170% of two peak hours	Northbound	29.9	2.004	Heavy	Case-11
		Southbound	30.1	1.993	Heavy	Case-12

10.5.2. Possible Operational Scenarios of IATM Strategies

Based on VSL, QW, and RM, the possible operational scenarios of IATM strategies were evaluated as follows:

- Only VSL
- Only QW
- Only RM
- VSL and QW (VSL/QW)
- VSL and RM (VSL/RM)
- QW and RM (QW/RM)
- VSL, QW, and RM (VSL/QW/RM)

The effectiveness of the above IATM strategies was analyzed based on the predetermined traffic conditions: extreme, heavy, and moderate traffic congestion. These analyses would help to determine the appropriate combination of strategies for the different traffic conditions.

For the effectiveness analysis of the possible operational strategies, the traffic simulation was run for the seven combinations between three IATM strategies and three different traffic demands of the downtown I-4 and Northern SR4- 417 areas. For each control strategy under each traffic demand, ten runs were conducted at each simulation area. Hence, a total of 420 simulations (7 combinations of control strategies*3 traffic demands*2 study areas* 10 runs) were conducted to test different IATM controls. Considering that the average running time is about 30 minutes, totally 210 hours were undertaken without considering the system debugging and adjustments. Initial results also accounted for route diversion, but any increase of traffic volume on an already congested arterial might not be feasible without other measures that are beyond the scope of this project, e.g., new adaptive signal control algorithms. Thus, in this work we check the effect of the three above mentioned strategies on the arterials/collectors and the whole network to guarantee no detrimental effects beyond the freeways/expressways occur.

10.5.3. Roadway Traffic Condition Indicators

Though there are many kinds of roadway traffic condition indicators to evaluate transportation problems and solutions, this research focused on the travel time index (TTI) and travel time rate (TTR, minute/mile). The traffic congestion of roadways and their segments can be measured by the travel time index (TTI). The TTI is defined as the ratio of average travel time to a free-flow or speed-limit travel time:

$$\text{Travel Time Index (TTI)} = \frac{\text{Average Travel Time}}{\text{Travel Time}_{\text{free flow or speed limit}}}$$

The TTI represents how much longer travel time is spent on average on the basis of the ideal traffic condition. All travel times were converted into Travel Time Rate (TTR) through the normalization by the distance of each link as follows (Jenks et al., 2008; Lomax & Margiotta, 2003):

$$\text{Travel Time Rate (TTR; minute/mile)} = \frac{\text{Travel Time (minute)}}{\text{Distance of each Link (mile)}}$$

TTR has been used in the calculation of the different travel time reliability measures. Based on the positive near-linear relation between the SD of TTR and the mean TTR (Mahmassani et al., 2012), the change of TTR can be considered as the change of travel time reliability.

10.6. Evaluation Results of Possible Operational Strategies of IATM

10.6.1. Analysis Results of the I-4 Corridor Network in Downtown Orlando Area

10.6.1.1. Extreme Traffic Congestion

In the study sites, the eastbound of the downtown I-4 (Case-1) has extreme traffic congestion. There are three on-ramps that could be metered in the eastbound of I-4 for the critical segments (see Figures 201 and 202). Table 80 shows the result of the effect of IATM strategies under extreme traffic congestion. QW significantly improved overall TTR of I-4 at a 90% confidence interval and TTI of I-4 at a 95% confidence interval, which did not have a negative impact on arterials/collectors. Furthermore, RM or other strategies including RM improved the TTR and TTI, which are statistically significantly different from the traffic condition without any IATM strategies at a 95% confidence interval. In cases of QW/RM and VSL/QW/RM, it seems that QW slightly expedites the effect of RM. However, RM or other combined strategies that includes RM have a negative impact on arterials/collectors in the downtown I-4 corridor network, which is also statistically significant. It represents that the traffic capacity of arterials/collectors under extreme traffic congestion cannot accommodate additional traffic flow due to the traffic capacity reduction of on-ramps caused by RM.

Table 80. TTR and TTI of the I-4 EB under the extreme traffic congestion.

CASE-1		No strategy	VSL alone	QW alone	RM alone	VSL /QW	VSL /RM	QW /RM	VSL/QW/RM
EB I-4	TTR	2.534	2.449	2.399**	2.205**	2.436	2.237**	2.196**	2.179**
	TTI	2.360	2.281	2.235**	2.056**	2.268	2.087**	2.048**	2.063**
Arterials/ collectors	TTR	3.920	3.910	3.872	4.083**	3.921	4.120**	4.109**	4.134**
	TTI	1.951	1.947	1.929	2.024**	1.953	2.044**	2.039**	2.030**

Note:
- The value of each cell is the average TTR [minute/mile] or TTI of 10 replications with different random seeds.
- The comparison results were tested statistically through the paired test (Wilcoxon signed-rank test)
- ** This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at 95% confidence interval.
- * This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at 90% confidence interval.

10.6.1.2. Heavy Traffic Congestion

The effects of IATM strategies under the heavy traffic congestion of I-4 were analyzed through Case-5 (the eastbound of I-4 with 90% of the original traffic demand). Table 81 shows the result of the effect of IATM strategies under the heavy traffic congestion. As with the results of the extreme traffic congestion, RM and other strategies including RM statistically significantly improved travel time rate on the eastbound of I-4 at a 95% confidence interval. Meanwhile, RM, VSL/RM, and QW/RM do not have a significantly negative impact on arterials/collectors. In the corridor networks with the heavy traffic congestion, it shows that RM for some of the on-ramps based on the ramp metering selection warrants of FDOT can improve the traffic flow condition of freeways/expressways while minimizing a negative impact on arterials/collectors. However, VSL/QW/RM has a negative impact on arterials/collectors at a 90% confidence interval.

Table 81. TTR and TTI of the I-4 EB under the heavy traffic congestion

CASE-5		No strategy	VSL alone	QW alone	RM alone	VSL /QW	VSL /RM	QW /RM	VSL/Q W/RM
I4 EB	TTR	2.015	1.972	2.027	1.884*	1.969	1.742*	1.730*	1.855*
	TTI	1.877	1.831	1.872	1.753*	1.827	1.625*	1.614*	1.730*
Arterials /collecto rs	TTR	3.654	3.535	3.553	3.665	3.540	3.606**	3.627**	3.690**
	TTI	1.820	1.766	1.773	1.824	1.767	1.797*	1.807*	1.836*

Note:
- The value of each cell is the average TTR [minute/mile] or TTI of 10 replications with different random seeds.
- The comparison results were tested statistically through the paired test (Wilcoxon signed-rank test)
- ** This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at 95% confidence interval.
- * This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at 90% confidence interval.

10.6.1.3. Moderate Traffic Congestion

The effects of IATM strategies under the moderate traffic congestion of I-4 were analyzed through Case-5 (the eastbound of I-4 with 80% of the original traffic demand). Table 82 shows the result of the effect of IATM strategies under the moderate traffic congestion. Although VSL improved TTR in CASE-5, CASE-5 did not show statistically significant improvement. Also, RM, VSL/RM, and VSL/QW/RM reduced TTR significantly at a 95% confidence interval without a negative impact on arterials/collectors. When RM is required, it seems that the integrated operation of VSL/QW/RM or VSL/RM is more proper for moderate traffic congestion than RM-alone.

Table 82. TTR and TTI of the I-4 under the moderate traffic congestion

CASE-7		No strategy	VSL alone	QW alone	RM alone	VSL /QW	VSL /RM	QW /RM	VSL/QW/RM
I4 EB	TTR	1.479	1.460	1.494	1.414*	1.482	1.418*	1.437	1.414**
	TTI	1.375	1.359	1.390	1.317*	1.379	1.321*	1.338	1.317**
Arterials/collectors	TTR	3.243	3.232	3.243	3.240	3.201	3.231	3.234	3.232
	TTI	1.627	1.623	1.628	1.625	1.609	1.621	1.622	1.623

Note:
- The value of each cell is the average TTR [minute/mile] or TTI of 10 replications with different random seeds.
- The comparison results were tested statistically through the paired test (Wilcoxon signed-rank test)
- ** This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at 95% confidence interval.
- * This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at 90% confidence interval.

10.6.2. Analysis Results of the Northern SR417 Corridor Network in East Orlando Area

10.6.2.1. Heavy Traffic Congestion

The effects of IATM strategies under the heavy traffic congestion of SR417 were analyzed through Case-11 (the northbound of SR417 with 170% of the original traffic demand) and Case-12 (the southbound of SR417 with 170% of the original traffic demand). As shown in Table 83, RM and other strategies including RM statistically significantly improved TTR and TTI on the northbound and southbound of SR417 at a 95% confidence interval. However, RM, VSL/RM, QW/RM, and VSL/QW/RM had a negative impact on arterials/collectors. In addition, it was confirmed that VSL-alone strategy improved TTR and TTI on the mainline of the southbound of SR417. However, VSL/QW affected adversely the northbound mainline of SR417.

Table 83. TTR and TTI of the SR-417 under the heavy traffic congestion

CASE-11/12		No strategy	VSL alone	QW alone	RM alone	VSL /QW	VSL /RM	QW /RM	VSL/Q W/RM
SR417 NB (Case-11)	TTR	2.004	1.958	2.103**	1.890**	2.120**	1.853**	1.862**	1.848**
	TTI	2.371	2.314	2.485**	2.239**	2.505**	2.195**	2.204**	2.187**
SR417 SB (Case-12)	TTR	1.993	1.941*	2.109	1.278**	1.993	1.252**	1.265**	1.315**
	TTI	2.350	2.289*	2.486	1.503**	2.350	1.472**	1.486**	1.546**
Arterials/col lectors	TTR	4.956	4.926	4.927	5.335**	4.949	5.365**	5.339**	5.348**
	TTI	3.289	3.268	3.269	3.517**	3.289	3.538**	3.524**	3.525**

Note:
- The value of each cell is the average TTR [minute/mile] or TTI of 10 replications with different random seeds.
- The comparison results were tested statistically through the paired test (Wilcoxon signed-rank test)
- **This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at 95% confidence interval.
- * This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at 90% confidence interval.

10.6.2.2. Moderate Traffic Congestion

As presented in Table 84, the effects of IATM strategies under the moderate traffic congestion of SR417 were analyzed through Case-9 (the northbound of SR417 with 145% of the original traffic demand) and Case-10 (the southbound of SR417 with 145% of the original traffic demand). Although VSL did not improve TTR and TTI in the northbound of SR417, the southbound o SR417 shows statistically significant improvement of TTR and TTI at a 90% confidence interval without a negative impact on the adjacent arterials/collectors. Also, RM, VSL/RM, and QW/RM reduced TTR and TTI significantly at a 95% confidence interval. However, all RM-including strategies have a significantly negative impact on arterials/collectors. Therefore, it seems that VSL can be applicable for the corridor network with moderate traffic congestion when strategies related to ramp metering cannot be chosen.

Table 84. TTR and TTI of the northern SR-417 corridor network under the moderate traffic congestion

		No strategy	VSL alone	QW alone	RM alone	VSL /QW	VSL /RM	QW /RM	VSL/QW/RM
SR417 NB (CASE-9)	TTR	1.525	1.550	1.564	1.354**	1.621**	1.372**	1.350**	1.370**
	TTI	1.803	1.832	1.848	1.602**	1.915**	1.623**	1.597**	1.621**
SR417 SB (CASE-10)	TTR	1.552	1.499*	1.544	1.160**	1.564	1.153**	1.151**	1.153**
	TTI	1.831	1.769*	1.820	1.364**	1.844	1.356**	1.354**	1.357**
Arterials/collectors	TTR	4.043	4.078	4.071	4.356**	4.050	4.351**	4.329**	4.348**
	TTI	2.680	2.707	2.702	2.868**	2.687	2.867**	2.851**	2.863**

Note:
- The value of each cell is the average TTR [minute/mile] or TTI of 10 replications with different random seeds.
- The comparison results were tested statistically through the paired test (Wilcoxon signed-rank test)
- ** This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at 95% confidence interval.
- * This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at 90% confidence interval.

10.6.3. Discussions

According to the effectiveness analyses results of seven types of IATM strategies on the downtown I-4 corridor network and the northern SR417 corridor network, it is obvious that the integration of IATM strategies is more favorable than stand-alone individual IATM strategies. Furthermore, it can be seen that it is difficult to determine only one IATM strategy for the different types of traffic congestion. Effects of each IATM strategy are as follows:

- VSL-alone strategy achieves the statistically significant improvement of TTR and TTI in the moderate and heavy traffic conditions (see Case-2, Case-10, and Case-12) without a negative impact on arterials/collectors during the recurring and non-recurring traffic congestion. However, VSL-alone strategy did not improve significantly TTR and TTI in the extreme traffic congestion. This shows that VSL does not work on over-congested conditions. Specifically, it can be recommended that DSS should deactivate VSL when V/C (Volume/Capacity) is less than 1 (Franz, 2018).

- QW-alone improved TTR of the mainline of freeways/expressways in the extreme traffic condition (see Case-1).

    - In all cases, RM-alone improved TTR of the mainline of freeways/expressways. But, only Case-5 and Case-7 did not deteriorate the overall TTR and TTI of arterials/collectors. Therefore, related to the RM implementation, it is not necessary to select all on-ramps for the target corridor network. Choice of on-ramps based on the ramp metering selection warrants of FDOT can improve TTR and TTI on the mainline of freeways/expressways and also can avoid the increase of TTR and TTI on the arterials/collectors.

- The integration of VSL and QW does not have a statistically significant improvement in TTR and TTI in any types of traffic congestion.
- Most of RM-integrated IATM strategies have a negative impact on arterials/collectors adjacent to freeways/expressways although RM and RM-included IATM strategies alleviated traffic congestion on freeways/expressways. However, Case-5 and Case-7 show that strategic selection of on-ramp metering can mitigate the negative impact on arterials/collectors during the recurring congestion. The strategic selection means that some on-ramps related to the bottleneck can be chosen, not all on-ramps.

10.7. Effectiveness of IATM Strategies with DSS

The IATM system on a corridor network linking freeways/expressways and arterials/collectors can be built in various forms. Since the IATM system will have at least more than two strategies, the stand-alone systems such as VSL-alone, QW-alone, and RM-alone was not included in the possible operation strategies of IATM. Also, VSL/QW was excluded because it is related to only freeways/expressways. Eventually, for the evaluation of the developed DSS, four types of the system regarding the IATM strategies can be established as follows:

- VSL and RM without DSS (VSL/RM)
- QW and RM without DSS (QW/RM)
- VSL, QW, and RM without DSS (VSL/QW/RM)
- VSL, QW, and RM with DSS through METANET (DSS)

Each type was executed 10 times with different random seeds, and the average result was reported for the final evaluation. Simulation results were analyzed into three aspects: freeway, arterial, and overall network (see Figures 203 and 204). The effects of DSS were analyzed in two scopes: 1) the eastbound I-4 and the I-4 adjacent arterials/collectors, and 2) the northbound SR4-417 and the SR4- 417 adjacent arterials/collectors. Specifically, DSSs on the I-4 and the SR4-417 were operated to select the best control value balancing traffic congestion of both freeways/expressways and arterials/collectors among the combinations of control values of VSL, QW, and RM. The westbound of I-4 was excluded because there is no RM, and the southbound of SR4- 417 that showed similar results to the northbound of SR4- 417 was also excluded for simplicity.

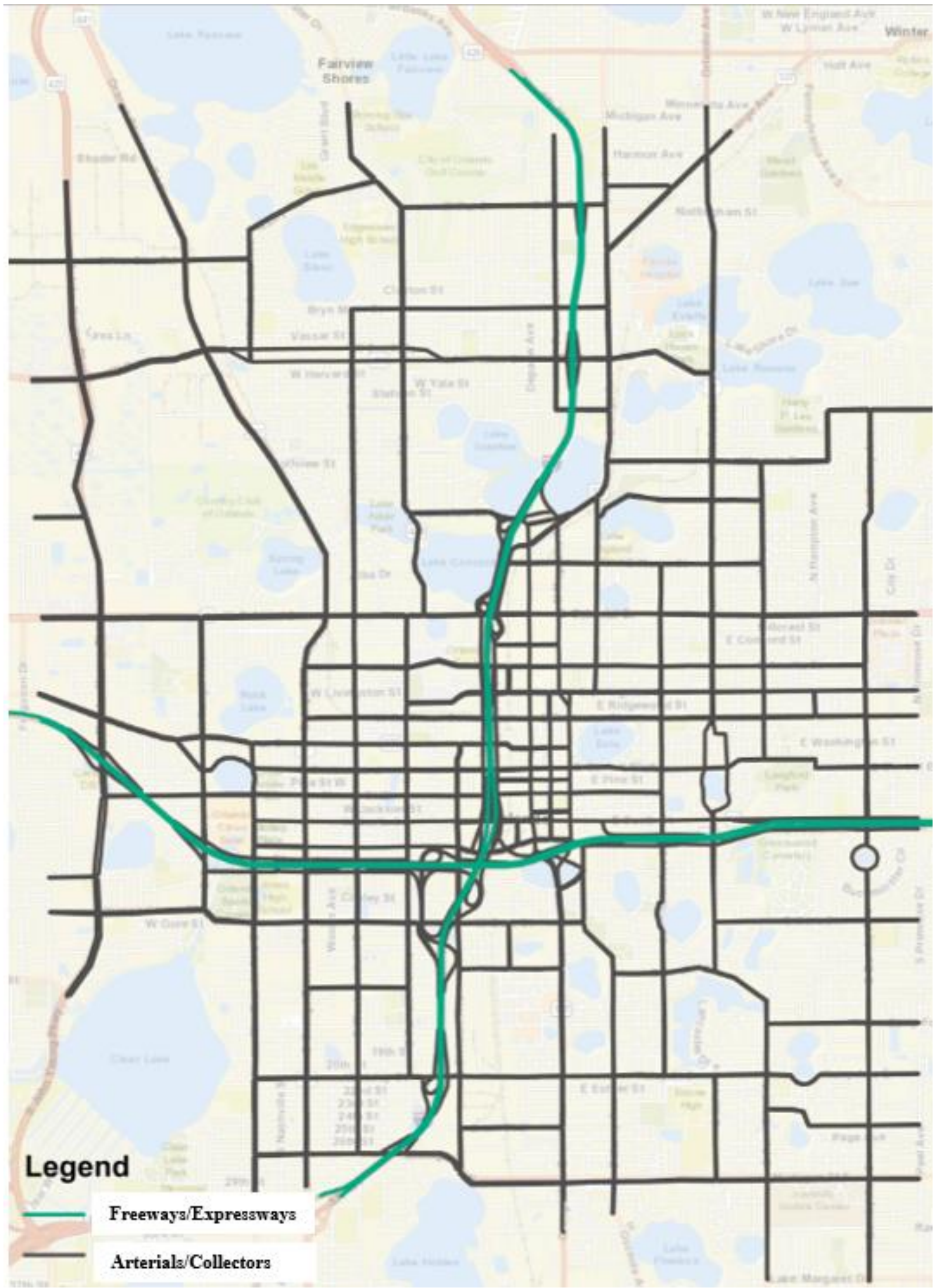


Figure 203. I-4 evaluation network

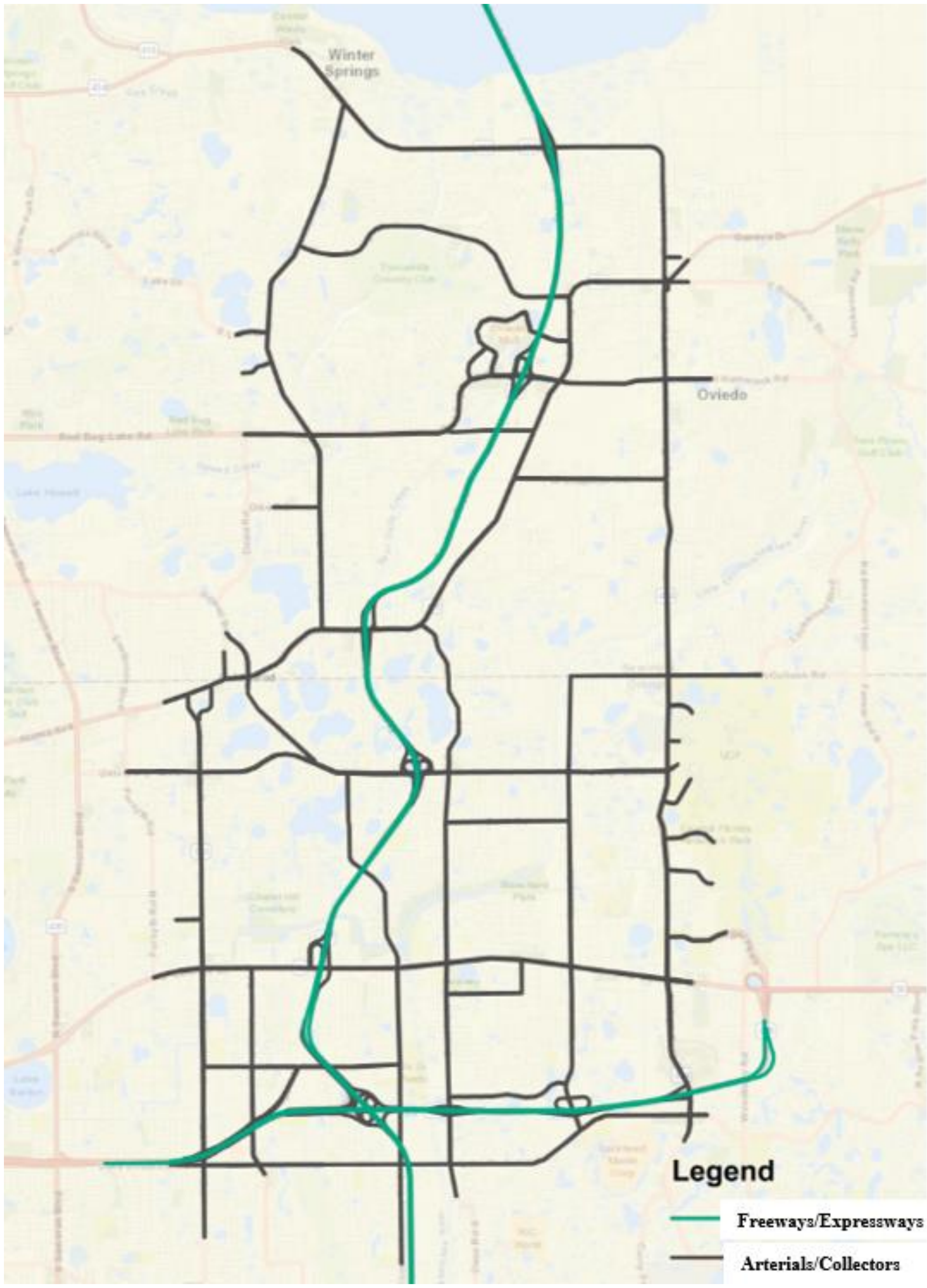


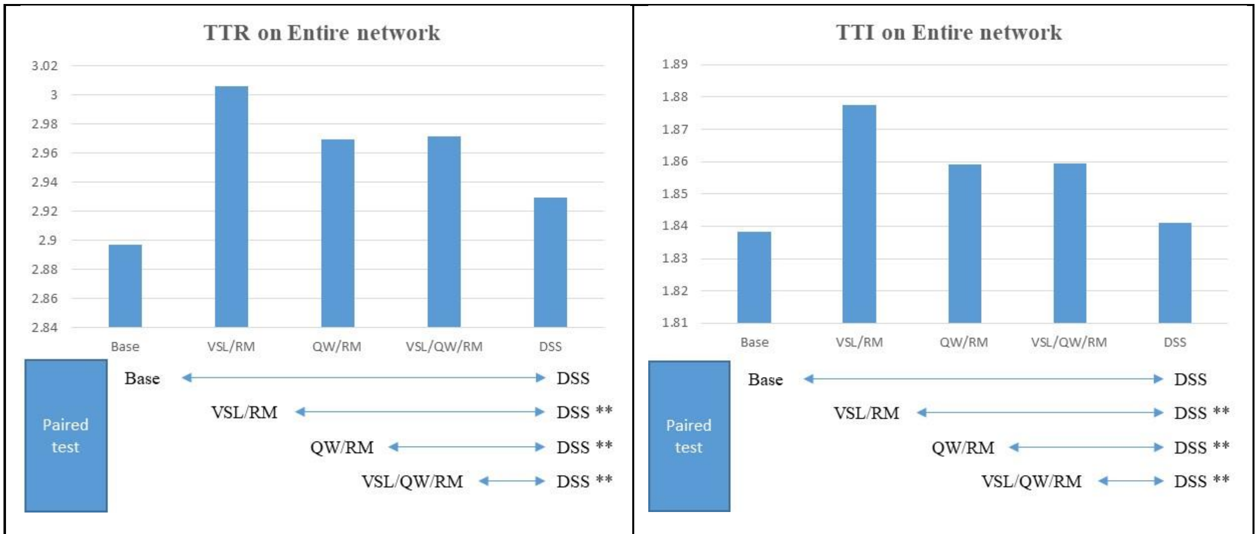
Figure 204. SR-417 evaluation network

The effectiveness of DSS was separately analyzed according to the traffic congestion level: extreme traffic, heavy traffic, and moderate traffic congestion. The effectiveness of DSS was compared with IATM system without DSS (VSL/RM, QW/RM, and VSL/QW/RM) individually at the entire network, freeway, and arterials/collectors. The comparison results were tested statistically through the paired test (Wilcoxon signed-rank test). To help understand the comparison results, scatter charts were used to show intuitively whether the traffic conditions at the corridor network level was improved or not. In the scatter charts, x-axis represents TTR or TTI of freeways/expressways and y-axis TTR or TTI of arterials/collectors. For example, it can be interpreted that if some points are positioned at the bottom left of the reference data, the performance of the points was better than the reference data in both aspects: freeways/expressways and arterials/collectors.

10.7.1. The I-4 Corridor Network (Downtown Orlando Area)

10.7.1.1. Extreme Traffic Congestion

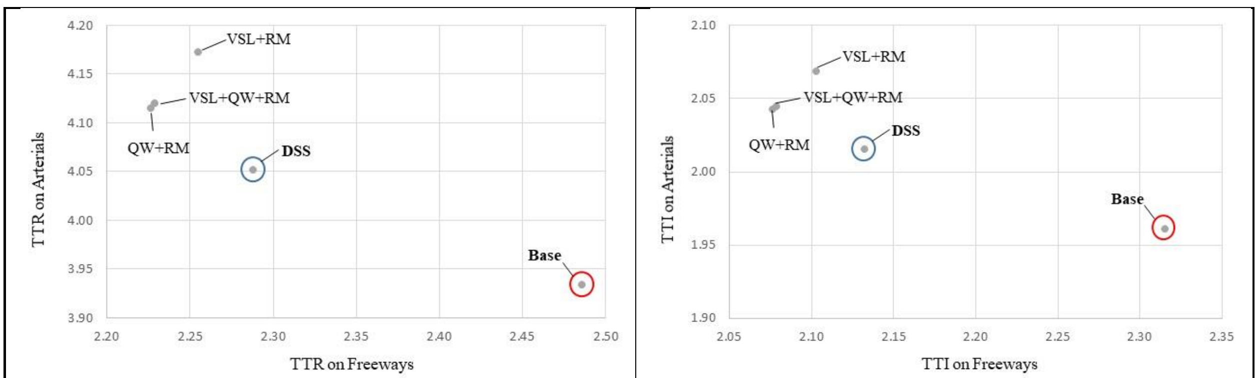
Figure 205 indicates that DSS has higher TTR and TTI than the base condition in the extreme traffic condition at the entire network in the downtown I-4 corridor network, but the difference is not statistically significant. Rather, DSS improved more TTR and TTI than IATM strategies: VSL/RM, QW/RM, and VSL/QW/RM. Statistically, DSS has significantly improved performance than VSL/RM and QW/RM at a 95% confidence interval. Specifically, Figure 206 shows how DSS has an impact on freeways/expressways and arterials/collectors. All types of IATM are located at the top left of the base condition, which means that they improved the traffic condition of freeways/expressways, but they didn't improve arterials/collectors. Relatively, DSS mitigated the adverse impact of VSL/RM, QW/RM, and VSL/QW/RM. Hence, it could be concluded that DSS achieved great improvement of freeways/expressways by mitigating the adverse impact on the entire network. In addition, in the extreme traffic congestion on the corridor network, there may be a limitation to improve both freeways/expressways and arterials/collectors. Nevertheless, DSS achieved more balanced traffic conditions at the entire network than IATM system without DSS (VSL/RM, QW/RM, and VSL/QW/RM). Moreover, it would be expected if adaptive signal control strategies integrated with the IATM strategies would even further improve the whole network. However, this could be a possible extension as it is beyond the scope of this study.



(a) TTR [minute/mile] on Entire Network	(b) TTI on Entire Network

Note: ** This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at a 95% confidence interval.

Figure 205. TTR [minute/mile] and TTI at the entire network under the extreme traffic condition (I-4)

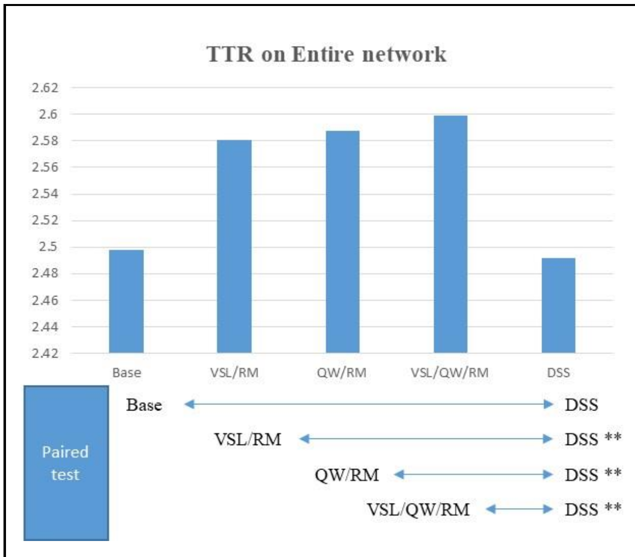


(a) TTR [minute/mile]	(b) TTI

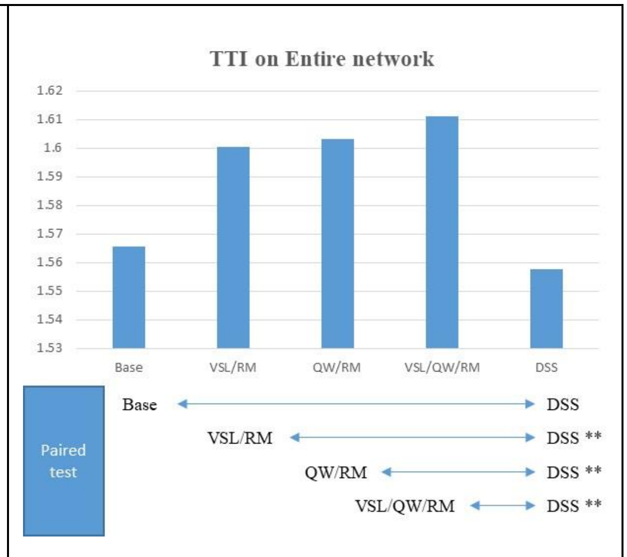
Figure 206. Scatter plot of TTR [minute/mile] and TTI of freeways/expressways and arterials/collectors under the extreme traffic condition (I-4)

10.7.1.2. Heavy Traffic Congestion

Similar to the extreme congestion, Figure 207 shows that DSS could improve IATM without DSS in terms of the entire network. As shown in Figure 208, it should be noted that DSS is located at the bottom left of the Base in both TTR and TTI. This effect shows that the benefit of DSS could be larger in the heavy traffic congestion than the benefit in the extreme traffic congestion. It is also believed that this effect is due to the allowable residual capacity of arterials/collectors in the heavy traffic congestion. This is because the TTI of the arterials/collectors (between 1.75 and 1.85) in the heavy traffic congestion is smaller than the TTI of the arterials/collectors (between 1.95 and 2.10) in the extreme traffic congestion (Figure 13 (b)).



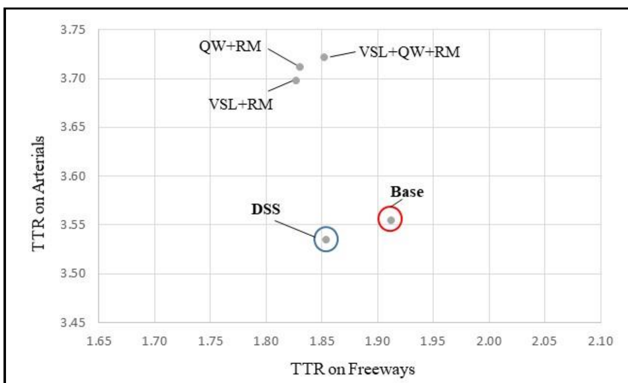
(a) TTR [minute/mile] on Entire Network



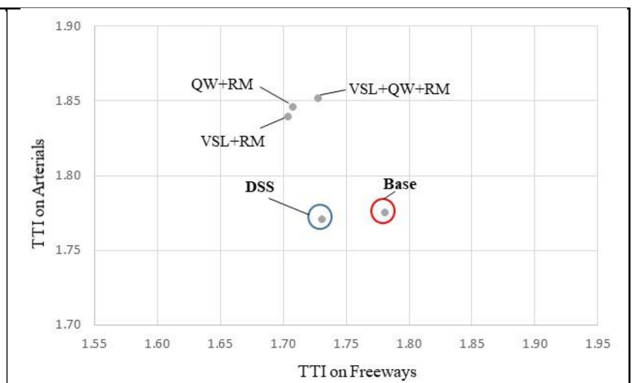
(b) TTI on Entire Network

Note: ** This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at a 95% confidence interval.

Figure 207. TTR [minute/mile] and TTI at the entire network under the heavy traffic condition (I-4)



(a) TTR [minute/mile]

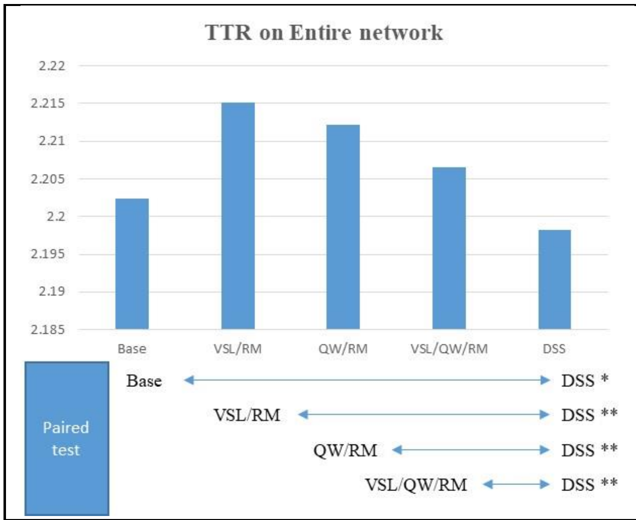


(b) TTI

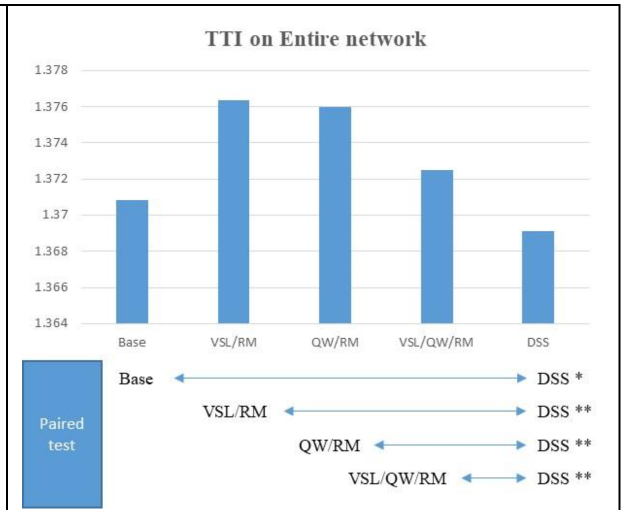
Figure 208. Scatter plot of TTR [minute/mile] and TTI of freeways/expressways and arterials/collectors under the heavy traffic condition (I-4)

10.7.1.3. Moderate Traffic Congestion

Figure 209 shows obvious improvement of DSS. Comparing DSS with other types of IATM as well as the base condition, the improvement of DSS is significantly different at a 90% confidence interval. As with the results of the heavy traffic condition, Figure 210 shows a similar scatter plot. That is, DSS has the ability to balance the traffic conditions of both freeways/expressways and arterials/collectors and could improve both freeways/expressways and arterials/collectors in the moderate traffic congestion.



