Evaluation of Connected Vehicle Applications on Mahan Corridor, Phase I

Final Report

Project No. BDV30-977-23

by

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DISCLAIMER

METRIC CONVERSION FACTORS

1 inch = 2.54 cm
1 mph = 1.609 km/h
1 pound = 0.4536 kg
Fahrenheit degrees = 9/5 x Celsius + 32
1 kip = 4.4482216 kN

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16. Abstract

The communication between roadside units (RSUs) and onboard units (OBUs) using dedicated short range communication (DSRC) was implemented across 22 intersections on Mahan corridor in the City of Tallahassee with the aim of broadcasting signal phasing and timing (SPaT) and intersection map (MAP) information to OBU-equipped vehicles. The overall goal of this project was to evaluate the efficacy of SPaT/MAP broadcasting in improving efficiency and safety of road users along a signalized corridor. There were four main tasks that were undertaken: (1) pre-ATSPM/CV operational and safety studies; (2) overall performance evaluation of SPaT/MAP broadcasting and the other underlying potential applications brought about by the DSRC implementation on the Mahan corridor; (3) evaluation of driver behavior and attitudes towards SPaT/MAP deployment; and (4) qualitative review of C-V2X communication systems in relation to enabling infrastructure owners and operators (IOO) to broadcast roadway, traffic, weather, and signalization information. The report is divided into four chapters detailing the tasks undertaken, the results obtained, and the conclusions and recommendations made.

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EXECUTIVE SUMMARY

Problem Statement

The signal phase and timing (SPaT) data were considered by the American Association of Highway and Transportation Officials (AASHTO), the Institute of Transportation Engineers (ITE), and the ITS America (ITSA) as a low-hanging fruit that can be used by infrastructure owners and operators (IOO) such as the City of Tallahassee to demonstrate the efficacy and the benefits of dedicated short-range communication (DSRC)-based vehicle-to-infrastructure (V2I) connectivity. To this end, AASHTO issued the SPaT Challenge in 2016, which urged "infrastructure owners and operators (IOO) to cooperate together to achieve the deployment of DSRC infrastructure with SPaT broadcasts in at least one corridor or network (approximately 20 signalized intersections) in each of the 50 states by January 2020." Consequently, the Florida Department of Transportation, in conjunction with the City of Tallahassee and a number of private technology integrators, installed 31 RSUs at 22 signalized intersections along the Mahan corridor.

Objectives

The overall goal of this project was to evaluate the efficacy of DSRC in improving efficiency and safety of road users along a signalized-intersections corridor. There were four main tasks that were undertaken: (1) pre-treatment automated traffic signal performance measures (ATSPM)/connected vehicle (CV) operational and safety studies; (2) overall performance evaluation of SPaT/MAP broadcasting and the other underlying potential applications brought about by the DSRC implementation on the Mahan corridor; (3) evaluation of driver behavior and attitudes towards SPaT/MAP deployment; and (4) qualitative review of cellular vehicle-to-everything (C-V2X) communication systems in relation to enabling infrastructure owners and operators (IOO) to broadcast roadway, traffic, weather, and signalization information, particularly SPaT and MAP data.

Findings

In Task 1, HERE, BlueTOAD, and Waze crowdsourced data were used to evaluate the pre-ATSPM and connected vehicle (CV) operational and safety characteristics of the Mahan study corridor. The results of the analysis using travel time reliability, level of service, and delay performance measures indicated that segments that intersect with major highways – Monroe St. and Capital Circle – had more constrained operations during the peak hours than other segments in the study corridor. Further analysis of crashes occurring in the corridor was conducted with the aim of determining contributing causes and crash types amenable to mitigation by the implementation of ATSPM and CV applications in the corridor. The implementation of dedicated short-range communication (DSRC) in the study corridor to enable vehicle-to-infrastructure (V2I) connectivity is expected to allow for the transmission of basic safety messages (BSM) and dynamic improvements in ATSPM. A number of CV safety applications were reviewed to determine their potential for mitigating vehicle-to-vehicle crashes as well as crashes involving pedestrians and bicyclists.

Task 2 was aimed at the overall performance evaluation of SPaT/MAP broadcasting and the other underlying potential applications brought about by the DSRC implementation in the Mahan corridor. Overall, the project has demonstrated, and continues to demonstrate, that V2I connectivity through DSRC is viable and operationally long lasting. The project was commissioned back in November 2017, and four years later, the installed systems were still working, and all stakeholders, i.e., Florida Department of Transportation, City, and private technology integrators and vendors were still displaying a high level of cooperation and willingness to ensure the project's durability and success. However, like any other trailblazing project, this project faced a number of operational, technical, equipment, and resource problems that needed to be addressed.

Provision of SPaT/MAP messages inside a vehicle has the potential to increase situational awareness and reduce driving stress, resulting in improved operations and safety. However, this move could have a potentially significant effect on driver behavior and, therefore, on the effective benefits of the system. In Task 3, driver behavior and attitudes towards SPaT/MAP deployment were evaluated. This study applied an experimental setup in a non-contrived setting to capture the effect that the experience of a ride with SPaT/MAP provided inside a vehicle. The information gathered after the subjects rode in SPaT-equipped vehicle showed that the rides had a positive and significant effect on attitudes towards provision of SPaT/MAP within a vehicle. One of the main upsides of SPaT information is to increase situational awareness at the signalized intersection particularly in relation to the countdown to the start of the green. However, concerns were expressed by the subjects regarding countdown to the end of green as they opined that this might encourage drivers to speed up to beat the light. Indeed, signal anticipation systems that were tried in the past resulted in more crashes at signalized intersections.

In Task 4, a qualitative review of DSRC and C-V2X communication systems was conducted in relation to enabling infrastructure owners and operators (IOO) to broadcast roadway, traffic, weather, and signalization information, particularly SPaT and MAP data. While it is clear that these technologies can also be used by IOO to collect important traffic information from mobile systems, the review was limited to *one-way communication* only, i.e., the broadcasting of SPaT to mobile entities. The collection of traffic information from mobile systems will require significant building of a cyber-physical infrastructure, the technology of which has not yet matured. Like DSRC, the deployment of C-V2X has to be assessed from a number of perspectives, including the maturity of the technology, cost, and scalability. The evaluation of safety performance and capabilities of C-V2X through small-scale or large-scale deployment must consider important issues such as congestion, interoperability, and complex transportation scenarios. The Florida Department of Transportation desire to deploy field equipment for small-scale prototype/proof-of-concept testing and for high-level conceptual development in cities of various sizes is important in providing relevant metrics needed to evaluate various performance measures.

Conclusions and Recommendations

The hosting of connected vehicle pilot projects by local agencies presents opportunities and challenges for the local agencies. The opportunities include showcasing of technological advancements and features that are aimed at improving mobility, safety, and the environment. This is good for public relations and for garnering community and management support. The cooperation among state, local agencies and technology integrators has proven successful in the deployment of connected vehicles testbeds. It has been learned from this project that the success and longevity of connected vehicles testbeds such as this can be achieved by empowering local agencies with technical know-how and resources to undertake procurement, installation, maintenance, and upgrades of the majority of the equipment, software, and systems being deployed.

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TASK 1: PRE-TREATMENT ATSPM/CV OPERATIONS AND SAFETY ANALYSIS

1.1 Purpose and Scope

The purpose of Task 1 was to quantitatively and qualitatively assess operations and safety characteristics along the study corridor prior to implementing Automated Traffic Signal Performance Measures (ATSPM) and connected vehicle (CV) applications in the corridor. Traditional measures of traffic operations, i.e., speed, travel time, level of service, and delay, were to be used in analyzing operations. The safety characteristics of the study corridor were assessed qualitatively by analyzing the types of crashes, occurring in the study corridor, that have the potential of being mitigated by ATSPM/CV applications over a long run.

This report is organized as follows. Section 1.2 describes the study corridor in detail in terms of geometric and traffic control characteristics. Section 1.3 describes the data sources that were considered in an effort to assess traffic operating and safety characteristics in the study corridor. Section 1.4 describes the traffic operating characteristics. Section 1.5 analyzes crash characteristics in relation to connected vehicle applications. Section 1.6 summarizes the results of the research findings and gives pointers to future research direction.

1.2 Characteristics of the Study Corridor

The study corridor is approximately 7.7 miles in length beginning at the intersection of US 90 and Duval Street on the west side and ending at the intersection of US 90[1] and Walden Road on the east side. The posted speed limit in the study corridor is mainly 35 MPH in some sections close to downtown but rise to 45 MPH in most sections in the outskirts of the city. The study corridor has a total of 22 intersections that currently have roadside units (RSUs) installed for the purposes of broadcasting signal phase and timing (SPaT) and geometric description (MAP) information in the near term. The study corridor is displayed in Figure 1.1.

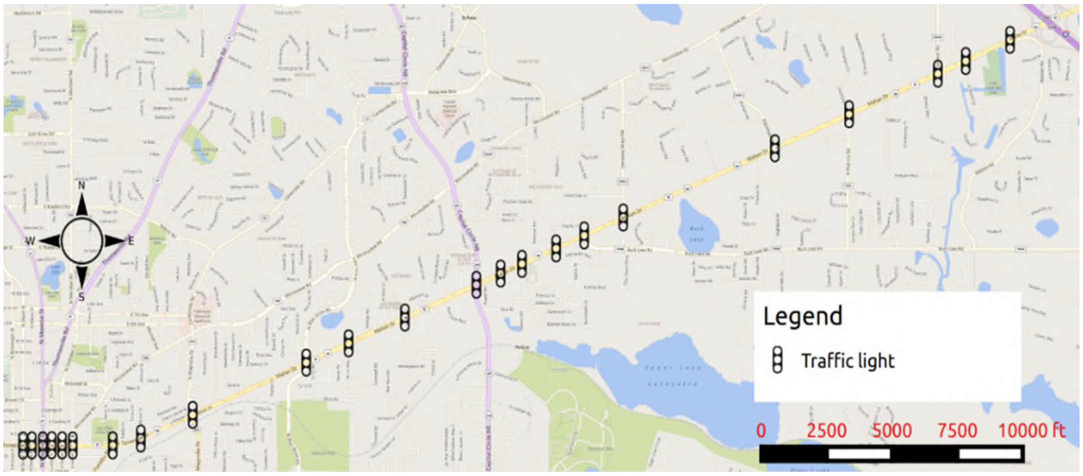

Figure 1.1 Study Corridor

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[1] US 90 is a major road in North Florida connecting Jacksonville to Pensacola and is locally known in Tallahassee as Tennessee Street in the west side of the city and Mahan Road in the east side of the city.

To perform the operational and safety analyses it was first necessary to quantify the intersection geometrics such as the number of lanes, presence of exclusive right and/or left turn lanes, length of turning bays, and overall traffic control parameters. Table 1.1 shows the intersection names, posted speed limit, number of lanes, and coordinates of the intersections along the study corridor.

Table 1.1 Location of intersections within the study corridor.

SN	Intersection	Number of through lanes	Number of left turn lanes	Number of right turn lanes	Posted speed limit (mph)	Coordinates
1	Tennessee St. & Duval St.	3	1	0	35	30.444694, -84.283084
2	Tennessee St. & Adam St.	3	1	0	35	30.444704, -84.282002
3	Tennessee St. & Monroe St.	2	1	0	35	30.444710, -84.280678
4	Tennessee St. & Calhoun St.	2	1	0	35	30.444721, -84.279587
5	Tennessee St. & Gadsden St.	2	1	0	35	30.444711, -84.278325
6	Tennessee St. & Meridian St.	2	1	0	35	30.444696, -84.277041
7	Tennessee St. & Franklin Blvd.	2	2	1	35	30.444708, -84.272188
8	Tennessee St. & Hillcrest St.	2	1	0	35	30.445359, -84.268767
9	Tennessee St. & Magnolia Dr.	2	2	1	45	30.447627, -84.262459
10	Mahan Dr. & Blair Stone Rd.	2	2	1	45	30.452634, -84.248665
11	Mahan Dr. & Hi Lo Way	2	1	0	45	30.454474, -84.243526
12	Mahan Dr. & Riggins Rd.	2	1	0	45	30.456949, -84.236682
13	Mahan Dr .& Capital Circle	2	2	1	45	30.460079, -84.227990
14	Mahan Dr. & Automotive way	3	1	0	45	30.461160, -84.225040
15	Mahan Dr. & Weems Rd.	3	1	0	45	30.462087, -84.222457
16	Mahan Dr. & Lagniapple Way	3	1	0	45	30.463561, -84.218301
17	Mahan Dr. & Buck lake Rd.	3	1	2	45	30.464814, -84.214896
18	Mahan Dr. & Dempsey Mayo Rd.	2	1	1	45	30.466525, -84.210140
19	Mahan Dr. & Edenfield	2	1	1	45	30.473154, -84.191717
20	Mahan Dr. & Champagne/Pedrick Rd.	2	1	1	45	30.476408, -84.182710
21	Mahan Dr. & Thornton	2	0	0	45	30.480289, -84.171917
22	Mahan Dr. & Vineland Dr.	2	1	1	45	30.481505, -84.168531
23	Mahan Dr. & Walden Rd.	2	1	0	45	30.483538, -84.163150

1.3 Data Sources

The analysis of the study corridor mobility characteristics required to first assess various data sources and the quality of data from each source. Traditionally, estimation of travel times (or speeds) on highway corridors and networks are conducted manually using procedures such as “floating car”. However, with the emergence of new technologies such as Global Positioning System (GPS), Wi-fi, cellular LTE, crowdsourcing, and Bluetooth, the research team explored the availability of data from these sources along the study corridor. A number of data sources were found to exist as discussed in the following sections.