(a) TTR [minute/mile] on Entire Network

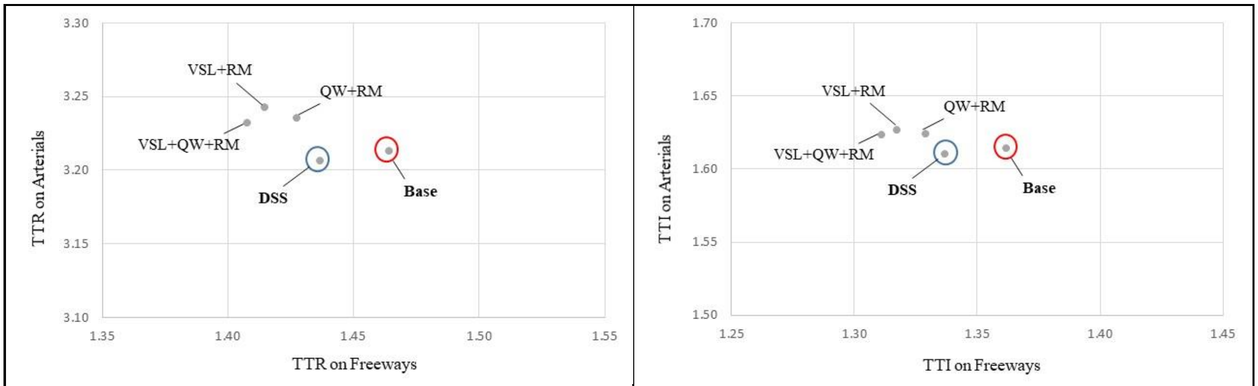


(b) TTI on Entire Network

Note:

- * This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at a 90% confidence interval.
- ** This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at a 95% confidence interval.

Figure 209. TTR [minute/mile] and TTI at the entire network under the moderate traffic condition (I-4)



(a) TTR [minute/mile]	(b) TTI

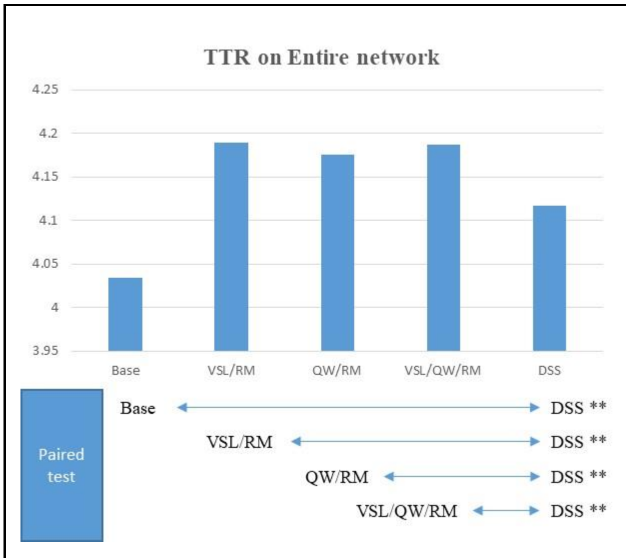
Figure 210. Scatter plot of TTR [minute/mile] and TTI of freeways/expressways and arterials/collectors under the moderate traffic condition (I-4)

10.7.2. The Northern SR4- 417 Corridor Network (East Orlando Area)

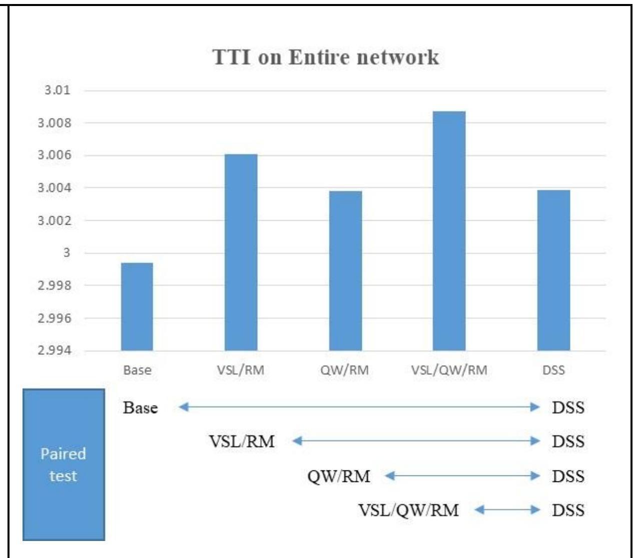
During the AM peak hour, SR4- 417 does not have traffic congestion. Thus, the traffic demand was increased to achieve heavy traffic, which could provide congested traffic conditions. It should be reasonable to assume that the network could experience non-recurring congestion with high demands due to big events such as football games. Existing capacity and IATM strategies should be able to improve the conditions and efficiently utilize the available capacity. The increase of the traffic demand caused serious traffic congestion on arterials/collectors. Because of that, the function of DSS balancing traffic loads between freeways/expressways and arterials/collectors was restricted although DSS showed better ability than IATM strategies without DSS.

10.7.2.1. Heavy Traffic Congestion

SR4- 417 has adjacent arterials/collectors that are more congested than the arterials/collectors adjacent to I-4. The TTI on arterials/collectors of SR4- 417 in the heavy traffic congestion is over 3.2, as shown in Figure 210 (b). Therefore, the effectiveness of the strategies is affected not only by freeway traffic conditions but also arterial traffic conditions. Figure 210 shows that DSS has higher performance than IATMs without DDS, which is similar to the case of I-4 in the heavy traffic congestion. However, as shown in Figures 210 and 211, DSS does not improve the traffic condition of arterials/collectors compared to the base condition of arterials/collectors, which has also worsened the TTR and TTI of the entire network. Nevertheless, it can be confirmed that DSS has the ability to balance the traffic conditions of both freeways/expressways and arterials/collectors as shown in Figure 18.



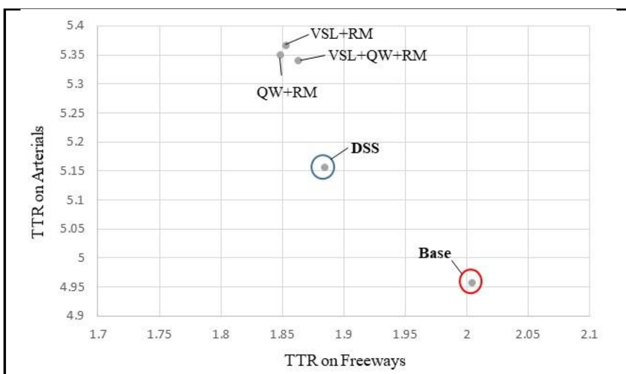
(a) TTR [minute/mile] on Entire Network



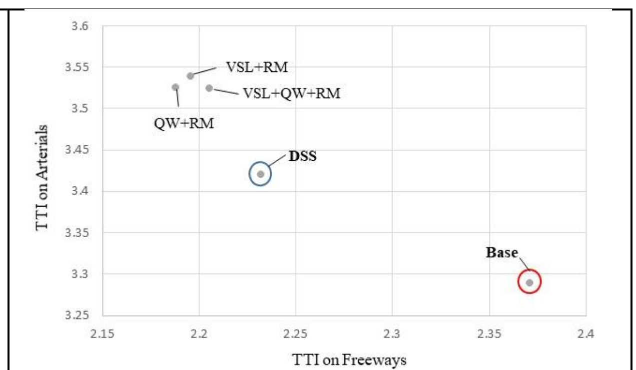
(b) TTI on Entire Network

Note: ** This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at a 95% confidence interval.

Figure 210. TTR [minute/mile] and TTI at the entire network under the heavy traffic condition (SR4- 417)



(a) TTR [minute/mile]

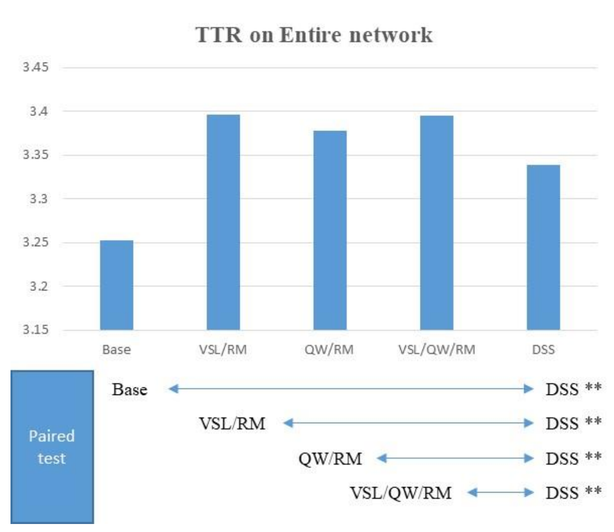


(b) TTI

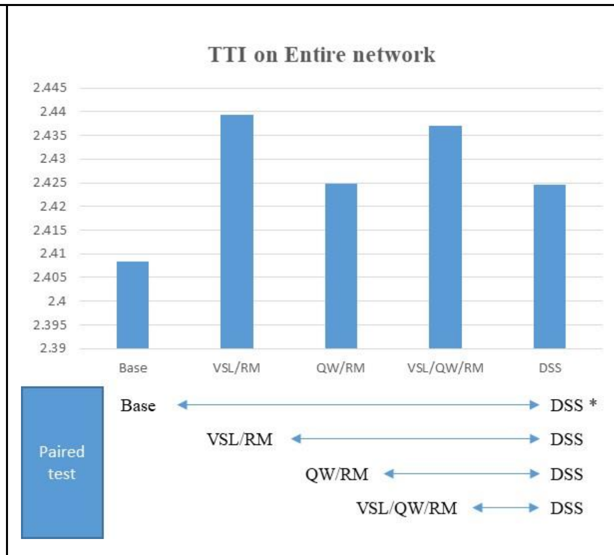
Figure 211. Scatter plot of TTR [minute/mile] and TTI of freeways/expressways and arterials/collectors under the heavy traffic condition (SR4- 417)

10.7.2.2. Moderate Traffic Congestion

The TTI on arterials/collectors of SR4- 417 in the moderate traffic congestion is over 2.6, as shown in Figure 212 (b). Figures 212 and 213 shows that the results are similar to the results of heavy traffic congestion. There is still a lack of residual capacity to handle the traffic volume that is controlled from freeways/expressways.



(a) TTR [minute/mile] on Entire Network

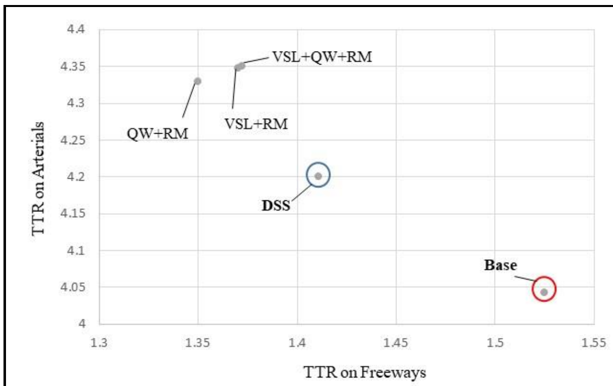


(b) TTI on Entire Network

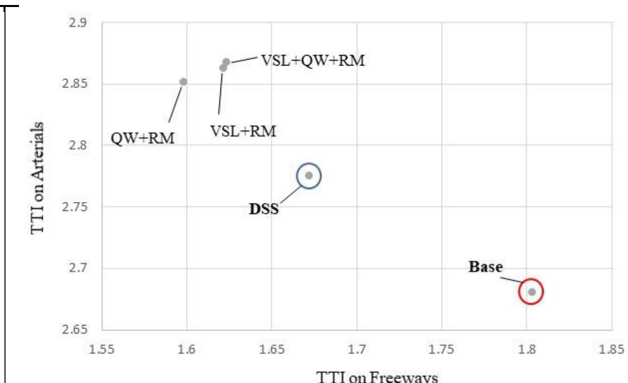
Note:

- * This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at a 90% confidence interval.
- ** This indicates rejection of the null hypothesis, there is mean difference between no-strategy and each strategy at a 95% confidence interval.

Figure 212. TTR [minute/mile] and TTI at the entire network under the moderate traffic condition (SR4- 417)



(a) TTR [minute/mile]



(b) TTI

Figure 213. Scatter plot of TTR [minute/mile] and TTI of freeways/expressways and arterials/collectors under the moderate traffic condition (SR4- 417)

10.7.3. Summary of IATM Controls

This research evaluated all kinds of combinations of VSL, QW, and RM under different recurring and non-recurring traffic congestions. Through the effectiveness analysis of the possible operational strategies, the generic rules were developed (see Table 85). In order to use the suggested generic rules, IATM should analyze the traffic congestion level of a corridor network. And then, according to the necessity of the balanced control between freeways/expressways and arterials/collectors, proper strategy can be selected.

Table 85. Generic rules to select proper IATM strategies

Freeways//Expressways Traffic Congestion Level of a corridor network	Freeways/Expressways Priority Policy		Freeways/Expressways and Arterial Balance Policy	
	Recurring	Non-recurring	Recurring	Non-recurring
Extreme (speed ≤ 25 mph)	QW/RM	n/a	QW alone	n/a
Heavy (25 mph < speed ≤ 35 mph)	VSL/RM or QW/RM	VSL/RM, QW/RM or VSL/QW/RM	VSL/RM or QW/RM	VSL-alone, QW-alone or VSL/QW
Moderate (35 mph < speed ≤ 45 mph)	VSL/QW/RM	VSL/RM QW/RM VSL/QW/RM	RM-alone or VSL/RM	VSL-alone or VSL/QW

The generic rules can help to choose proper strategies according to the traffic condition and the requirements of the balanced control between freeways/expressways and arterials/collectors. However, static decision rule cannot always dynamically reflect all kinds of traffic situations. Thus, DSS using METANET was developed, which was evaluated in terms of the balanced control ability between freeways/expressways and arterials/collectors. According to the evaluation results, the developed DSS successfully balanced traffic condition between freeways/expressways and arterials/collectors in all types of traffic congestion: extreme, heavy, and moderate. Therefore, for the balanced traffic operation between freeways/expressways and arterials/collectors, it is effective to use DSS considering travel time reliability.

It should be noted that the research team suggested two IATM control strategies based on different operation conditions. If the operation agency could be set up the developed METANET model to select the proper control strategies in real time, the general rules of "Freeway and Arterial Balance Policy" are recommended. Otherwise, the general rules of "Freeways/Expressways Priority Policy" are recommended as it could be directly used for the current control system.

While we attempted to consider route diversion as a strategy to balance the traffic congestion on both Freeways/expressways and Arterials/collectors, the effort was not successful as the network is already congested. Future research that account for improvements of I-4 and adaptive signal control might be needed. However, based on Task 3 of this project (Appendix A), we can conclude that route choice decisions in the Central Florida area are influenced by travel time, travel cost and delay indicating lower preference for routes with higher values specific to these variables. Respondents preferred arterials/collectors over expressways as route alternative. In terms of availability of traffic information (Appendix B), the results indicated that road users preferred pre-trip and en-route information, while en-route traffic information through mobile app and radio were found to influence the route choice decision positively. From the models 33% of respondents prefer expressways to arterials/collectors and 67% of respondents prefer arterials/collectors. Coefficient of delay being negative for 89% of the respondents indicating high sensitivity to Travel Time Reliability. The parameter estimate is intuitive with the en-route traffic information through mobile app coefficient being positive for three-fourth of the respondents. In short drivers in central Florida have sensitivity to delays, prefer arterials/collectors by a margin 2:1 to minimize cost/toll, and mobile app play an important role in information dissemination.

10.8. Summary

In this research, a decision support system for active traffic management systems integrating freeways/expressways and arterials/collectors was developed and evaluated. The DSS with three representative ATM strategies, VSL, QW, and RM, were implemented for the downtown I-4 corridor network and the northern SR4- 417 corridor network. For VSL and QW, a new logic was developed to recommend variable speed limits. RM logic was based on the local actuated control method. For the prediction of near-future traffic condition with/without traffic control strategies, METANET model was employed and calibrated for freeways/expressways and arterials/collectors. To analyze the effectiveness of IATM strategies under the recurring traffic congestion, in addition to the original demand, the traffic demand of the downtown I-4 corridor was reduced. Whereas, for the effectiveness of IATM strategies under the non-recurring traffic congestion, the traffic demand of the northern SR4- 417 corridor network was increased. The simulation results suggested that different combinations of control strategies provided the best traffic performance under different congestion levels. Besides, the developed control strategy based on the METANET model could better balance the traffic between freeways/expressways and arterials/collectors. Hence, it could be concluded that the research team has successfully developed a Decision Support System for integrated traffic management in this task. Based on extensive simulation-based analysis, the generic decision rules have been recommended to operators under different traffic conditions. In the following task, the research team will draft the final report to conclude all efforts and findings of this project.

CHAPTER 11. I-4 ULTIMATE

11.1. Introduction

According to the U.S. Census Bureau (US Census Bureau, 2019), Florida has become one of the 3 most populous states which may generate more traffic demand and require higher capacity of transportation facilities. Interstate-4 (I-4) has been playing an important role in the transportation system in Central Florida. According to Florida Department of Transportation (FDOT) online traffic database, the traffic volume on I-4 is increasing day by day. Due to the increased traffic volume, FDOT took an initiative back in 2014 to build the I-4 ultimate which is expanding and reconstructing 21 miles of I-4 between west of Kirkman Road in Orange County and east of State Road 434 in Seminole County (Figure 214).

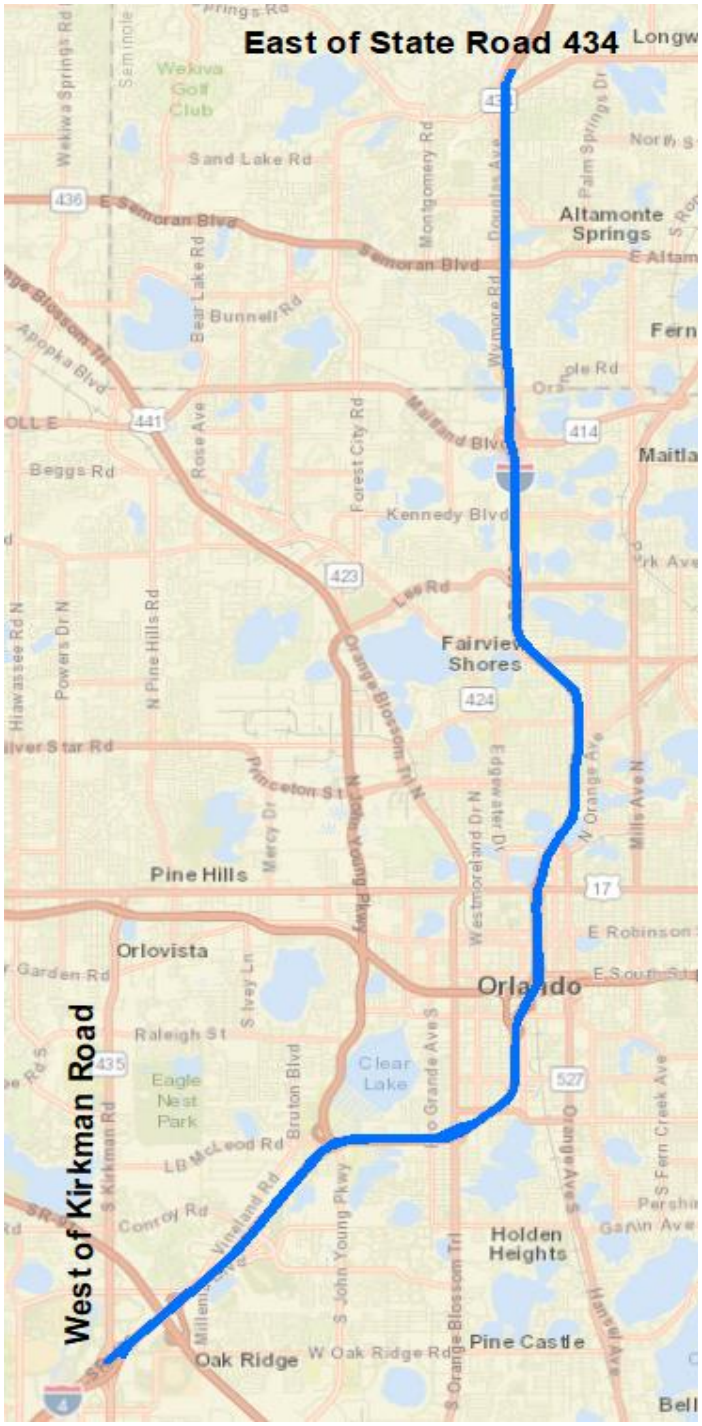


Figure 214 I-4 Ultimate area

The main purpose of the I-4 ultimate project is to provide better connectivity between communities and better quality of life and to boost up the economy. In order to reduce the congestion in the I-4 area, the new design proposed a new geometric configuration which consists of six lanes in each direction where four of them are general use lanes and the other two are tolled express lanes (Figure 215). The express lanes are physically separated from the general use lanes.

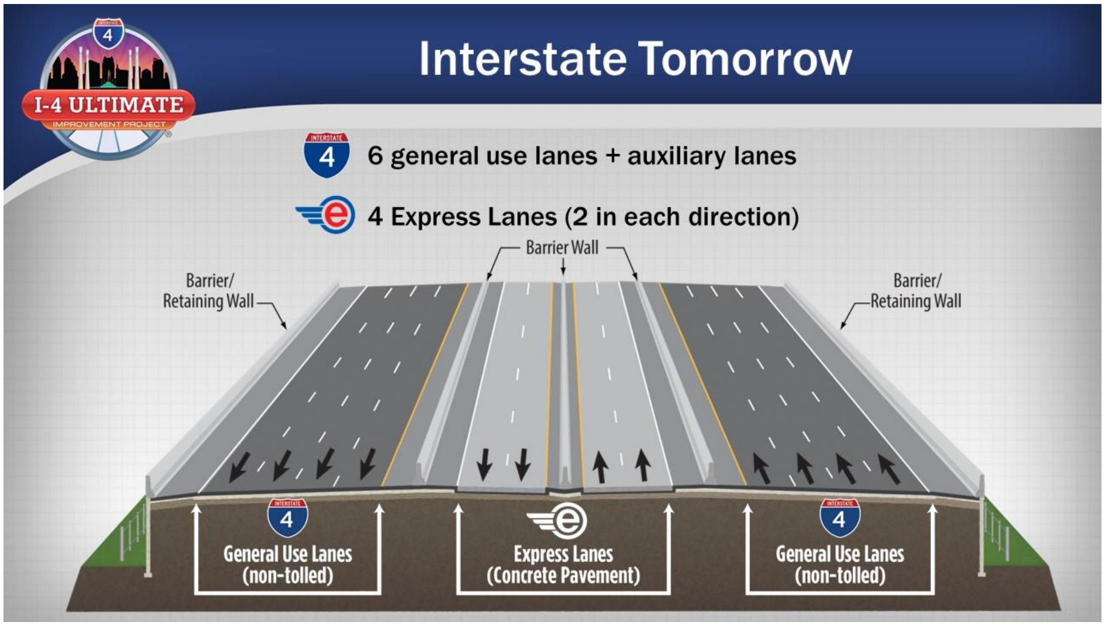


Figure 215 Lane configuration of I-4 Ultimate (*source: I-4 Ultimate project*)

Since the new configuration of I-4 would have higher capacity than the current I-4, it would attract more traffic and it is necessary to analyze the change of traffic that the future I-4 will bring. The objective of this study is to analyze the performance of I-4 Ultimate by using mesoscopic simulation environment. Also, the research team evaluates the impact of I-4 Ultimate on its surrounding roadway network.

11.2. Simulation Model

11.2.1. Selection of Mesoscopic Area

In order to analyze the traffic condition on I-4 Ultimate, the research team used the same calibrated mesoscopic area (Figure 216). The Mesoscopic area has 18,350 links, 8,942 nodes, and 2,417 signalized intersections. For replicating the Future I-4 in the simulation environment, the number of lanes has been modified (six lanes in each direction) only for the specified I-4 Ultimate segment.

Figure 216 Screenshot of mesoscopic area from Aimsun Next

In addition, for replicating tolled express lanes, the research team assumed that the capacity of tolled road will be LOS C (Neudorff and MaCabe., 2015).

11.2.2. Calibration of the Mesoscopic Area

The research team has calibrated the mesoscopic area based on the current volume on I-4. To calibrate the network for the I-4 Ultimate, traffic data were collected for the morning peak period on future I-4 for the year of 2030 from the project website As shown in the left side Figure 217, the arrows indicate the different roadway facilities: the black and bold lines are regular freeway lanes, the green lines are the express lanes, the grey lines are ramps, and others are arterials. The right side of Figure 1-4 illustrates the projected hourly traffic volumes during AM(PM) peaks for different types of road facilities. The volumes are used for the simulation calibration.

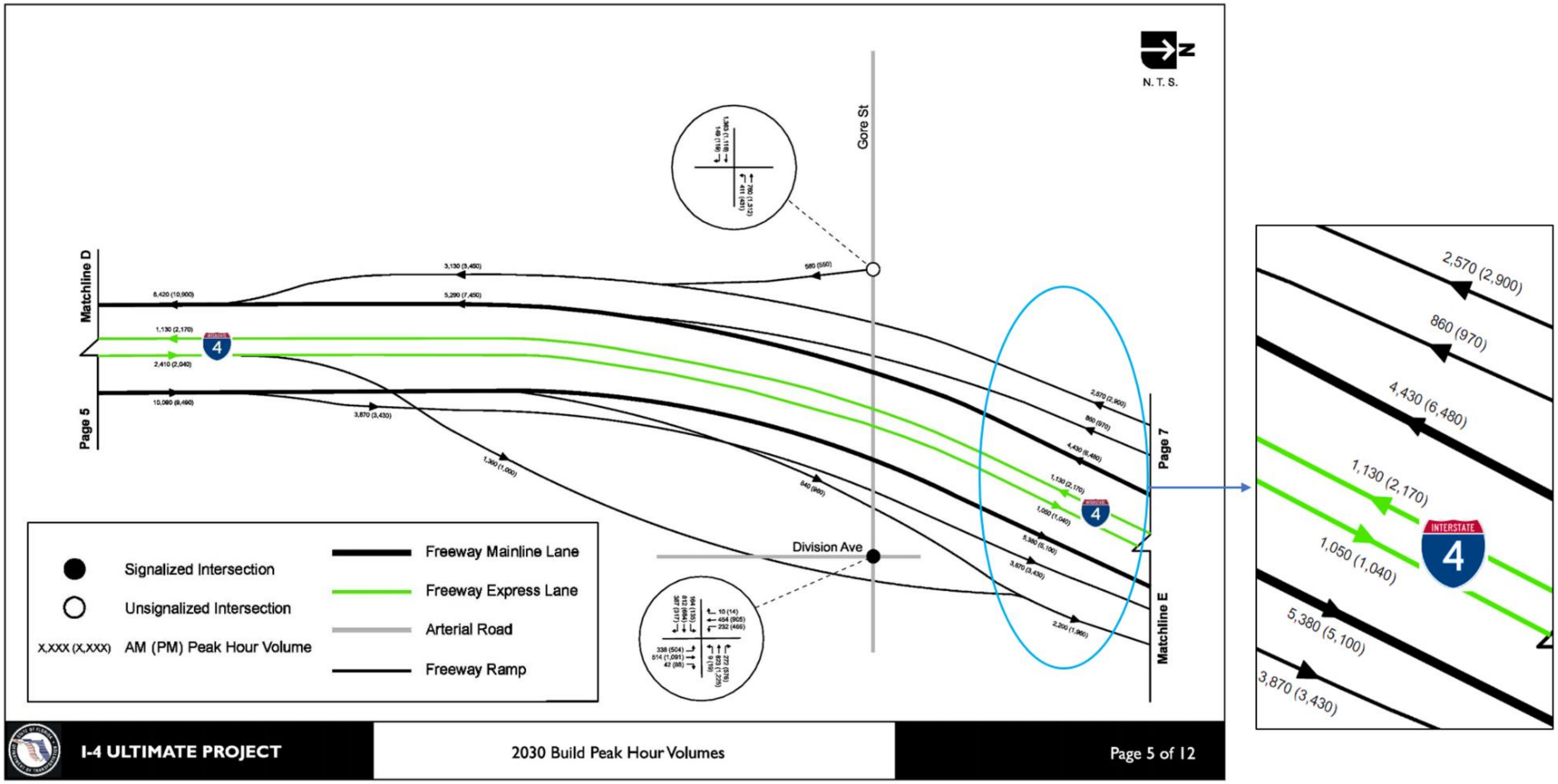
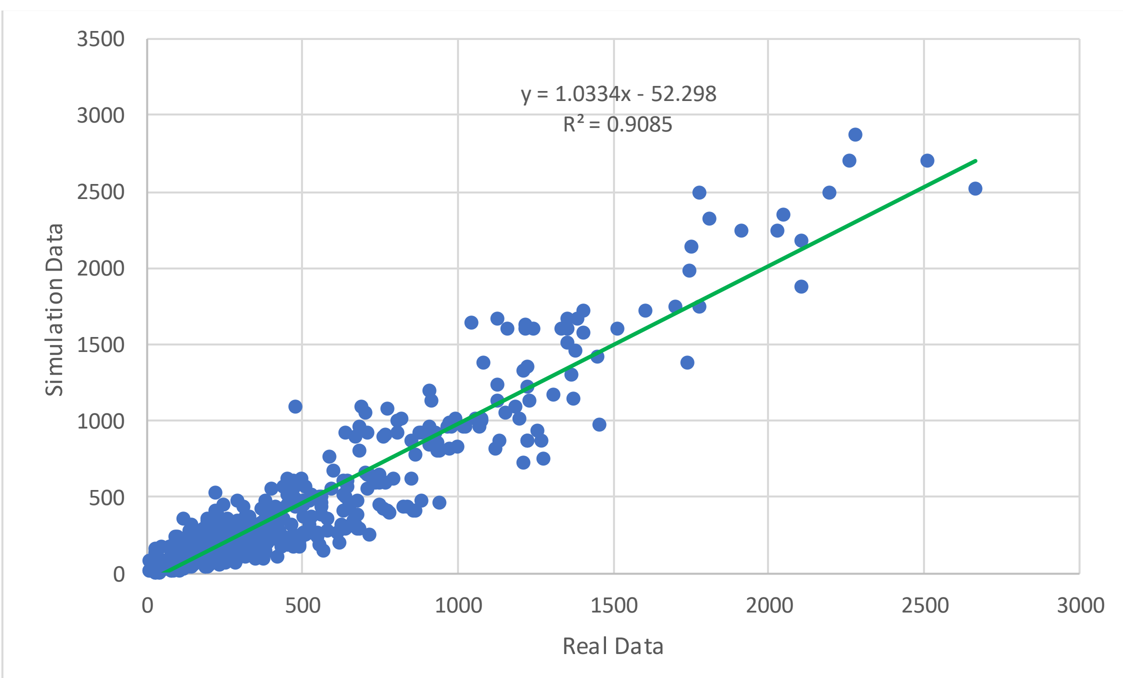


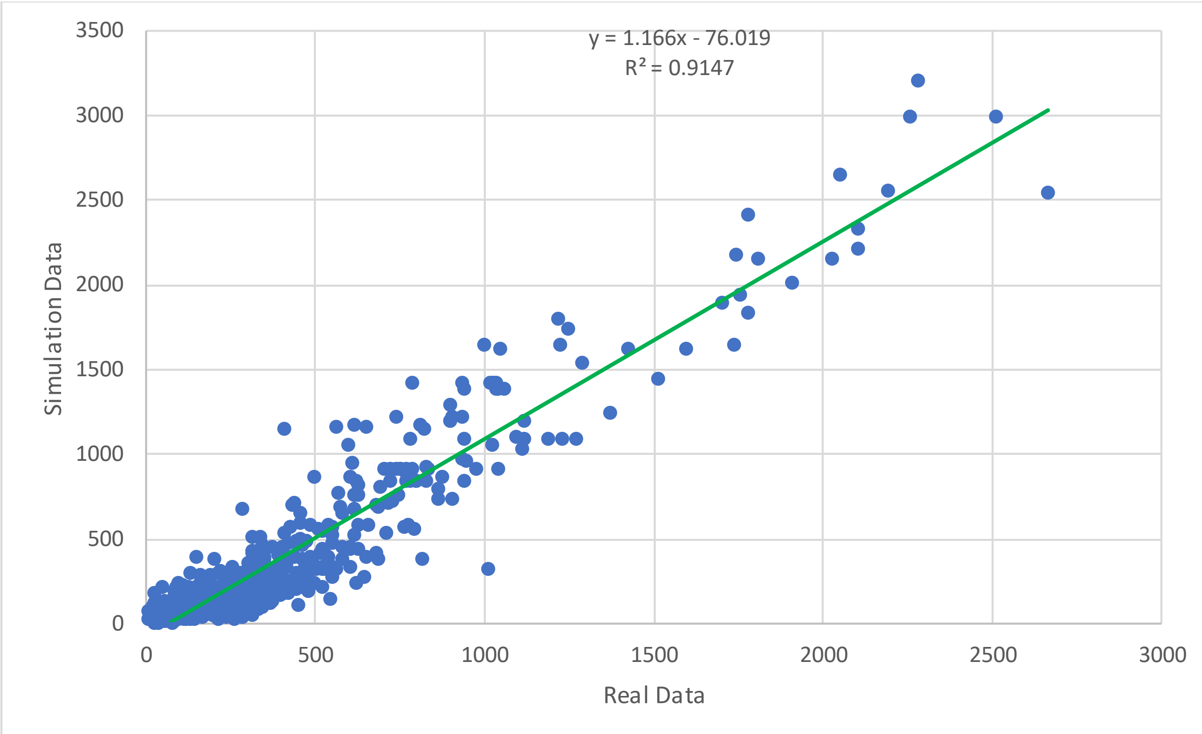
Figure 217 Traffic demand on Future I-4 by 2030 (source: I-4 Ultimate project)

Based on the future traffic demand, the research team provided 24 new detectors on future I-4 segment in both direction (east and westbound). Furthermore, data were aggregated into 15 minutes interval for calibration and there were of totally 674 detectors for the full mesoscopic area. The simulation time was set from 6.15am to 9:00 am while the first 45 minutes (6:15 am-7:00 am) was kept for the warm-up period.

For a good calibrated large-scale network, the R^2 value of every 15 minutes interval for the simulated and real traffic volume should be greater or equal to 0.90 (Hadi et al., 2016; Shafiei et al., 2018; Zitzow et al., 2015). From the analysis, the R^2 value was found higher than 0.90 for each time interval. Figure 218 shows two examples of the regression lines with R^2 value for the first two intervals. Meanwhile, the research team also used GEH (Geoffrey E. Havers) statistics which is a modified Chi-square test. The test could incorporate both relative and absolute differences to compare between field and simulated traffic volumes.



a. Regression line for first time interval (7:00:00 AM to 7:15:00 A.M.)



b. Regression line for second time interval (7:15:00 AM to 7:30:00 A.M.)

Figure 218 Mesoscopic results for first two 15-minute intervals

Figure 219 shows the result of GEH for the first interval from 7:00:00 am to 7:15:00 am. The green dot indicates a GEH value of less than 10, the yellow dot indicates a GEH value between 10 to 25, and the red dot denotes a GEH value greater than 25. Moreover, the research team found that about 49% of the cases could have GEH values less than 10 and about 86.2% cases have GEH values less than 25. Since the travel time data is not available for the I-4 Ultimate, the validation of the simulation model was not conducted.

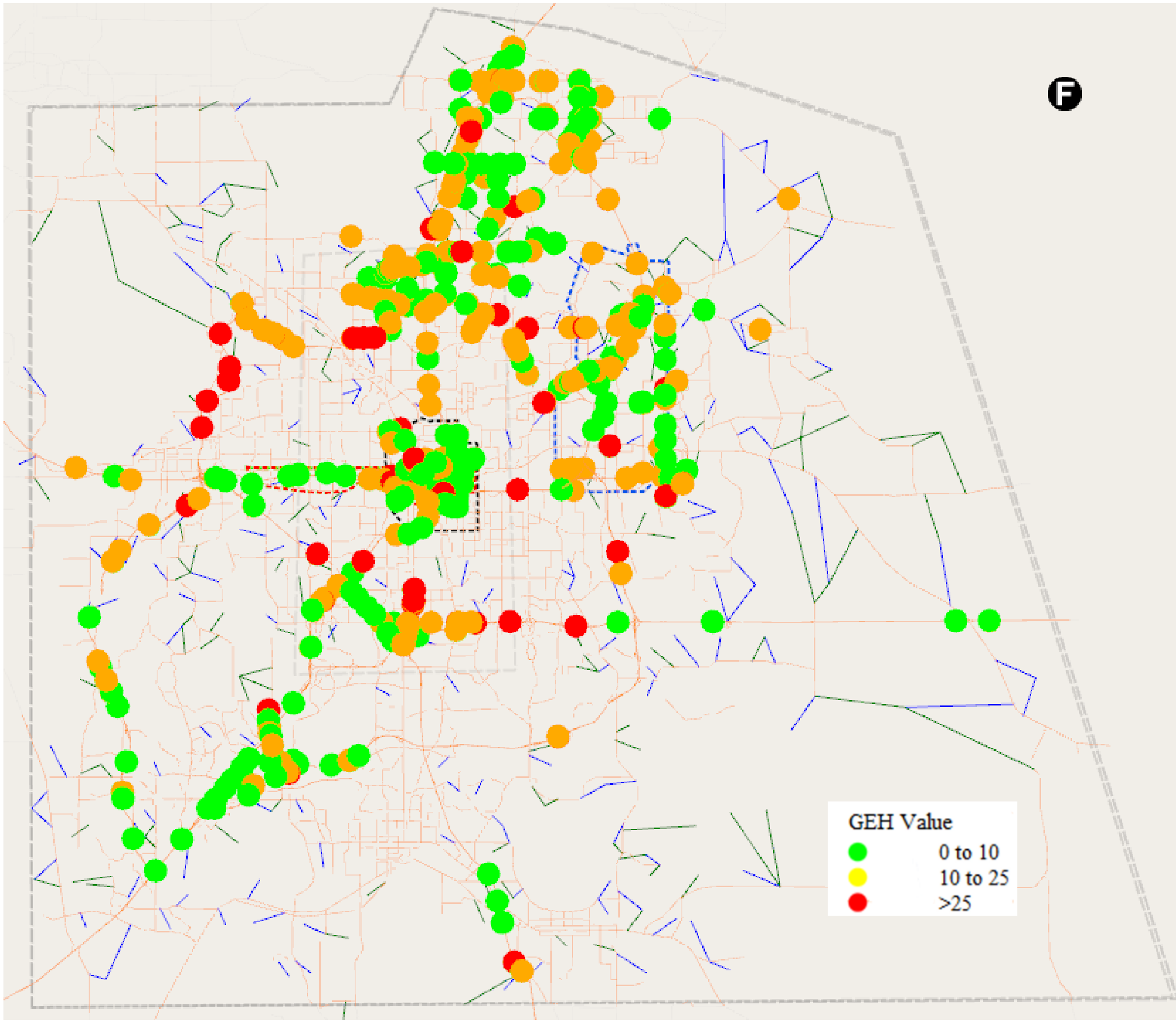


Figure 219 GEH value for model calibration (7:00:00-7:15:00 A.M.)

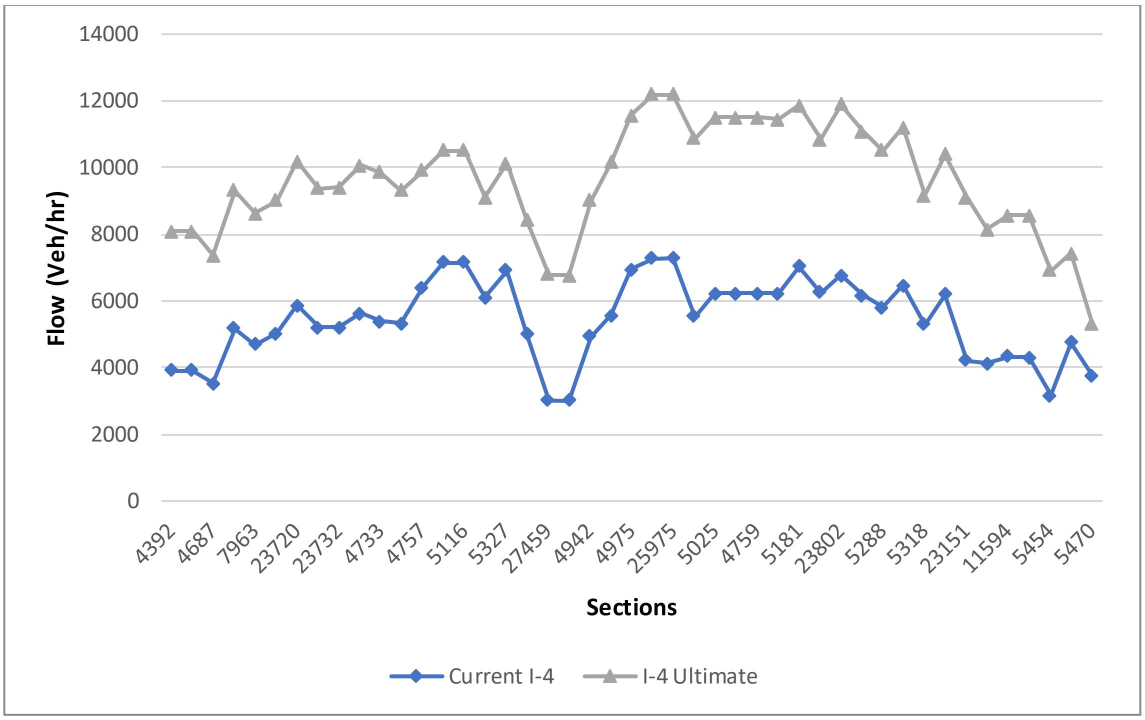
11.3. Effect of I-4 Ultimate

As mentioned earlier, the new design of I-4 could attract more traffic as well as the surrounding areas. So, the research team analyzed the effect of I-4 Ultimate in two folds:

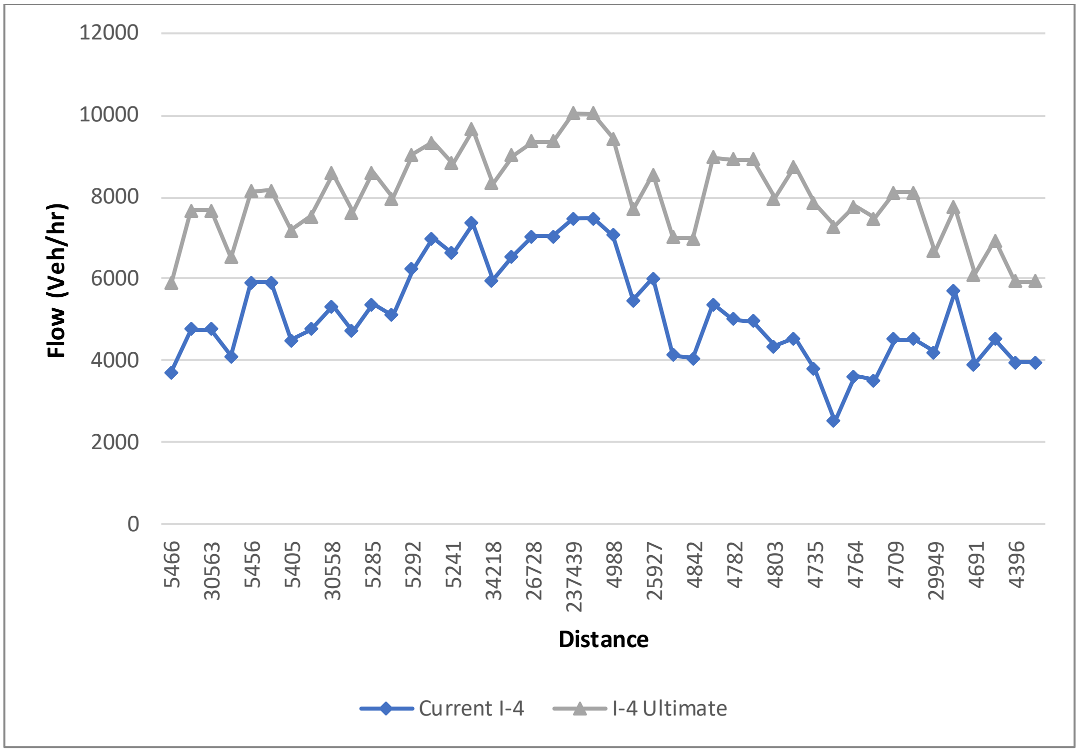
- Performance of I-4 Ultimate compared with the current I-4
- Impact of I-4 Ultimate on the surrounding roadways

11.3.1. Performance of I-4 Ultimate compared with the current I-4

In this section, the performance of I-4 Ultimate was compared with the current I-4 based on various traffic parameters such as traffic flow and travel time. Figure 220 shows the flow of I-4 for each section in both directions (Eastbound and Westbound) for current and future traffic demands. As shown in the figure, traffic flow increased (almost doubled) for I-4 Ultimate compared with the current I-4.



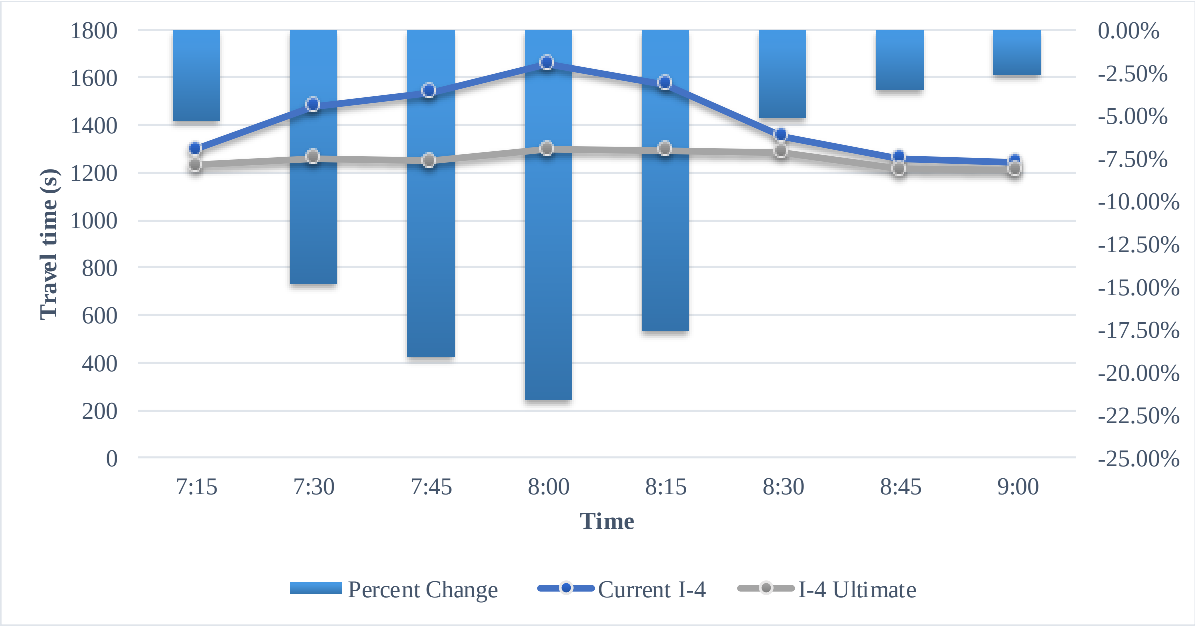
a. Flow on I-4 eastbound



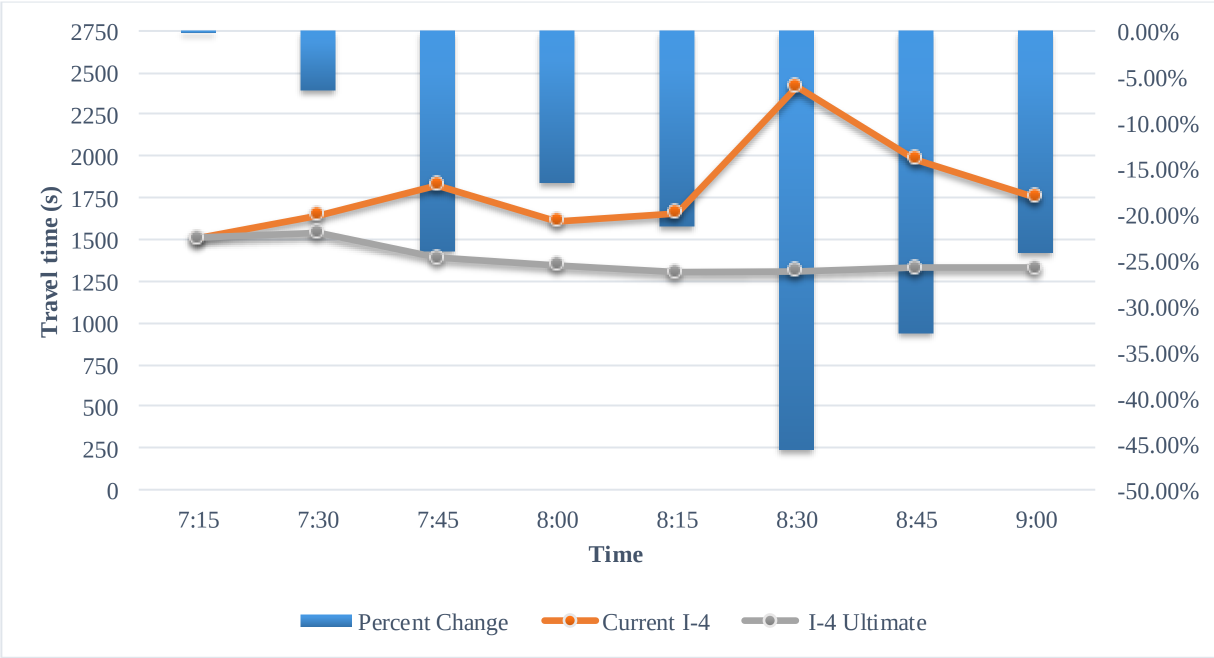
b. Flow on I-4 westbound

Figure 220 Traffic flow on current and future I-4

Moreover, the research team evaluated the travel time of the current I-4 and I-4 Ultimate for both directions separately, which is shown in Figure 221. Also, the reduction percentage was calculated by comparing the I-4 Ultimate scenario with the current I-4. The negative reduction percentage indicates that I-4 Ultimate with the new design could reduce the travel time on the freeway and vice versa. Figure 221 illustrates that the reduction percentage ranged from 4% to 22% for the eastbound direction and the reduction percentage values varies from 0.03% to 46% for the westbound direction. Although the traffic flow on I-4 Ultimate has substantially increased compared with the current I-4, travel time was reduced significantly.



a. Travel time on I-4 eastbound



b. Travel time on I-4 westbound

Figure 221 Travel time on current and future I-4

The performance of I-4 Ultimate was further compared with current I-4 based on the level of service (LOS). For each section, LOS was estimated based on density for each time interval for both scenarios (current and future I-4). For example, totally 360 LOS values were calculated for 8 time intervals (15 minutes for each) for 45 sections on I4 eastbound. LOS was calculated for both directions separately. Hence, a matrix table has been constructed where column indicates LOS for I-4 Ultimate and Row denotes LOS for current I-4 (Table 86). The diagonal of the matrix table indicates that how many times the LOS value is same for I-4 Ultimate and current I-4. The other cells of the matrix indicate that how many of them change from current I-4 to I-4 Ultimate. For example, in eastbound table, Row 2 and Column 1 value is 80 which means LOS "B" on current I-4 turns into LOS "A" on I-4 Ultimate for 80 times. Hence, the higher the value on the cells below the diagonal means I-4 Ultimate improves the LOS compared with the current I-4. The two tables suggested that I-4 Ultimate would significantly improve the level of service. Specifically, the I-4 Ultimate could provide at least LOS "C" for both directions. Six LOS "F" values on the current I-4 Eastbound could be changed to LOS "A" while the current I-4 Westbound could have 26 LOS values changing from "F" to "A".

Table 86. Level of service for I-4 eastbound and westbound

Eastbound		I-4 ultimate					
		A	**B**	**C**	**D**	**E**	**F**
Current I-4	**A**	224	15	1	0	0	0
	B	80	14	4	0	0	0
	C	9	0	1	0	0	0
	D	5	0	0	0	0	0
	E	1	0	0	0	0	0
	F	6	0	0	0	0	0
Westbound		I-4 ultimate					
		A	**B**	**C**	**D**	**E**	**F**
Current I-4	**A**	216	11	1	0	0	0
	B	59	4	0	0	0	0
	C	15	7	0	0	0	0
	D	7	0	0	0	0	0
	E	6	0	0	0	0	0
	F	26	0	0	0	0	0

11.3.2. Impact of I-4 Ultimate on the surrounding network

In order to analyze the effect of I-4 Ultimate on the surrounding roadways, traffic flow data was collected for all the roadway sections for both scenarios (current and future I-4). For example, one section has eight (15 minutes interval) traffic flow observations during the whole simulation period (two hours) for each scenario. Since the number of data point is less than 30, a non-parametric test named Wilcoxon Sign Rank was performed to evaluate the significant difference between two scenarios at the 95% confidence interval. Figure 222 shows the result of the non-parametric test where green segments indicate flow is significantly lower for those sections and blue segments denote flow is significantly higher for those sections due to the effect of I-4 Ultimate. In addition, the black segments denote there is no significant difference between two scenarios. It could be seen from the figure that most of the blue segments are near the I-4 area, indicating that I-4 ultimate attracts more traffic which increase the traffic demand on the surrounding roadways. On the other hand, most of the green segments are away from the I-4 area which means traffic patterns on these roadways have been changed due to I-4 Ultimate.

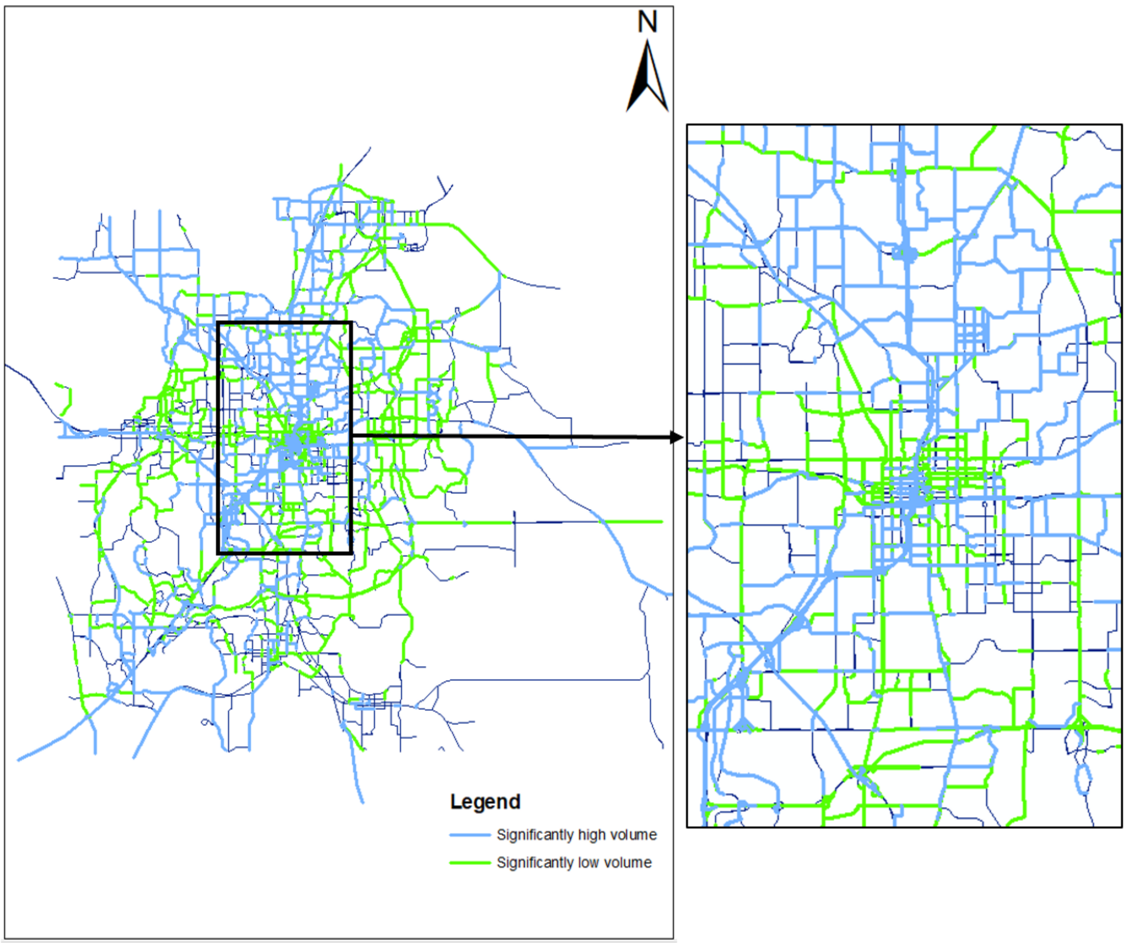


Figure 222 Statistical analysis of traffic flow for the current and future I-4

11.4. Summary

In this chapter, the performance of I-4 Ultimate was evaluated and compared with the current I-4 scenarios. Also, the effect of I-4 Ultimate on the surrounding roadways was analyzed based on traffic flow and LOS. First, the design of I-4 was changed to mimic the I-4 Ultimate design and calibrated the network by using mesoscopic simulation. The calibrated I-4 Ultimate was compared with the current I-4 in terms of traffic flow, travel time and LOS by using simulation output data. The result showed that the new design of I-4 Ultimate would attract more traffic and flow could be increased by almost twice compared to the current I-4. Also, the results indicated that I-4 Ultimate design could reduce travel time of the freeway compared with the current I-4. Regarding the level of service (LOS) analysis, it was found that I-4 Ultimate design could improve LOS where there is no LOS under Level "C" during the study period. Furthermore, more traffic will be attracted to the I-4 Ultimate area, which means further consideration is needed to investigate the traffic in the surrounding area.

Based on the evaluation results, the research team can provide insights about the new design of I-4 Ultimate. With the new design, I-4 Ultimate could better serve the future demand in terms of travel time, flow, and LOS. On the other hand, I-4 ultimate with future demand will create problems in the surrounding areas as it attracts more traffic to I-4. Hence, it is necessary to conduct studies to provide solutions such as adjusting signal on the surrounding roadways to improve the capacity.

CHAPTER 12. SUMMARY AND CONCLUSIONS

12.1. Summary

In this research project, there were eight major objectives. All the main objectives of this project have been achieved as follows:

1. **Review traffic data collection technologies**

   The research team has comprehensively reviewed the output data characteristics, operation mechanism, availability, and implementability of the infrastructure-based traffic data collection technologies, vehicle based third party from vendors, and crowd source platforms (Chapter 3).

2. **Identify the study area**

   In Chapter 4, the Greater Orlando Metropolitan Area was selected as the study area to develop IATM strategies. The roadway networks included all limited-access freeways and expressways, the RoS, and most of the arterials.

3. **Collect traffic data in the study area**

   A wide array of data sources has been collected in Chapter 5. The collected data size reaches up to 160 GB per month, including different source such as MVDS, HERE, NPMRDS, AVI, BlueTOAD, and BlueMAC. Data availability for the study area were summarized for both freeways/expressways and arterials/collectors.

4. **Evaluate all existing traffic detection data and develop fusion algorithms**

   Extensive comparison experiments were conducted to evaluate the data quality to measure travel time and its reliability. The evaluated data included: MVDS, HERE, NPMRDS, and AVI on freeways/expressways and HERE, BlueTOAD, BlueMAC, on arterials/collectors

(Chapter 6). Besides, fusion algorithms were developed to fuse multiple data sources on freeways/expressways and arterials/collectors to obtain more accurate travel time and its reliability values. Based on evaluation results and fusion algorithms, a guideline has been provided to help select the appropriate data sources for different purposes such as real-time monitoring, roadway evaluation, and the simulation platform development.

5. **Evaluate roadways and select study corridors**

   Around 600 miles of roadways with around 1,200 segments in total were evaluated by using multiple data sources (Chapter 7). Three measures (i.e., TTI, PTI, and BTI) were used for the evaluation considering the traffic congestion and the travel time reliability. The critical roadways and segments were identified based on the evaluation results. Two critical corridors (I-4 corridor in Downtown Orlando and SR-417 corridor in East Orlando) were selected to test IATM control strategies.

6. **Develop a simulation platform to test different control strategies**

   By using Aimsun Next, the research team has developed a Dynamic Traffic Assignment (DTA) simulation platform, involving Multi-Resolution Modeling (MRM) framework (Chapter 8). To our best knowledge, this platform is the largest DTA based simulation network attempted in the United States. The microscopic simulation models were developed to test IATM control strategies and develop the Decision Support System (DSS) for the selected two corridors.

7. **Evaluate benefits of IATM control strategies**

   Based on the developed microscopic simulation platform, different IATM control strategies including Variable Speed Limit (VSL), Queue Warning (QW), and Ramp

Metering (RM) were tested separately on the I-4 Corridor in Downtown Orlando Area (Chapter 9). Each strategy was implemented to investigate the potential benefits on I-4 and the impact on the adjacent arterials and network. The evaluation analysis could help confirm the benefits of each strategy, which could help develop the DSS of IATM.

8. **Develop a Decision Support System (DSS) for IATM controls**

   A decision support system has been developed in Chapter 10 to integrate different IATM control strategies considering traffic performance on both freeways/expressways and arterials/collectors. METANET models were developed for both freeway/expressways and arterials/collectors to predict traffic status, which were used to select the appropriate control strategies. Based on 420 simulation runs on the two critical corridors (I-4 in Downtown Orlando and SR-417 in East Orlando), generic rules of IATM were summarized and a decision support system for IATM controls was developed under three different congestion conditions.

12.2. Conclusions

Active Traffic Management (ATM) is a well-defined concept in the Transportation Systems Management & Operations (TSM&O) realm, mainly focusing on freeways and expressways. They generally include control strategies such as speed harmonization, queue warning, advanced information, and ramp metering. The research team at the University of Central Florida (UCF) has taken the concept to a new level by addressing what we labeled "Pro-"active Traffic Management (PATM) concepts. The concept is to predict the adverse situation as it develops and pro-actively ameliorate the expected problem. Besides, we extended the ATM by integrating arterials (Integrated Active Traffic Management (IATM)) with the advent and availability of big data. For the successful implementation of IATM, a decision support system (DSS) was developed to help predict traffic conditions, evaluate all possible response plans related to the identified events, and then recommend response plans to enhance traffic conditions. The developed DSS of IATM could reduce travel time and improve travel time reliability.

First, the research team has reviewed a variety of traffic data collection technologies including infrastructure-based traffic data, vehicle-based traffic data system, signal control system data, dynamic message signs, crowd source data. The data characteristics and limitation have been well summarized. With the initial investigation of traffic detection data sources, the Greater Orlando Metropolitan Area was selected as the study area.

Subsequently, the research team has devoted great efforts to coordinate with different agencies in Florida District 5 to obtain a variety of existing data sources to reflect the traffic status on freeways/expressways and arterials/collectors. The collected data size reaches up to 160 GB per month, including different sources such as MVDS, HERE, NPMRDS, AVI, BlueTOAD, and BlueMAC. As different data sources have different data formats, coverages, detection penetration rates, and update frequencies, the raw data were processed to make sure that all data reflected the same traffic conditions. Extensive comparison experiments have been conducted to evaluate the data source accuracy. Considering the limitation of using the single data source, algorithms were developed to fuse traffic data from multiple data source to better reflect the traffic congestion and travel time reliability. A guideline is provided to help select the appropriate data sources for different purposes such as real-time monitoring, roadway evaluation, and the simulation platform development. The evaluation results and guideline could not only be applied in District 5, but also be adopted in the whole state.

By using the appropriate data sources, around 600 miles of roadways with around 1,200 segments in total were evaluated. Three measures (i.e., TTI, PTI, and BTI) were used for the evaluation considering the traffic congestion and the travel time reliability. The three measures were aggregated at the segment and roadway levels to identify the critical segments and roadways, which experienced serious congestion and travel time unreliability problems. Two critical corridors (I-4 Downtown Orlando and SR-417 East Orlando) were selected to develop the DSS of IATM. Three alternative IATM control strategies including Variable Speed Limit (VSL), Queue Warning (QW), and Ramp Metering (RM) were selected.

To test the developed control strategies, the research team has developed a data intensive simulation platform for deployment, calibration, and validation of a dynamic traffic assignment (DTA) model for the Orlando metropolitan area by using Aimsun Next. The simulation platform involves Multi-Resolution Modelling (MRM) framework, which could serve as the simulation platforms for different purposes. The macroscopic model could successfully replicate the traffic patterns in the Greater Orlando Metropolitan Area. The mesoscopic model could be used to simulate traffic changes due to changes of demands and geometric designs for the network of the Greater Orlando Metropolitan Area, including 4,264 miles roadways, 1,416 Traffic Analysis Zones (TAZs), 18,350 links, 8,942 nodes, and 2,417 signalized intersections. On the other hand, the microscopic model could be adopted as a platform to test IATM strategies and decision support system. The microscopic model covers networks of two critical corridors, including 412 miles roadways, 307 TAZs, 2,436 links, 1,135 nodes, and 286 signalized intersections.

Based on the developed microscopic simulation platform, different IATM control strategies including Variable Speed Limit (VSL), Queue Warning (QW), and Ramp Metering (RM) were tested separately on the I-4 Corridor in the Downtown Orlando area. Considering measures including travel time, travel time reliability, and safety, each strategy was implemented to investigate the potential benefits on I-4 and the impact on the adjacent arterials and network. To measure the travel time reliability from the simulation, the research team has developed two models to calculate travel time reliability (i.e., standard deviation of travel time rate) for both freeways/expressways and arterials/collectors. The models considered different factors such as travel time rate, geometric designs, weather, crashes, day of week. Noteworthy, the developed models could also be extended to calculate the traffic time reliability of the roadway network in real time. The evaluation analysis could help confirm the benefits of each strategy, which could help develop the DSS of IATM.

Finally, a DSS has been developed to coordinate different IATM control strategies considering traffic performance on both freeways/expressways and arterials/collectors. METANET models were developed for both freeway/expressways and arterials/collectors to predict traffic statuses, which were programed in the simulation platform and used to select the appropriate control strategies. Based on 420 simulation runs on the two critical corridors (I-4 in Downtown Orlando and SR-417 in East Orlando), generic rules of IATM controls were summarized for three different congestion conditions (i.e., moderate traffic congestion, heavy traffic congestion, and extreme traffic congestion) and a DSS for IATM controls was developed. The simulation results suggested that the proposed DSS of IATM could improve the performance of freeways/expressways mainline and balance traffic between freeways/expressways and arterials/collectors.

With all efforts, the products for implementation from this project are summarized as follows:

- A guideline of selecting the appropriate traffic data sources for different purposes.

- Maps of critical roadways and segments experiencing serious traffic congestion and unreliability problems in the Greater Orlando Metropolitan Area.
- A Dynamic Traffic Assignment (DTA) simulation platform to analyze traffic conditions under different demands, geometric designs and control strategies.
- Two models to calculate travel time reliability on freeways/expressways and arterials/collectors under different conditions. The models could be used to evaluate travel time reliability in the simulation and also be used in real time to monitor the traffic reliability of the roadway network.
- Two MATENET models to predict traffic conditions on freeways/expressways and arterials/collectors.
- Generic rules for IATM controls (see Table 88)
- A Decision Support System (DSS) of IATM to help select the appropriate control strategies dynamically to reduce congestion and improve travel time reliability with the balance between freeways/expressways and arterials/collectors.

Table 87. Summary of generic rules to select proper IATM strategies

Freeways//Expressways Traffic Congestion Level of a corridor network	Freeways/Expressways Priority Policy		Freeways/Expressways and Arterial Balance Policy	
	Recurring	Non-recurring	Recurring	Non-recurring
Extreme (speed ≤ 25 mph)	QW/RM	n/a	QW alone	n/a
Heavy (25 mph < speed ≤ 35 mph)	VSL/RM or QW/RM	VSL/RM, QW/RM or VSL/QW/RM	VSL/RM or QW/RM	VSL-alone, QW-alone or VSL/QW
Moderate (35 mph < speed ≤ 45 mph)	VSL/QW/RM	VSL/RM QW/RM VSL/QW/RM	RM-alone or VSL/RM	VSL-alone or VSL/QW

As the ongoing I-4 Ultimate project is reconstructing and widening I-4 in the study area, the research team took a further step to investigate the future traffic of roadways networks in the I-4 Ultimate area. The mesoscopic simulation analysis was conducted to compare the traffic performance between the current I-4 and I-4 Ultimate. The simulation results suggested that the I-4 Ultimate with the new design could better serve the future demand in terms of travel time, flow, and Level of Service (LOS). In the future, the I-4 Ultimate could attract more traffic, which means further consideration is needed to explore the traffic on the surrounding roads.

Nevertheless, it is worth to note that there are several limitations to this study. First, the developed DSS of IATM mainly focused on traffic problems caused by high traffic demand such as recurring traffic congestion and non-recurring traffic congestion due to big events. It is necessary to extend the DSS of IATM to handle traffic congestion and unreliability caused by incidents. Besides, three alternative control strategies were investigated in this study. Other control strategies such as detour routing and adaptive signal control could be added to further improve the developed DSS of IATM. Furthermore, great benefits are expected if a real-time traffic control platform could be developed by incorporating the developed DSS.

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APPENDIX A- INVESTIGATION OF ROAD USER'S PREFERENCES

A.1. Background

Active Traffic Management (ATM) is a well-defined concept in the Transportation Systems Management & Operations (TSM&O) realm and includes freeways and expressways. They generally include management techniques such as speed harmonization, queue warning, advanced information, ramp metering, hard shoulder running, and truck restrictions. In the current project, the main goal is to develop an integrated system of traffic management that not only evaluates the real-time traffic operation performance of both arterials and freeways, but also integrates them. The objectives of the project are to identify strategies that could increase corridor throughput, improve travel time reliability and improve incident management system. The suggested integration will enable; (a) strategies to deal with congestion and travel time reliability within a specific corridor, (b) improve the use of the existing infrastructure assets, identify the gaps and leverage unused capacity along the urban corridors, (c) support transportation network managers and operators and (d) achieve improved user satisfaction.

The success of any traffic management system depends on several factors, such as accuracy, cost of the system to the consumer and type of information (Ng et al. 1995). The consumer is the ultimate road user, who make trips to meet his/her needs. All the segments of the road users that can be broadly classified as private vehicle drivers, commercial vehicle drivers and dispatchers, accord varying levels of importance to the types of the information provided from the traffic management systems. Private vehicle drivers are mostly interested in reducing travel time and thus are prime candidates to choose alternate routes (Barfield et al. 1991). So, private vehicle drivers form candidate divertible groups between arterials and expressways. So, to achieve the objectives of the project, there is a need to explore the road user preferences of private vehicle drivers in and around the study region. To that extent, we develop and conduct a Stated Preference (SP) survey to understand road users' preferences in the context of IATM and information.

The survey component of the project is designed to evaluate the impact of attributes such as travel time and travel time reliability on user route choice preferences. The hypothesis being tested is – "if these attributes affect route choice and if so what is the magnitude of their impact". These quantitative measures will be integrated into a Freeway/Arterial Traffic Management system. The objective of this technical report is to present and document the survey design procedure and the data collection effort. We further present the results from data analysis that we conducted by using information collected and compiled from the survey.

The remaining document is organized as follows: The next section focuses on earlier research. Further, we present the description of survey design followed by data compilation and data analysis sections. Finally, the conclusions are presented.

A.2. Earlier Research

Several research efforts in existing literature adopted survey-based methodology for understanding the route choice behaviour for both motorists and non-motorists. A detailed review of earlier literature using different methods of survey is presented in Table 1. The table provides information on the study, location, user group, type of road, independent attributes considered, and the modeling framework employed. Studies presented in Table 1 are categorized along four streams: (1) Likert Scale Survey - in this method, the respondent are asked to scale their importance for various attributes; (2) Stated Preference Survey (SP) - a choice set with the exhaustive choices, attributes and combinations are provided to the respondent which represents a mimic of real world scenario; (3) Revealed Preference Survey (RP) - questioner based surveys are conducted, where the respondent reveals the choice along with the attributes associated with the chosen alternative and (4) RP and SP surveys – a survey approach that elicited both revealed and stated preferences of respondents.