1.3.1 Bluetooth Data

The Bluetooth-based travel time data collection uses media access control (MAC) readers to identify the unique address of each turned-on Bluetooth device. The travel time is estimated by matching the detected MAC address of the device between two locations (upstream and downstream). The City of Tallahassee so far has installed 38 Bluetooth MAC readers at various locations in the city, of which 9 MAC readers are in the study corridor as seen in Figure 1.2.

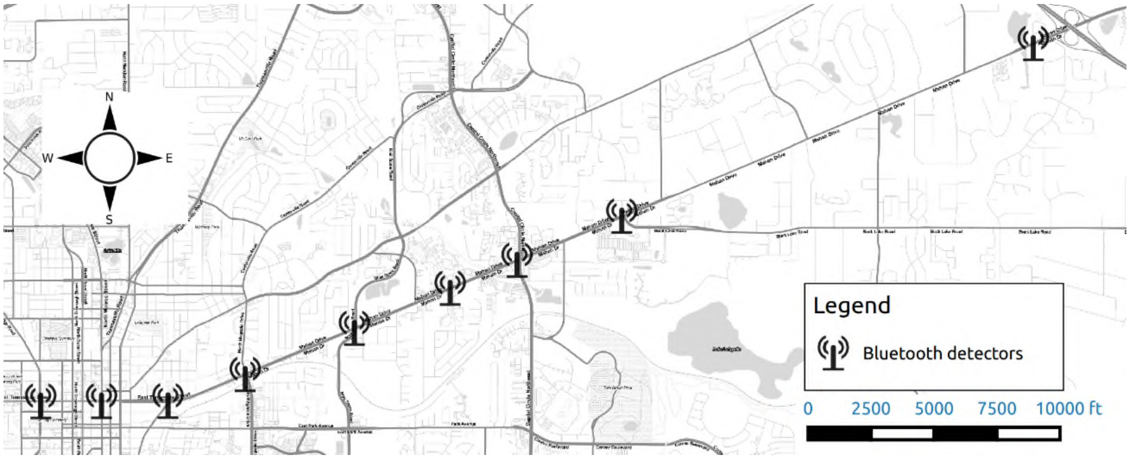


Figure 1.2 Location of Bluetooth detectors on the study corridor

The collected travel time data from corridor are stored at the BlueARGUS TRAFFICAST server and can be viewed in real-time. Access to these data in the server was accomplished using login details provided by the City of Tallahassee, Traffic Signal Systems Office. At the time of writing Task 1 report, historical travel time and speed data from these detectors collected from October 2017 to January 31, 2018 were accessible. Several data aggregation intervals were available for download including smoothed 5-min interval data, smoothed 15-min interval data, individually filtered 5-min interval data, individually filtered 15-min interval data, and individual raw data for each pair. Closer examination of these five aggregation interval types revealed that the individually filtered data aggregated at a 5-min interval were suitable for further analysis. This data type had no outliers since they were omitted during the aggregation process. The attributes of the BlueTOAD data were 'RouteID', 'Measurement_tstamp', 'TravelTime', and 'Speed'. The 'RouteID' is a unique code that was used to identify data of each BlueTOAD segment. The 'Measurement_tstamp' attribute has time and the date at which speed and travel time were recorded.

A total of 16 segments that had Bluetooth travel times were determined to be within the study corridor (see Appendix Table A1). This table shows that the longest segment is between Walden Rd. and Buck Lake Rd. (3.3 miles) and the shortest segment is Macomb St. to Monroe St. and Monroe St. to Franklin Blvd, each 0.5-mile long.

1.3.2 HERE and TomTom Data

Other data sources of a category of their own were HERE and TomTom, which are available at the Regional Integrated Transportation Information System (RITIS) website (Regional Integrated Transportation Information System (RITIS), 2018). The HERE and TomTom vendors rely on a "floating car" technique to collect travel speeds on a typical roadway segment. A fleet of vehicles with GPS devices sends coordinates, speeds, and direction of travel to their databases through cloud data transfer. These companies also use smartphones with the GPS enabled applications and government road sensors to collect travel time and speed data (TomTom, 2015). The collected data are then aggregated, processed, and summarized at the traffic message channel (TMC) level using their proprietary algorithms, not publicly disclosed. The TMC is a type of road segmentation whereby traffic and weather information can be broadcasted in real-time. Apart from TMC attribute, there are five other attributes in the dataset, i.e., ‘Measurement_tstamp’, ‘Speed’, ‘Reference_speed’, ‘Travel_time_minutes’, and ‘Confidence’. The ‘Measurement_tstamp’ is the unique identifier of a day, hour, minute, second, and millisecond at which traffic data were collected. The ‘Speed’ attribute corresponds to the historical space mean speed of the roadway segment in miles per hour (mph). The ‘Reference speed’ attribute provides the calculated “free-flow mean speed” which represents the 85th-percentile observed speed for all times with a maximum value of 65 mph (Elefteriadou *et al,* 2014).

1.3.3 Android and Apple Smart Phone Applications

The “floating car” technique is one of the most common approaches for collection of travel time data along the corridor. This approach uses a GPS-equipped device to collect speed and location-based information that enables tracking of a GPS device in a test vehicle along the study corridor. There are several open-source mobile applications with a GPS-enabled system that can be used in the “floating car” technique to collect travel speed and travel time data. Two cellular mobile applications, Android GPS Logger and IOS MyTracks, were evaluated by the researchers. It was found that it was easy to retrieve data from these apps and download to a local computer for further analysis. The Android GPS Logger and IOS MyTracks applications gather coordinates, speed, direction, elevation, and the time stamp at which these parameters were recorded. Also, these apps allow users to select a time interval of data collection, such as 1 second, 2 seconds, 3 seconds, etc. In an experiment, the raw data from the Android GPS Logger app were downloaded from the mobile device and pre-processed in the local computer by matching with an OpenStreetMap (in Python) to obtain the travel time between origin and destination.

1.3.4 Google Location History

The Google location history is another service that can be used to estimate travel time. This service requires a user to activate the location-tracking feature called “location history” on their Android cellular device. When this feature is turned-on, speed and location-based information (coordinates, direction, and elevation) are sent at predetermined intervals to Google’s server. Using the Google account logging details, users can view their data in a map and can download the location history in an XML or JavaScript Object Notation (JSON) format at any time with no charges. A trial run of this method of data collection showed good outcome – in both ease of use and quality of data. Based on the experiment conducted by the researchers, it was found that this service could be used in the “floating car” technique to collect travel time data.

1.3.5 Google Maps API

The Google Maps Application Program Interface (API) service was also found useful in estimating travel times and distances between points. This service supports four major modes of transportation: transit, driving (passenger car), walking, and bicycling. The Google Maps API service requires users to have a Google account and an API key. The API key allows developers to download travel time data or to create an application or software that requests services from Google. Both Google account and API for travel time data are available at no cost to the user when a standard plan is chosen. The standard plan can provide up to 2,500 downloads per day with a maximum of 23 origins or destinations per request and 50 requests per second. Beyond that extra requests are charged $0.5 per 1,000 requests.

It is worth noting that the Google Maps API service does not provide historical travel time data except for the transit mode of travel. The data available for most modes are either the current real-time or the predicted travel time. To overcome the challenge of lack of historical data for driving from this source, a Python code was written by the research team to download the real-time travel time during for the peak periods only. Also, the segmentation that was used to download Google travel time data on the study corridor followed that of BlueTOAD data to reduce the number of download points and requests per second.

1.3.6 Waze Traffic Data

Google also operates a very popular App known as Waze, which is a smartphone app relying on GPS to provide turn-by-turn navigation information. According to Wikipedia, the app relies on user-submitted travel times and route details, while downloading location-dependent information over a mobile telephone network. Unlike the Google Maps API and the Google location history applications, Waze does not require users to have an API key or an account to download traffic data. Also, the Waze API application allows downloading real-time and historical average travel time of a segment at a current time. As an experiment, an algorithm was developed by the research team to capture the segment's travel times in the study corridor – real and historical – every 5 minutes. The BlueTOAD segmentation discussed earlier was used in capturing Waze Traffic Data.

1.3.7 Microsoft Bing Map API

One of the Microsoft Bing Map services also allows third-party developers to download and use travel time data from their website using an API. This service has two major travel modes: driving and walking. As with Google Maps API, the Microsoft Bing Map API for travel time data download requires a key to access the data and it has a limit of 125,000 requests per year for free. An algorithm was developed to automatically download data in JSON format in real-time to a local computer. Attributes of interest that were downloaded are distance, free-flow travel time, real-time travel time, and the congestion level. The congestion level attribute classifies congestion severity as heavy, medium, or mild. The downloaded data were aggregated at a 5-min resolution following segmentation used in BlueTOAD data analysis.

1.3.8 MapQuest Traffic Data API

MapQuest Traffic API is another "crowdsourced" traffic data outlet owned by Verizon that allows developers to download or share data. This service also provides turn-by-turn GPS voice navigation for walking or driving directions. MapQuest digital mapping uses some of the TomTom's services in its mapping system (Harlan, 2015). Review of the MapQuest traffic data revealed that in addition to real-time travel time and distance data, the service offers the estimated amount of fuel that a vehicle is likely to use in traversing the segment. The research team developed an algorithm to download the data from a web in JSON format. The data were subsequently processed and stored in a local computer in Microsoft Excel spreadsheets. As with other "crowdsourced" traffic data outlet, the download process was segmented following the BlueTOAD segments at a 5-minute interval.

1.3.9 Summary of Data Sources for Operational Analysis

The eight data sources discussed above can be categorized into three major groups: RITIS (HERE and TomTom data), BlueTOAD, and API "crowdsourced" (Waze, Google Map, MapQuest, and Bing Map traffic data). One data source from each group was selected for further analysis. The downloaded travel time data from the RITIS database (HERE and TomTom data) were from January 1, 2017 to January 31, 2018. The preliminary analysis of these data showed that the majority of the TomTom data were recorded in the summer of 2017 and had missing records for some of the days. Because of these shortcomings of the TomTom data, the HERE data source was selected to be used in the operational analysis from the RITIS data group. For API "crowdsourced" group, the research team selected Waze traffic data for further analysis over the MapQuest, Bing Map, and Google Map API traffic data. The other data sources, i.e., Google location history, MapQuest, Bing Map, and Google map API are still viable for operational analysis and would likely be considered for use in the future.

The selected operational analysis periods were peak periods (morning and evening peak hours). The evening peak period from 4 p.m. to 6 p.m. was used for outbound traffic while the morning peak period from 7 a.m. to 9 a.m. was used for inbound traffic. As part of preprocessing, weekends, Mondays, and Fridays were omitted from the dataset because they were not representative of commuter peak traffic conditions. For BlueTOAD and HERE data sources, travel time data for a period beginning January 16, 2018 to January 31, 2018, was used in the analysis. Meanwhile, Waze "crowdsourced" traffic data were downloaded from March 7, 2018 to March 23, 2018 but Spring Break days were excluded from the dataset.

1.3.10 Crash Data

For safety analysis, crash data for 2017 were acquired from the Signal Four Analytics website maintained by the University of Florida. Section and intersection crashes occurring in the corridor were downloaded. For the crashes that occurred at intersections, a Geographic Information Systems (GIS) software was used to retrieve all the crashes that occurred within 250 ft. from the center of the intersection. This procedure was conducted to ensure that all intersection-related crashes were captured including those occurring on approaches on cross streets. Important attributes coded for each crash included crash severity level, the manner of collision, age of the driver, crash date and time, weather conditions, light conditions, road surface conditions, work zone, distracted driver, drug and alcohol, contributing road circumstance, and contributing road environment. Based on an amalgamation of the literature review, these attributes will be used to associate crashes with the CV safety applications that are likely to address these crashes.