Several observations can be made from Table 1. In terms of motorists, earlier research explored drivers' route choice behaviour on both arterial and freeway. However, for non-motorists, most of the studies considered bike route and residential road for their study. Based on earlier literature, in case of motorists, various factors are identified to influence drivers' route choice decision including route characteristic, travel time, travel cost and traffic information. On the other hand, for non-motorists (specifically for bicyclists), bike facility, traffic and road characteristics are found to be the most relevant factors affecting cyclists' route choice. Methodologies considered in these studies include binomial and multinomial logit model, ordered logit model and structural equation modelling techniques. Among advanced econometric approaches, researches have employed mixed effect multinomial logit model, panel mixed multinomial logit model, nested logit model and neural network models.

Table A-1 Literature review matrix

No.	Study	Study Area	Target	User	Type of Facility	Attributes Considered	Methodological Approach
Likert Scale Survey							
1.	Ng et al., 1995	Puget Sound region of Washington state	Obtain user information requirement for ATIS*	Motorists	Arterial and Freeway	• Navigation system • Road & Traffic information • Roadside services • Communication	• Anova procedure • Duncan's multiple range test
2.	Chorus et al., 2007	Nederland	Examine travelers' need regarding traffic information	Motorists (car/transit)	Any road	• Demographic characteristics • Current travel behavior • Traffic information • Service of travel information • Mode	Structural equation modeling (SEM)
Stated Preference (SP) Survey							
1.	Zhang et al.,2014	Central Texas	Effect of traffic information on toll road usage	Motorists	Freeway (toll road)	• Traffic information dissemination • Routing behavior • Traveler commuting behavior • Demographic characteristic	Nested and Multinomial Logit Model
2.	Abdel-Aty et al., 1997	California	Effect of ATIS on route choice	Commuters	Surface street and Freeway	• Traffic information • Demographic characteristics • Travel time • Roadway facilities	Panel mixed binary logit model

Table A-1 Literature review matrix (continues)

3.	Mahmassani et al., 2003	City of Austin	Examine factors influencing switch of route and destination	Non-commuters (motorists)	Any road	• Demographic Characteristic • Traffic information • Destination information • Alternate route information	Binary choice model
4.	Khoo and Asitha, 2016	Klang Valley region of Malaysia	Evaluate effect of traffic app on driver's route choice behavior	Motorists	Arterial and Freeway	• Perceived traffic information accuracy • Traffic information coverage • Real time rerouting advice • Incident and delay estimation • Navigation & service subscription	Bivariate probit models
5.	Gan and Ye, 2014	Shanghai Pudong international airport.	Examine motorist's diversion decision behavior under VMS*	Motorists	Freeway	• Driver characteristics • Diversion decision under VMS	• Cross sectional logit model • Mixed logit model
6.	Petrella et al., 2014	US-75 corridor in Dallas, Texas; I-15 corridor in San Diego, California	Explore travelers' response to real time traffic and traveler information	Motorists	Freeway	• Demographic characteristic • Level of satisfaction with trip • Level of traffic congestion • Predicted trip time • Overall driving time • Traffic information	• Panel design • Comparison exercise

Table A-1 Literature review matrix (continued)

7.	Zhang et al., 2008	Prince George's County, Maryland (The university of Maryland)	Examine real time transit information on travelers' characteristics	Commuters (transit)	Local and arterial roads	• Demographic characteristic • Commuting pattern • Attitude • Use and perceptions of shuttle	Random-effects-ordered probit models
8.	Anowar et al., 2017a	Toronto, Montreal, Calgary, New York, and Orlando	Evaluate the trade-off of cyclist for avoiding air pollution	Commuter (cyclists)	Arterial and Residential road	• Personal and household characteristics • Cycling habit • Roadway characteristics • Bicycle route characteristic • Trip characteristics	Panel mixed multinomial logit model
9.	Anowar et al., 2017b	Toronto, Montreal, Calgary, New York, and Orlando	Explore the characteristics of different types of cyclists	Commuter and Non-commuter (cyclists)	Arterial and Residential road	• Personal and household characteristics • Cycling habit • Roadway characteristics • Bicycle route characteristic • Trip characteristics	Ordinal logistic regression (OL) model
10.	Hunt and Abraham, 2007	Edmonton, Canada	Explore factors influencing bicycle use	Non-recreational (bicyclist)	Bike route	• Cycling facility • Trip characteristics • Demographic characteristics	Logit choice model
11.	Tilahun et al., 2007	University of Minnesota	Evaluate the trade-off of cyclist for additional facilities	Commuter (cyclists)	Bike route	• Demographic characteristic • Bike facility • Route characteristics • Weather	Generalized linear mixed model

Table A-1 Literature review matrix (continued)

12.	Stinson and Bhat, 2003	Across United States	Explore route and link level factors influencing commuter bicyclists' route choice	Commuter (cyclists)	Bike route	• Route level characteristics • Link level characteristics	Binary logit model
13.	Caulfield et al., 2012	Dublin, Ireland	Explore factors influencing cyclists' route choice	Commuter and Non-commuter (cyclists	Bike route	• Traffic speed • Type of infrastructure • Demographic characteristics • Route characteristics • Cycle traffic	Multinomial logit model
14.	Abdel-Aty et al., 1995a	California	Effect of ATIS on route choice	Commuters	Surface street and Freeway	• Traffic information • Demographic characteristics • Travel time • Roadway facilities and characteristics • Safety	Mixed binary logit model
Revealed Preference (RP) Survey							
1.	Tseng et al., 2013	Dutch A12 motorway corridor	Effect of traffic information on traveler behavior	Motorists	Freeway	• Expected travel time • Time difference • Delay • Weather	Mixed logit model
2.	Javid et al.	Lahore, Pakistan	Effect of radio on traveler route choice behavior	Commuters (motorists)	Any road	• Demographic characteristic • Trip characteristic • Tendency to listen radio • Performance service attribute of radio	Structural equation modeling (SEM)

Table A-1 Literature review matrix (continued)

3.	Bagloee et al., 2014	Tehran, Iran	Examine drivers' response to radio (traffic information)	Commuters (motorists)	Any road	• Demographic information • Work-related information • Driver behavior information • Traffic information (radio)	• Neural network model • Ordered probit • Binary logit model
4.	Pozsgay and Bhat, 2001	Dallas-Fort Worth	Destination choice model for urban recreational trips	Non-commuter (motorists)	Urban road	• Travel impedance characteristics • Trip characteristics • Attraction-end zone variable • Attraction-end zonal spatial structure	Multinomial logit model
5.	Menghini et al., 2010	Zürich	Develop a route choice model for bicyclists	Commuter and Non-commuter (cyclists)	Bike route	• Route characteristics • Cycling trip	Multinomial logit model
6.	Hood et al., 2011	San Francisco, California	Develop a model for understanding the cyclists' decision making	Commuter and Non-commuter (cyclists)	Bike route	• Traffic volume • Traffic speed • Bike facility • Route characteristics • Demographic characteristics	Path Size Multinomial Logit model
7.	Broach et al., 2012	Portland metropolitan area	Explore the contributing factors for cyclists' route choice	Commuter and Non-commuter (cyclists)	Bike route	• Route characteristics • Bike facility • Traffic characteristics	Path-Size Logit (PSL) model

Table A-1 Literature review matrix (continued)

8.	Yeboah and Alvanides, 2015	Newcastle upon Tyne (North East England)	Evaluate the influence of network restriction on commuter cyclists' movement	Commuter (cyclists)	Bike route	• Route characteristics • Bike facility	Parametric and Non-parametric statistical techniques
9.	Yang et al., 1993	California	Effect of ATIS on route choice	Motorists	Side road and freeway	• Demographic characteristics • Traffic information • Driving experience	Neural network model
Both SP and RP Survey							
1.	Choocharuk ul,2008	Bangkok, Thailand	Explore the contributing factors for drivers' route diversion	Motorists	Intersection	• Traffic delay • Demographic characteristics • Travel characteristics • VMS	Structural equation modeling (SEM
2.	Meng et al., 2017	Northern and Eastern side of Singapore	Examine the travel behavior of commuter motorists	Commuters (motorists)	Any road	• Demographic characteristics • Travel characteristics • Traffic delay and cost	Binary logit model
3.	Khattak et al., 1996	Golden Gate Bridge	Examine pre-trip response of commuters to unexpected traffic congestion	Commuters (motorists)	Bridge road	• Demographic characteristics • Travel pattern • Traffic information (Pre-trip/En-route • Change of driving pattern	Tree logit framework

Table A-1 Literature review matrix (continued)

4.	Yang and Mesbah, 2013	University of Queensland, Australia	Explore the contributing factors for cyclists' route choice	Commuter and Non-commuter (cyclists)	Bike route	• Route characteristics • Demographic characteristics • Traffic safety • Type of facility	Logit choice model
5.	Abdel-Aty et al. 1995b	Los Angeles	Effect of ATIS on route choice	Commuters	Surface roadways	• Travel information • Demographics • Household information • Roadway attributes	Attrition Model

* Note: ATIS (Advanced Traveler Information System)

* Note: VMS (Variable Message Sign)

A.3. Survey Design

Our survey focuses on obtaining responses from road users along three different dimensions. These are: (1) Demographic information (including gender, age, education level, employment type, years of driving experience and car availability), (2) Trip level information (including use of expressway, smartphone owner, current mode of accessing traffic information and preferred mode of accessing traffic information), and (3) Hypothetical route choice scenarios (SP survey) with three route options per scenario.

Among the aforementioned dimensions, first two sections are designed for direct responses to the questions related to the respondent demographics and their trip characteristics. The main focus of the survey is section 3 - hypothetical route choice scenarios. This requires development of an experimental design to allow the road user to compare various trip making attributes among the different route choice options. Prior to the experimental design exercise, an important step in SP survey design includes identifying and defining, clearly and adequately, the attributes that characterize the available alternatives of the choice context (Hensher 1994; de Dios Ortúzar and Rodríguez 2002; Anowar et al., 2017a). The attributes that are adopted in our study are roadway type, travel time, added delay, availability of traffic information, media for accessing traffic information and toll cost. These attributes are incorporated in designing SP survey section. A detailed description of different dimensions considered in our survey along with the description of the SP part are presented in the following sections.

No personal information is collected in the survey (i.e. name and address). To ensure confidentiality of information, we use a numeric code throughout this study. The participation of the respondents is voluntary. The respondent has to be at least 18 years of age to take part in the survey.

A.3.1. Demographic Information

General demographic information of the respondents including age, gender, level of education, year of driving experience, availability of car, location of house (zip code), location of work/frequent travel (zip code) and access to smart phone are collected in this section. Most of these variables are collected as categorical or ordered variables as presented in Table 2.

Table A-2. List of demographic information included in the survey

Variable	Categories
Gender	Male
	Female
Age	18-24
	25-34
	35-44
	45-54
	55-64
	>64
Education	Less than high school
	High school
	College
	Bachelors
	Graduate or higher
Employment type	Student
	Full-time worker
	Part-time worker
	Retired
	Not/Self-employed
Year of driving experience	Did not drive
	0-2 years
	3-5 years
	5-10 years
	>10 years
Car availability	Always
	Usually
	Sometimes
	less than sometimes
	Never
City and Zip code of home location	City
	Zip code
City and Zip code of work/most frequent travel location	City
	Zip code
Smartphone owner	Yes
	No

A.3.2. Trip Level Information

The information collected under this category includes the use of expressway, currently used media for accessing traffic information and preferred media of receiving traffic information. The options provided for each of these variables are as listed below in Table 3.

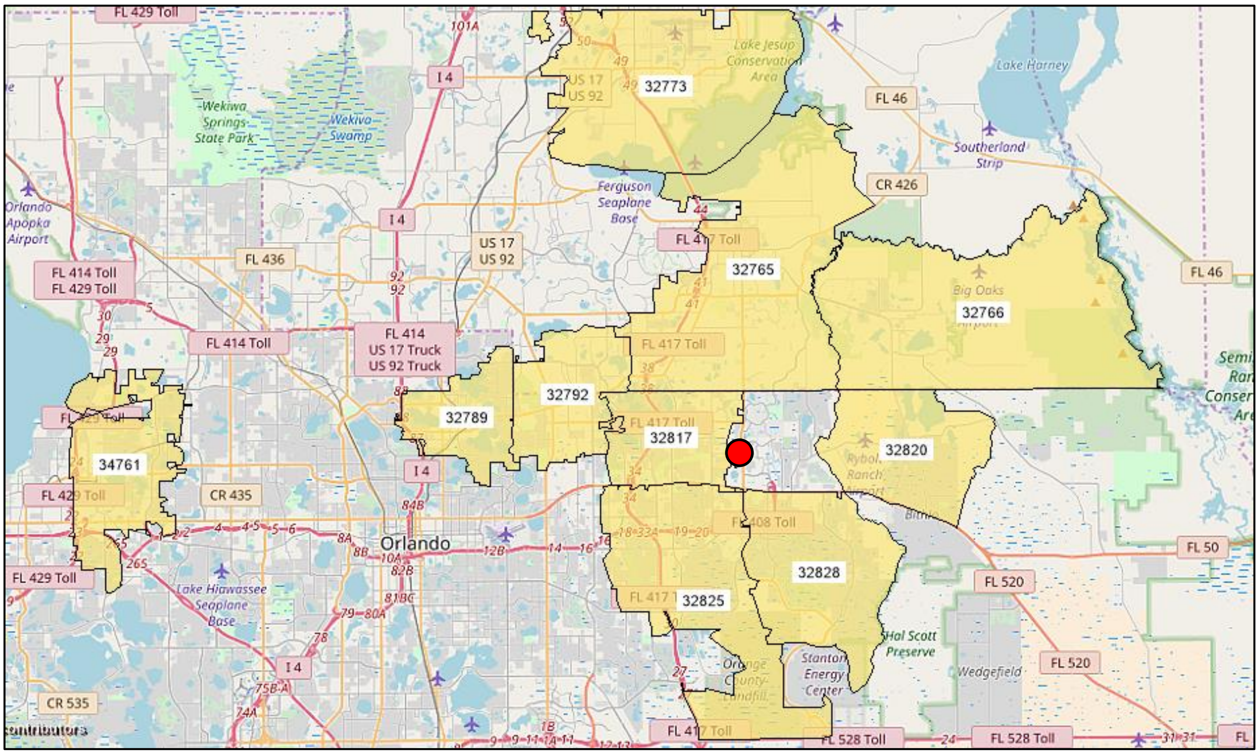
Table A-3. List of trip attributes collected from respondents

Variable name	Option
Expressway use frequency	Almost every day
	2-3 days per week
	Once a week
	Several times a month
	Less than once per month
	Rarely
Current mode of receiving traffic information	None
	Variable message sign
	Mobile app
	Social media
	511 calls
	Radio
	Other
Preferred mode of receiving traffic information	None
	Variable message sign
	Mobile app
	Social media
	511 calls
	Radio
	Other

A.3.3. Hypothetical Route Choice Scenario (SP part)

We have generated the hypothetical route choice scenario for two different cases: (1) Scenarios for identified ZIP codes and (2) scenarios for unidentified ZIP codes. In order to understand the route choice preference of road users' living or driving within greater Orlando region, we have identified several ZIP code areas and designed scenarios for this group of people. Figure 1 represents the study area in Greater Orlando region along with our considered ZIP code locations.

Please note that, ZIP code 32816 is a very small region including UCF area. It is highlighted next to 32817.



ZIP code 32816 is very small region of UCF area, highlighted next to 32817.

Figure A-1. Study area along with ZIP codes

The respondents are asked to provide their ZIP codes for the locations where they are currently residing and for the locations where they work or most frequent travel. If both of these ZIP codes are outside of our defined locations, we defined those cases as scenarios for undefined ZIP codes cases. A detailed description of the attribute along with the definition considered for the SP part are presented in Table 4. We used the experimental design routines in SAS (fractional factorial design) to develop the route choice alternatives in each scenario presented to the respondents. The fractional factorial design is adopted to ensure extraction of the most amount of information regarding the effects of route attributes on route choice decisions. The design was checked to ensure that the attribute levels of the alternatives did not create dominating alternatives. The SP scenarios were preceded by clear definitions of the attributes.

Table A-4. Attributes and description of attributes

Attribute	Definition
Roadway types	**Roadway types** refers to the class of roadway. **Arterials** – speed limits 25 to 55 mph **Expressway** – speed limit greater than 55 mph
Travel time (minutes)	**Travel time** refers to the time that you are likely to observe while travelling from your trip origin to trip destination.
Added delay (minutes)	**Added delay** refers to the additional time required to travel from your trip origin to trip destination if there were congestion due to heavy traffic or some other incidents (such as a crash).
Availability of traffic information	**Availability of traffic information** refers to the stage of traffic information. **None** – traffic information will be unavailable for the trip. **Pre-trip** – traffic information will be available before starting the trip. **En-route** – traffic information will be available on-route during the trip.
Media for accessing traffic information	**Media for accessing traffic information** refers to the media sources available for traffic information. **None** – traffic information will be unavailable for the trip. **Mobile app** – traffic information will be available via mobile app such as Waze, Google Maps, INRIX, Bing map etc. **Twitter** – traffic information will be available via twitter. **Radio** – traffic information will be available via radio.
Toll cost ($)	**Toll cost** refers to the charge payable for permission to use a particular road.

A.3.3.1. Scenarios for identified ZIP codes

In designing the scenarios for identified ZIP codes, the attributes that we have considered are travel time, added delay, availability of traffic information, media for accessing traffic information and toll cost. To be sure, the major objective of the survey is to identify the impact of travel related information on choosing different named alternative routes within Greater Orlando region. In order to achieve this objective, we have identified 11 ZIP code areas as presented in Figure 1. The considered ZIP codes are:

(1) 32765,

(2) 32789,

(3) 32817,

(4) 32828,

(5) 32766,

(6) 32792,

(7) 32820,

(8) 34761,

(9) 32773,

(10) 32816 and

(11) 32825.

In order to understand route choice preferences among travelers, given different level of traffic information, we have generated route maps with three alternative routes along with their corresponding travel time by using Google Mapss API. The procedure of identifying travel times is presented in APPENDIX A. The alternative route maps are generated for each pair of identified ZIP codes as listed above by considering one ZIP code location as origin of trip and another ZIP code location as destination. In generating these images, we have identified three possible alternative routes along with their corresponding travel times. We extracted the travel time information from Google API for all three possible alternative routes for the time period 7-8 AM on Monday to simulate the scenario of morning peak period. However, in designing the SP part for the identified ZIP code locations, we have excluded the following images:

- The ZIP code pair for which we did not get three alternative routes from Google API (for instance: ZIP code pair 32765-32773). Images for some of these cases are presented in APPENDIX B.
- The ZIP code pair for which the alternative routes has high (or low) travel times relative to other route/routes that it is highly unlikely to be considered (or only possible route) as an alternative route by trip makers. (for instance: ZIP code pair 32766-32789). If the alternative routes have same travel time, we have also excluded those scenarios. Images for some of these cases are presented in APPENDIX C.
- Images for intra-zonal trips.

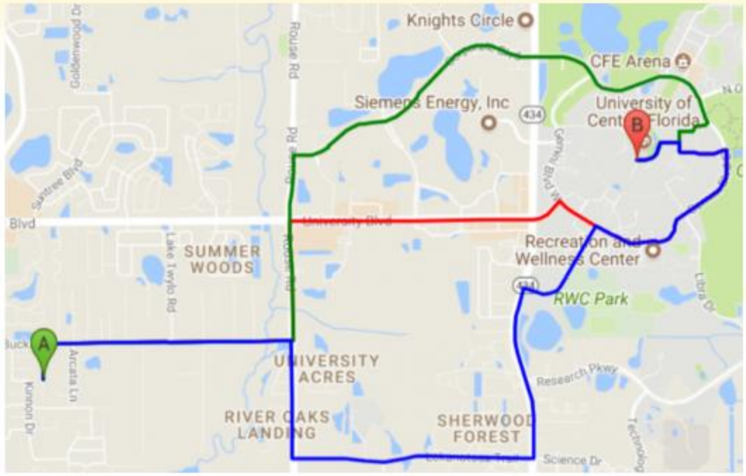
Finally, we have generated total 45 images for the survey design. All of these generated images are presented in APPENDIX D. In generating the alternative routes image, we have used different color (red, blue and green) for different routes so that it is easier for the survey participants to identify different routes easily. The ZIP code pairs for which we did not generate images are considered in the categories of unidentified ZIP code locations.

After identifying the travel times for different ZIP code pairs as explained above, we have generated different levels of travel time attributes for the hypothetical scenario analysis by considering "travel time generated from Google API + (-6, -3, 0, +3 or +6) minutes". It allows us to replicate different driving environment of peak and off-peak period. In terms of added delay, we have considered four different attribute levels by representing scenarios from without any delay to high delay conditions. Availability of traffic information and media for accessing traffic information have 3 and 4 attribute levels in our study context. However, in designing the hypothetical scenario, we ensure that if availability of traffic information in none, the respective media for accessing traffic information is also none. In terms of trip cost, we have assigned 0$ for arterial roadway alternative. It is worthwhile to mention here that, for the identified ZIP code locations, since the routes are known, roadway types are not considered for designing the hypothetical scenarios. However, we have SP scenarios for four different types of roadway combinations: (1) all arterials, (2) two arterials and one expressway, (3) one arterial and two expressways and (4) three expressway. We have generated hypothetical scenarios for all of these roadway type combinations for the identified ZIP code location pair.

The attributes that we have considered along with the attribute levels for the identified ZIP code locations are presented in Table 5 below. For the SP part, within each choice question, three alternative routes (with different levels of the five route attributes selected) were presented, and the individual was asked to make a choice among the alternatives presented. A figure with three alternate routes was provided along with their respective travel time. The respondent was asked to choose an alternative among the choices. A sample map with alternate choices is presented in Figure 2. Each respondent was presented with six choice experiments in the survey for the identified ZIP code locations.

Table A-5. Attributes and description of attributes for identified ZIP code locations

Attribute	Attribute Levels
Attribute 1: Travel time (minutes)	**6 attribute levels defined as** 1. Travel time extracted from Google Maps – 6 2. Travel time extracted from Google Maps – 3 3. Travel time extracted from Google Maps 4. Travel time extracted from Google Maps + 3 5. Travel time extracted from Google Maps + 6
Attribute 2: Added delay (minutes)	**4 attribute levels defined as** 1. 0 2. 3 3. 6 4. 10
Attribute 3: Availability of traffic information	**3 attribute levels defined as** 1. None 2. Pre-trip 3. En-route
Attribute 4: Media for accessing traffic information	**4 attribute levels defined as** 1. None 2. Mobile app 3. Twitter 4. Radio
Attribute 5: Toll cost ($)	**4 attribute levels defined as** 1. 0 2. 1.5 3. 3 4. 4



Three routes – red, green and blue – are shown in the figure above. The attributes for these routes are presented below. From these options, please choose your preferred route.

Attributes	Red Route	Green Route	Blue Route
Travel time (Minutes)	8	19	13
Additional travel time due to congestion (Minutes)	3	10	6
Availability of traffic information	En-route	Pre-trip	Pre-trip
Media for accessing traffic information	Radio	Twitter	Mobile app

	Red Route	Green Route	Blue Route
Choose a route from these 3 alternatives	O	O	O

Figure A-2. Sample map with alternative routes

A.3.3.2. Scenarios for unidentified ZIP codes

In designing the scenarios for unidentified ZIP codes, the attributes that we have considered along with the attribute levels are presented in Table 6 below. Two attribute levels – arterial and expressway – are considered in roadway types. In terms of travel time, we have considered ten attribute levels assigning five levels for arterials and five for expressways. In terms of added delay, we have considered four different attribute levels by representing scenarios from without any delay to high delay conditions. Availability of traffic information and media for accessing traffic information have 3 and 4 attribute levels in our study context. However, in designing the hypothetical scenario, we ensure that if availability of traffic information in none, the respective media for accessing traffic information is also none.

Table A-6. Attributes and description of attributes for the unidentified ZIP code locations

Attribute	Attribute Levels
Attribute 1: Roadway types	**2 attribute levels defined as** 1. Arterial 2. Expressway
Attribute 2: Travel time (minutes)	**6 attribute levels defined as (Expressway/Arterial)** 1. 15/20 2. 20/25 3. 25/30 4. 30/35 5. 35/40
Attribute 3: Added delay (minutes)	**4 attribute levels defined as** 1. 0 2. 3 3. 6 4. 10
Attribute 4: Availability of traffic information	**3 attribute levels defined as** 1. None 2. Pre-trip 3. En-route
Attribute 5: Media for accessing traffic information	**4 attribute levels defined as** 1. None 2. Mobile app 3. Twitter 4. Radio
Attribute 6: Toll cost ($)	**4 attribute levels defined as** 1. 0 2. 1.5 3. 3 4. 4

In terms of trip cost, we have assigned 0$ for arterial roadway alternative. Within each choice question, three alternative routes (with different levels of the six route attributes selected) were presented, and the individual was asked to make a choice among the alternatives presented. The respondent was asked to choose an alternative among the choices. A sample case with alternate choices is presented in Figure 3. Each respondent was presented with five choice experiments in the survey for the unidentified ZIP code locations.

The attributes for three routes are presented below. From these options please choose your preferred route.

Attributes	Route 1	Route 2	Route 3
Roadway types	Arterial	Expressway	Arterial
Travel time (Minutes)	35	20	15
Additional travel time due to congestion (Minutes)	10	6	0
Availability of traffic information	En-route	Pre-trip	Pre-trip
Media for accessing traffic information	Mobile app	Twitter	Radio
Toll cost ($)	0	1.5	0

	Route 1	Route 2	Route 3
Choose a route from these 3 alternatives	○	○	○

Figure A-3. Sample scenario from SP section with origin or destination not in study region

A.3.4. Survey Administration

The survey is disseminated through a web-based system and it was designed for the internet, using a combination of JavaScript and Java programs. The survey design was coded on Qualtrics platform of UCF (https://ucf.qualtrics.com/) for web dissemination. A randomization process was developed in the survey platform to evenly present only one group of scenarios to a respondent for both identified and unidentified ZIP code cases. For the identified and unidentified ZIP code scenarios, respondents will answer 6 and 5 questions respectively. Before disseminating the survey, we have gathered information through a pilot survey. After several iterations based on feedback gathered from pilot surveys, the survey was finalized with 16 and 15 questions for identified and unidentified ZIP code locations, respectively. The final version of the survey instrument is available at:

https://ucf.qualtrics.com/jfe/form/SV_1SLGc01ehgW0o1D

The SP scenarios were preceded by clear definitions of the attributes. Participation in the survey is completely voluntary. Individuals can choose not to participate in the survey and can quit the survey at any time.

The survey was administered through the survey link hosted by UCF. We adopted several survey dissemination, distribution, and advertisement schemes for collecting responses. For instance, web-links to the surveys were emailed to individuals, university electronic mailing lists, organizations, and groups; posts related to the survey were uploaded in different social media platforms including Facebook, LinkedIn, and Twitter. Individuals who learnt about our survey from these sources may have distributed it to their peers, colleagues, family, and friends. The poster is presented in Appendix E. Owing to the sampling technique, it is likely that most of the respondents were with access to computers and/or smart phones. The final survey questionnaire for one of the selected ZIP code pairs is presented in APPENDIX F.

A.3.5. Ethics Approval

Any survey that deals with human subjects should get approval from Institutional Review Board (IRB). IRB reviews the survey design, potential candidates to the survey, risks associated with the survey/experiment to the respondents, conflict of identity and privacy related to the respondents, whether consent is taken from the respondents etc. to ensure the survey/experiment doesn't violate any research ethics. Before disseminating the survey, we have provided all the required information to UCF IRB board for review and approval. The survey has been approved by UCF IRB. The protocol submitted for IRB approval is presented in APPENDIX G. The approval letter is presented in APPENDIX H.

A.4. Data

The survey data was compiled and processed from the Qualtrics survey platform in an SPSS compatible file format. After removing all the incomplete information, we finally have 1238 choice scenarios from 243 respondents. Descriptive statistics for the sample used in this study are presented in Table 7.

Table A-7. Sample characteristics

Attributes	Percentages within Sample of Respondents (243)
Demographic Information	
Gender	Males: 55.2%
	Females: 44.8%
Age	18-24 years: 34.3%
	25-34 years: 38.4%
	35-44 years: 10.3%
	45-54 years: 5.8%
	55-64 years: 8.3%
	≥ 65 years: 2.9%
Education	High school: 11.6%
	College: 21.5%
	Bachelors: 37.6%
	Graduate or higher: 29.3%
Employment Type	Student: 33.5%
	Full-time worker: 55%
	Part-time worker: 9.5%
	Retired: 0.8%
	Not/self-employed: 1.2%

Years of Driving Experience	Did not drive: 1.7%
	0-2 years: 7.5%
	3-5 years: 22.8%
	6-10 years: 24.9%
	>10 years: 43.2%
Car Availability	Always: 92.5%
	Usually: 4.6%
	Sometimes: 1.2%
	Less than sometimes: 0.8%
	Never: 0.8%
Trip Level Information	
Use of Expressway	Almost every day: 36.4%
	2-3 days per week: 25.2%
	Once a week: 12%
	Several times a month: 12.4%
	Less than once per month: 9.9%
	Rarely: 4.1%
Smartphone Owner	Yes: 99.2%
	No: 0.8%
Current Mode of Receiving Traffic Information	None – Yes: 6.2%, No: 93.8%
	Variable message sign – Yes: 39.9%, No: 60.1%
	Mobile app – Yes: 85.6%, No: 14.4%
	Social media – Yes: 4.5%, No: 95.5%
	511 calls – Yes: 2.5%, No: 97.5%
	Radio – Yes: 35%, No: 65%
	Other – Yes: 5.8%, No: 94.2%
Preferred Mode of Receiving Traffic Information	None: 2.5%
	Variable message sign: 8.7%
	Mobile app: 76.9%
	Radio: 10.3%
	Other: 1.7%
Route Choice Characteristic	
	En-Route: 35%

Availability of Traffic Information	Pre-trip: 44.4%
	Never: 20.6%
Media for Accessing of Traffic Information	Mobile app: 30.1%
	Radio: 30.3%
	Twitter: 19.3%
	Never: 20.3%

From Table 7, we can see that out of 243 respondents, 55.2% are male and 44.8% are females. In terms of age categories, almost three-fourth of the respondents belong to younger age group category (18-34 years). Only 2.9% of the respondents are aged above 65 years. Majority of respondent are highly educated (67%) amongst which almost 30% held at least graduate degree while around 37% had completed a bachelor's degree. One third of the respondents are students and more than half are fully employed. Around 9% are employed part-time and 1% have a flexible work schedule. Among the full-time employee, around 72% have higher degree.

Out of 243 respondents, around 45% of them have the driving experience more than 10 years while only about 2% did not drive at all. In case of use of expressway, more than one-third of the respondents use expressway on a daily basis. However, around one-fourth of the respondents do not use expressway very frequently. From Table 7 we can see that, almost 93% of the respondents have the car available to them always. In the survey, we also asked the participants about their current mode of receiving traffic information and we allow them to select multiple options. Result shows that more than 85% people used mobile app as their source of traffic information. From the table, it is evident that respondents often also use multiple modes for accessing traffic information. Moreover, we asked the respondents about their preferred mode for accessing traffic information and from the sample, we found that, more than three-fourth of the people preferred mobile app as their source for traffic information.

Further, from the chosen scenarios of the participants, we found that majority of the people like to have traffic information available for their route. Among them, around 45% of them like to know the traffic information for their route even before starting their trip. In case of using media for accessing traffic information, it is found that around 60% of the respondents used mobile app and radio as their source of traffic information.

In order to understand preferred mode and level of accessing traffic information across different respondents based on their demographic characteristics, we also present several crosstab analysis in this section. Figure 4 represents the distribution of media for accessing traffic information by different age categories. From Figure 4, we can see that young and adult people are more likely to use mobile app for accessing traffic information. Almost one-third of the people between 18-44 years age used mobile app as their primary source of traffic information. On the other hand, older people are likely to use radio more. For people over 45 years old, more than 35 % used radio as their primary source of accessing traffic information.

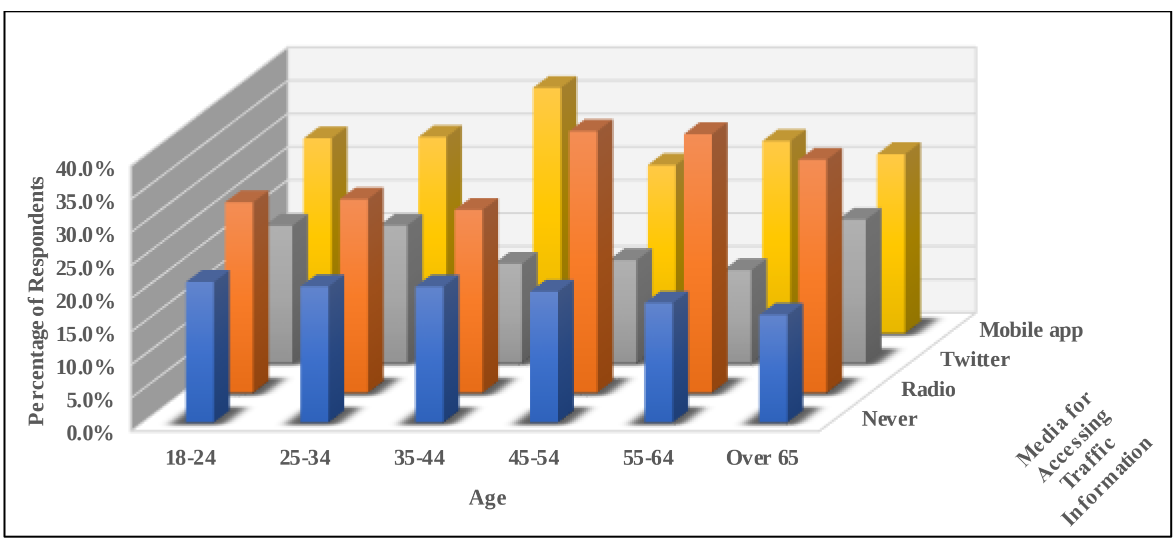


Figure 4: Age vs. Media for accessing traffic information

Figure 5 presents the distribution of media for accessing traffic information across different employment categories. From the figure, we can see that most of the full-time workers used mobile app as their primary source of accessing traffic information while radio is the most used media by retired people. Approximately one-fourth of the students and retired people used Twitter also for accessing information related to traffic.