1.4 Traffic Operational Analysis

Three performance measures that were used to evaluate the operational characteristics of all segments of the study corridor are travel time reliability (TTR), delay, and level of service (LOS). These performance measures were calculated using the procedures recommended by the 6th edition of the Highway Capacity Manual (HCM-6, 2016). Among the TTR metrics, the planning time index (PTI) was selected to represent the TTR in a segment. The PTI compares the 95th percentile travel time to the travel time at the base free-flow speed. This metric reflects the time that a traveler should plan on spending to ensure that the on-time arrival is within the 95% probability (Equation 1). For delays metrics, the average delay per trip (d_{trip}) was used in the analysis (Equation 2).

$$\text{PTI (unitless)} = \frac{95th\ percentile\ travel\ time}{TT_f} \text{ ....(1.1)}$$

$$d_{trip} = TT_f\ x\ (TTI_{mean} - 1) \text{ ....(1.2)}$$

$$\text{TTI}_{\text{mean}}\text{(unitless)} = \frac{Average\ of\ travel\ times}{TT_f} \text{ ....(1.3)}$$

where,
TT_f is the travel time at base free-flow speed, and
TTI_{mean} is the mean based travel time index.

The 85th percentile operating speed of each segment for each direction was extracted in order to determine the LOS of each segment using criteria shown in Table 1.2. Guidelines contained in Chapter 16, 17, and 36 of the HCM were followed in the analysis. Moreover, it is worth noting that the majority of the traffic operation measures require base free-flow speed an input parameter in the analysis. Consistent with previous studies, base free-flow speed used in the analysis was set 5 mph over the posted speed limit (Moses & Mtoi, 2013).

Table 1.2 LOS criteria for motorized vehicle mode *(Source: Exhibit 16-3, HCM-6)*

LOS	**Travel speed threshold by base free-flow speed (mi/h)**							**Volume-to-capacity ratio**
	55	**50**	**45**	**40**	**35**	**30**	**25**	
A	>44	>40	>36	>32	>28	>24	>20	≤ 1.0
B	>37	>34	>30	>27	>23	>20	>17	
C	>28	>25	>23	>20	>18	>15	>13	
D	>22	>20	>18	>16	>14	>12	>10	
E	>17	>15	>14	>12	>11	>9	>8	
F	≤17	≤15	≤14	≤12	≤11	≤9	≤8	
F	Any							> 1.0

1.4.1 Operational Analysis using BlueTOAD Data

(a) Travel Time Reliability

The results of PTI analysis, as a measure of TTR, indicates that Franklin Blvd. to Monroe St. (PTI = 6.69) is the most congested segment, followed by the Buck Lake Rd. to Capital Circle segment (PTI = 5.11) in the westbound direction (Table 1.3). These findings could be attributed to the fact that the Capital Circle and Monroe St. are two major arterial roads that intersect with the study corridor. It is important to also note that the Monroe St. intersect with US 90 in the CBD area while Capital Circle and US 90 intersection is located in the suburban area. In the eastbound direction, the highest PTI is 9.19, which is on the Riggins Rd. to Capital Circle segment followed by Macomb St. to Monroe St. segment with PTI = 4.36. The segment between Walden Rd. and Buck Lake Rd.

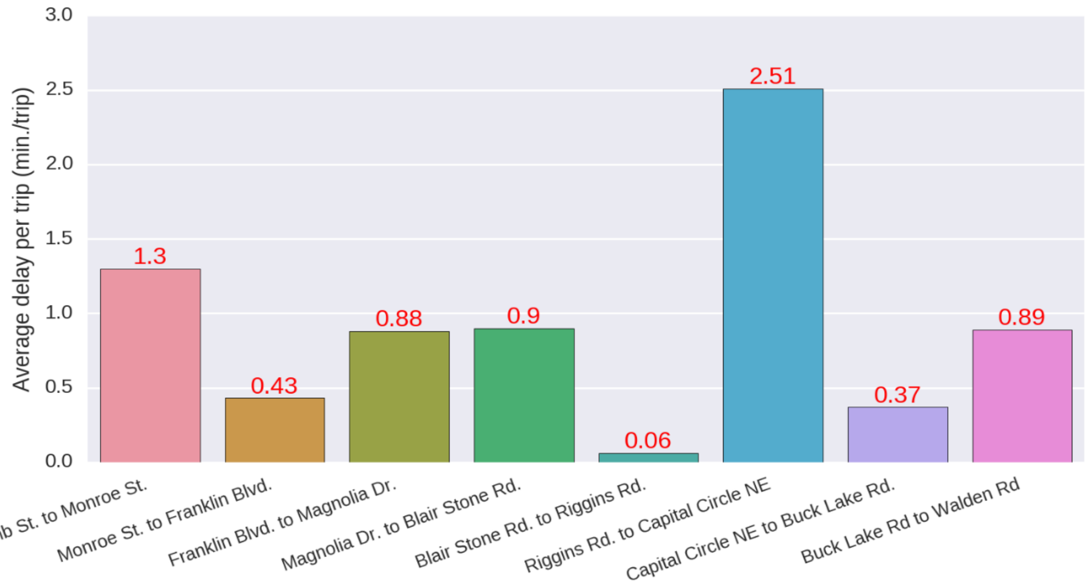
was found to have the lowest PTI in both directions, probably because the segment is at the end of the corridor and end of the built-up area in the east side.

Table 1.3 Estimated TTR – BlueTOAD data

Direction	SN	Segment name	Distance (miles)	PTI
Eastbound – p.m. peak	1	Macomb St. to Monroe St.	0.5	4.36
	2	Monroe St. to Franklin Blvd.	0.5	2.03
	3	Franklin Blvd. to Magnolia Dr.	0.6	3.46
	4	Magnolia Dr. to Blair Stone Rd.	0.9	2.04
	5	Blair Stone Rd. to Riggins Rd.	0.8	1.92
	6	Riggins Rd. to Capital Circle	0.6	9.19
	7	Capital Circle to Buck Lake Rd.	0.8	1.75
	8	Buck Lake Rd to Walden Rd	3.3	1.33
Westbound – a.m. peak	1	Walden Rd. to Buck Lake Rd.	3.3	1.32
	2	Buck Lake Rd. to Capital Circle	0.8	5.11
	3	Capital Circle to Riggins Rd.	0.6	0.98
	4	Riggins Rd. to Blair Stone Rd.	0.8	1.82
	5	Blair Stone Rd. to Magnolia Dr.	0.9	2.82
	6	Magnolia Dr. to Franklin Blvd.	0.6	1.77
	7	Franklin Blvd. to Monroe St.	0.5	6.69
	8	Monroe St. to Macomb St.	0.5	2.33

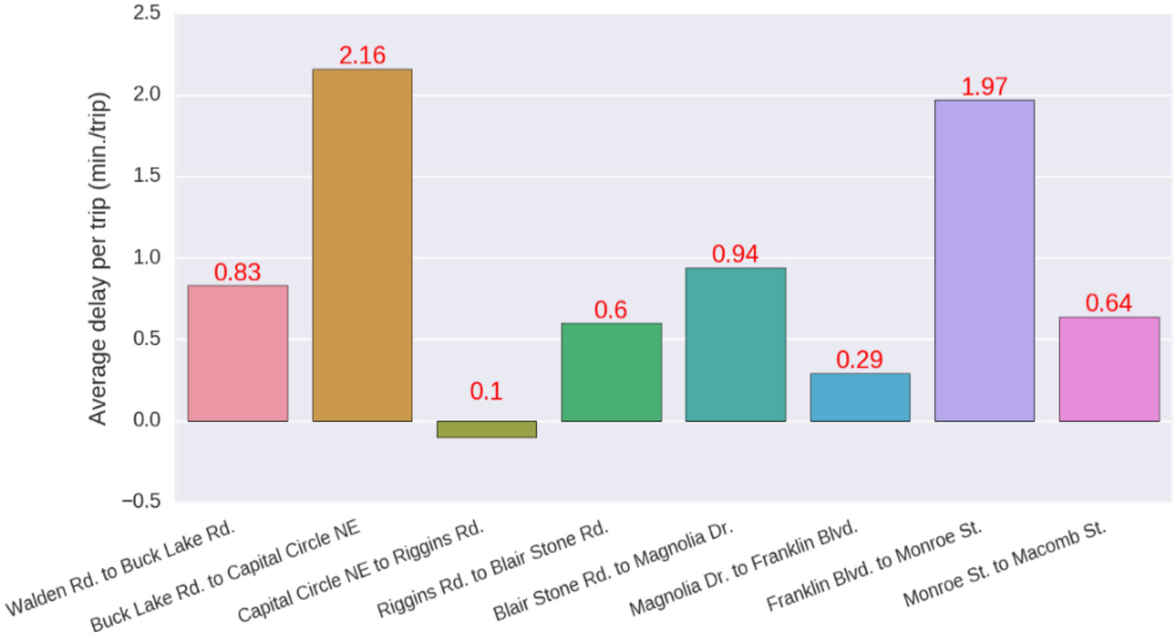
(b) Average Delay

As seen in Figure 1.3, the segment between Riggins Rd. and Capital Circle has the higher average delay per trip ($d_{trip} = 2.51\ min./trip$) than other segments in the eastbound direction during the evening peak period. This finding is consistent with that reported by PTI metric above. Figure 1.3 also suggests that the Blair Stone Rd. and Riggins Rd. segment has the lowest delay per trip ($d_{trip} = 0.06\ min./trip$) than the rest of the segments. The analysis of mobility in the westbound direction (morning peak) indicates that the Buck Lake Rd. to Capital Circle segment has the highest delay per trip. Note that Capital Circle to Riggins Rd. segment has a negative value because the average operating speed was higher than the estimated free-flow speed.



(a) Eastbound

Figure 1.3 Average Delay Per Trip - BlueTOAD Segments



(b) Westbound

Figure 1.3 Average Delay Per Trip - BlueTOAD Segments

(c) Level of Service

As seen in Table 1.4, the Riggins Rd. to Capital Circle and Macomb St. to Monroe St. segments (p.m. peak) have the worst LOS (D) than the rest of the segments. On the other hand, the Franklin Blvd. to Monroe St. and Buck Lake Rd. to Capital Circle segments during the a.m. peak hour were found to have a worse level of service than the rest of the segments (LOS D). Broadly speaking, these results are correlated to those revealed by the average delay per trip and TTR performance measures.

Table 1.4 Estimated LOS – BlueTOAD data

Direction	SN	Segment name	85th speed (mph)	LOS (based on 85th speed)
Eastbound (p.m. peak)	1	Macomb St. to Monroe St.	17.3	D
	2	Monroe St. to Franklin Blvd.	29.6	B
	3	Franklin Blvd. to Magnolia Dr.	29.1	B
	4	Magnolia Dr. to Blair Stone Rd.	28.7	C
	5	Blair Stone Rd. to Riggins Rd.	54	A
	6	Riggins Rd. to Capital Circle	20.9	D
	7	Capital Circle to Buck Lake Rd.	44.5	A
	8	Buck Lake Rd to Walden Rd	43.8	A
Westbound (a.m. peak)	1	Walden Rd. to Buck Lake Rd.	25.5	C
	2	Buck Lake Rd. to Capital Circle	19.7	D
	3	Capital Circle to Riggins Rd.	37.6	A
	4	Riggins Rd. to Blair Stone Rd.	42.9	A
	5	Blair Stone Rd. to Magnolia Dr.	33.6	B
	6	Magnolia Dr. to Franklin Blvd.	60.6	A
	7	Franklin Blvd. to Monroe St.	23.8	D
	8	Monroe St. to Macomb St.	44.7	A

1.4.2 Operational Analysis Using HERE Data

(a) Travel Time Reliability

Table 1.5 shows the results of the TTR analysis using HERE data. Overall, the analysis of eastbound and westbound directions across all metrics consistently shows that the segments that have a major intersection (Monroe St. and Capital Circle) are more congested than other segments. The highest index (PTI = 5) was observed on the Macomb St. to Monroe St. segment located in the CBD area followed by the Capital Circle Inter TMC (PTI = 4.9) in the eastbound direction. For the westbound direction, the Franklin Blvd. to Monroe St. segment (PTI = 5.43) had the highest PTI followed by the Capital Circle Inter TMC (PTI = 3.77).

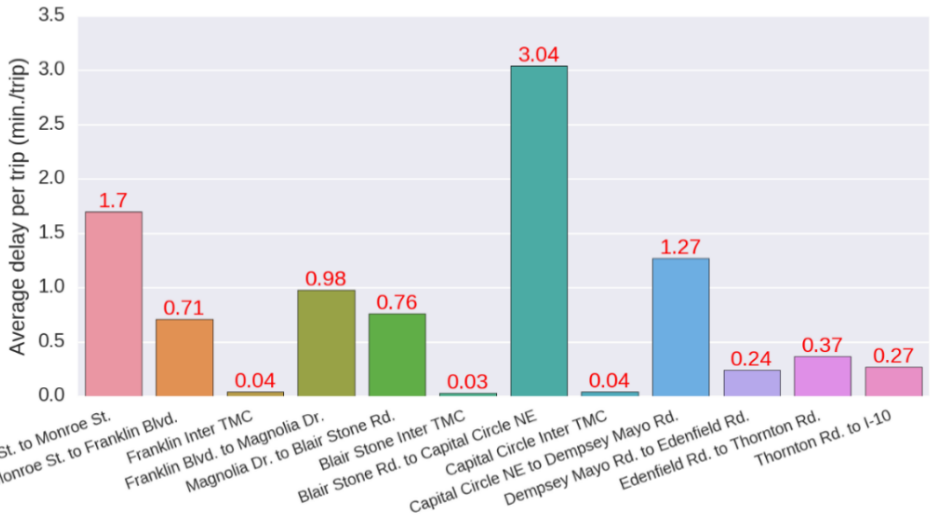
Table 1.5 Estimated travel time reliability – HERE data

Direction	SN	TMC	Segment name	Distance (miles)	PTI
Eastbound (p.m. peak)	1	102+08112	Macomb St. to Monroe St.	0.47	5
	2	102+09616	Monroe St. to Franklin Blvd.	0.49	2.9
	3	102P09616	Franklin Inter TMC	0.03	2.95
	4	102+08113	Franklin Blvd. to Magnolia Dr.	0.62	3.82
	5	102+09617	Magnolia Dr. to Blair Stone Rd.	0.86	2.26
	6	102P09617	Blair Stone Inter TMC	0.03	2.32
	7	102+08114	Blair Stone Rd. to Capital Circle	1.32	4.79
	8	102P08114	Capital Circle Inter TMC	0.01	4.9
	9	102+09618	Capital Circle to Dempsey Mayo Rd.	1.15	2.58
	10	102+09619	Dempsey Mayo Rd. to Edenfield Rd.	1.19	1.35
	11	102+09620	Edenfield Rd. to Thornton Rd.	1.28	1.47
	12	102+08115	Thornton Rd. to I-10	0.68	1.72
Westbound (a.m. peak)	1	102-09620	I-10 to Thornton Rd.	0.72	1.45
	2	102-09619	Thornton Rd. to Edenfield Rd.	1.28	1.31
	3	102-09618	Edenfield Rd. to Dempsey Mayo Rd.	1.19	1.41
	4	102-08114	Dempsey Mayo Rd. to Capital Circle	1.13	3.74
	5	102N08114	Capital Circle Inter TMC	0.03	3.77
	6	102-09617	Capital Circle to Blair Stone Rd.	1.29	2.08
	7	102N09617	Blair Stone Inter TMC	0.04	2.02
	8	102-08113	Blair Stone Rd. to Magnolia Dr.	0.89	2.57
	9	102-09616	Magnolia Dr. to Franklin Blvd.	0.62	2.17
	10	102-08112	Franklin Blvd. to Monroe St.	0.51	5.43
	11	102-09615	Monroe St. to Macomb St.	0.47	3.1

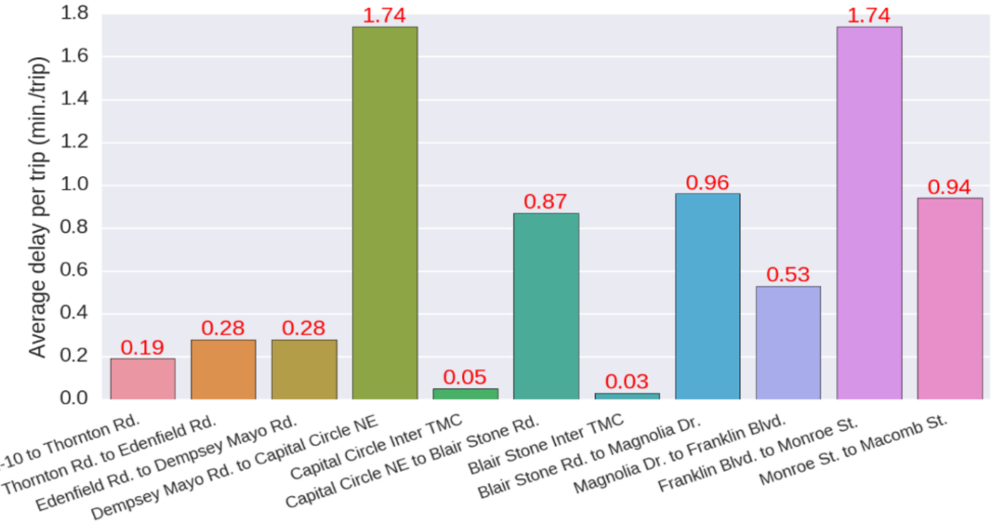
Note: Inter TMC refers to segments that are at the intersection

(b) Average Delay Analysis

Figure 1.4 shows the average delay per trip of all the segments on the study corridor. As illustrated in this figure, travelers experience more congestion on the Blair Stone Rd. to Capital Circle segment ($d_{trip} = 3.04\ min./trip$) than the rest of the segments in the eastbound direction. The Macomb St. to Monroe St. segment ($d_{trip} = 1.7\ min./trip$) was the next most congested segment followed by the Capital Circle to Dempsey Mayo Rd. segment ($d_{trip} = 1.27\ min./trip$). Furthermore, the average delay per trip in the westbound direction reveals that the Dempsey Mayo Rd. to Capital Circle and the Franklin Blvd. to Monroe St. segment ($d_{trip} = 1.74\ min./trip$) is the most congested segment. Conversely, Blair Stone Inter TMC segment was estimated to have the least delay per trip ($d_{trip} = 0.03\ min./trip$).



(a) Eastbound



(b) Westbound

Figure 1.4 Average Delay per Trip – TMC segments

(c) <u>Level of Service</u>

Using the 85th percentile operating speed of each segment on the study corridor, the level of service was determined based on HCM thresholds that were shown in Table 1.2. The results of the analysis using the HERE travel time speeds are presented in Table 1.6. The findings from this table indicate that the Macomb St. to Monroe St. segment has the worst level of service (LOS E) in the eastbound direction. On the other hand, the Franklin Blvd. to Monroe St. segment has the worst level of service (LOS D) in the westbound direction. These observations are consistent with those revealed by the PTI metric as discussed earlier.

Table 1.6 Level of service at TMC segment level

Direction	SN	TMC	Segment name	Average speed (mph)	Std. speed (mph)	85th speed (mph)	LOS (based on 85th speed)
Eastbound (p.m. peak period)	1	102+08112	Macomb St. to Monroe St.	12.38	2.8	15.58	E
	2	102+09616	Monroe St. to Franklin Blvd.	21.21	4.48	25.67	C
	3	102P09616	Franklin Inter TMC	21.21	4.48	25.67	C
	4	102+08113	Franklin Blvd. to Magnolia Dr.	22.91	5.35	28.46	C
	5	102+09617	Magnolia Dr. to Blair Stone Rd.	29.53	4.86	34.78	B
	6	102P09617	Blair Stone Inter TMC	29.53	4.86	34.78	B
	7	102+08114	Blair Stone Rd. to Capital Circle	19.38	6.52	27.99	C
	8	102P08114	Capital Circle Inter TMC	19.38	6.52	27.99	C
	9	102+09618	Capital Circle to Dempsey Mayo Rd.	26.93	4.99	32.98	C
	10	102+09619	Dempsey Mayo Rd. to Edenfield Rd.	43.02	3.24	46.38	A
	11	102+09620	Edenfield Rd. to Thornton Rd.	40.69	3.5	44.00	A
	12	102+08115	Thornton Rd. to I-10	38.63	5.38	43.79	A
Westbound (a.m. peak period)	1	102-09620	I-10 to Thornton Rd.	41.5	4.36	46.20	A
	2	102-09619	Thornton Rd. to Edenfield Rd.	42.4	2.67	45.09	A
	3	102-09618	Edenfield Rd. to Dempsey Mayo Rd.	42.11	3.67	45.39	A
	4	102-08114	Dempsey Mayo Rd. to Capital Circle	23.55	5.89	29.38	C
	5	102N08114	Capital Circle Inter TMC	23.55	5.89	29.38	C
	6	102-09617	Capital Circle to Blair Stone Rd.	32.8	4.89	37.56	B
	7	102N09617	Blair Stone Inter TMC	32.8	4.89	37.56	B
	8	102-08113	Blair Stone Rd. to Magnolia Dr.	27.53	5.82	33.77	B
	9	102-09616	Magnolia Dr. to Franklin Blvd.	26.42	4.88	31.49	B
	10	102-08112	Franklin Blvd. to Monroe St.	13.56	4.43	17.77	D
	11	102-09615	Monroe St. to Macomb St.	17.68	3.41	21.00	C

1.4.3 Operational Analysis Using Waze Data

(a) Travel Time Reliability

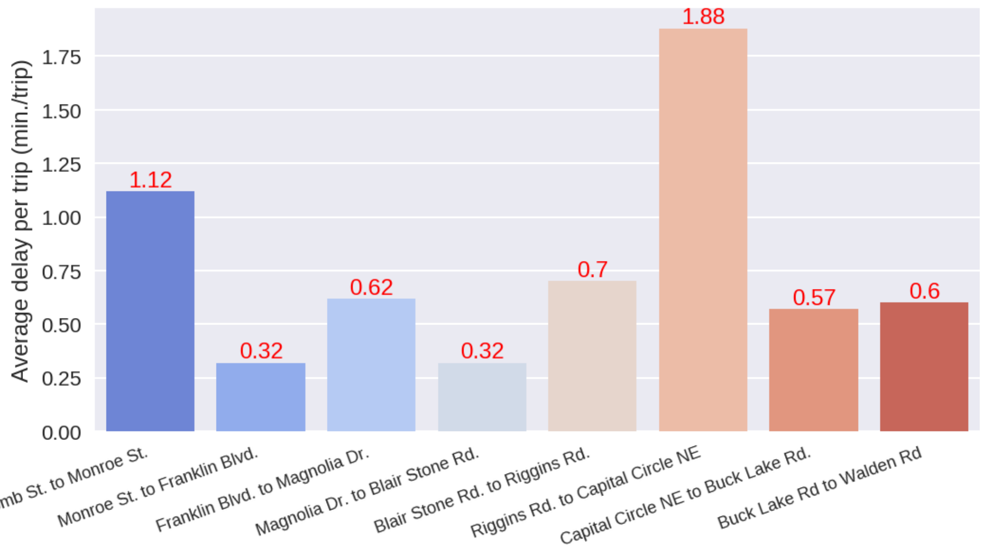
The analysis of Waze data also reveals that segments comprising of major intersections (Monroe and Capital Circle) are the most congested (Table 1.7). In particular, the PTI for the Riggins Rd. to Capital Circle segment is 5.7 while for the Macomb St. to Monroe St. is 4.36 in the eastbound direction. Furthermore, for the westbound direction, the Franklin Blvd. to Monroe St. segment has the highest PTI (3.15) followed by the Buck Lake Rd. to Capital Circle segment with PTI of 2.79.