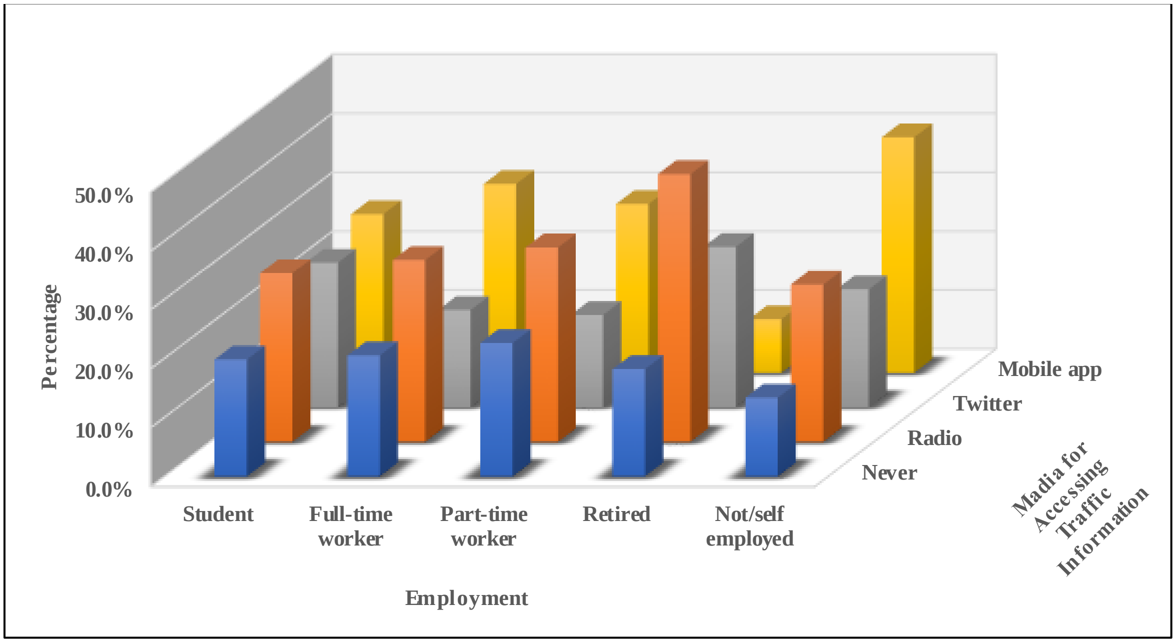


Figure 5: Employment vs. media for accessing traffic information

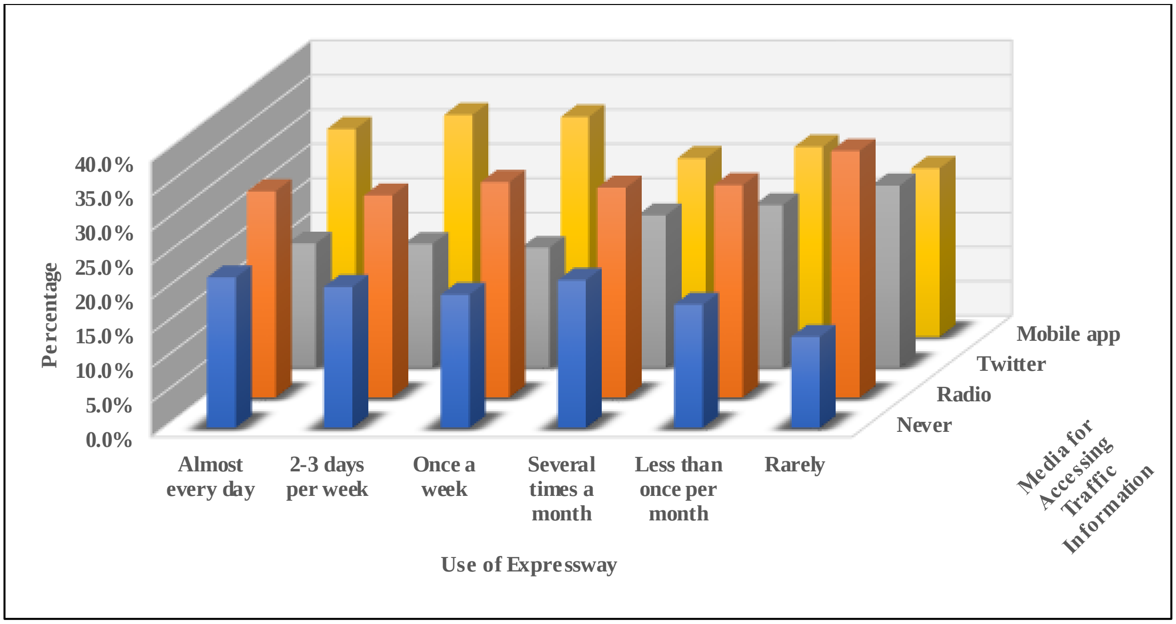


Figure A-6. Use of expressway vs. media for accessing traffic information

Figure 6 presents the media for accessing traffic information across different group of respondents based on the use of expressway for making trips. One interesting trend that can be observed from Figure 6 is that for people who use expressways frequently, mobile app is most commonly adopted for accessing traffic information. On the other hand, people who do not use expressways more frequently, prefer radio as their preferred source for accessing traffic information. It is also interesting to observe that individuals who rarely use expressways have preference towards Twitter as their media for accessing traffic information than those who use expressway frequently.

A.5. Empirical Analysis

A.5.1. Modeling Framework

In the current research effort, we assume a random utility-based framework (Multinomial Logit (MNL) Model) for modeling road user's route choice (following McFadden, 1978). In this section, we explain the econometric framework of the MNL model employed in the current study.

Let j $(j = 1,2,3,\ldots,J)$ be the index to represent a route among a set of C_i route alternatives of trip i. Thus, the route choice takes the familiar discrete choice formulation as the linear function as follows:

$$u_{ij}^{*} = \left(\boldsymbol{\delta}\boldsymbol{z}_{ij} + \xi_{ij}\right) \tag{1}$$

where u_{ij}^{*} is the latent variable of destination choice for trip i with alternative j.

Within the traditional random utility maximization-based discrete choice framework as presented in Equation 1, route j will be chosen for trip i if $u_{ij}^{*} > \max_{\substack{d=1,2,3,\ldots,J \\ d \neq j}} u_{iJ}^{*}$. $\boldsymbol{z}_{ij}$ is a vector of trip level attributes corresponding to route j. $\boldsymbol{\delta}$ is a vector of coefficients to be estimated. ξ_{ij} is an idiosyncratic error term assumed to be identically and independently standard logistic distributed across trip i with route alternative j. Thus, the probability of trip i representing the route choice of trip makers takes the typical MNL form given by:

$$R_{ij} = \frac{exp\left(\boldsymbol{\delta}\boldsymbol{z}_{ij}\right)}{\sum_{j \in C_i} exp\left(\boldsymbol{\delta}\boldsymbol{z}_{ij}\right)} \tag{2}$$

Finally, the log-likelihood function is:

$$LL = \left(\sum_{i} Ln(R_{ij}) \right) \quad (3)$$

All the parameters in the model are estimated by maximizing the logarithmic function LL presented in Equation 3.

A.5.2. Model Results

The final specification of the model development was based on removing the statistically insignificant variables in a systematic process based on 90% confidence level. Table 8 presents the estimation results of the route choice model. In the MNL model, the positive (negative) coefficient corresponds to increased (decreased) likelihood of route choice. The effects of exogenous variables in model specifications are discussed in this section by variable groups.

A.5.2.1. Trip Characteristics

The coefficient for travel time has a negative impact on route choice preference indicating a disinclination of people towards longer routes. This is as expected and indicating that road user prefer route with shorter travel time. The delay variable refers to the additional travel time required to travel from trip origin to trip destination due to heavy traffic or some other incidents (bad weather). This parameter is also found to have a negative impact on route choice behavior. Travel cost in our study is defined as the toll cost of expressways. The arterial alternative has been assigned with zero toll cost. The variable indicating travel cost is found to have a negative impact on route choice. This indicates that with an increase in travel cost, the likelihood of choosing that route reduces.

A.5.2.2. Availability of Traffic Information

With regards to availability of traffic information, the estimated result shows that pre-trip traffic information has a positive impact i.e. the likelihood of choosing a route increases if the traffic information is available to the person beforehand compared to routes with unavailable traffic information. En-route traffic information also has positive impact on route choice preferences. However, as is evident from Table 8, we can see that pre-trip information has greater impact.

A.5.2.3. Media for Accessing Traffic Information

Media for accessing traffic information refers to the media source available for accessing traffic information. Both radio and twitter indicators have negative impacts indicating lower preferences for radio and twitter in accessing traffic information than mobile app for choosing their route for a specific trip.

Table A-8. Model estimation results

Attribute Levels	Coefficient	t-statistics
Trip Characteristics		
Travel Time (in minutes)	-0.139	-18.441
Delay (in minutes)	-0.112	-11.095
Travel Cost ($)	-0.497	-15.466
Availability of Traffic Information (Base: No information available)		
Pre-Trip	0.460	4.598
En-Route	0.341	3.261
Media for Accessing Traffic Information (Base: Mobile App)		
Radio	-0.209	-2.081
Twitter	-0.526	-5.223

A.6. Recommendations

The main objective of the proposed research project is to develop an integrated active traffic management tool to enhance traffic flow on roadway facilities. The most basic component of the research project is targeted at estimating travel times and providing that information to road users in real-time. However, we need to recognize that this information is being generated for the benefit of individuals. Thus, in addition to examining travel times, we will also need to account for individual preferences. For instance, some travellers might not consider the "fastest" route provided by the IATM tool as their choice because of their inherent experiences on these facilities. We need to consider such individual preferences to ensure we do not incorrectly estimate the demand (for diversion or new facility being added). Through our survey, we are interested in evaluating how various attributes influence user preferences. Finally, it is also essential to evaluate how individuals would like to review the information to be generated by the tool. For this purpose, we evaluated information on what are most commonly employed methods for information access and the preferred alternatives. Our survey has provided us a ranking of preferences across various data provision platforms. The quantitative findings documented will be integrated with the research conducted on travel times.

The research team envisions a tiered structure to the final IATM tool. While the travel time evaluation and fusion exercise will provide the primary tier of the tool, the survey results will provide us the second tier information on route preferences for road users. The second tier will allow us to evaluate expected shifts in demand in response to travel time changes while accounting for intrinsic user preferences. For example, a crash on freeway increases travel time by 15 minutes. Based on our model results, we will be able to generate the proportion of users who will shift to the alternative arterial routes. The survey results show that while low travel time is preferred, individuals are also influenced by cost and other attributes. Thus, with our approach, we can accurately evaluate expected reduction of demand on the freeway and prepare for the appropriate increase of demand on arterials. Ignoring for the individual preferences would result in suggesting larger or smaller demand shifts than those that are actually experienced.

A.7. Conclusion

The current research effort explored the road users' preferences of private vehicle drivers in and around greater Orlando region through a web-based state preference (SP) survey. Based on the responses, we developed a random utility based multinomial logit framework to understand the contribution of different attributes on route choice behavior. Based on the empirical analysis, we found that trip related attributes including travel time, travel cost, and both stage and source of traffic information have highly significant impact on route choice preferences. Further, the survey results will be integrated within an integrated platform of traffic information provision. It will be integrated with the IATM strategies under development by the other tasks of the IATM project.

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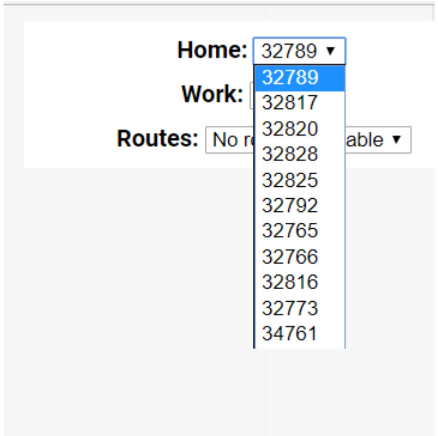
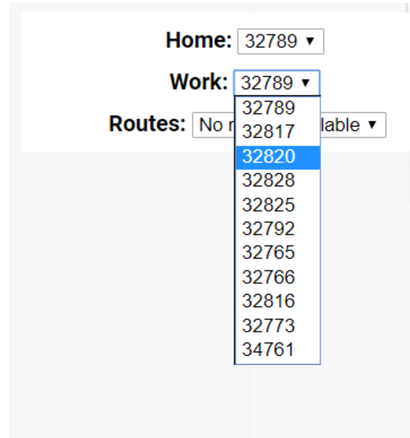
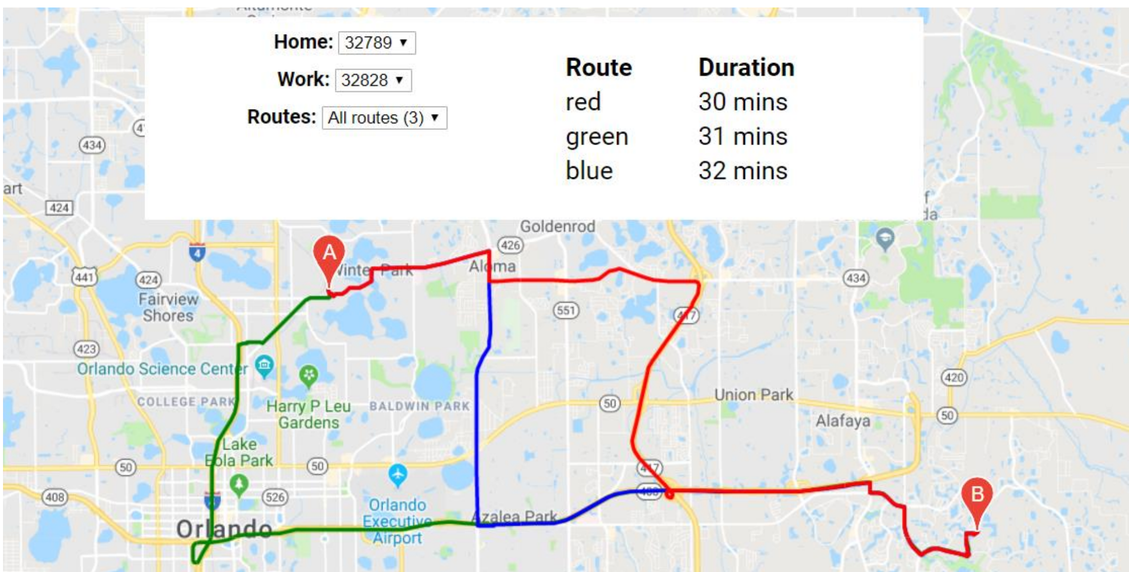
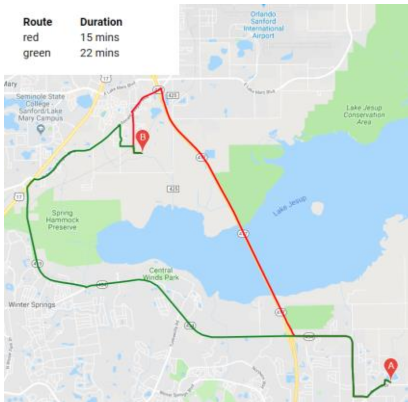
APPENDIX A-A: Process of Generating Travel Times from Google API







APPENDIX A-B: Images for Routes with Two Alternatives



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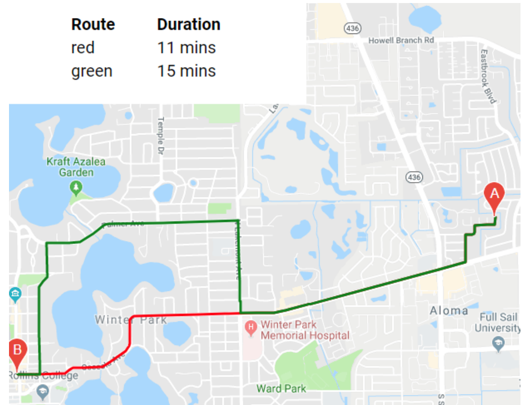

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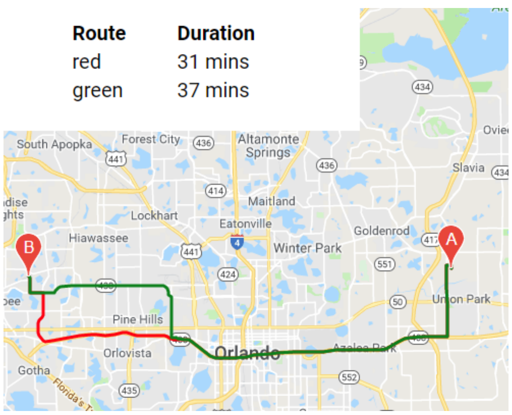

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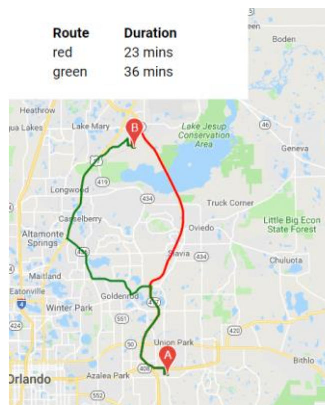

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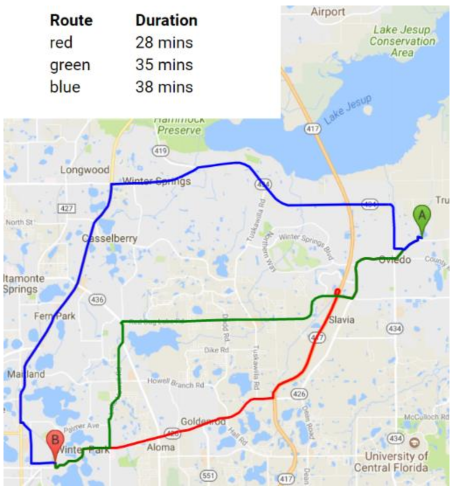
APPENDIX A-C: Route Alternatives with Equal, High or Low Travel Time for One of the Alternatives



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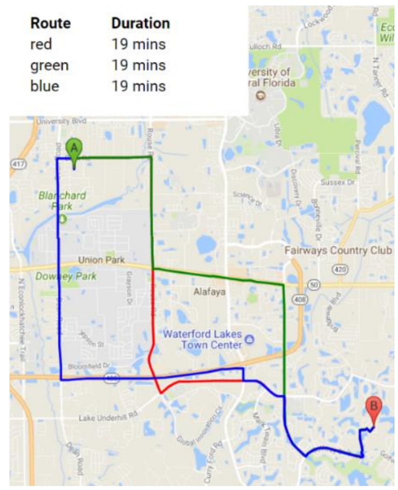

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APPENDIX A-D: Image of Alternative Routes of Identified ZIP Code Areas within Greater Orlando Region

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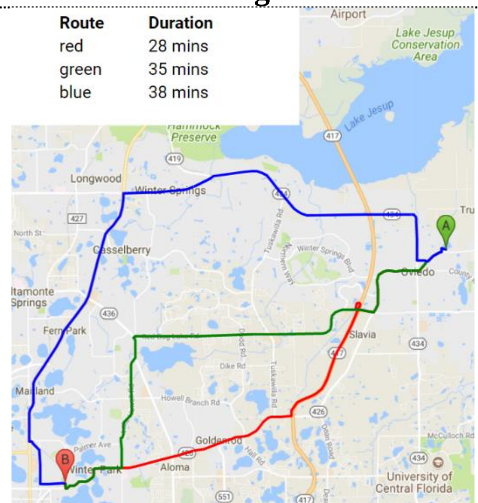
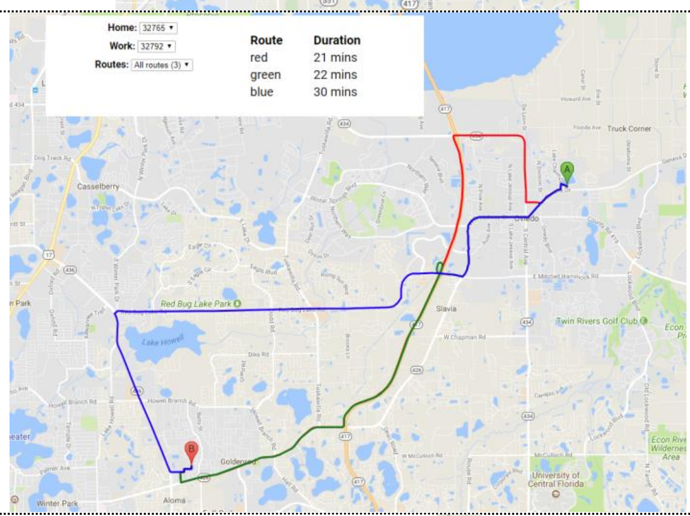
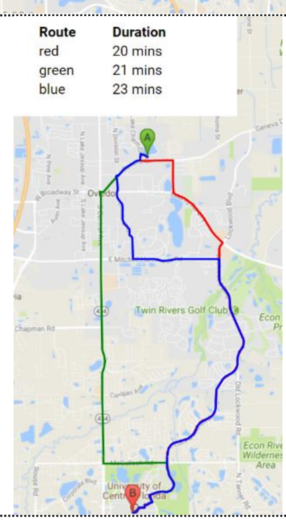
1.		32789	
2.	32765	32789	
3.		32816	

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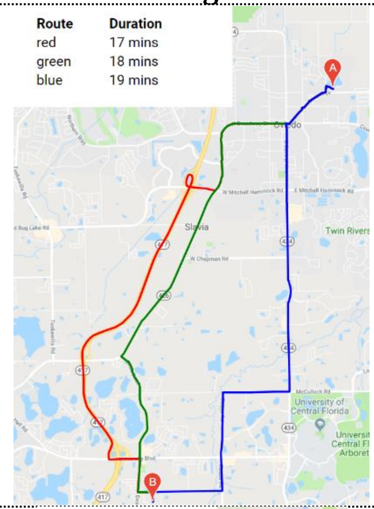
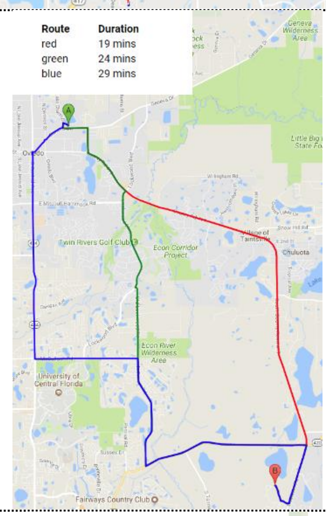
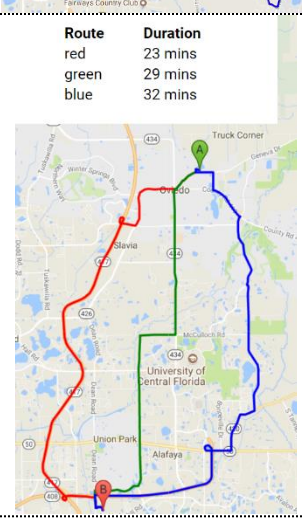
4.		32817	
5.	32765	32820	
6.		32825	

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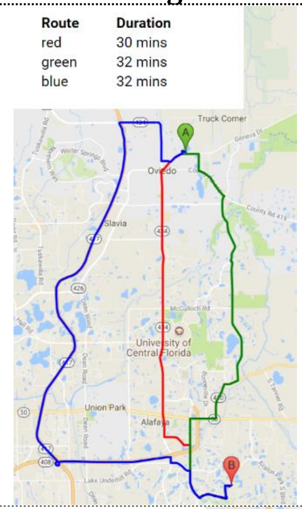
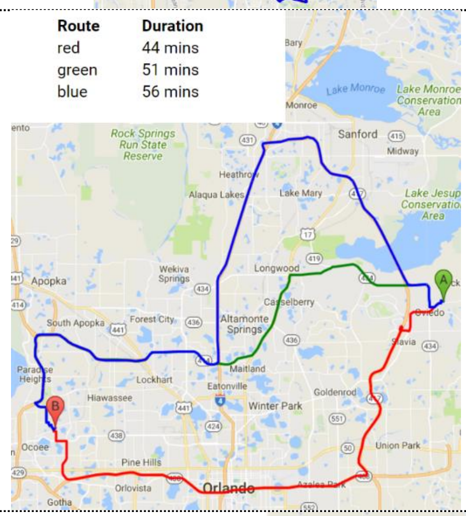
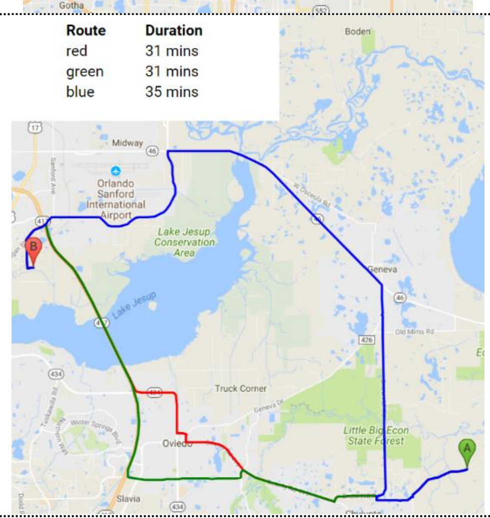
<tr><td>7.</td><td rowspan="2">32765</td><td>32828</td><td></td></tr>
<tr><td>8.</td><td>34761</td><td></td></tr>
<tr><td>9.</td><td>32766</td><td>32773</td><td></td></tr>
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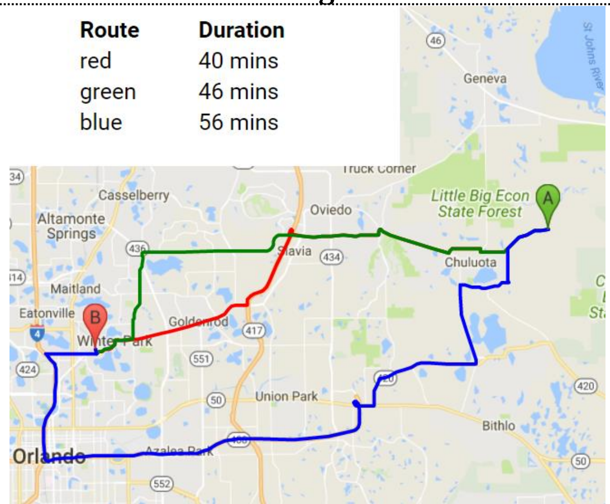
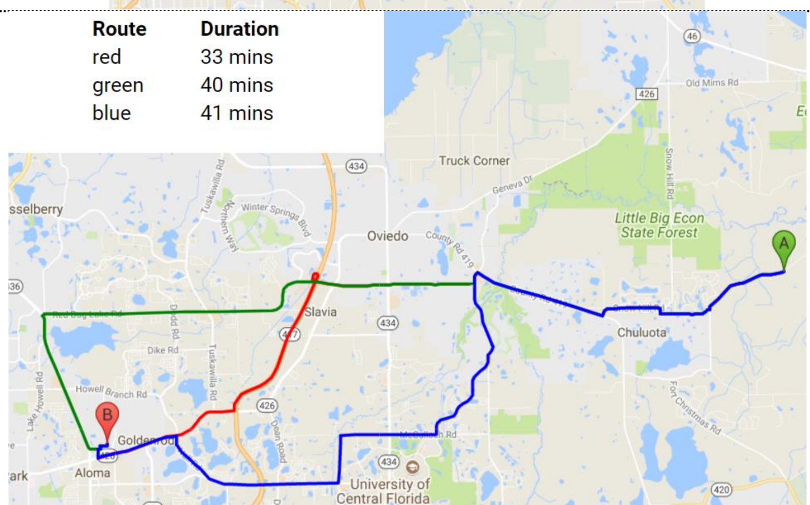
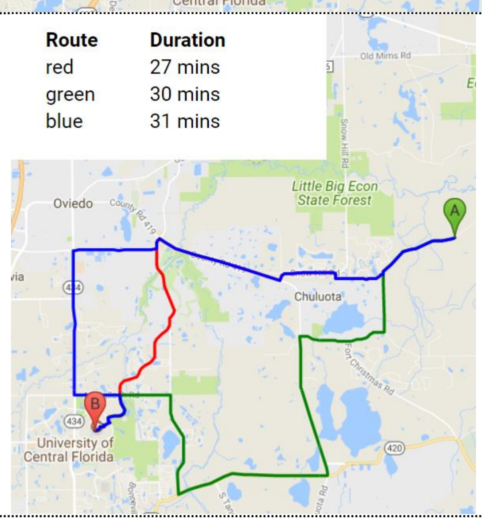
10.		32789	
11.	32766	32792	
12.		32816	

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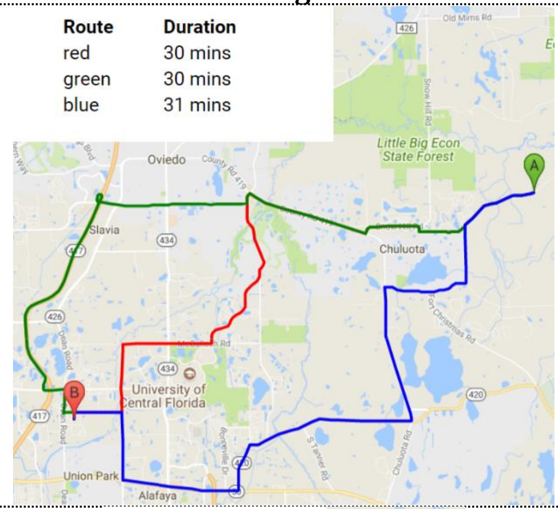
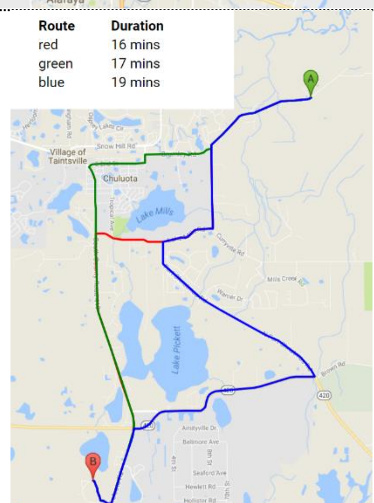
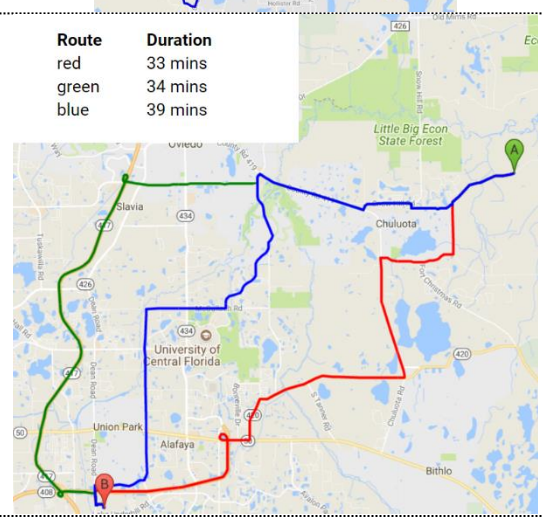
13.		32817	
14.	32766	32820	
15.		32825	

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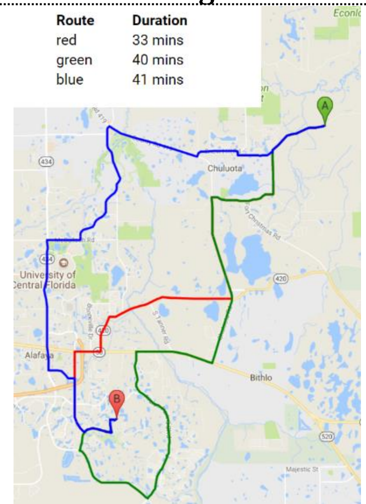
<tr><td>16.</td><td rowspan="2">32766</td><td>32828</td><td>
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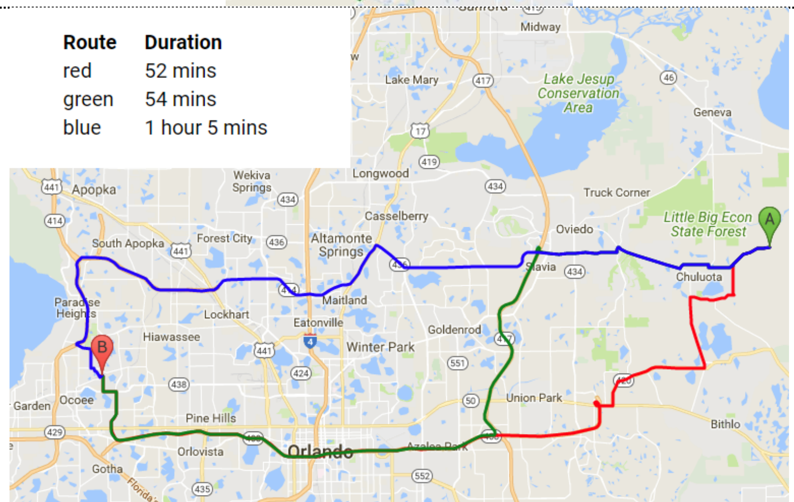
<tr><td>17.</td><td>34761</td><td>
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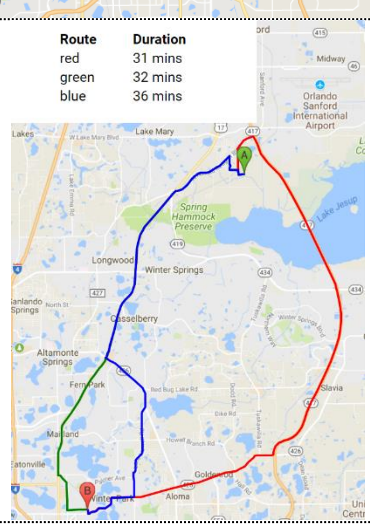
<tr><td>18.</td><td>32773</td><td>32789</td><td>
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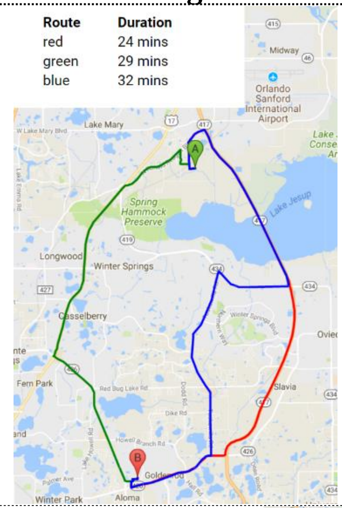
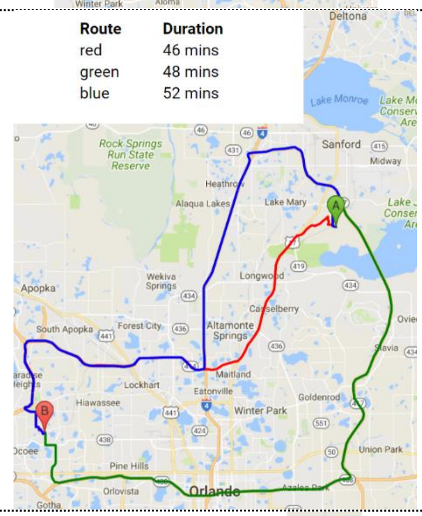
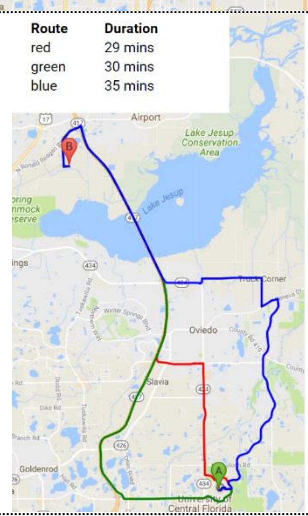
19.		32792	
20.	32773	34761	
21.		32816	

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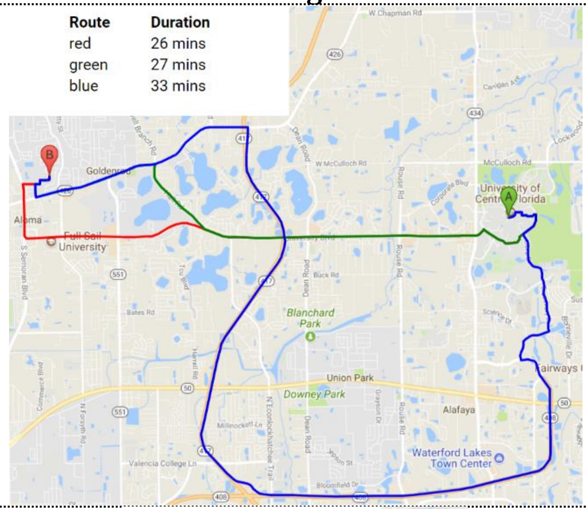
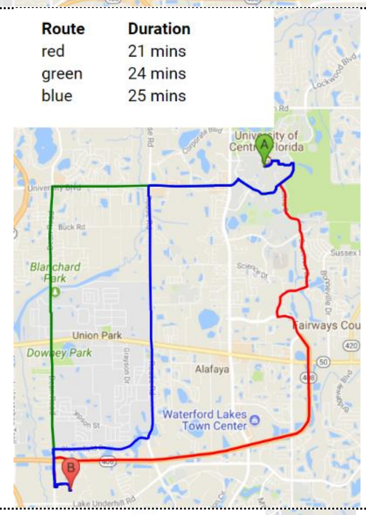
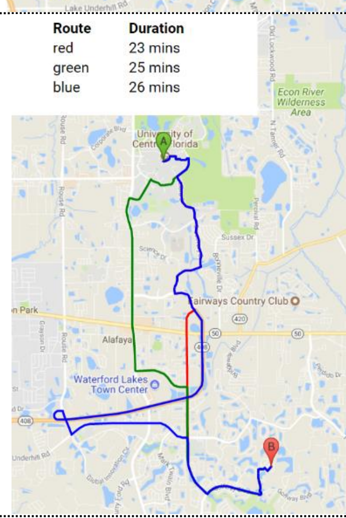
22.		32792	
23.	32816	32825	
24.		32828	