Table 1.7 Estimated TTR – Waze data

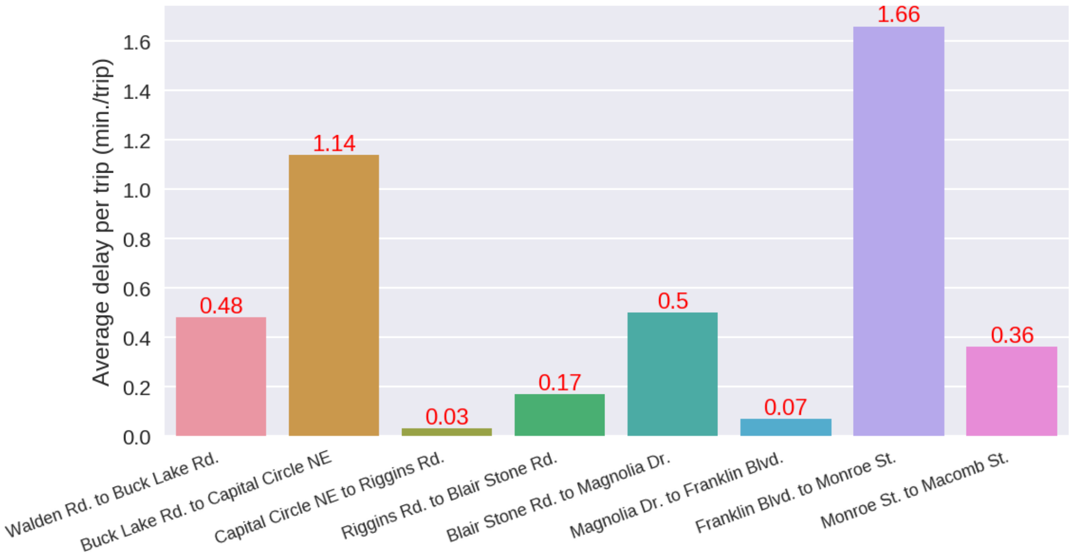
Direction	SN	Segment name	Distance (miles)	PTI
Eastbound – p.m. peak	1	Macomb St. to Monroe St.	0.5	4.36
	2	Monroe St. to Franklin Blvd.	0.5	1.6
	3	Franklin Blvd. to Magnolia Dr.	0.6	2.02
	4	Magnolia Dr. to Blair Stone Rd.	0.9	1.36
	5	Blair Stone Rd. to Riggins Rd.	0.8	3.68
	6	Riggins Rd. to Capital Circle	0.6	5.7
	7	Capital Circle to Buck Lake Rd.	0.8	1.69
	8	Buck Lake Rd to Walden Rd.	3.3	1.18
Westbound – a.m. peak	1	Walden Rd. to Buck Lake Rd.	3.3	1.16
	2	Buck Lake Rd. to Capital Circle	0.8	2.79
	3	Capital Circle to Riggins Rd.	0.6	1.07
	4	Riggins Rd. to Blair Stone Rd.	0.8	1.2
	5	Blair Stone Rd. to Magnolia Dr.	0.9	1.55
	6	Magnolia Dr. to Franklin Blvd.	0.6	1.09
	7	Franklin Blvd. to Monroe St.	0.5	3.15
	8	Monroe St. to Macomb St.	0.5	1.49

(b) Average Delay Analysis

Consistent with TTR results discussed above, the average delays shown in Figure 1.5 reveal that the most delay occurs on the Riggins Rd. to Capital Circle segment ($d_{trip} = 1.88\, min./trip$) followed by the Macomb St. to Monroe St. segment ($d_{trip} = 1.12\, min./trip$) in the eastbound direction. The Franklin Blvd. to Monroe St. segment has the most delay in the westbound direction ($d_{trip} = 1.66\, min./trip$) followed by the Buck Lake Rd. to Capital Circle segment ($d_{trip} = 1.14\, min./trip$).



(a) Eastbound



(b) Westbound

Figure 1.5 Average Delay per Trip – Waze data

(c) Level of Service

The LOS analysis using the Waze data (Table 1.8) shows that the Riggins Rd. to Capital Circle segment has the worst level of service (LOS E) followed by the Macomb St. to Monroe St. segment

(LOS D) in the eastbound direction. For the westbound direction, the Franklin Blvd. to Monroe St. segment has the worst level of service (LOS E) followed by the Buck Lake Rd. to Capital Circle segment (LOS C).

Table 1.8 Level of service – Waze data

Direction	SN	Segment name	85th speed (mph)	LOS (based on 85th speed)
Eastbound - p.m. peak	1	Macomb St. to Monroe St.	18.40	D
	2	Monroe St. to Franklin Blvd.	30	B
	3	Franklin Blvd. to Magnolia Dr.	26.79	C
	4	Magnolia Dr. to Blair Stone Rd.	40	B
	5	Blair Stone Rd. to Riggins Rd.	36.92	B
	6	Riggins Rd. to Capital Circle	18.75	E
	7	Capital Circle to Buck Lake Rd.	32.43	C
	8	Buck Lake Rd to Walden Rd	44	A
Westbound - a.m. peak	1	Walden Rd. to Buck Lake Rd.	45.21	A
	2	Buck Lake Rd. to Capital Circle	25.67	C
	3	Capital Circle to Riggins Rd.	49.32	A
	4	Riggins Rd. to Blair Stone Rd.	42.86	A
	5	Blair Stone Rd. to Magnolia Dr.	35.53	B
	6	Magnolia Dr. to Franklin Blvd.	37.89	A
	7	Franklin Blvd. to Monroe St.	13.04	E
	8	Monroe St. to Macomb St.	25.42	B

1.4.4 Summary of Operational Analysis

Although the three data sources generally revealed slightly different results within the same performance measure, the estimated operational pattern was consistent suggesting that segments intersecting with a major highway (Monroe St. or Capital Circle) perform poorer than other segments. It was also observed that on the average, the Waze traffic data have somewhat higher speed than the BlueTOAD and HERE traffic data for nearly all the segments (Appendix B). In comparing these traffic data, only four HERE links had identical segmentation to those of the BlueTOAD and Waze traffic data (see Appendix B). Furthermore, the analysis of the standard deviation shows the opposite of the average speed findings, suggesting that Waze traffic data have consistently lower standard deviation in all the segments.

1.5 Pre-treatment ATSPM/Connected Vehicle Safety Analysis

A crash analysis was carried out on the study corridor to establish the benchmark for safety characteristics before connected vehicles (CVs) and ATSPM applications are made fully operational. To accomplish this task, a comprehensive literature review was conducted to associate these two applications with type (manner) of collisions that are likely to be mitigated when the applications have been implemented on a larger scale. The discussion in this section starts by analyzing crash topology in the study corridor followed by a qualitative discussion on the potential of ATSPM/CV mitigating the occurrence of crashes in the corridor.

1.5.1 Corridor Crash Topology

There is abundant literature on the likely safety benefits of the implementation of connected vehicle applications (Yanagisawa *et al.*, 2017; Yang *et al.*, 2017; Li *et al.*, 2014; Khazraeian *et al.*, 2017). Once fully implemented, two-way communication through DSRC as envisioned in the

Mahan study corridor will facilitate the transmission of basic safety messages (BSMs) to in-vehicle systems and mobile systems in the hands of pedestrians, bicyclists, and other non-motorized traffic. When the infrastructure knows the location, heading, speed, and path history of a vehicle, a pedestrian, or a bicyclist, the infrastructure can then broadcast the information to all entities (vehicles, peds, cyclists) in the vicinity. The broadcasted data can then be used to increase situational awareness, to determine immediate threats, alert travelers, and allow the evasive action to be taken by drivers, pedestrians, or bicyclists. The basic safety messages can also be used by signal controllers to monitor traffic and optimize signal timing through the online implementation of ATSPM.

The level of safety benefits likely to accrue in the Mahan corridor due to the implementation of CV applications and ATSPM can be assessed qualitatively by analyzing the crash topology in the corridor and predicting the likelihood of crash reduction by type based on the preponderance of literature review. To this end, year 2017 crash data for the corridor were reviewed. The review concentrated mainly on intersection crashes that have the potential of being mitigated by the implementation of CV applications and ATSPM.

Figure 1.6 shows the crash density map in the study corridor. Consistent with the operational analysis discussed earlier, it is clear that the major intersections across the corridor that exhibit high traffic volumes and low levels of service also seem to have a large concentration of crashes. The review of the crash data further shows that 401 (85.1%) were intersection-related crashes while 70 (14.9%) were section related crashes. It is worth noting that intersection-related crashes are defined as crashes occurring within 250 ft. from the center of the intersection in either direction, including intersecting roads.

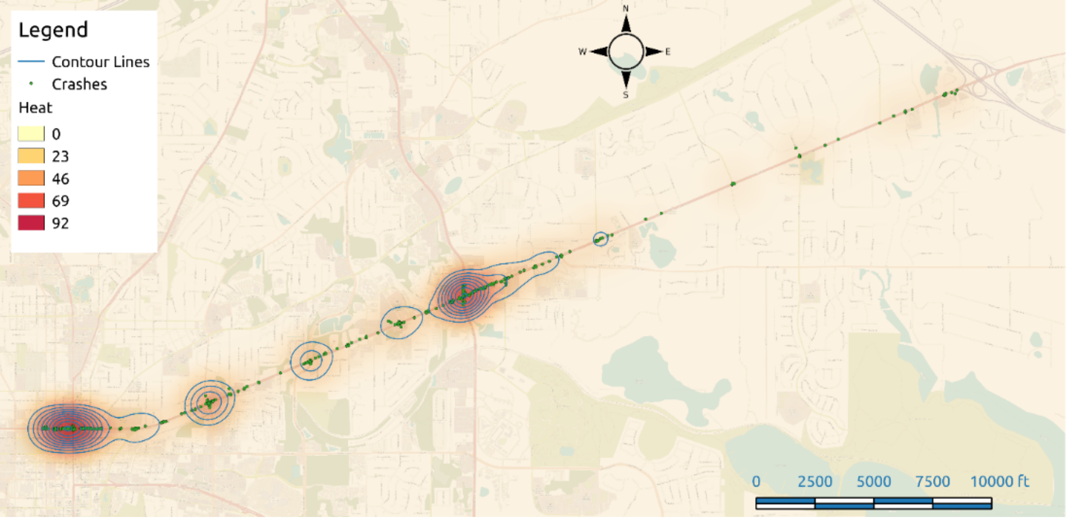


Figure 1.6 Crash Density Map Along the Study Corridor

Further disaggregation of year 2017 crashes occurring in the corridor by crash type is shown in Figure 1.7. As expected, most of the crashes were rear-end (286) followed by sideswipe (77), angle (67), runoff (9) and head on crashes (7). The manner of collision for 55 crashes was categorized in the database as unknown. These crash types were further examined to determine the contributing causes of each crash.

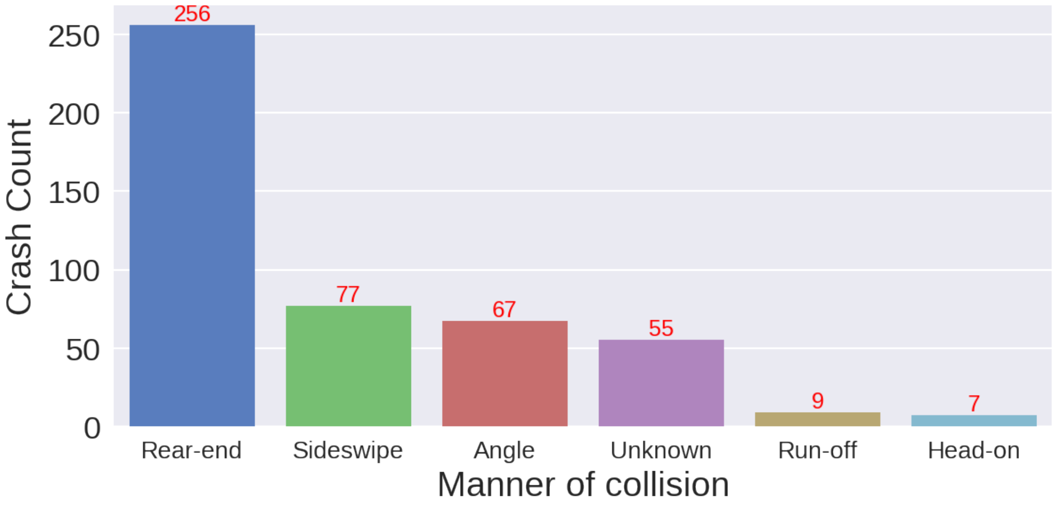


Figure 1.7 Manner of Collision Descriptive Statistics

1.5.2 Crash Contributing Causes

Understanding the contributing circumstances to crash occurrences can lead to a better prediction of the likely effect of CV/ATSPM applications in crash mitigation. Review of crashes in the study corridor revealed four major contributing behavioral factors: careless driving, running a red light, aggressive driving, and driving under influence (DUI) of alcohol or drugs. Careless driving is defined as “driving a vehicle or street car on a highway without due care and attention or without reasonable consideration for other persons using the highway”. Careless driving citation thus captures offenses such as distracted driving, tailgating, driving too fast, and improper lane change.