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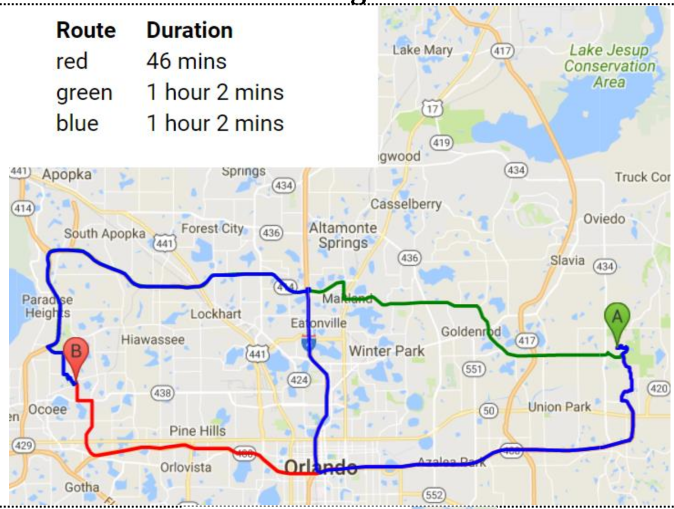
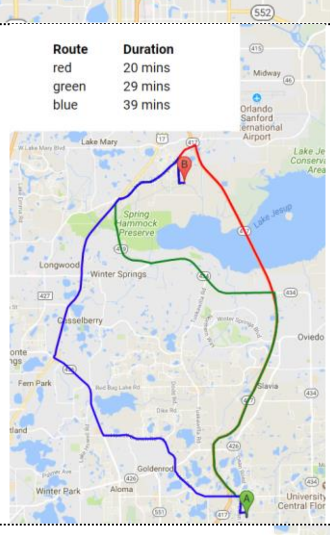
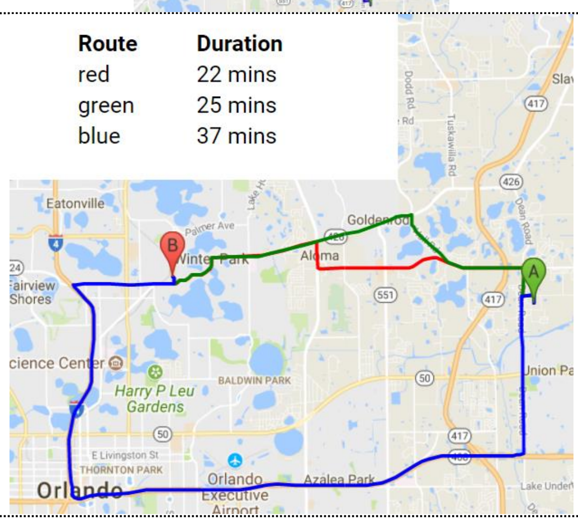
25.	32816	34761	
26.	32817	32773	
27.		32789	

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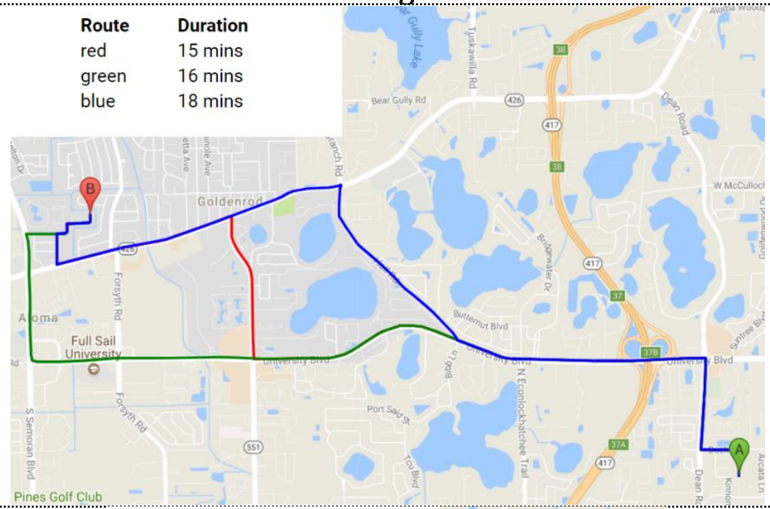
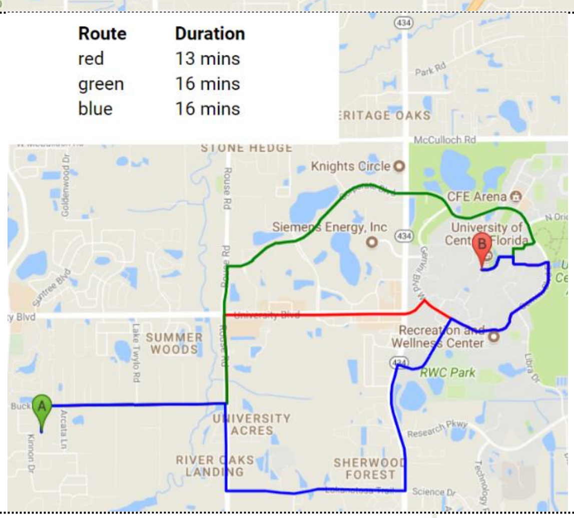
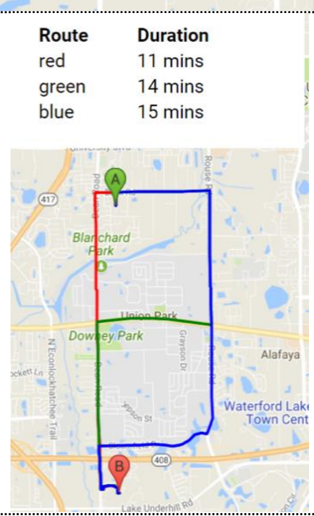
28.		32792	
29.	32817	32816	
30.		32825	

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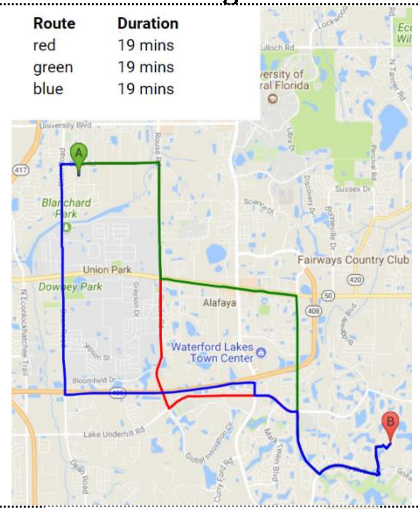
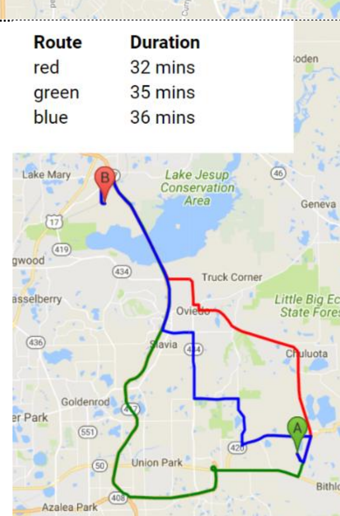
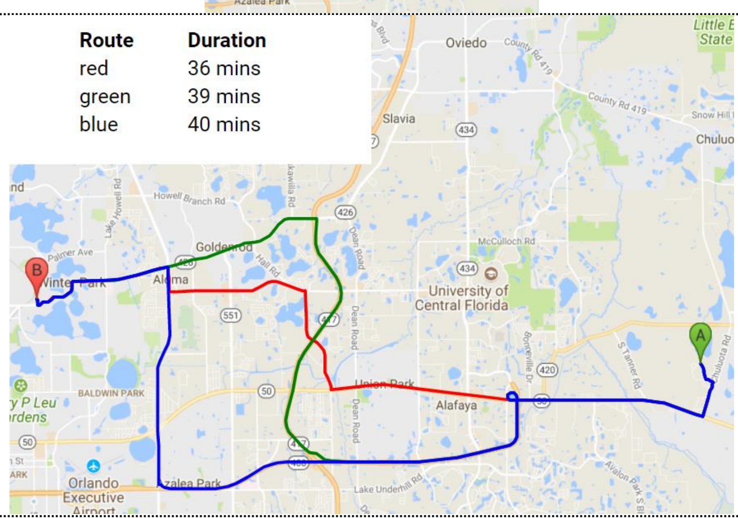
31.	32817	32828	
32.	32820	32773	
33.	32820	32789	

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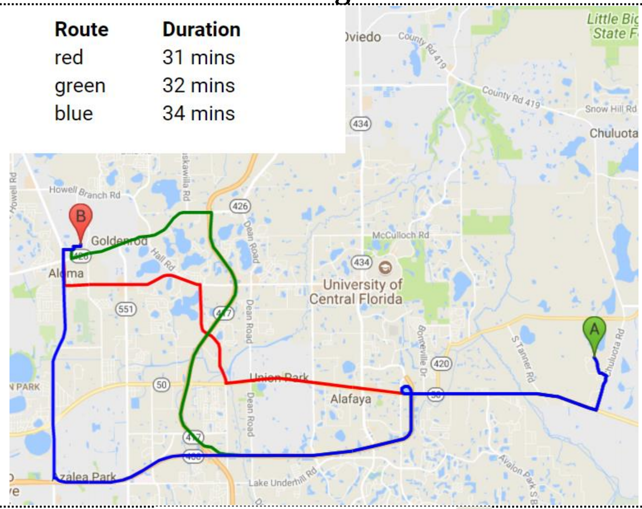
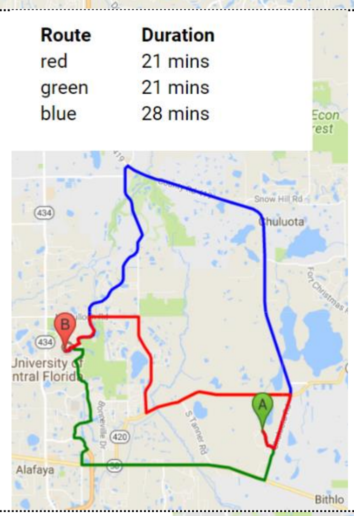
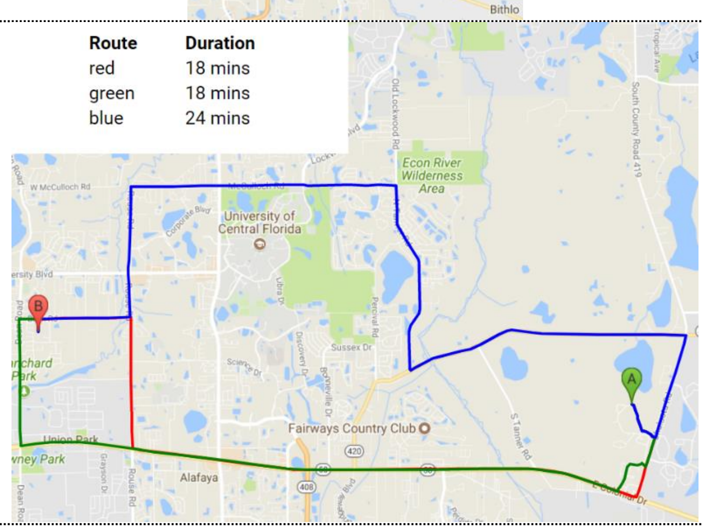
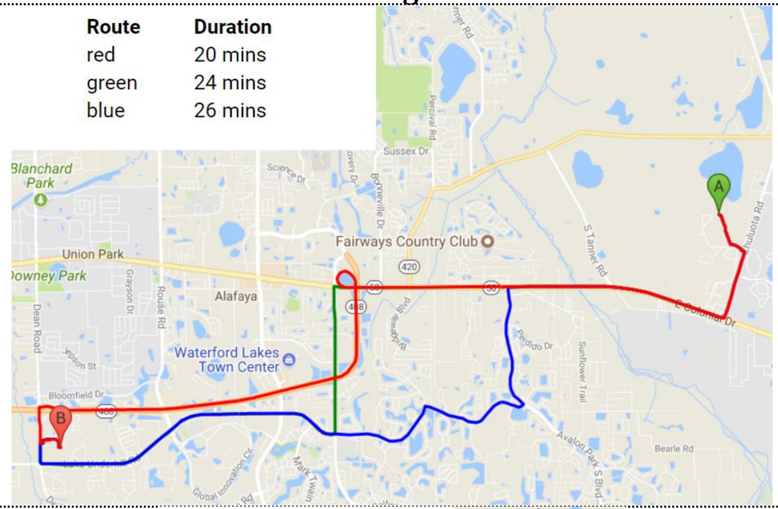
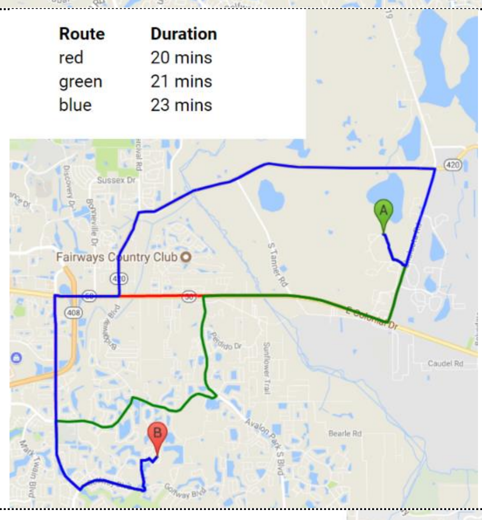
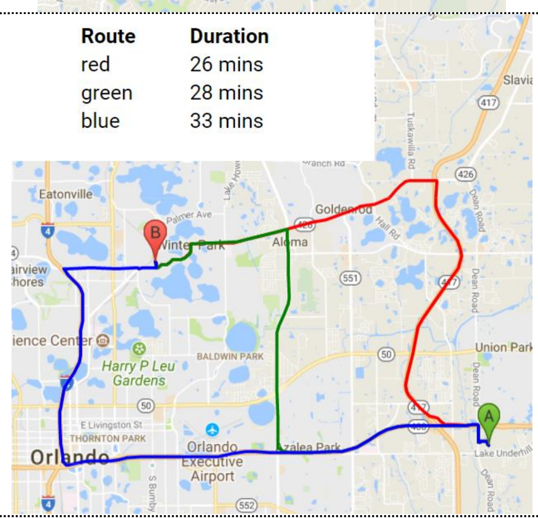
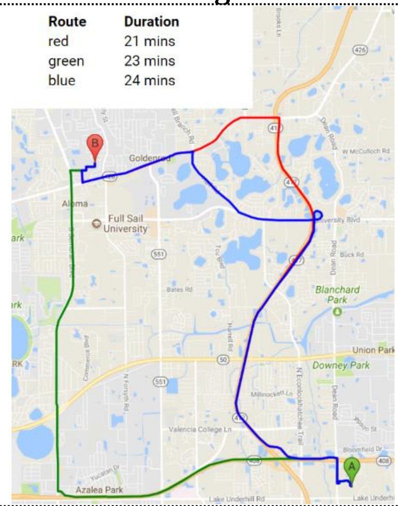
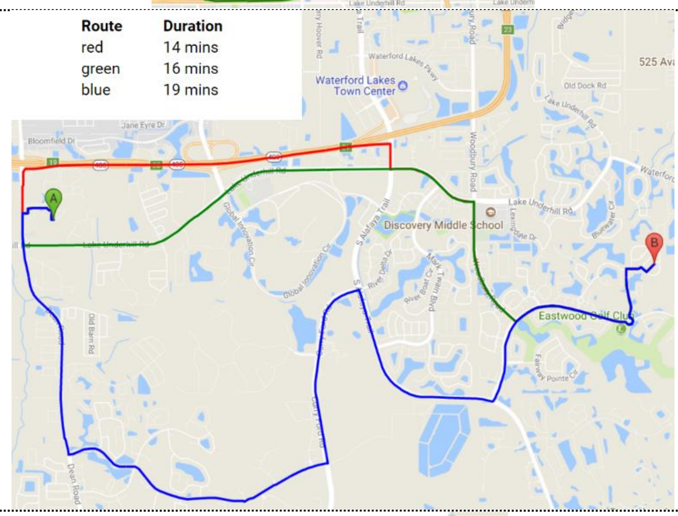
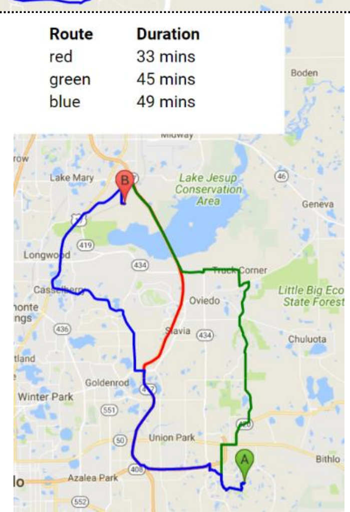
34.		32792	
35.	32820	32816	
36.		32817	

No.	Origin	Destination	Image
37.	32820	32825	
38.		32828	
39.	32825	32789	

No.	Origin	Destination	Image
40.	32825	32792	
41		32828	
42.	32828	32773	

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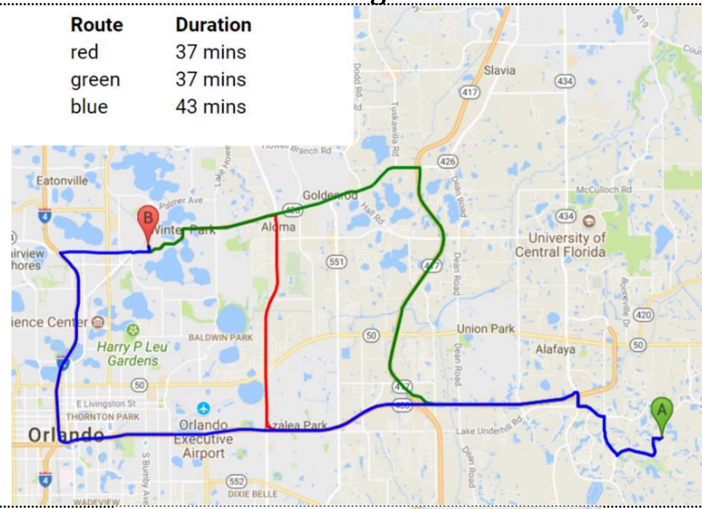
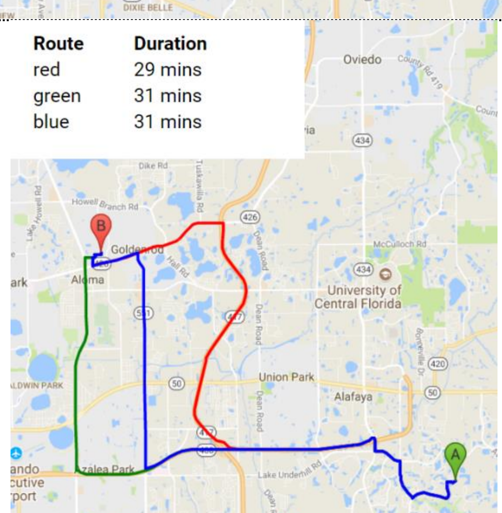
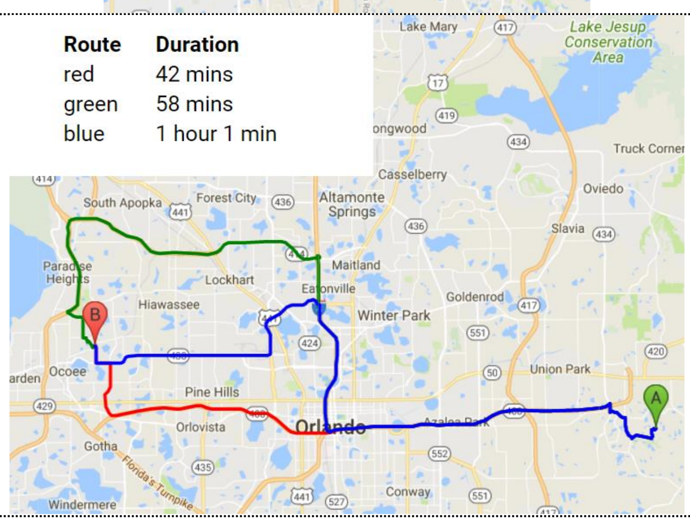
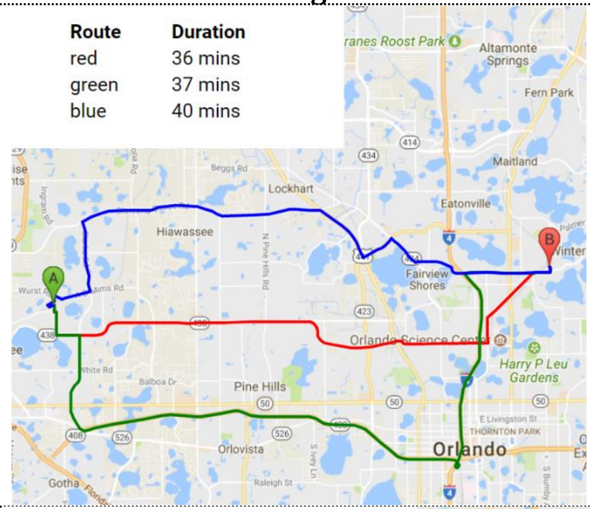
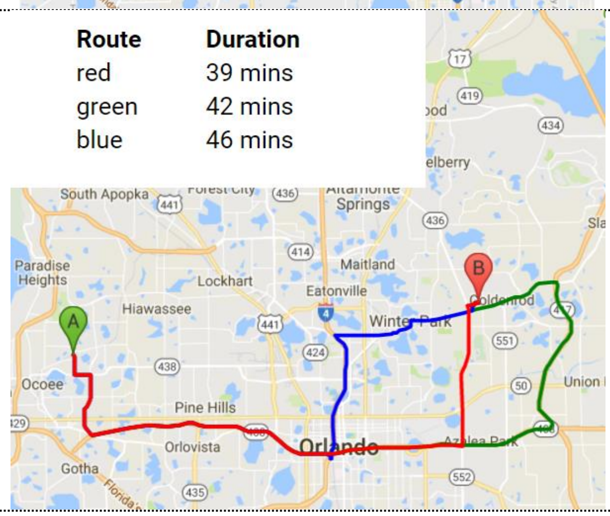
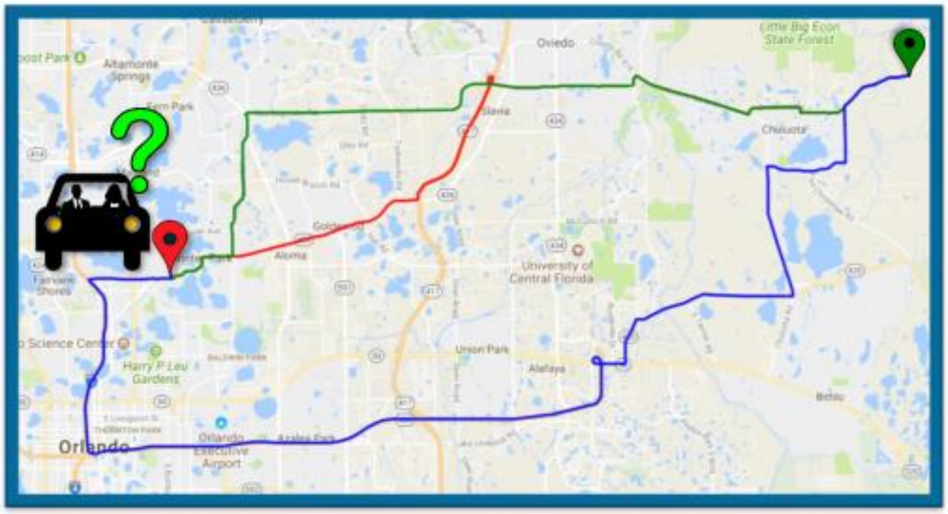
43.		32789	
44.	32828	32792	
45.		34761	

No.	Origin	Destination	Image
46.	34761	32789	
47.	34761	32792	

APPENDIX A-5: Poster for Survey Dissemination



Researchers at the University of Central Florida are working with Florida Department of Transportation to understand route choice decisions on Expressways and Arterial Roads.

Interested in helping us out??

Just fill out a survey to help us understand your route choice decisions.

https://ucf.qualtrics.com/jfe/form/SV_1SLGc01ehgW0o1D

University of Central Florida

FDOT

APPENDIX A-E: Survey Questionnaire (Presented for ZIP code Pair 32765-32817)

A Survey To Understand Road Users' Preferences

Thank you in advance for taking the time to respond to the survey. Your participation is valuable to our research effort.

We are conducting this survey to understand road users' preferences in the context of developing an Integrated Active Traffic Management (IATM) system.

In this project, the main objective is to develop an integrated system of traffic management that not only evaluates the real-time traffic operation performance of both arterials and freeways but also integrates them. Conditions that cause congestion, queues, flow turbulence and/or delays would be detected in real time and potential alternatives will be suggested in real time. These aim at improving situational awareness, enhancing response and control, by better informing travelers and improving corridor performance. The survey will provide the research team with information on individual route preferences that can be embedded in the broader IATM system.

Before proceeding, please read the consent form carefully.

No personal information will be collected in the survey (i.e. name and address). To ensure confidentiality of information, we will use a numeric code throughout this study. The results of this study may be published in scientific journals and communicated in other ways, but you will not be identifiable in any communications resulting from this study. All information will be stored on computers that are protected using passwords.

Your participation is voluntary. You have to be at least 18 years of age to take part in the survey. It will take you approximately 10-15 minutes to complete the survey. You can refuse to participate or can withdraw from this study at any time for any reason. If you close the browser tab, you will be allowed to exit from the survey and your progress will be saved. However, we will discard all of your responses if you do not attempt the survey within 2 weeks of your starting date. Refusal to participate or your withdrawal from the study will not involve any penalty.

If you have any questions and/or comments and/or would like to know about the study findings, feel free to contact: Shamsunnahar Yasmin (shamsunnahar.yasmin@ucf.edu), Postdoctoral Associate; or Naveen Eluru (naveen.eluru@ucf.edu), Associate Professor, University of Central Florida, Orlando, Florida, USA. You can also contact the Office of Research Ethics at irb@ucf.edu or 407-823-2901, if you have questions about your right as a participant.

The researchers have no conflicts of interest in this study.

Do you agree to the above terms? By clicking Yes, you consent that you are willing to answer the questions in this survey.

Yes

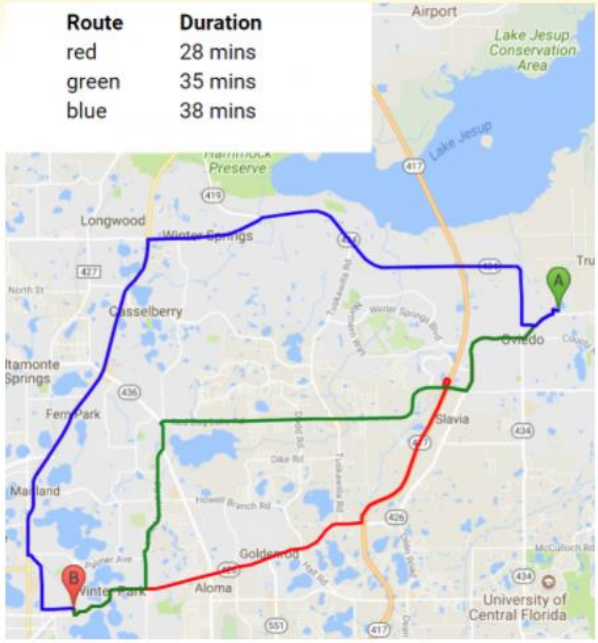
No

Please provide the zip code location that you are currently residing in

32765	32789	32817	32828
32766	32792	32820	34761
32773	32816	32825	Other, specify

Please select the zip code location of your work/most frequent travel location

32765	32789	32817	32828
32766	32792	32820	34761
32773	32816	32825	Other, specify



	Red Route	Green Route	Blue Route
Which route do you use (usually)?	●	○	○

The survey has two sections.

Section 1 presents a series of hypothetical scenarios and you are asked to state your preference.

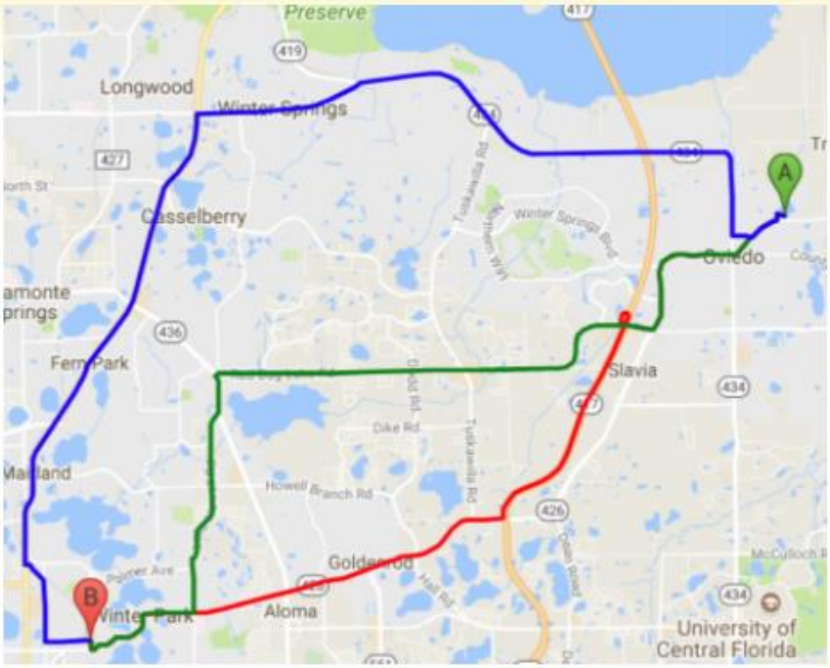
Sections 2 covers questions about you and your trip characteristics.

The next section presents a series of 6 hypothetical scenarios describing the characteristics of a set of routes and asks you to select your preferred route. Please take your time answering these questions - they are the most important part of the survey.

The scenarios are created based on a set of attributes. The definitions for these attributes are presented in the next slide. You can always come back to the attribute definition page using the previous button from any scenario page. The definition page is again repeated after 3 scenarios for your convenience.

Before you begin, Please read the following definitions carefully

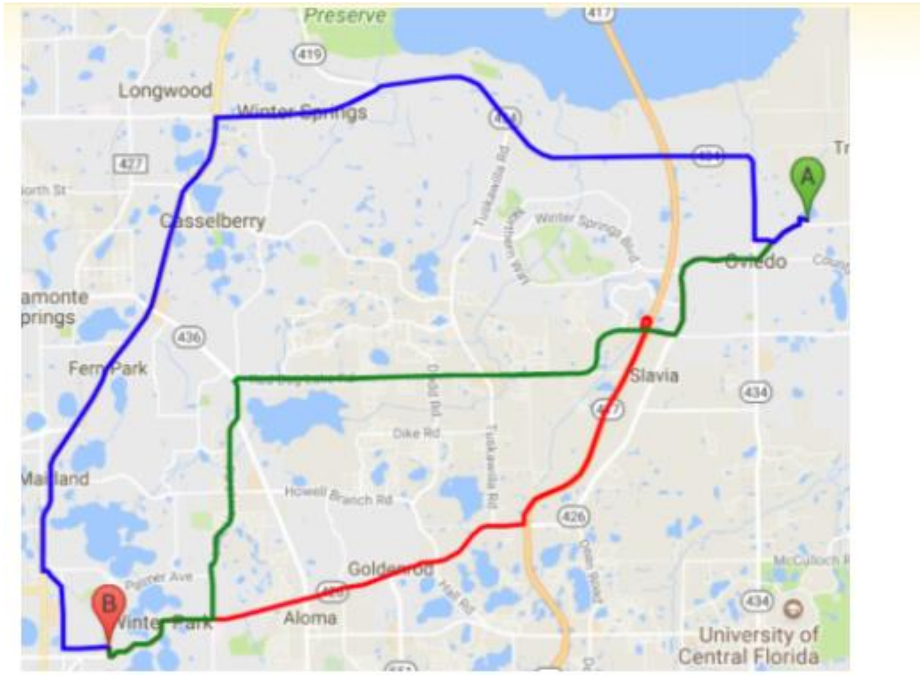
Attribute	Definition
Travel time (minutes)	**Travel time** refers to the time required to travel from your trip origin to trip destination with congestion or other adverse conditions (such as bad weather).
Additional travel time due to congestion (minutes)	**Additional travel time due to congestion** refers to the additional time required to travel from your trip origin to trip destination if there were congestion due to heavy traffic or some other incidents (such as a crash).
Toll cost ($)	**Toll cost** refers to the charge payable for permission to use a particular road.
Availability of traffic information	**Availability of traffic information** refers to the stage of traffic information. **None** – traffic information will be unavailable for the trip. **Pre-trip** – traffic information will be available before starting the trip. **En-route** – traffic information will be available on-route during the trip.
Media for accessing traffic information	**Media for accessing traffic information** refers to the media sources available for traffic information. **None** – traffic information will be unavailable for the trip. **Mobile app** – traffic information will be available via mobile app such as Waze, Google map, INRIX, Bing map etc. **Twitter** – traffic information will be available via twitter. **Radio** – traffic information will be available via radio.



Three routes – red, green and blue – are shown in the figure above. The attributes for these routes are presented below. From these options please choose your preferred route.

Attributes	Red Route	Green Route	Blue Route
Travel time (minutes)	28	40	41
Additional travel time due to congestion (Minutes)	0	10	3
Availability of traffic information	Never	En-route	Pre-trip
Media for accessing traffic information	Never	Mobile app	Twitter
Toll cost ($)	3	0	0

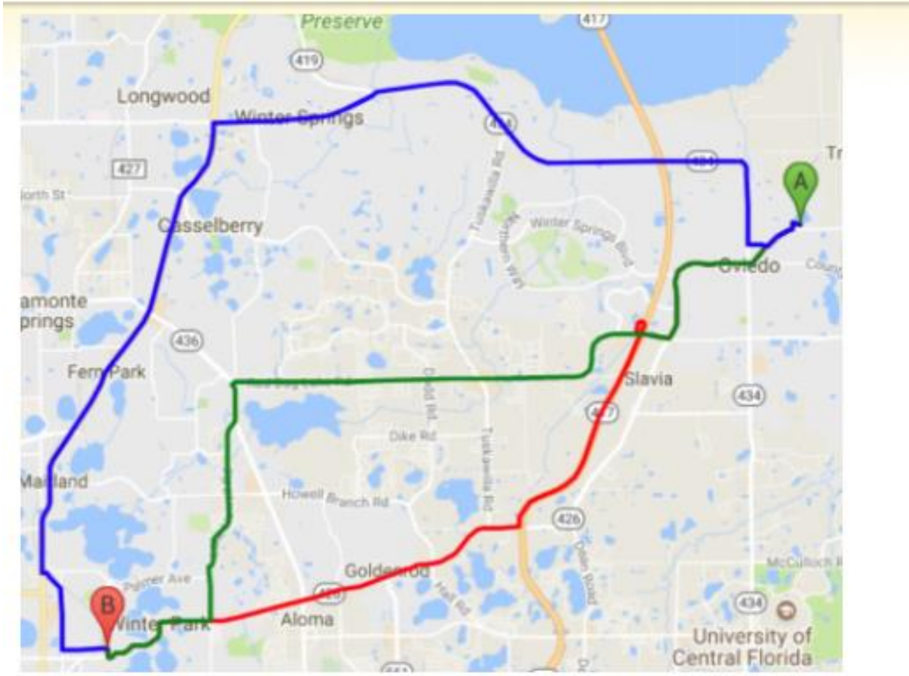
	Red Route	Green Route	Blue Route
Choose a route from these 3 alternatives	○	○	○



Three routes – red, green and blue – are shown in the figure above. The attributes for these routes are presented below. From these options please choose your preferred route.

Attributes	Red Route	Green Route	Blue Route
Travel time (minutes)	28	40	41
Additional travel time due to congestion (Minutes)	10	6	0
Availability of traffic information	En-route	Pre-trip	En-route
Media for accessing traffic information	Twitter	Radio	Mobile app
Toll cost ($)	3	0	0

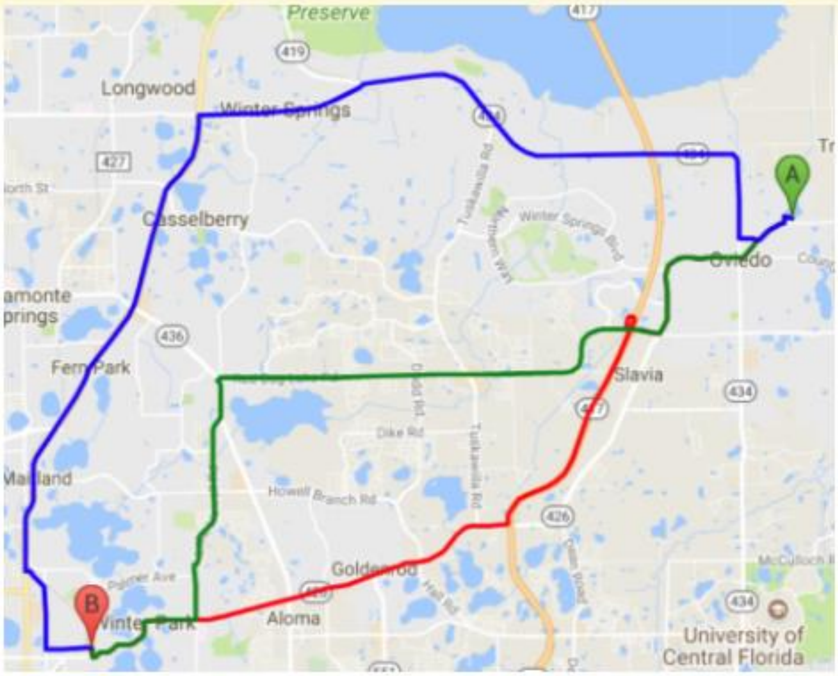
	Red Route	Green Route	Blue Route
Choose a route from these 3 alternatives	○	○	○



Three routes – red, green and blue – are shown in the figure above. The attributes for these routes are presented below. From these options please choose your preferred route.