Another main contributing cause often cited for intersection crashes is “running the red light”. Crashes involving running red light occurs when a driver proceeds through the intersection while a red light (or red turn arrow) is displayed on a traffic signal. According to the National Highway Traffic Safety Administration (NHTSA) aggressive driving occurs when a driver has committed two or more of the following actions: speeding, failure to yield to right-of-way, improper or unsafe lane changes, improper passing, following too closely or the failure to obey traffic signals. Finally, one of the top contributing causes in intersection crashes is driving under the influence. In Florida, driving under the influence (DUI) is defined as “driving or being in actual physical control of a motor vehicle while was under the influence of alcohol or a chemical/controlled substance to the extent that your normal faculties are impaired”.

Table 1.9 shows the types of crashes in the study corridor each contributing cause is responsible for. Careless driving contributed to the most crashes (50) followed by running a red light (27), aggressive driving (13), and DUI (9). It is important to note that more than half of all crashes that occurred in the study corridor did not have information about their contributing behavioral factors in the database. The CV applications are anticipated to significantly reduce these behavioral-related crashes by increasing situation awareness to drivers about the impending crash through the on-board units (OBUs). When these applications are in place, the drivers will get additional time to assess the situation and apply preventive measures to avoid a crash. In the following sections, we discuss the potential of CV/ATSPM in mitigating the predominant intersection crash types similar to those occurring in the Mahan study corridor.

Table 1.9 Contributing causes, crash types, and connected vehicles safety applications

Contributing behavioral causes	**Crash type**	**Total crashes in the study corridor**	**Likely CV/ATSPM applications**
Careless driving	Angle collision	3	• Left Turn Assist • Intersection Movement Assist
	Rear-end collision	44	• Forward Collision Warning • Emergency Electronic Brake Lights • Red Light Violation Warning
	Sideswipe collision	3	• Blind Spot Warning • Lane Change Warning • Red Light Violation Warning
Running the red light	Angle collision	23	• Red Light Violation Warning • Left Turn Assist • Intersection Movement Assist
	Rear-end collision	1	• Forward Collision Warning • Emergency Electronic Brake Lights • Red Light Violation Warning
	Sideswipe collision	2	• Blind Spot Warning • Lane Change Warning • Red Light Violation Warning
	Head on	1	• Red Light Violation Warning
Aggressive driving	Angle collision	9	• Left Turn Assist • Intersection Movement Assist
	Rear-end collision	1	• Forward Collision Warning • Emergency Electronic Brake Lights • Red Light Violation Warning
	Sideswipe collision	4	• Blind Spot Warning • Lane Change Warning • Red Light Violation Warning
Driving under influence (DUI)	Angle collision	2	• Left Turn Assist • Intersection Movement Assist
	Rear-end collision	2	• Forward Collision Warning • Emergency Electronic Brake Lights • Red Light Violation Warning
	Sideswipe collision	2	• Blind Spot Warning • Lane Change Warning
	Runoff road	3	• Lane Departure Warning

1.5.3 Potential of Angle Crashes Mitigation

About 34 percent of all angle crashes that occurred in the study corridor were attributed to a vehicle running a red light (Table 1.9). Based on literature review, the Red Light Violation Warning (RLVW) CV system is designed to purposely to mitigate this type of crashes (Chang, *et al.*, 2015; Hill, 2013). The RLVW application is the vehicle to infrastructure (V2I) system that uses SPaT information, GPS system, and speed of the approaching vehicle to estimate the potential of a vehicle running a red light. Using the DSRC network, the infrastructure sends a message to the vehicle OBU to warn the driver about the potential of running a red light, thus, it helps the driver in taking the necessary action. A nearby vehicle also can be notified of the signal light status via the vehicle to vehicle (V2V) communication system to prevent it from running a red light as well. The RLVW is predicted to reduce the running red light crashes by 235,000 per year, which cost approximately $13.1 billion per year (Eccles *et al.,* 2012).

Furthermore, the Left Turn Assist (LTA) and Intersection Movement Assist (IMS) are CV safety applications that are likely to address angle crashes at intersections. The LTA application warns a driver if there is an approaching vehicle in the opposite direction; thus a driver should not attempt to turn left on “unprotected left turn signal” due to the high probability of a crash to occur. The IMS application sends a message about an imminent situation that could lead to a collision if a driver attempts to enter an intersection. These safety applications are forecasted to reduce the number of angle crashes by 36 percent to 70 percent (Yue *et al.,* 2018).

1.5.4 Potential of Rear-end Crash Mitigation

Table 1.9 showed that 44 rear-end crashes were caused by careless driving, one was due to running a red light, one due to aggressive driving, and two were DUI related. There are several CV safety applications that are envisaged to reduce rear-end crashes, i.e., Emergency Electronic Brake Lights (EBL), Forward Collision Warning (FCW), and RLVW system explained above. The EBL application is a V2V application which sends a message to the vehicle(s) following behind if there is a hard-braking event in front of them. Such information will lead to speed harmonization for vehicles approaching a signalized intersection thus reducing the potential for rear-end crashes. The FCW application is designed to alert a driver about an imminent frontal collision. The literature review shows that about 17 percent to 70 percent rear-end crashes can be reduced if this application was fully operational, depending on the vehicle type, i.e., heavy trucks or light vehicles (Yue *et al.,* 2018). The cited study found that the potential of FCW applications in reducing rear-end crashes was more pronounced for heavy vehicles than light vehicles (passenger cars) (Yue *et al.,* 2018).

1.5.5 Potential of Sideswipe Crashes Mitigation

The literature review revealed that there are two CV safety applications aimed at preventing sideswipe crashes, i.e., Blind Spot Warning and Lane Change Warning. The sideswipe crashes are mainly associated with one vehicle drifting or a changing lane maneuver. In the study corridor, out of 77 sideswipe crashes, only 7 had contributing causes identified. The study by Yue *et al*. suggests that these two CV applications have the potential of reducing this type of crashes by between 28 percent and 70 percent (Yue *et al.,* 2018).

1.5.6 Potential for Pedestrian and Bicycle Crashes Mitigation

The analysis of non-motorized crashes in the corridor involving pedestrians and bicyclists showed that there was one crash involving a bicyclist and two involving pedestrians. Thus, in this corridor, there is the potential of using CV/ATSPM applications to prevent these types of crashes. Although there were no test data to evaluate the effectiveness of the Pedestrian Crash Avoidance/Mitigation (PCAM) System, Yue *et al.* (2018) highlights that this system could potentially reduce pedestrian crashes by 59 percent to 70 percent. The PCAM system is the vehicle-based application that warns the driver about the crash-imminent situation with a pedestrian or bicyclist. A different study (Yanagisawa *et al.*, 2017) argued that PCAM can address approximately 10 percent to 78 percent of vehicle-pedestrian crashes.

Furthermore, the Pedestrian in Signalized Crosswalk Warning (PCW) is another CV safety application responsible for addressing the pedestrian-vehicle crashes. The PCW is the V2I application that uses pedestrian detection and traffic signal information to warn vehicle drivers about the potential conflict with pedestrians at signalized intersections. It is predicted that this application will address about 17,800 crashes per year when fully operational, however, its effectiveness will depend on accurately identifying the position of the pedestrian (Chang *et al.,* 2015). The literature review also revealed that there is the CV safety application designed specifically to assist visually impaired pedestrians in a crosswalk at signalized intersections. This application is called Mobile Accessible Pedestrian Signal system (PED-SIG). The PED-SIG application operates in a portable personal device (e.g., smartphone), which uses GPS system, Street names, DSRC, and SPaT information to inform a pedestrian when to cross the street. It also allows pedestrians to automatically call the traffic signal controller using a smartphone (Liao, 2012; Intelligent Transportation Systems Joint Program Office, 2018; Chang *et al.*, 2015). Although there are no benefit data presented in the literature, this application is predicted to address significantly the pedestrian-vehicle crashes not only for impaired pedestrians but also other non-motorists.

1.6 Conclusions and Recommendations

The objective of this task was to evaluate the pre-ATSPM and connected vehicle (CV) operational and safety characteristics of the study corridor on US 90 in Tallahassee, Florida. A number of data sources were investigated to determine the quality of data and their efficacy in conducting robust operational analysis. Three data sources were subsequently chosen, i.e., HERE, BlueTOAD, and Waze crowdsourced data. Travel time reliability (TTR), level of service (LOS), and the average travel time delay per trip metrics were used to assess the operational characteristics of the study corridor. The safety characteristics of the study corridor were evaluated using year 2017 crash data downloaded from the Signal Four Analytics database.

The results of the analysis from all three performance measures (TTR, LOS, and delay) indicated that segments that intersect with major highways – Monroe St. and Capital Circle – had more constrained operations during the peak hours than other segments in the study corridor. Also, these observations were consistent across the different travel time data sources. The analysis of crash topology in the corridor mirrored the findings of operational analysis in that major intersections (Monroe St. and Capital Circle) had the most crashes due to higher volumes.

Further analysis of crashes occurring in the corridor was conducted to determine contributing causes and crash types amenable to mitigation by the implementation of ATSPM and CV applications in the corridor. Consistent with the results of the previous studies, careless driving, red light running, aggressive driving, and DUI were frequently cited as the major contributing causes of crashes occurring in this corridor. Similarly, rear-end, angle, and sideswipe were the most frequently occurring crash types in the corridor. The implementation of dedicated short-range communication (DSRC) in the study corridor to enable V2I connectivity is expected to allow for the transmission of basic safety messages (BSM) and dynamic improvements in ATSPM. A number of CV safety applications were reviewed to determine their potential for mitigating the above mentioned crash types as well as crashes involving pedestrians and bicyclists. Thus, the baseline pre-ATSPM/CV operational and safety data can be compared with future results following partial or full deployment of ATSPM/CV applications.

Despite the best efforts put into creating baseline conditions of operational and safety characteristics in the study corridor, there will be some challenges in conducting comparative analysis of before-and-after conditions following the implementation of ATSPM/CV applications in the corridor. One of the challenges is due to the expected incremental implementation of ATSPM/CV systems. Thus, it might take many years to get sufficient market penetration of vehicles equipped with systems enabling V2I communication, particularly through DSRC. Another challenge is the fact that pre-ATSPM/CV safety analysis relied on aggregated crash data from the Signal Four Analytics database. This database currently does not have attributes related to automated or connected vehicles systems installed in the vehicles. Unless in the future such data are captured, it will be difficult to compare crashes involving automated/connected vehicles and those involving legacy vehicles. Similarly, future ATSPM systems will evolve into systems that are integrated with automated/connected (A/C) vehicles systems in a manner that A/C vehicles will act as probes supplying information to ATSPM systems for the purpose of optimizing signal timing. Quantification of operational and safety benefits of such ATSPM and A/C integration for the purpose of before-and-after analysis will pose a challenge. It is thus recommended that these issues should be carefully thought of and researched in the next phase of this project.

TASK 2: EVALUATION OF DATA QUALITY

2.1 Purpose and Scope

Following the successful conclusion of Task 1 of this project, which was aimed at conducting quantitative and qualitative assessment of operations and safety characteristics along the corridor prior to implementing ATSPM and connected vehicle systems in the corridor, the research team embarked on the implementation of Task 2. As narrated in the scope of services, the objectives of Task 2 were:

- to evaluate the effectiveness of Dedicated Short-Range Communication (DSRC) system in communicating with Onboard Units (OBUs) at the study intersections along the corridor,
- to explore two-way communications with the test devices to receive data at the City of Tallahassee Advanced Traffic Management Center (TATMS), perform Automated Traffic Signal Performance Measure (ATSPM) system test and identify enhancements/develop dashboard concepts as it relates to the V2I and ATSPM data,
- to identify how V2I and SPaT/MAP data can be collected and disseminated to/from cloud using City's central system software for the third party use, and
- to evaluate security credential management system (SCMS) in providing security and privacy when information is exchanged between RSUs and OBUs.

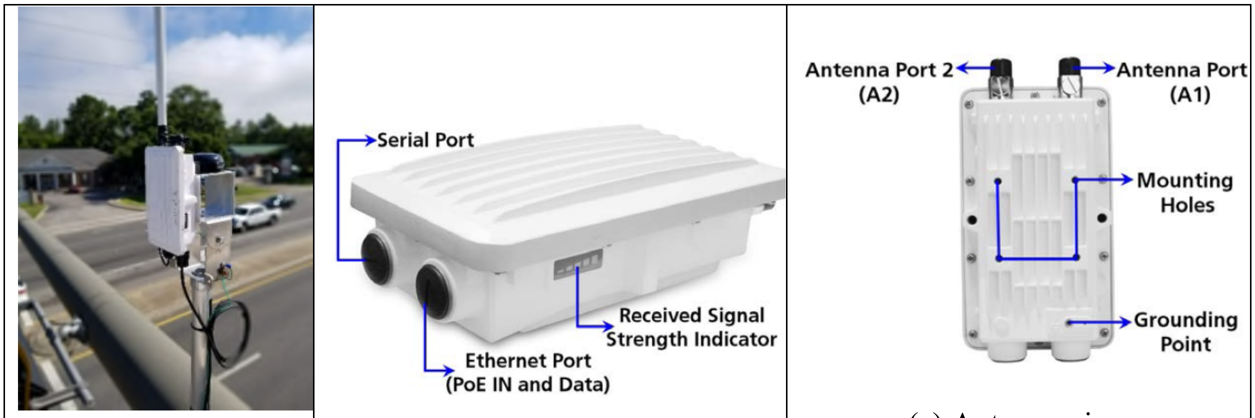
2.2 Evaluation of Major DSRC Communication Elements

The broadcast of SPaT and MAP data requires communication between the infrastructure, in this case a signal controller, and the onboard units (OBUs). The roadside units (RSUs) provide an interface or connection to the signal controller where the SPaT data is generated and stored. In the study corridor, the RSUs are connected to the traffic signal controller through a CAT 5 Ethernet cable. This cable supplies power and data to the RSUs. Thus, the major communication elements in this corridor are the RSUs, the radio, and the onboard units. The following sections discuss the performance of these elements in the corridor during the evaluation period.

2.2.1 DSRC Roadside Units (RSUs)

RSUs that are installed in the study corridor provide wireless communication, which is based on the Dedicated Short Range Communications (DSRC). These devices are capable of broadcasting SPaT, Traveler Information Messages (TIM), and MAP data from the infrastructure to the OBUs but are currently configured to broadcast SPaT/MAP data only. In addition, the system is currently configured for one-way communication only (i.e., RSU to OBU) but two-way communication has to be enabled if the Basic Safety Messages (BSMs) are to be transmitted from OBUs to the RSUs. Due to topography layout issues that were found to affect the line of sight (connectivity) of RSUs and OBUs in the study corridor, some of the intersections operate with two RSUs. As a result, 31 RSUs were installed on this corridor, which has 22 signalized intersections. The DSRC RSUs in this corridor are integrated with a backhaul system to enable distant management. Features of an RSU include an antenna system and a networkable computer. In this corridor, all RSUs are installed on traffic signal mast arms.

Figure 2.1 shows the hardware installed on the Mahan Corridor. This hardware was provided by Wave Mobile Solutions Company. The device is comprised of an auto-sensing 10/100/1000 BASE-T Ethernet port with configurable Tx modes and speeds which allows the user to connect to the LAN using Cat5e/Cat6 Ethernet cable, and also power ON the device using the Power over Ethernet (PoE) injector supplied with the product package. The device also comes with a Serial Port, which can be used for debugging and management as well as GPS Sync. The serial connection is established with an RJ11 to DB9 connector (also referred to as a “dongle”) by connecting the RJ11 end of the dongle connector to the device and the other end to a personal computer.



(a) Field view (b) Port view (c) Antenna view

Figure 2.1 Roadside Units on Mahan Corridor

The device also has antenna ports A1 and A2 for connecting to external antenna(s). These antenna connectors are of N-Type female with built-in surge protection. To protect the device against lighting or ESD events, the device must be grounded properly. The manufacturer’s user guide further indicated that to ensure proper grounding, either of the ground points that are situated at the bottom corner of the device and the grounding screw (M4 thread size) provided to attach a ground wire of at least 12 AWG stranded to the device must be used.

The review of performance of the RSUs over the evaluation period showed that they were performing fairly reliably in terms of hardware robustness and communication with the Traffic Management Center. However, there were some RSU breakdowns that could be expected from first generation products. The breakdowns had a significant effect on the research undertaking. In the following sections, the performance issues of concern are discussed with the purpose of highlighting areas that corrective measures were taken and documenting lessons learned for future deployments. The lessons learned will be further discussed in Section 2.9.

2.2.2 Hardware Performance

The review of data provided by the City showed that only 3 RSUs installed in the corridor, a total of 31 RSUs experienced failure of one sort or another and at different times. As shown in Figure 2.1c above, the RSU supplied by Wave Mobile Solutions has two ports pointing upwards on which antennas are supposed to be screwed upon. The major problem that was discovered earlier on was that the connection between the antenna and the radio system was not sufficiently protected against moisture intrusion which resulted in the shorting of the RSU’s circuit boards. The manufacturer has since corrected the problem in two ways:

- changing the design of the antenna to improve encapsulation, and
- using Permatex Dielectric Grease to seal the antenna port.

The Site Visit Report prepared by Wave Mobile Solutions, which is attached as Appendix A, further discusses hardware and software corrective actions that were undertaken. Figure 2.2 shows the difference between the original design and the improved design of the antenna. These efforts were successful in reducing the RSUs failure rate.

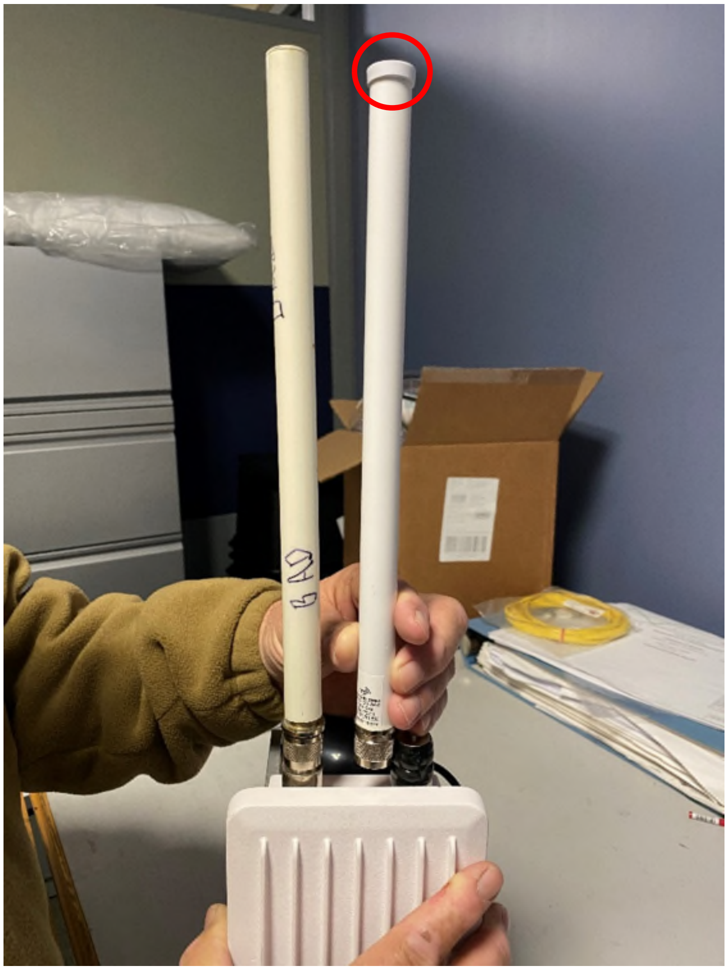


Figure 2.2 Antenna Design Changes Made by the Vendor

2.2.3 Communication Performance

Communication between the RSUs and the central office is important to enable status monitoring, remote management, and updating. The upgrading of software in the RSUs was needed to improve communication between the RSUs and the controllers. After Hurricane Michael, which hit Tallahassee in October 2018, it was reported that the Traffic Management Center could not communicate with all RSUs in the field for an extended period of time. The problem was solved six months later when the RSU vendor visited Tallahassee to upgrade the radios to the latest version of firmware.

2.2.4 Onboard Units (OBUs)

An On-Board Unit (OBU) is a hardware device mounted on the vehicle. The main purpose of OBU is to communicate with RSUs and other OBUs. The OBUs being used in this project were supplied by the Control Technologies Company. Five OBUs have been acquired so far for use in the study corridor. One OBU was provided to the research team by the Florida Department of Transportation. One more OBU was purchased by the Florida State University from Control Technologies Company. The architecture and key components of the onboard unit are:

a. *Radio antenna* – to access the wireless channel in order to communicate with RSUs and other OBUs.
b. *GPS antenna* – to obtain location information, which is useful for several operations including MAP data geolocation, speed, etc.
c. Processor - raspberry PI
d. Wi-fi modem
e. Display unit

The OBUs, designed to be vehicle-mounted, supplied for this project are configured as shown in Figure 2.3. The supplied OBU has a module, an antenna box, low-loss cabling connecting antenna to the main unit, tablet, and a bracket mount with suction cup to hold the tablet on the vehicle's windshield.

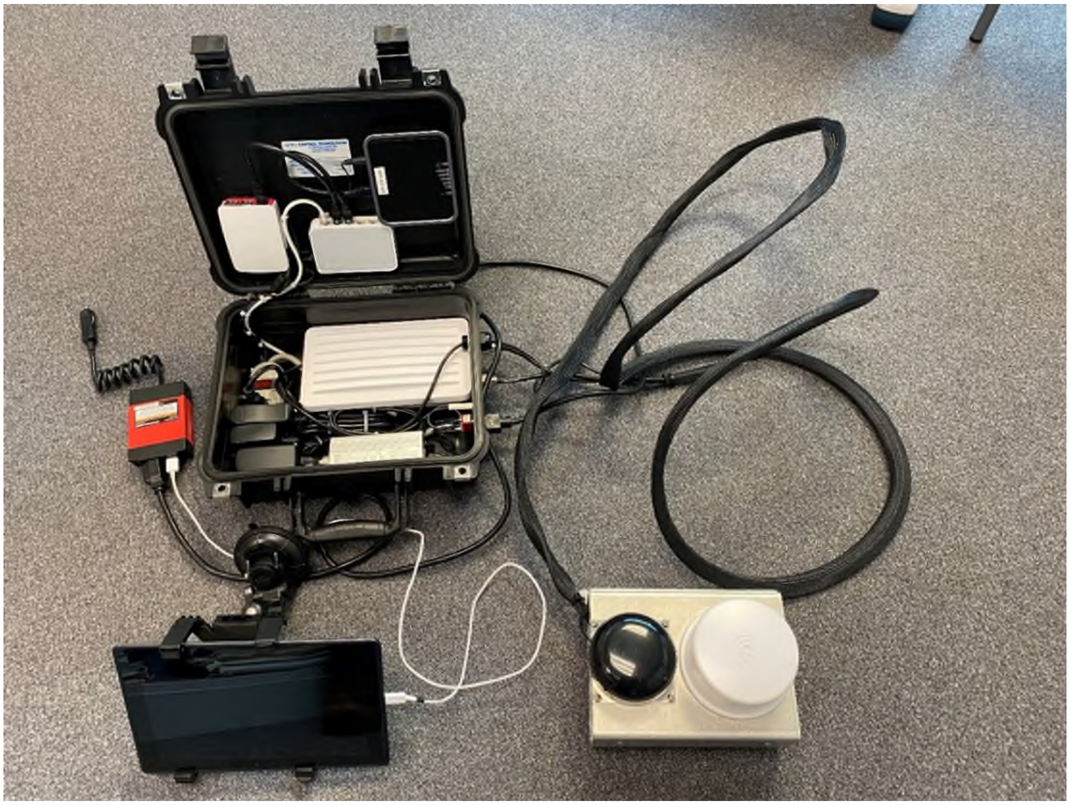


Figure 2.3 Components of Project OBU

The two OBUs acquired and used for this project both experienced breakdowns at different times and on different components. A number of failures were observed in individual components of the OBU including loose connection, broken mount, and damaged circuit board. Malfunctioning OBUs were sent to Orlando for repairs. One of the lessons learned with acquisition and repair of OBUs is that there was a considerable production time and repair turnaround time. For example, there was a 5-month delay in the delivery of OBU ordered by FSU and some OBUs sent for repairs took over a month to get back.

2.2.5 Radio Communication

For the past two decades, the 5.9 GHz band (5.850-5.925 GHz) has been reserved for use by Dedicated Short Range Communications (DSRC), a service in the Intelligent Transportation System (ITS) designed to enable vehicle-related communications. This is a short to medium range communication service restricted for use in the outdoor environment only. The 5.9 GHz band and its channel for DSRC is presented in Figure 2.4. From this figure, the SPaT infrastructure system broadcast SPaT, MAP, and RTCM messages using Channel 172 of the DSRC spectrum.