Attributes	Red Route	Green Route	Blue Route
Travel time (minutes)	25	40	38
Additional travel time due to congestion (Minutes)	3	0	6
Availability of traffic information	En-route	Never	Pre-trip
Media for accessing traffic information	Mobile app	Never	Radio
Toll cost ($)	3	0	0

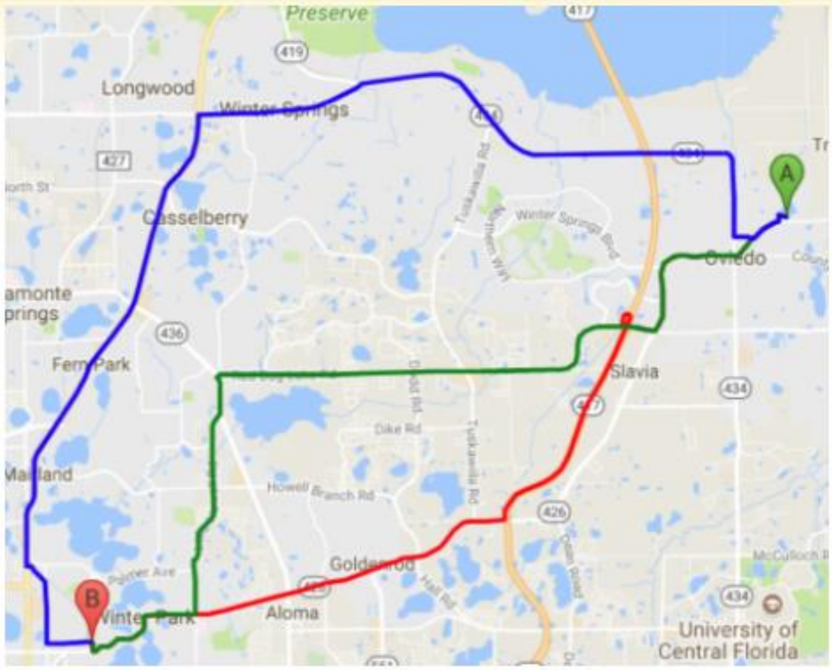
	Red Route	Green Route	Blue Route
Choose a route from these 3 alternatives	○	○	○



Three routes – red, green and blue – are shown in the figure above. The attributes for these routes are presented below. From these options please choose your preferred route.

Attributes	Red Route	Green Route	Blue Route
Travel time (minutes)	20	38	38
Additional travel time due to congestion (Minutes)	0	6	10
Availability of traffic information	En-route	Pre-trip	Never
Media for accessing traffic information	Twitter	Mobile app	Never
Toll cost ($)	4	0	0

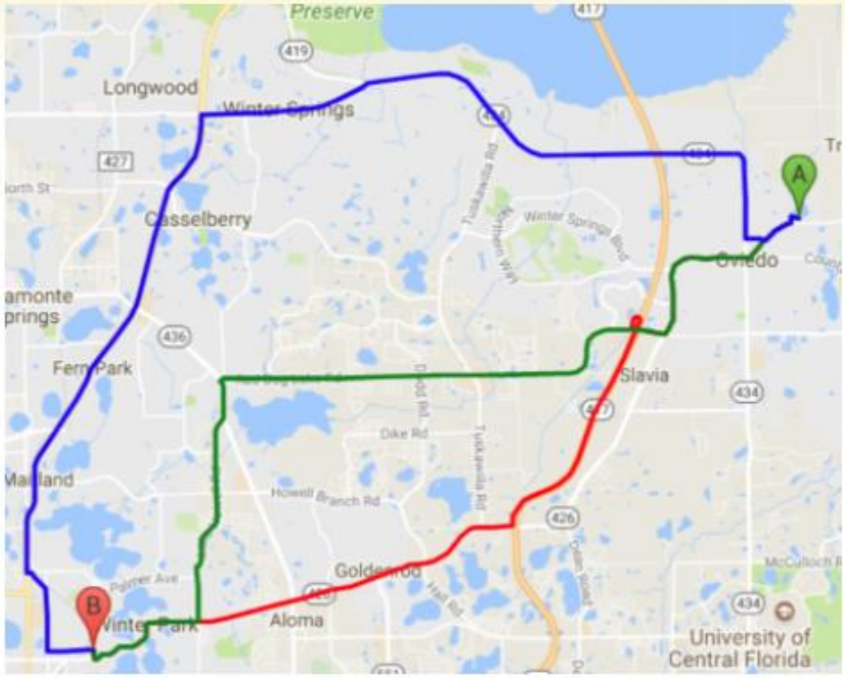
	Red Route	Green Route	Blue Route
Choose a route from these 3 alternatives	○	○	○



Three routes – red, green and blue – are shown in the figure above. The attributes for these routes are presented below. From these options please choose your preferred route.

Attributes	Red Route	Green Route	Blue Route
Travel time (minutes)	28	40	41
Additional travel time due to congestion (Minutes)	10	6	0
Availability of traffic information	Pre-trip	Never	En-route
Media for accessing traffic information	Mobile app	Never	Radio
Toll cost ($)	4	0	0

	Red Route	Green Route	Blue Route
Choose a route from these 3 alternatives	○	○	○



Three routes – red, green and blue – are shown in the figure above. The attributes for these routes are presented below. From these options please choose your preferred route.

Attributes	Red Route	Green Route	Blue Route
Travel time (minutes)	28	38	43
Additional travel time due to congestion (Minutes)	6	0	3
Availability of traffic information	En-route	Pre-trip	Pre-trip
Media for accessing traffic information	Twitter	Mobile app	Radio
Toll cost ($)	4	0	0

	Red Route	Green Route	Blue Route
Choose a route from these 3 alternatives	○	○	○

The next section includes questions about you and your trip characteristics.

Are you?

- Male
- Female

What is your age?

- 18-24
- 25-34
- 35-44
- 45-54
- 55-64
- Over 65

What is the highest level of education you have completed?

- Less than high school
- High school
- College
- Bachelors
- Graduate of higher

What is your current working status?

- Student
- Full-time worker
- Part-time worker
- Retired
- Not/self employed

How long have you been driving?

- Did not drive
- 0-2 years
- 3-5 years
- 6-10 years
- >10 years

How frequently the car is available to you for making trips?

- Always
- Usually
- Sometimes
- Less than sometimes
- Never

Do you own a smartphone?

- Yes
- No

How frequently do you use Expressways?

- Almost every day
- 2-3 days per week
- Once a week
- Several times a month
- Less than once per month
- Rarely

How do you currently access traffic information? (Multiple selections are allowed)

- None
- Variable message sign
- Mobile app (Waze, Google map, INRIX, Bing map etc)
- Social media (Twitter)
- 511 call
- Radio
- Other; Specify

What is your preferred mode of receiving traffic information?

- None
- Variable message sign
- Mobile app (Waze, Google map, INRIX, Bing map etc)
- Social media (Twitter)
- 511 call
- Radio
- Other; Specify

We thank you for your time to complete this survey.
We truly value your feedback and that is really important to us.

UCF

Powered by Qualtrics

APPENDIX A-F: IRB Protocol

PROTOCOL TITLE:

"A SURVEY TO UNDERSTAND ROAD USERS' PREFERENCES"

1. Objectives*

1.1

The overall goal of the project is to develop an integrated system of traffic management that not only evaluates the real-time traffic operation performance of both arterials and freeways, but also integrates them. The objectives of the project are to identify strategies that could increase corridor throughput, improve travel time reliability and improve incident management system. The suggested integration will enable the following

a. Strategies to deal with congestion and travel time reliability within a specific corridor.

b. Improve the use of the existing infrastructure assets, identify the gaps and leverage unused capacity along the urban corridors.

c. Support transportation network managers and operators.

d. Achieve improved user satisfaction.

To achieve the objectives of the project, there is a need to explore the road user preferences of trips.

1.2

The survey component of the project is designed to evaluate the impact of attributes such as travel time and travel time reliability on user route choice preferences. The hypothesis being tested is – "if these attributes affect route choice and if so what is the magnitude of their impact". These quantitative measures will be integrated into a Freeway/Arterial Traffic Management system.

2. Background*

2.1

The success of any traffic management system depends on several factors, such as accuracy, cost of the system to the consumer and type of information (Ng Linda et al. 1994). All the segments of the road users that can be broadly classified as private vehicle drivers, commercial vehicle drivers and dispatchers, have varying levels of importance to the types of the information provided from the traffic management systems. Private vehicle drivers are mostly interested in reducing travel time and thus are prime candidates to choose alternate routes (Barfield et al. 1990).

Ng Linda, Woodrow Barfield, and Fred Mannering. "A survey-based methodology to determine information requirements for advanced traveler information systems." Transportation Research Part C: Emerging Technologies 3, no. 2 (1995): 113-127.

Barfield, Woodrow, Mark Haselkorn, Jan Spyridakis, and Loveday Conquest. "Integrating commuter information needs in the design of a motorist information system." Transportation Research Part A: General 25, no. 2 (1991): 71-78.

In this project, the main objective is to develop an integrated system of traffic management that not only evaluates the real-time traffic operation performance of both arterials and freeways, but also integrate them. Conditions that cause congestion, queues, flow turbulence and/or delays would be detected in real time and provide solutions in real time. This integrated system is also consistent with the Federal Highway Administration’s (FHWA) initiative. They aim at improving situational awareness, enhancing response and control, better travelers’ informing and improving corridor performance. This project aims at reviewing these sites and develop Integrated Active Traffic Management (IATM) system applicable for the State of Florida.

2.2

Not Available.

2.3

This work studies driver behavior on route choice. Many researchers have worked on route choice behavior and advanced traffic management systems. Different models were estimated by the researchers to establish the importance of communicating real time data with the road users in route choice. As geographic and socio-demographic features change between regions and due to lack of similar research in the study region, the outcomes of the study will establish the users’ preferences in the route choice, with specific focus on the travelers of the Greater Orlando region. Some of the scholarly articles relevant to our study objective are listed below.

Ng Linda, Woodrow Barfield, and Fred Mannering. "A survey-based methodology to determine information requirements for advanced traveler information systems." Transportation Research Part C: Emerging Technologies 3, no. 2 (1995): 113-127.

Barfield, Woodrow, Mark Haselkorn, Jan Spyridakis, and Loveday Conquest. "Integrating commuter information needs in the design of a motorist information system." Transportation Research Part A: General 25, no. 2 (1991): 71-78.

Mahmassani, Hani S., Nathan N. Huynh, Karthik Srinivasan, and Mariette Kraan. "Tripmaker choice behavior for shopping trips under real-time information: model formulation and results of stated-preference internet-based interactive experiments." Journal of Retailing and Consumer Services 10, no. 6 (2003): 311-321.

Al-Deek, Haitham M., Asad J. Khattak, and Paramsothy Thananjeyan. "A combined traveler behavior and system performance model with advanced traveler information systems." Transportation Research Part A: Policy and Practice 32, no. 7 (1998): 479-493.

Zhang, Guohui, Zhong Wang, Khali R. Persad, and C. Michael Walton. "Enhanced traffic information dissemination to facilitate toll road utilization: a nested logit model of a stated preference survey in Texas." Transportation 41, no. 2 (2014): 231-249.

Khoo, Hooi Ling, and K. S. Asitha. "User requirements and route choice response to smart phone traffic applications (apps)." Travel Behaviour and Society 3 (2016): 59-70.

Tseng, Yin-Yen, Jasper Knockaert, and Erik T. Verhoef. "A revealed-preference study of behavioural impacts of real-time traffic information." Transportation Research Part C: Emerging Technologies 30 (2013): 196-209.

3. Inclusion and Exclusion Criteria*

3.1

This survey is being conducted to establish the road user choice preference of trips and their route choice. So, all the individuals who live in the greater Orlando region or surrounding regions and make frequent trips would become the part of the survey. The individuals are screened based on the questions listed below

1. Are you older than 18 years? (Yes/No)

If the individual responds “yes” to the question above, then the individual is eligible to participate in the survey.

3.2

The inclusion criteria is described in Section 3.1.

3.3

The survey concentrates only on the adults (> 18 years). Infants, children and teenagers will be excluded from the survey. Any individual who is not interested to provide the details can quit the survey at any time. Pregnant women and prisoners would not be considered as a special category in the survey.

4. Study-Wide Number of Subjects*

4.1

Not applicable

5. Study-Wide Recruitment Methods*

5.1

The survey is conducted through a web-based system. Participation in the survey is completely voluntary. The survey will be posted through posters and emails sent through various university associations. Individuals can choose not to participate in the survey and can quit the survey at any time by using quit button on the survey sheets.

5.2

Participation is completely voluntary for adults. There is no specific methods that will be used to identify the subjects. Any individual who is eligible according to the section 3.1 can participate in the survey.

5.3

The research is conducted as part of a research project. The research team does not have a large financial component for the survey. Hence, the survey will be disseminated via emails (with links to the survey) and postings on various websites.

6. Multi-Site Research*

6.1

Not applicable

6.2

Not applicable

6.3

Not applicable

7. Study Timelines*

7.1

The duration of the survey for each respondent would be around 10 to 15 minutes. The survey would be open to the public for 6 months.

8. Study Endpoints*

8.1

The survey collection will be the primary endpoint. Subsequently data analysis and model development will constitute the secondary study endpoint.

8.2

Not applicable

9. Procedures Involved*

9.1

We will be conducting a web-based survey.

9.2

There are no safety risks involved in our study. The respondents will be completing an online questionnaire at their convenience.

9.3

There are no risks involved in the survey

9.4

The data that will be collected from the survey can be broadly classified into three categories. They are (a) personal level information (b) trip level information (c) Stated Preference choice survey.

<u>Personal Level Information:</u> General information of the respondents namely; age, gender, level of education, driving experience, availability of car, location of house (zip code), location of work/frequent travel (zip code) and type of phone are

collected in this section. Most of these variables are collected as categorical or ordered variables which can be seen in the survey form.

Trip Level Information: The information collected under the section includes the frequency of use of expressway, frequently used source to receive traffic information and the preferred source to receive traffic information.

Stated Preference Component: For the trips made by the respondent, between their location zip code and frequent destination zip code, maps are generated that shows various alternative routes for the trip. The respondent must choose a route from the given routes. The characteristics of route such as travel time, delay, travel cost and availability of traffic information will be provided to the respondents. More details can be seen in the survey sheet.

9.5

Not applicable

10. Data and Specimen Banking*

10.1

The data is collected strictly for the project and research purposes. So, the data will be stored till 2020, as the project is expected to be completed by December 2018.

10.2

The collected data might have incomplete responses. Such data would be deleted and cleaned. The final cleaned data will be stored. The final stored data will have all the variables collected from the survey.

10.3

The project is being funded by Florida Department of Transportation (FDOT). The data would be released to any institution that gets consent from the FDOT.

11. Data Management* and Confidentiality

11.1

The dataset would be cleaned such that it doesn’t have any incomplete responses. The cleaned data set will be used to estimate behavioral choice models (advanced logistic regression models) to understand the behavior of the respondents in route choice.

11.2

Empirical equation proposed by Johnson and Orme (2003)* for experiments considering two-way interaction effects. The equation is given by

$$n \geq \frac{500C}{ta}$$

where number of tasks (t) are 5, the number of alternatives (a) is 3, and the number of analysis cells (c, is the largest product of levels of any two attributes since we are considering two-way interaction effects in addition to the main effects) is 9. The estimated minimum number of respondents required for the survey are 300.

*Johnson, R., & Orme, B. (2003). Getting the Most from CBC. Sequim: Sawtooth Software Research Paper Series, Sawtooth Software; 2003

11.3

The data would be stored in excel and SPSS data sheets. The data in its disaggregate form would be accessible only to research team members from UCF. The transmission of data will be only through secured e-mails.

11.4

Not applicable.

11.5

All the cleaned data and the collected data will be stored till 2022 i.e. four years after the end of the project (expected to be completed by December 2018). The funding agency (FDOT) and the investigators at UCF will have access to the data, which will be transmitted between the parties by secured e-mails.

12. Provisions to Monitor the Data to Ensure the Safety of Subjects*

12.1

The participation in the survey is completely voluntary and there are no potential risks or individual benefits from being part of the survey.

13. Withdrawal of Subjects*

13.1

The participation in the survey is completely voluntary. Any respondent who doesn't want to continue in the survey can withdraw by option to quit out of the survey at any point during the survey. Any responses from the participants that are incomplete will be withdrawn from the research.

13.2

Not applicable

13.3

Not applicable

14. Risks to Subjects*

14.1

There are no potential risks to the subjects.

14.2

Not applicable

14.3

Not applicable

14.4

Not applicable

15. Potential Benefits to Subjects*

15.1

There will be no potential individual benefits from the survey.

15.2

No direct benefit.

16. Vulnerable Populations*

16.1
Not applicable

17. Community-Based Participatory Research*

17.1
Not applicable

18. Sharing of Results with Subjects*

18.1
The results of the aggregated responses and the outcomes from the analysis will be submitted to peer-reviewed journal articles. The results will also be provided on the survey website for interested public.

19. Setting

19.1

The research will be conducted only by UCF as web-based survey.

20. Resources Available

20.1
The Principal Investigator of the Project is Dr. Naveen Eluru, who will be responsible for the overall management and direction of the project. He is an expert in stated preference (SP) surveys and data analysis, and he will work on identifying the study area, data collection, evaluation and fusion. He has worked on multiple data collection effort through surveying during his tenure in McGill University and UCF on various research projects.

20.2
Not Applicable.

21. Prior Approvals

21.1
The funding agency, Florida Department of Transportation (FDOT), has approved the research proposal. The team has submitted a review on state of practice on freeway/arterial/integrated ATM and a review on current traffic data collection technologies.

22. Recruitment Methods

22.1

The survey is a web based online survey. The potential subjects will be contacted through the e-mails and posters describing the objectives and goals of the survey along with the link to the survey page.

22.2

The driving community will be the source of our subjects

22.3

The research team will rely on survey information dissemination through various forums and personnel.

22.4

The survey is conducted through a web-based system. Participation in the survey is completely voluntary. The survey will be posted through posters and emails sent through various university associations. Individuals can choose not to participate in the survey and can quit the survey at any time by quit button on the survey sheets.

22.5

The survey takes 10 to 15 minutes for each respondent, which is completely voluntary. No payment will be made to the participants.

23. Local Number of Subjects

23.1

5000.

24. Provisions to Protect the Privacy Interests of Subjects

24.1

No personal information that can identify the individual are being collected as a part of the survey. So, the privacy of the respondents is preserved by the survey design itself.

24.2

The survey is voluntary, and the respondents are provided with an option to quit at any point of time

24.3

Not applicable

25. Compensation for Research-Related Injury

25.1

Not applicable.

25.2

Not applicable.

26. Economic Burden to Subjects

26.1

There will be no cost inquired to the participants for being a part of the research.

27. Consent Process

27.1

We will be obtaining consent from the survey participants before they can proceed with the survey. The terms of participating in the survey is explained in the survey interface and only participants that agree to the terms and select "yes" will be allowed to participate in the rest of the survey.

The survey is solely in English language.

The survey is open to adults only (>18). No other specific information status is sought.

28. Process to Document Consent in Writing

28.1

Not applicable

28.2

Not applicable

28.3

Not applicable

29. Drugs or Devices

29.1

Not applicable

29.2

Not applicable

APPENDIX A-G: IRB Approval Outcome Letter

University of Central Florida

University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Determination of Exempt Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **Naveen Eluru**

Date: **March 16, 2018**

Dear Researcher:

On 03/16/2018, the IRB reviewed the following activity as human participant research that is exempt from regulation:

Type of Review:	Exempt Determination, Category 2
Project Title:	A Survey to Understand Road Users' Preferences
Investigator:	Naveen Eluru
IRB Number:	SBE-18-13853
Funding Agency:	FL Department of Transportation
Grant Title:	Integrated Freeway/Arterial Active Traffic Management
Research ID:	1061640

This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If changes are made and there are questions about whether these changes affect the exempt status of the human research, please contact the IRB. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

This letter is signed by:

Renea Carver

Signature applied by Renea C Carver on 03/16/2018 11:59:03 AM EDT

Designated Reviewer

Page 1 of 1

APPENDIX B

B.1. Introduction

With the ubiquity of mobile devices, virtual platforms offer a unique opportunity to instantly share information with a large number of people. Crowdsourcing platforms facilitate fast, easy, and rapid communication of information at a mass scale producing a huge amount of digital content. Twitter is one of the most widely used crowdsourcing platforms in the USA with 67 million active users ("Twitter by the Numbers: Stats, Demographics & Fun Facts," 2017). It is a social media based microblogging service used to share views, activities, and thoughts through a 280-character message known as a 'tweet'. Most of the state DOTs are using Twitter accounts to spread critical information regarding traffic congestion, crashes, incidents and planned roadworks. Apart from the text portion of a tweet, there are a number of features that carry important information on users' social media activities, influence, and effectiveness. In this task, we have developed a framework to gather and disseminate real-time traffic information connected with a crowd-sourcing platform Twitter. The developed component will be known as **S**ocial **M**edia-based **A**daptive **R**eal-time **T**raffic **Feed** (**SMART-Feed**) which will be potentially integrated with a future IATM decision-making tool.

In this report, we present our investigations on how Twitter can be used as a crowdsourcing platform to *pull* and *push* traffic information in real time. We have developed techniques to gather traffic incident related information from travelers in real time. To explore how to share real-time traffic management strategies with travelers, we have analyzed data collected from 14 Florida Department of Transportation (FDOT) Twitter accounts and the comparative effectiveness of these accounts sharing real-time information. Using state-of-the-art machine learning and data analysis tools, we have investigated the potential of collecting and sharing real-time information to travelers.

B.2. Framework for the SMART-Feed

Florida Department of Transportation (FDOT) 511 services manages Twitter accounts to share information related to regular traffic updates, roadway management, and emergency scenario or alert. These accounts may overburden users with repetitive information. We propose a framework to obtain the value of the shared information. We develop a filtering process which will allow us to compute the potential value of the shared information based on past trends on user response to such information. If the value is less than a threshold value, then the content will be discarded form being shared.

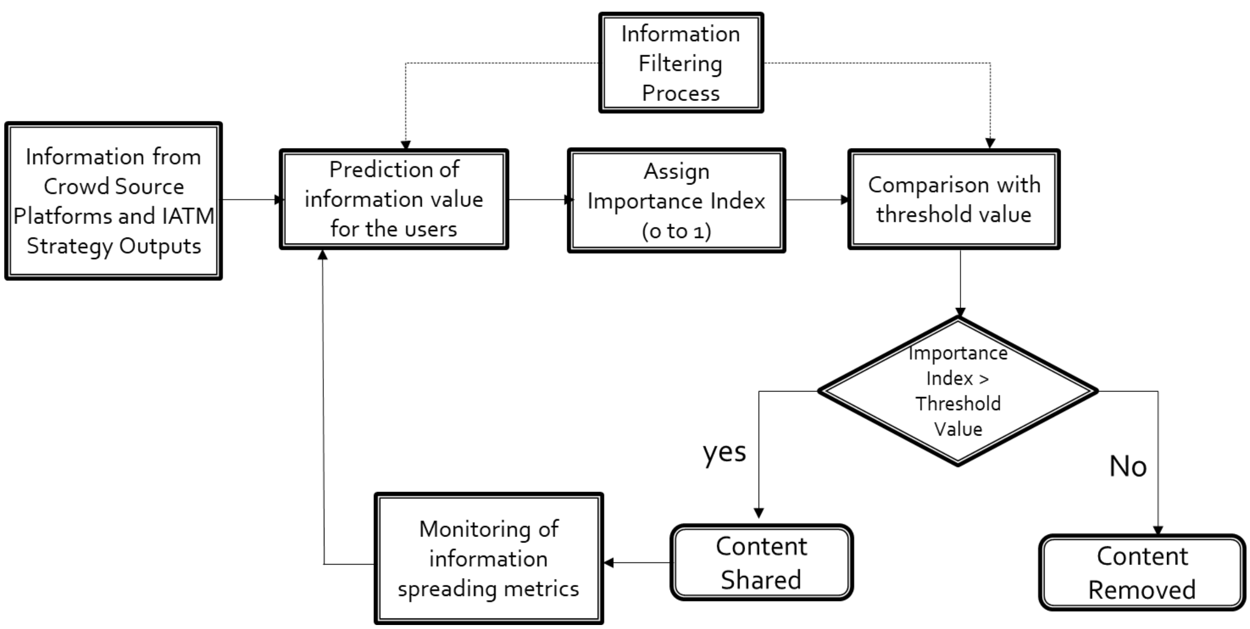


Figure B-1. SMART-Feed framework

The value of a shared information depends on its chances of getting attention from users. The more an information content is shared by users, the more valuable it will be to other users. In the proposed framework, we are computing the importance value for a shared content based on the probability of it being retweeted. So, the estimated information value will vary between 0 to 1. For the information filtering process, we will select an initial threshold value which will be updated based on monitoring the improvement in efficiency metrics for a particular account. The proposed framework includes some information spreading metrics for monitoring the effectiveness of the information sharing.

The proposed framework will potentially be integrated with the decision-making tool to support the information dissemination function of IATM strategies. The updates from the IATM strategies will be shared with users through crowdsourcing platforms (e.g., Twitter). We can further measure the importance of this information to users analyzing their responses. Moreover, there will be some informative updates which require maximum attention, hence the proposed method will help us to share the information more effectively (through specific users, time of day etc.) so that they get maximum attention.

B.3. Implementation of the Framework

To implement the framework, we have divided the process into several steps. The first step is to collect data from a crowdsourcing platform; we have selected Twitter for this purpose. Other crowdsourcing platforms (e.g., Waze) can also be used if their data are accessible. We have written a Python script to collect data from Twitter accounts using its API. To extract relevant information from the raw data, we have also written several Python scripts. At the next step, we have applied a machine learning model (i.e. topic model) to analyze the content of the tweets. Based on the analysis, we have classified them into different categories. Finally, we have developed a model to determine the factors that contribute to an information content to be shared. We have estimated the probability of a content whether it will be retweeted or not. We have written Python scripts to implement the models. We will combine all the scripts written so far with required instructions and the data collected in a storage device to be transferred to FDOT.

B.4. Data Collection and Processing

B.4.1. Information Gathering from Twitter

We have selected Central Florida region to collect information from the travelers using twitter streaming API. During streaming process, we have filtered the data using specific keywords related to regular traffic updates, traffic-related incidents or emergency information. The keywords are selected based on previous research works which include incident detection using twitter data. For our exploratory analysis, about 1762 tweets have been collected from March 11, 2018, to March 19, 2018. After preprocessing the data, we obtained following information user id, text id, time and date of the posted tweet, text and geolocation.

Table B-1. List of keywords used to filter traffic-related information using boundary search tool

Keywords List
'police', 'accident', 'traffic', 'crash', 'road', 'cars', 'car', 'vehicle', 'highway', 'driver', 'county', 'injured', 'injuries', 'driving', 'lanes', 'vehicles', 'lane', 'struck', 'hit', 'hitting' 'congestion', 'incident', 'alert', 'jam', 'roads', 'signal', 'signaled', 'sign', 'queue', 'crashes', 'roads', 'street', 'streets', 'miles', 'event', 'events', 'mile', 'truck', 'emergency', 'fog', 'flooding', 'i75', 'i95', 'i10', 'i4', 'roadwork', 'maintenance', 'construction', 'disabled', 'alert', 'damage', 'damages', 'block'

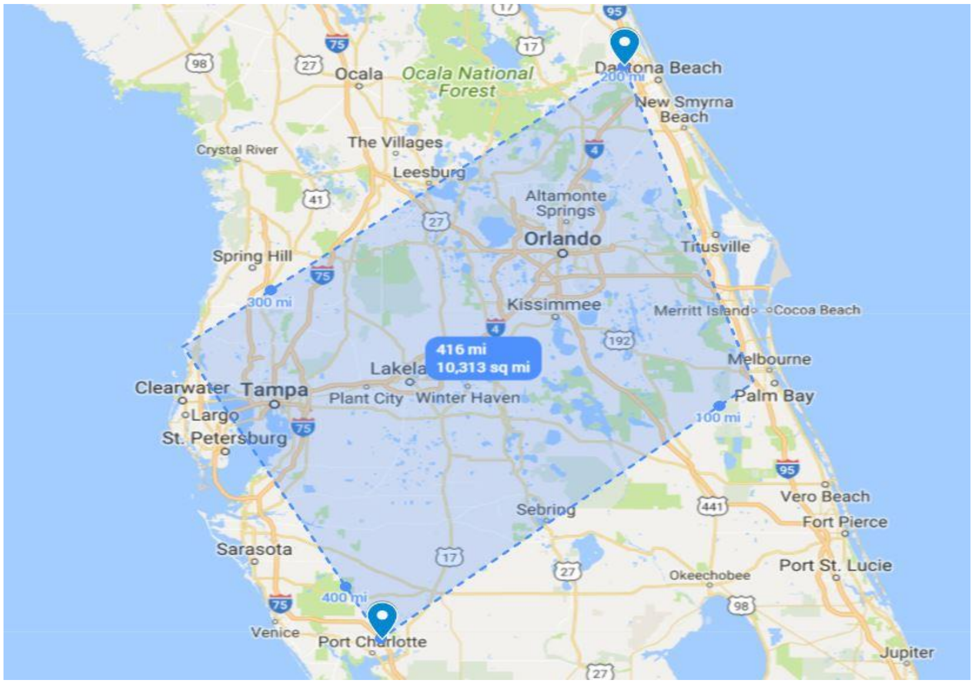


Figure B-2. Selected region for collecting traffic information (Google Maps, 2018)

B.4.2. Information Dissemination to Travelers

Florida Department of Transportation (FDOT) 511 service manages 14 Twitter accounts to share incidents and real-time traffic information throughout the state. Each account provides traffic information for specific regions and/or facilities maintained by FDOT. Among these accounts, tweets have been collected from 13 accounts which use English language (Table 2) except the account named 'FL511_Estatal' which uses the Spanish language. We have also collected data from the account 'I4-Ultimate' which provides real-time updates about incidents and traffic disruptions in different segments of I-4 caused by the I-4 Ultimate construction project. Using Twitter's REST API ("Twitter Developer Documentation: REST API," 2006) we have collected 100,527 tweets for the 14 FDOT accounts. For collecting user-specific tweets, there is a limitation which imparts that an API can collect only the latest 3200 tweets of any user account. We ran the search for each user account once in every two weeks starting from April 08, 2017 to July 21,

2017. Table 2 provides a short description of the accounts considered in this study and the total number of tweets collected during the data collection period.

Table 2 Twitter Data from FDOT accounts

No.	User Screen Name	Region/Facility	#Locations	Account Created at
1	@fl_511_i4	I-4	#Florida #Tampa #Lakeland #LakeBuenaVista #Orlando #LakeMary #Daytona	1/12/2012
2	@FL511_95Express	I-95 express lanes	#Florida #FortLauderdale #Miami	1/24/2017
3	@fl511_central	Central Florida	#Orlando #Daytona #SpaceCoast #Kissimmee #Ocala #Brevard	10/6/2010
4	@fl511_i10	I-10	#Florida #Jacksonville #Tallahassee #Pensacola #LakeCity #Crestview	10/6/2010
5	@fl511_i75	I-75	#Florida #Gainesville #Ocala #Tampa #Sarasota #FortMyers #LakeCity	10/6/2010
6	@fl511_i95	I-95	#Florida #Jacksonville #DaytonaBeach #FortLauderdale #Miami	10/6/2010
7	@fl511_northeast	Northeast Florida	#Jax #StAugustine #Gainesville #StJohns #LakeCity	10/7/2010
8	@fl511_panhandl	Panhandle	#Tallahassee #Pensacola #PanamaCity #Destin #Crestview	1/12/2012
9	@fl511_southeast	Southeast Florida	#SEFL #Miami #FtLauderdale #Broward #PalmBeach	5/10/2017
10	@fl511_southwest	Southwest Florida	#Naples #FtMyers #CapeCoral #Sarasota #SWFL	10/6/2010
11	@fl511_state	traffic reports from @myfdot	#Tampa #Orlando #Miami	10/7/2010
12	@fl511_tampabay	traffic info provided by @MyFDOT	#Tampa #Hillsborough #Pinellas #Pasco #Lakeland #Polk #SRQ	10/6/2010
13	@fl511_turnpike	Florida's Turnpike Mainline	#Miami #FortLauderdale #Orlando #PortStLucie	10/6/2010
14	@I4Ultimate	Real-time traffic of I-4	Official page of @MyFDOT_CFL's I-4 Ultimate project	11/25/2014

Note: The name of a place beside a # (known as a hashtag to Twitter users) indicates the location covered by a particular facility and thereby locality covered by the account

B.5. Data Analysis for Real-time Information Gathering from Twitter

In this task, we have investigated if Twitter can be used to collect traffic incidents and user response to such incidents in real time. We have gathered one week of data from Twitter using its search API (see section 4.1) and applied a machine learning model (topic model) to find the probability distribution of certain words in tweets. Figures 3 shows the results of topic model runs. The figures show the probability distributions of words in a given topic. We can observe from figure 3 that Topics #15, #17 contain words like ‘traffic’, ‘accident’, ‘car’ which clearly indicates travelers are likely to share incident related information through social media. Moreover, topic #3 is about the tweets informing the lane blockages due to crashes or heavy traffic. They also share other information like police activity, lane block or status updates while stuck in traffic congestion. A sample of tweets posted by travelers is given below:

- "*Closed due to accident in #StPetersburg on 4th St N SB between I-275 and Gandy Blvd #traffic*"
- "*Accident with northbound lanes blocked on Orange Blossom Trail NB at Sand Lk Rd #traffic*"
- "*Accident with bumper blocking left lane in #Orange on SR-429 SB at W Rd #traffic"*
- "*The Florida Turnpike is the most boring road to drive on in America \ud83d\ude34*"

Apart from traffic information, raw data may contain other information which is closely related to the keyword dictionary, but unrelated to any traffic incident or updates. Therefore, we need a classification technique to filter out the information related to traffic incidents. Since the tweets collected through boundary search contains geolocation and time stamp, we are able to locate both the position and approximate time of occurrence of a particular traffic incident.

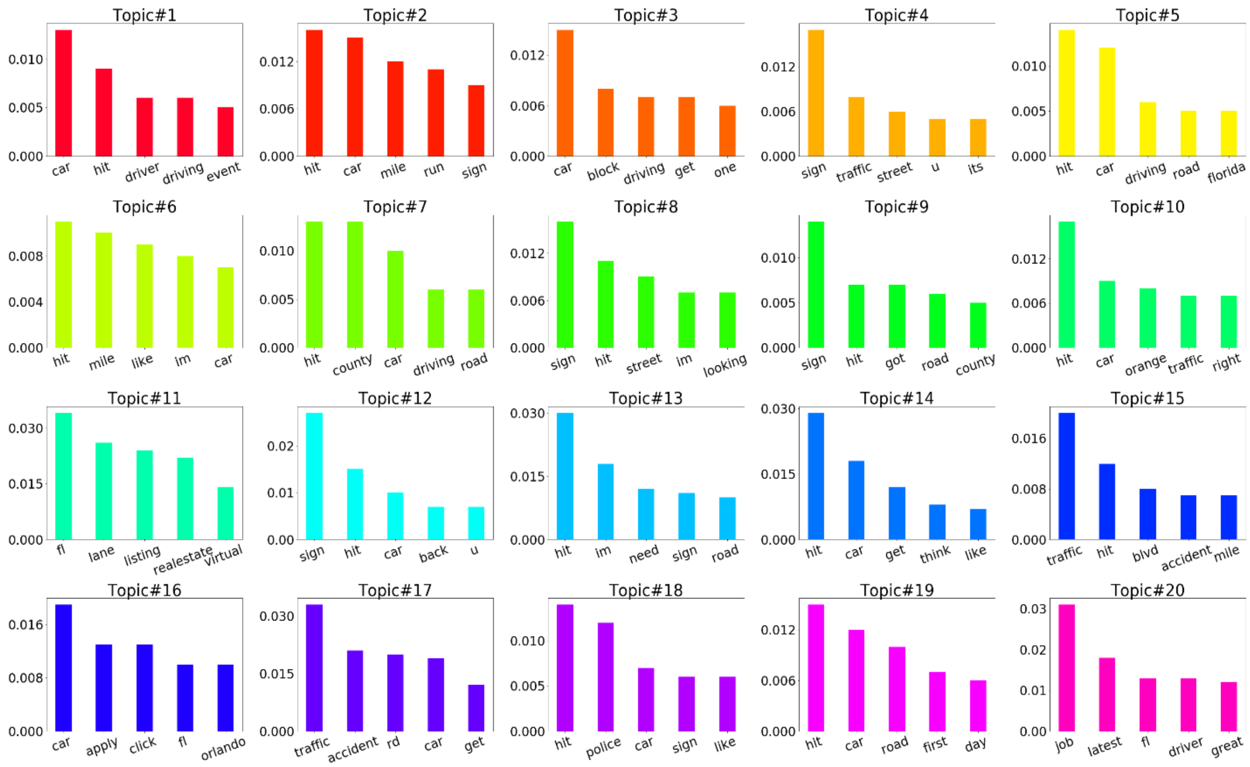


Figure B-3. Probability distributions of words in a topic for the data obtained from boundary search

B.6. Data Analysis for Real-time Information Sharing in Twitter

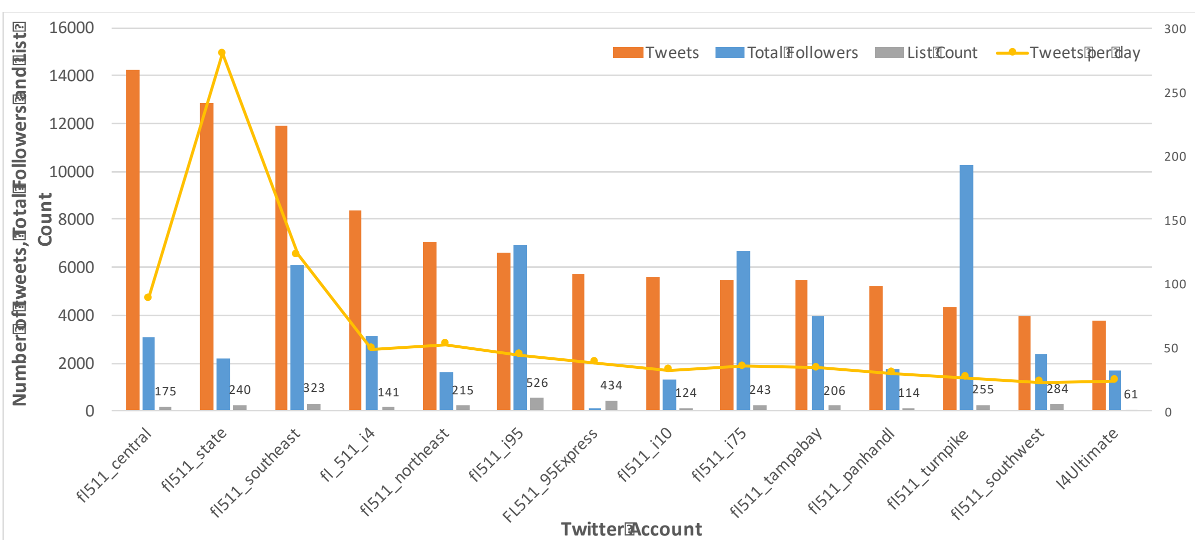
B.6.1. Activity Trends in FDOT Twitter Accounts

A Twitter account with more followers is likely to spread information to more people and hence has a greater influence. Similarly, the influence of an account to other users can be measured from the list count, assuming that other users will only consider putting this account into a separate list among its friends as far as they find the account giving useful information. Thus, the number of followers and lists added indicate the influence or importance of an account.

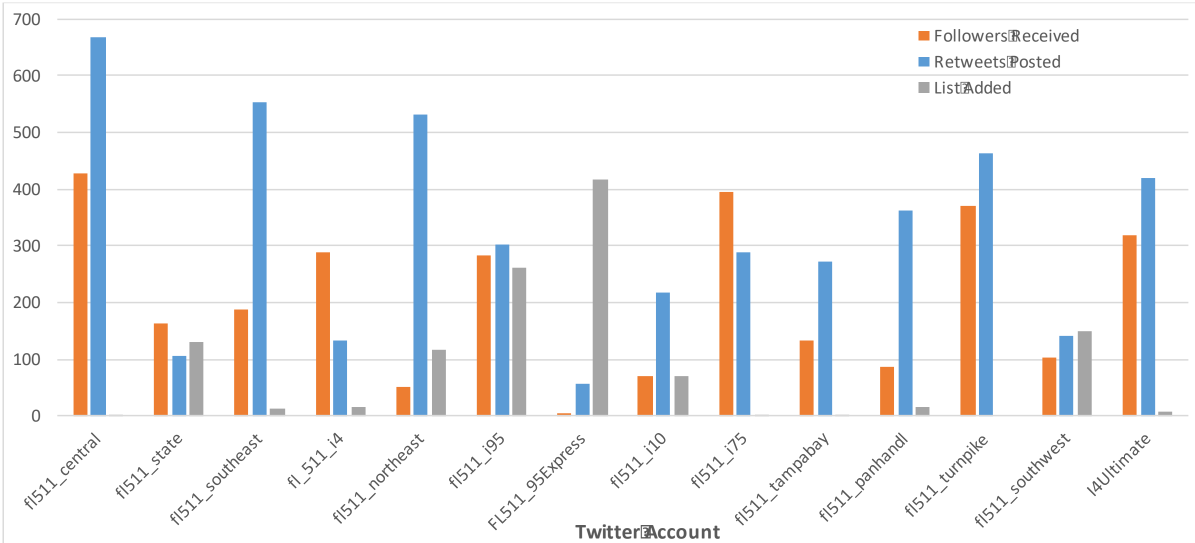
Whether people consider the information shared in a tweet as important or not can be measured by the number of times it has been shared by others (known as a *re-tweet* to Twitter users). Table 3 shows some of the important features extracted from data collected from FDOT Twitter accounts. Figure 3 shows the activity, influence, and attention gained by these 14 accounts.

Table B-3. Total days, followers (FWs), re-tweets (RTs), lists and efficiency of FDOT accounts

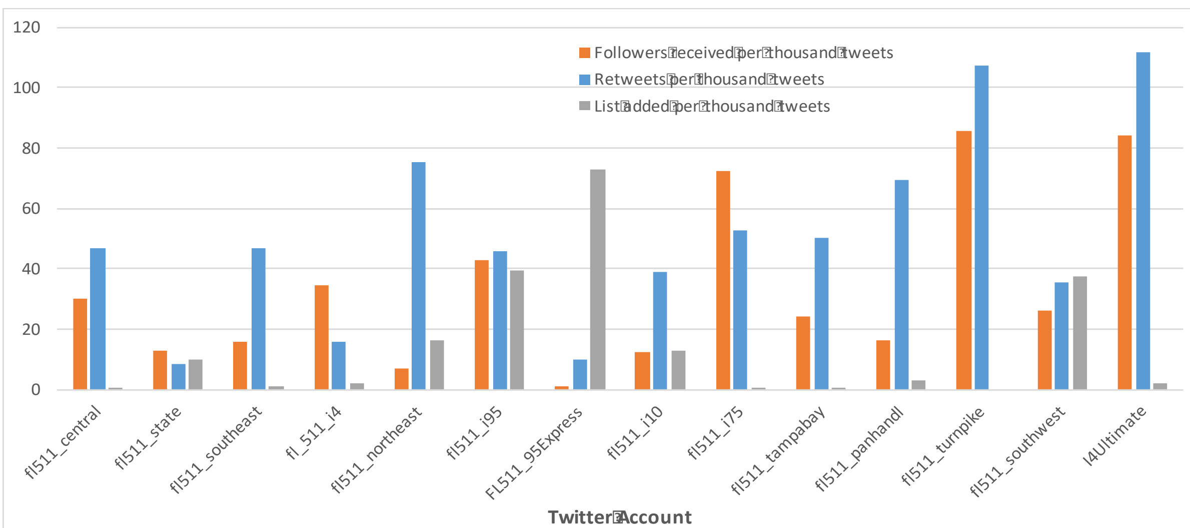
		Extracted Information from User Twitter Account							Efficiency Metrics		
Sl No	Account Name	Days in the data	Tweets	Total FWs	List Count	FWs Gained	RTs Posted	List Added	FWs received/ 1000 tweets	RTs/ 1000 tweets	List added/ 1000 tweets
1	fl511_central	162	14,263	3,053	175	428	667	2	30.01	46.76	0.14
2	fl511_state	46	12,856	2,174	240	163	107	129	12.68	8.32	10.03
3	fl511_southeast	97	11,871	6,080	323	189	554	13	15.92	46.67	1.10
4	fl_511_i4	173	8,387	3,144	141	289	132	17	34.46	15.74	2.03
5	fl511_northeast	135	7,058	1,648	215	50	531	116	7.08	75.23	16.44
6	fl511_i95	150	6,602	6,928	526	283	302	261	42.87	45.74	39.53
7	FL511_95Express	150	5,709	128	434	5	56	416	0.88	9.81	72.87
8	fl511_i10	175	5,600	1,289	124	69	219	71	12.32	39.11	12.68
9	fl511_i75	156	5,453	6,654	243	396	288	2	72.62	52.81	0.37
10	fl511_tampabay	163	5,445	3,953	206	132	273	1	24.24	50.14	0.18
11	fl511_panhandl	177	5,201	1,778	114	86	362	15	16.54	69.60	2.88
12	fl511_turnpike	168	4,323	10,262	255	371	464	0	85.82	107.33	0.00
13	fl511_southwest	180	3,986	2,366	284	104	141	150	26.09	35.37	37.63
14	I4Ultimate	161	3,771	1,696	61	318	421	7	84.33	111.64	1.86



(a)



(b)



(c)

Figure B-4. Activity, influence, attention by FDOT Twitter accounts: (a) activity and influence metrics, (b) attention gained and (c) attention gained per thousand tweets.

Figure 4(a) shows the total number tweets posted starting from the earliest to the latest tweets collected during the data collection period and the total number of followers and list count during the same time frame for each account. It is seen that 'fl_511_central' (the account responsible for broadcasting information about Orlando, Daytona, Space Coast, Kissimmee, Ocala, and Brevard) posted the maximum number of tweets (14,263) and ‘fl_511_state’ posted the highest number of tweets per day. ‘fl511_turnpike’ has the highest number of followers showing its overall influence in disseminating information to travelers.

Figure 4(b) shows that ‘fl_511_central’ received the maximum number of followers (428) during the data collection period and its tweets have been re-tweeted for the highest number of times (667) showing its increasing usefulness of the information shared by this account.

To normalize the attention received over account activities, we have plotted the number of followers received, re-tweets posted, and lists added per thousand of tweets posted. ‘fl511_turnpike’ is the most efficient account for gaining new followers per thousand tweets (85.82). On the other hand, ‘I4Ultimate’ is the most efficient account for receiving most re-tweets per thousand tweets (111.64) indicating the relative relevance of information posted by this account. ‘FL511_95Express’ is a relatively new account starting from January 2017 and had the highest rate of list added with lower numbers of re-tweets posted and followers added per thousand tweets. Although established later, ‘I4Ultimate’ is proving to be more efficient in spreading information than ‘fl_511_i4’ with real-time traffic updates.

B.6.2. Efficiency Analysis

Efficiency is measured by the amount of attention received per unit activity. Efficiency (η) of a user account (u) for a specific period (t_i to t_f) is defined as the ratio between total attention received and total activity performed within the time frame as shown in Equation (1):

$$\eta_u(t_i, t_f) = \frac{\sum_{t=t_i}^{t_f} att_t(\mathrm{u})}{\sum_{t=t_i}^{t_f} act_t(\mathrm{u})}$$

where, att_t(u) is the amount of attention received by the account u, during the time period t and act_t(u) is the total activities or tweets posted by the account u in the time period *t*. *Attention* can be defined as the number of new followers received, lists added, or re-tweets posted, and *activity* can be defined as the number of tweets posted by a user account extracted during the data collection period. Using Equation (1), we calculate the overall efficiency of the accounts for three variables (new followers received, re-tweets posted, and lists added).

To better understand the dynamics of real-time information sharing, we have plotted daily activity and efficiency metrics for all the accounts. Figure 5(a) presents the daily activities of the 14 accounts and Figure 5(b) to Figure 5(d) present the daily efficiencies of the accounts in terms of follower gain, re-tweet count and listed count respectively. The highest daily activity can be found for the accounts 'fl511_state' and 'fl511_central' with daily activities of 400+ tweets. The white portion of the heatmap in Figure 5(a) represents the days with zero or missing information (data not collected or exceeded the limit of 3200 tweets during the search process). Up to the last part of February 2017, most of the account had an activity of 55 to 148 (4 to 5 in natural logarithm scale). 'fl511_central', 'fl511_i4', 'FL511_95Express' had a constant trend of daily activity.

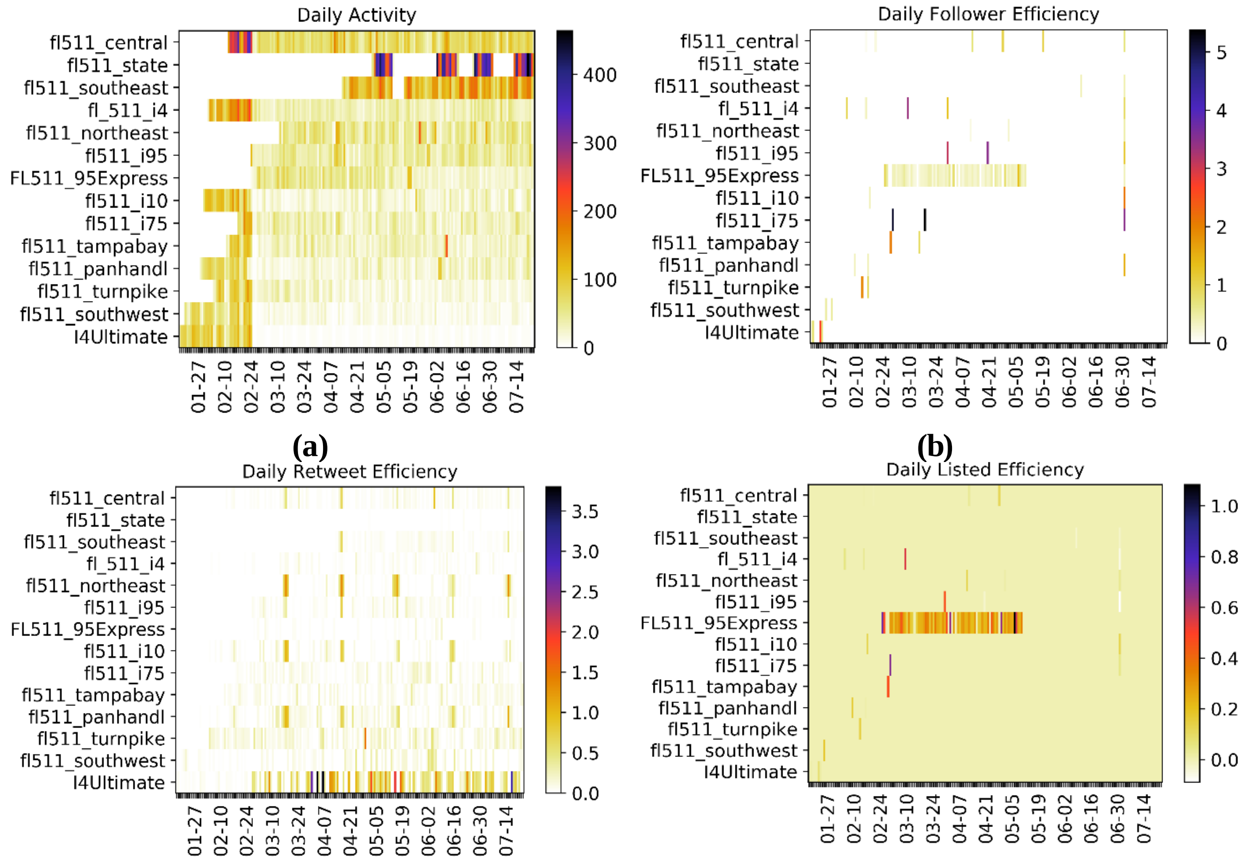


Figure 5. Daily activity and efficiency of FDOT Twitter accounts. (a) daily activity, (b) daily efficiency in terms of follower gain, (b) efficiency in terms of re-tweet count, and (c) efficiency in terms of listed count.

From Figure 5(b) it can be found that most of the time the daily efficiency is zero or close to zero, meaning the number of followers gained is zero or very low compared to the daily activities. An interesting pattern can be seen for the account 'Fl511_95Express' as it has a continuous growth in a number of followers from the end of February till mid of May 2017, whereas from the beginning till the end of data collection period this account has gained only 5 followers (Table 4). The result is not misleading as this account has lost some of the followers (negative efficiency) which are not shown in Figure 5(b). The daily re-tweet efficiency (Figure 5(c)) is higher for 'I4Ultimate', 'fl511_pandhandl', 'fl511_i10' and 'fl511_northeast' etc. 'i4Ultimate' is consistent in re-tweet counts, meaning its posted tweets have been re-tweeted more often than the tweets of other accounts. 'fl511_state' with high activity has low efficiency for both follower gain and re-tweet count. From the listed count efficiency (Figure 5(d)) it is found that 'Fl511_95Express' has similar kind of trend in listed count efficiency as its follower gain efficiency. From Table 4 we can see that this account has the highest list added count (equal to 416), that means more user in its follower list have added this account into a separate list among their friends.

B.6.3. Content Analysis for User-Specific Data

Previous studies pointed out that the content studies is a critical issue in order to understand the spatial reach of FDOT accounts (Kocatepe et al., 2015). We have applied topic models to find out the probability distribution of certain words in the posted messages or Tweets of FDOT user accounts. We run topic models on two sets of tweet texts: i) tweets that were re-tweeted at least once and ii) tweets that were not re-tweeted. Before running the topic model, we carefully filtered out the time stamps from the tweet texts. Figures 6 and 7 show the results of topic model runs. The top panels of both figures show the probability distribution of each user account in the corresponding topics. The bottom panel of the figures show the probability distributions of words in a given topic.

In Figure 6, the top user account for topic #3 is 'fl511_turnpike' (the account with the highest efficiency in follower gains) and the top 5 words of topic #3 include Turnpike, Florida, Exit, Traffic, MiamiDade. From Table 2 we found that 'fl511_central' has the highest number of re-tweeted posts. From the topic distribution, we can see that 'fl511_central' highly contributes to topics #2, #4, #6, #7, #11, #12, #13, #14 and #18. The top words on these topics include cleared, stuck, Crash, vehicle, Planned, I4, I75, Delays, Pkwy, drive, traffic etc.

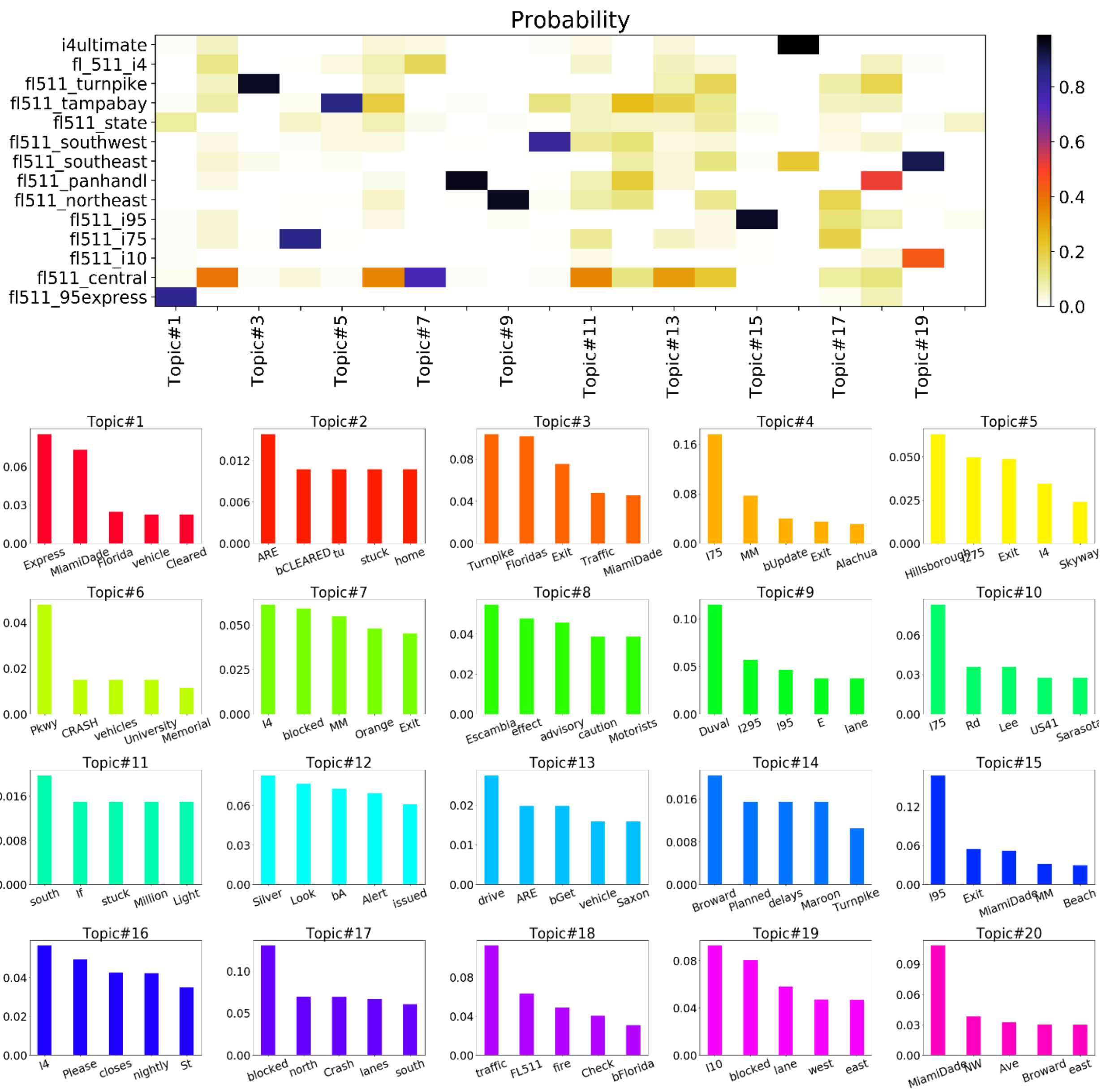


Figure B-6. For re-tweeted posts, (top) probability of each user in a topic (the color bar shows the probability scale) and (bottom) probability of each word in a topic.

These topics refer that 'fl511_central' received more attention when it broadcasted information about Interstate I-4 and I-75 freeways. We can also interpret the results going over a specific topic. For instance, topic #17 is about the tweets informing travelers about the lane blockages due to crashes. If we go to the top panel, we see that majority of accounts have contributed this topic. This means that tweets related to crashes from most of the accounts are more likely to re-tweeted.

All the topics in Figure 6 indicate the types of information that are more relevant to travelers as the tweets considered in this analysis have been re-tweeted. However, the words found in the word-topic distribution shown in Figure 7 are mostly related to roadway directions (i.e. west, north etc.), locations (i.e. MiamiDade, Duval etc.), dates (i.e. July 4th) and other less informative words (i.e. lane, shoulder etc.). Although it has some similar words like the topics in Figure 6, but the amount is much lower. This indicates that tweets posted about regular updates are less likely to propagate among other users. By Manual checking of the tweets, it has been clear that most of the tweets of this set are about different types of updates such as accident, construction, congestion, weather condition (e.g. fog), emergency information and other traffic-related information (e.g. lane blocked, lane cleared). Given below are the sample tweets of these kinds:

- Cleared: Off ramp backup Brevard I-95 south Exit 173 SR-514 right lanes blocked. Last updated 06:31:41 PM
- Cleared: Planned construction Martin I-95 north Mile Marker 89 right lanes blocked. Last updated 12:57:21 AM
- Update: Planned construction Volusia I-95 south MM 262 left lane blocked. Last updated 12:28:06 PM

We have removed the time stamps (i.e. Last updated 06:31:41 PM) before running the topic models. The first tweet has been posted three times and the second and third tweets have been posted twice. These repeated updates, however, do not carry any new information, hence are less likely to be relayed by travelers.

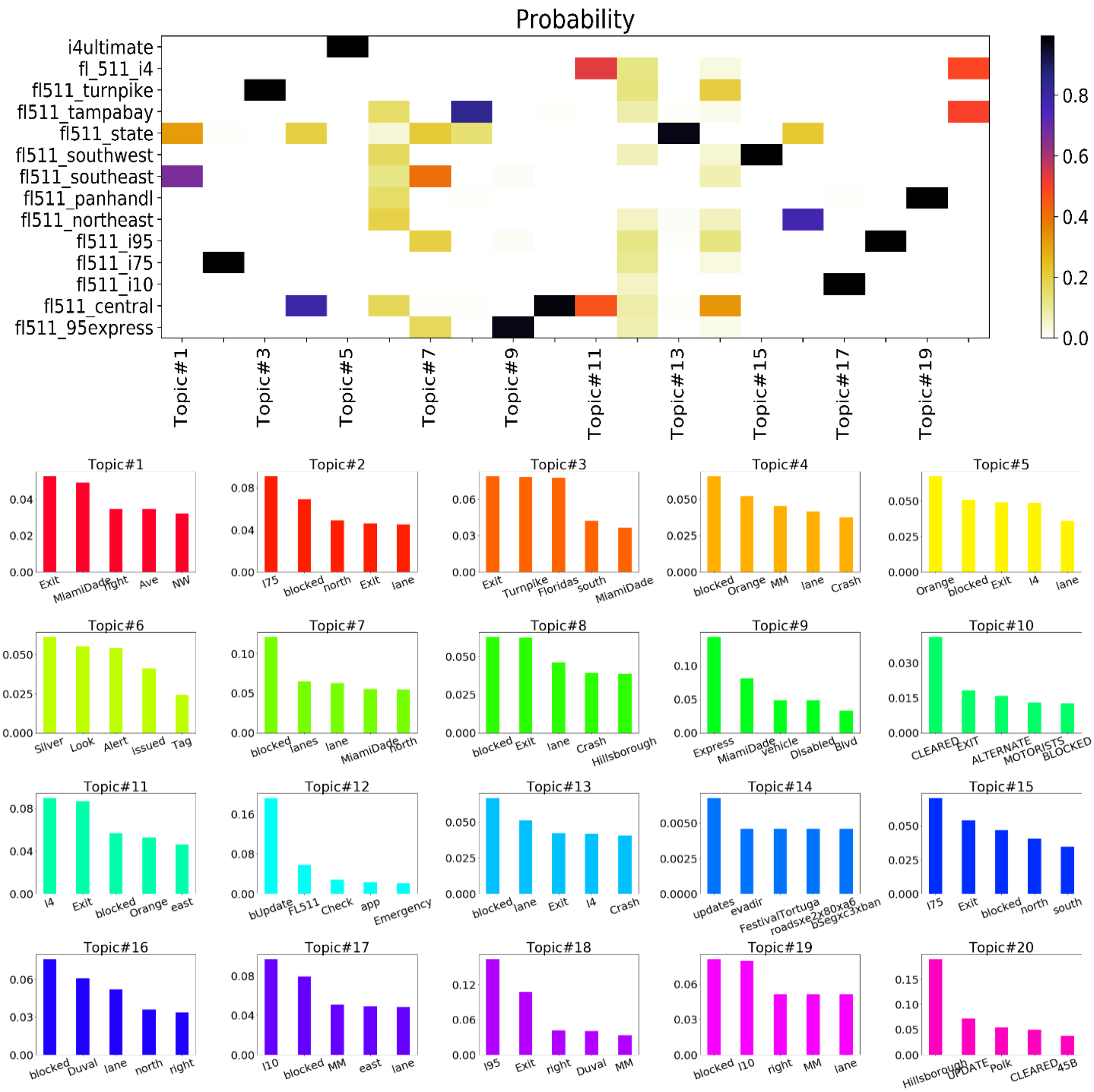


Figure B-7. For non-re-tweeted posts, (top) probability of each user in a topic (the color bar shows the probability scale) and (bottom) probability of each word in a topic.

B.6.4. Contextual Tweet Classification

We have generated 20 topics combining both retweeted and no-retweeted samples. Among them only a few were meaningful words such as a crash, updated, disabled, flooding, traffic, emergency etc. Based on the topic, we have categorized tweets as crash related updates, traffic congestion related updates, information regarding a disabled vehicle, roadway and lane condition, emergency situation or police activity on the roadway, weather-related updates. There were few other information such as information related to starting of holidays, preparedness alert ahead of hurricane season etc. which cannot be classified into a specific category. So, we have added them to another category which contains other information except the information those are available to these six categories. So, in total, we have created seven categories of the shared content (Table4).

Table B-4. Categories based on word distribution in different topics

Topic No	Sample words in different categories				Category
	1st Word	**2nd Word**	**3rd Word**	**4th Word**	
1	blocked (0.0628)	Exit (0.0618)	lane (0.0445)	Crash (0.0397)	Crash related updates
2	Turnpike (0.079)	Exit (0.079)	Traffic (0.0370)	congestion (0.0369)	Congestion related updates
3	blocked (0.079449)	lane (0.0486)	Exit (0.0365)	Disabled (0.0268)	Information regarding disabled vehicle, roadway and lane condition
4	update (0.166)	last (0.0228)	emergency (0.0201)	police (0.0194)	Emergency situation or police activity on roadway,
5	Alert (0.0517)	Issued (0.0438)	fog (0.0119)	effect (0.00996)	Weather related updates
6	blocked (0.0323)	lane (0.0447)	south (0.0421)	construction (0.0323)	Roadway improvement and construction related updates

Among the 100,527 tweets, about 35% of the tweet are crash related and only 0.5 % of the tweets contain weather alerts. About 9% of the tweets have not been classified into any category.

B.6.5. Computing Information Value

In this task, we have a developed a model to determine the effects of different variables on retweeting behavior. In particular, we have estimated an ordered logit model that will give us the probability of an information content being retweeted considered the following variables:

User favorites count: User favorites count means the number of Tweets a particular user has liked in the account's lifetime. The coefficient corresponding to this variable is positive which means if all others remain same, then the possibility of more retweets will increase with the increase in a number of favorite counts. The possible reason is that if a user likes the content shared by other people then he will get more attention and those people will follow his post. So, the chances of getting retweeted increases.

Network size: Network size of a User is indicated by the number of followers and friends connected with his account. After controlling all other variables, the likelihood of more retweets increases for a shared content if the number of followers for that user increases. This is because if the number of followers for a particular user is high then the content shared by this user will get attention from more people and the chances of being retweeted will be higher.

Table B-5. Ordered Logit model estimates

Descriptions	Estimates	t-stat
Threshold	5.93	25.23
Threshold	8.31	31.96
Number of tweets liked by a user	0.291	9.25
Number of people who receive updates from a user(follower)	0.333	8.26
FL511_95Express	0.946	2.76
fl511_central	1.14	7.43
fl511_i10	1.31	5.05
fl511_northeast	1.99	9.94
fl511_panhandl	2.17	10.69
fl511_southwest	1.24	5.31
I4Ultimate	-	-
Tweet posted between 12 am to 8 am	0.724	8.51
Tweet posted between 8 am to 12 pm	0.682	6.47
Tweet posted between 7 pm to 12 pm	-	-
Crash related updates	0.324	3.57
Disabled vehicle, roadway and lane condition	-	-
Emergency situation or police activity on roadway	0.742	5.30
Other Information	1.01	8.30
Number of cases	199,77	
Log-likelihood at convergence	-3,254.954	
Log likelihood for constants only model	-3,478.002	
Rho^2	0.852	
Adjusted Rho^2	0.851	

Note: "-" sign is used to indicate the base variable for specific category

Users entity: The tweet posted by a particular user entity has a significant influence on getting attention. From table5, we can observe that while tweets are posted by FL511_95Express, fl511_central, fl511_i10, fl511_northeast, fl511_panhandl, fl511_southwest user entity there is a higher chance of getting attention form the people hence chances of being retweeted is higher. Moreover, we can conclude that fl511_central, ffl511_northeast, fl511_panhandl are the most influential user entity in case of getting attention from the people.

Time of the day: If a tweet is posted after midnight (12 am to 8 am) and in morning hour (8 pm to 12 am) then the chances of getting retweeted increases. The reason is that normally morning hour is important to time period for the people and they prepare for their work trip, so they are more likely to check the overall condition what is going outside, whether there is any blockage or congestion on the way to the office etc. That is why tweets posted during this period get more attention and chances of getting retweeted increases.

Tweet type: Controlling other parameters, if the shared content contains crash related updates then the chances of getting retweeted increases. This is reasonable because people are more concerned about traffic incidents and post-incident roadway condition while preparing for their trips. Moreover, the information such as whether there is any emergency alert or police activity on the roadway gets more attention from users and is more likely to be shared. Road construction related updates are less likely to be retweeted.

B.7. Conclusions and Recommendations

Though most transportation agencies in the U.S. have adopted Twitter as a medium to instantly communicate traffic information to travelers they lack proper strategies to disseminate the information effectively. So, the primary focus of this task is to investigate the potential and effectiveness of real-time information gathering and sharing via a crowd sourcing platform such as Twitter. For this purpose, we have proposed several metrics to measure influence, attention, and efficiency in gaining attention by these accounts. We have also done an empirical analysis to identify the contributing factors for a shared content to get retweeted. Finally, we have combined these steps into a framework called as SMART-feed which will be integrated with IATM decision making tool to effectively disseminate information.

We proposed an approach to collect traffic updates or incident-related information from travelers via Twitter. This system will continuously collect information from the twitter using Twitter's streaming API for a specific region. This information will be used to feed a model detecting traffic incidents.

The results of our exploratory analysis indicate that FDOT Twitter accounts have a significant number of followers ranging from 128 to 10,262 and the messages posted by these accounts have gained reasonable attention. We also found that a higher number of activities is not necessarily associated with a higher efficiency value. ‘I4Ultimate’, the account posting the least number of updates about the recent I-4 construction project, has received the highest number of retweets per thousand tweets. The result from our empirical analysis shows that user entities like fl511_central, ffl511_northeast, and fl511_panhandl have more chances of getting attention, hence more effective in sharing information. Both the content and empirical analysis showed that tweets repeatedly posted about regular updates are less likely to be shared by users. On the other hand, tweets with contents like congestion, roadway blockage, clearing updates with specific route mention gain more attention. Moreover, the information like whether there is any emergency alert or police activity on the roadway, which are quite unusual news. Such news could get more attention from the users and they are more likely to share this information.

Our analysis shows that Twitter has a substantial potential to become a part of a successful active traffic management system by delivering relevant timely updates to travelers in a cost-effective way. Though we have developed a filtering technique to determine relevant posts and avoid information overloading for users, we need further refinements and tests of our proposed approach when integrated with the freeway/arterial active traffic management system.

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Appendix B-A

Tweet Types

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	0	35,681	35.5	35.5	35.5
	1	10,401	10.3	10.3	45.8
	2	15,119	15.0	15.0	60.9
	3	6,600	6.6	6.6	67.4
	4	549	.5	.5	68.0
	5	23,397	23.3	23.3	91.3
	6	8,780	8.7	8.7	100.0
	Total	100,527	100.0	100.0	

Retweet Categories

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	0	96,668	96.2	96.2	96.2
	1	3,450	3.4	3.4	99.6
	2+	405	.4	.4	100.0
	Total	100,525	100.0	100.0	
Missing	System	2	.0		
Total		100,527	100.0		