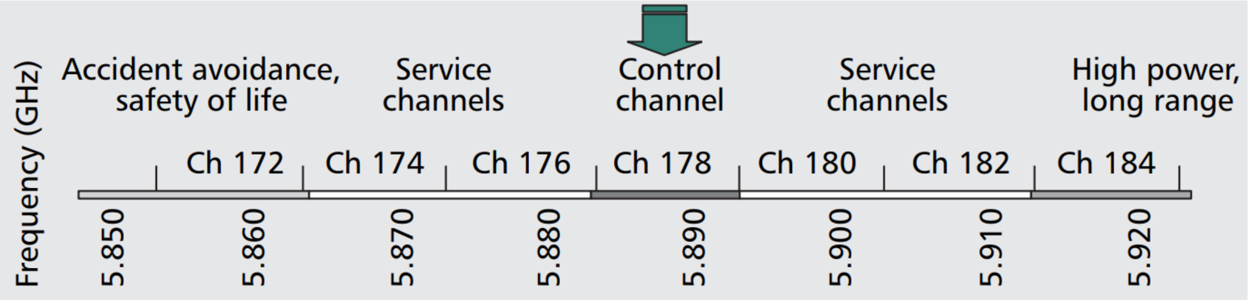


Figure 2.4 DSRC Channels

The radio communication between RSU and OBU has to be highly reliable with low latency if the benefits of connectivity for mobility and safety applications are to be realized. Many factors affect DSRC radio communication including antenna placement, altitude, line of sight blockage, etc. One of the major objectives of Task 2 of this project was to analyze DSRC performance in this corridor in terms of transmission range, transmission delay (latency), fading transmission channel, message arrival in different traffic environment, omnidirectionality of the transmission, and the effect of vehicle body and antenna placement on DSRC performance.

At the beginning of the project, the project team was provided with a Multi-Channel Test Tool (MCTT) for use in evaluating some aspects of DSRC communication as narrated in the above paragraph. The test tool is designed to verify that a DSRC RSU transmitter is sending the correct information to the OBUs. In a nutshell, the MCTT is in itself an OBU emulator which can be configured to perform various research tasks. To this end, technical support was requested from the vendor to reprogram the MCTT for acquisition of the requisite data. The vendor could not provide the technical support because of the amount of technical work involved. The research team sought alternative support through FDOT consultants but it become clear that the original equipment vendor has to be involved.

In the future, installation and deployment agreements should proactively require the DSRC RSU vendor to test their DSRC radio transmission range and other transmission-related parameters that are likely to affect CV applications. In the meantime, the research team creatively used a cellular phone and OBU to test signal reach upstream of an intersection as discussed in the following section.

2.3 Operational Evaluation of SPaT/MAP Broadcasting

In lieu of using the multi-channel test tool (MCTT) to conduct DSRC signal strength studies, the research team devised creative ways of evaluating the efficacy of SPaT/MAP broadcasting through the DSRC system installed in the corridor. The operational evaluation that was conducted involved determining the DSRC signal strength and signal reach, display of information to the driver, and vehicle positional accuracy on the static map displayed on the screen. The following subsections describe in detail the results of the operational evaluation.

2.3.1 Signal Strength and Signal Reach

Ideally, as discussed earlier, the use of MCTT for sniffing RSU broadcast at each intersection would have been the better method of determining the relationship between signal strength and approach or departure distances. For reasons explained in Section 2.3 above, the research team was not able to use the provided MCTT. Thus, the research team decided to analyze the upstream distance at which the SPaT data first appeared on the screen. This was achieved by the use of OBU display, smart phone, and video camera. The video camera was set in the back seat of the test vehicle and focused on the OBU display to record the time at which the SPaT information first appeared on the OBU display. An app in the smartphone was used to collect GPS coordinates and time stamps of events during travel runs.

Currently in the study corridor, the RSUs are configured to broadcast Intersection ID rather than the intersection name. It was important to correlate Intersection ID to the Intersection Name, particularly for closely spaced RSUs in the downtown area because there were overlaps of SPaT information; that is, in some cases, the SPaT data displayed were for one or two downstream intersections. To identify the local names of the 22 intersections in the SPaT corridor, the City of Tallahassee MAP data were requested. The data were provided in GEOJSON format, which could only be opened in the MAP creator software developed by the U.S. Department of Transportation (USDOT). To simplify the process of extracting the intersection names and their corresponding SPaT intersection IDs, an algorithm was written in the *Python* software to extract relevant parameters and store them in a *.csv* file. Table 2.1 shows the intersection names and their corresponding Intersection IDs extracted from MAP data.

Table 2.1 Intersection IDs and the Corresponding Intersection Names

Intersection Code	Intersecting Street	SPaT Intersection ID	GPS Coordinates
MAHN-WALD	Walden Road	4778	30.483538, -84.163150
MAHN-VNLD	Vineland Drive	32883	30.481505, -84.168531
MAHN-PDRK	Pedrick Road	16464	30.476408, -84.182710

Table 2.1, continued

EDFD-MAHN	**Edenfield Road**	**28292**	**30.473154, -84.191717**
MAHN-DEMP	Dempsey Mayo Road	39846	30.466525, -84.210140
BUCK-MAHN	Buck Lake Road	22326	30.464814, -84.214896
MAHN-LAGN	Lagniappe Way		30.463561, -84.218301
MAHN-WEEM	Weems Road	7267	30.462087, -84.222457
MAHN-PUBX	Automotive Way	29718	30.461160, -84.225040
CCNE-MAHN	Capital Circle Road	27711	30.460079, -84.227990
MAHN-RIGG	Riggins Road	40723	30.456949, -84.236682
HILO-MAHN	Hi Lo Way	17545	30.454474, -84.243526
BLAR-MAHN	Blair Stone Road	12387	30.452634, -84.248665
MAGN-MAHN	Magnolia Drive	1675	30.447627, -84.262459
HILL-MAHN	Hillcrest Street	24759	30.445359, -84.268767
FRNK-TENN	Franklin Boulevard	5433	30.444708, -84.272188
MRDN-TENN	Meridian Street	33464	30.444696, -84.277041
GADS-TENN	Gadsden Street	39278	30.444711, -84.278325
CALH-TENN	Calhoun Street	47501	30.444721, -84.279587
MNRO-TENN	Monroe Street	43488	30.444710, -84.280678
ADAM-TENN	Adam Street	19288	30.444704, -84.282002
DUVL-TENN	Duval Street	12349	30.444694, -84.283084

After data extraction, matching, and reduction, several graphical displays were prepared and analyzed. Figure 2.4 shows the distance at which SPaT data first appeared on the screen when driving east (Trip No. 1) and when driving west (Trip No. 2).

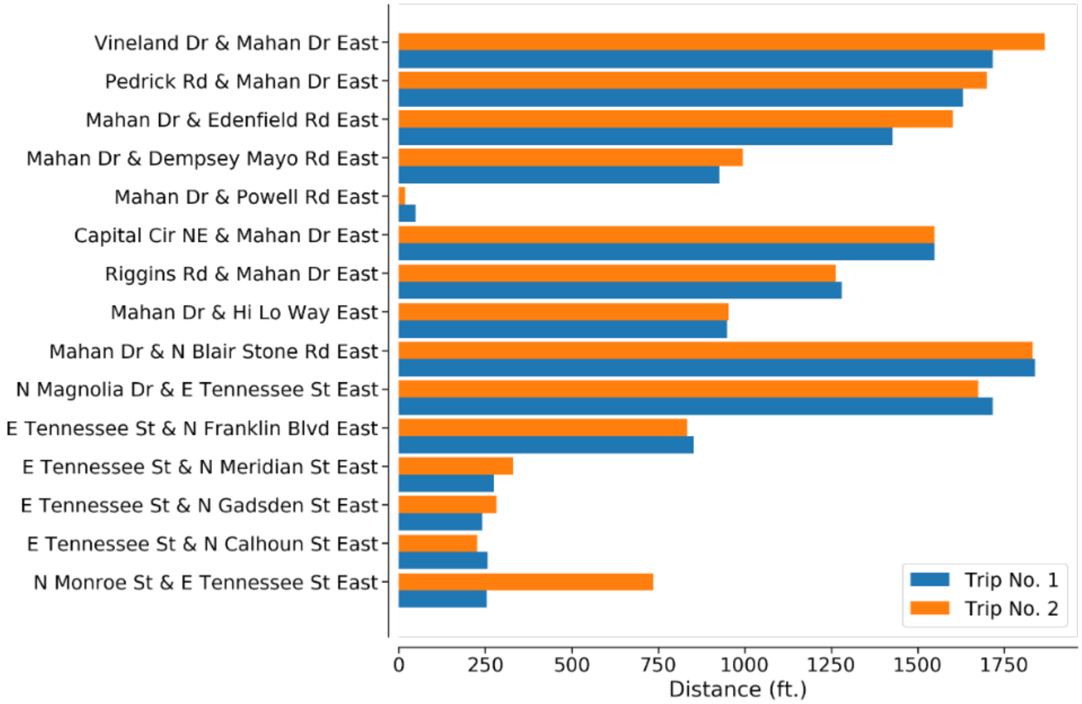


Figure 2.5 Upstream Distance of First SPaT Data Display

The results in Figure 2.5 show that on the average SPaT data is first picked up around 1,000 feet from the center of the upcoming intersection. While some intersections exhibited pick-up distances of more than 1,750 feet, other intersections, particularly the closely-spaced intersections in the downtown area exhibited pick-up distances of less than 300 feet. These results may have both positive and negative implications if Basic Safety Messages (BSMs) were to be collected for the purposes of queue detection and speed harmonization.

2.3.2 Display of SPaT Information

Numerous runs were conducted in the study corridor to assess how SPaT information is configured for display to the driver. The following section describes the type of information displayed and how it is displayed. Subsequent to this section, the results of the trials runs are comprehensively discussed.

Description of Information Displayed

Figure 2.6 shows how the display screen is configured. On the left side of the screen, the Intersection ID number is displayed on top. The Intersection ID number represents the intersection whose signal status is being relayed to the driver. Again, as mentioned earlier, there were cases in which the Intersection ID was not of the immediate downstream intersection but that of one further downstream. The display also shows a green arrow pointing upward which changes to yellow and red depending on the signal phase status. The arrow shown is for through lane but left turn arrow and right turn arrow are also displayed depending on which approach lane the vehicle is in.

Figure 2.6 Display of SPaT Information on the Screen

Below the arrow are three values. The left value is supposed to be the minimum green time left. The middle value is the average while the right value is the maximum value. In the last row on the left, there are three speed values in miles per hour. The speed highlighted in yellow is supposed to be progression speed suggested by the device. The middle speed value is the vehicle speed as calculated through GPS coordinates. The speed on the right is supposed to be the prevailing speed limit in the section.

Discussion of the Results of Trial Runs

The following sections narrate the observations made after numerous trial runs were conducted in the corridor. The discussion is sectionalized by the type of information displayed.

Intersection ID

As indicated earlier, the display of the Intersection ID instead of the actual intersection name initially made it difficult to know which intersection SPaT data was being displayed. It was initially assumed that the data was that of the immediate downstream intersection. The research team later discovered that that was not necessarily the case as, particularly in the closely spaced intersections; the Intersection ID was of one or two downstream intersections. Although the display of signal status of an intersection, which is not the immediate downstream intersection, is confusing and might be difficult to address at this juncture, a design change to at least display the name of the intersection would help reduce the confusion.

Display Arrow

There were three types of arrows displayed, i.e., left turn, through, and right turn. It was observed that right turn arrow was sometimes being displayed even on approaches that do not have a dedicated right turn lane. On approaches with two through lanes, driving on the outside lane very close to the edge would trigger a right turn arrow being displayed while driving in the inside lane very close to the left turn lane sometimes resulted in the left turn arrow being displayed. There were numerous incidents in which the displayed arrow alternated between left turn arrow and through arrow while stopped close to the stop bar waiting for the green light.

Min, Avg, Max Countdown

The display of signal status countdown is probably the primary purpose of SPaT messaging. The phase countdown can be implemented numerically or symbolically. Also, the countdown can be limited to start when the phase is within 10 seconds of termination or the entire duration of the phase can be counted down. In this project, the OBU vendor adopted numerical countdown for the entire duration of the phase and to display the minimum, average, and the maximum values of that phase. It was not clear to the researchers what the minimum, average, maximum values represented as in some instances the values were the same as was seen in Figure 2.6 above. It was also observed that while driving close to the intersection or when stopped at an intersection, the countdown values were jumping up and down. For instance, the display might show 75 seconds of red then jump down to 15 seconds before jumping back up to, say 45 seconds.

The jumping up and down of the countdown might be a manifestation of fixed traffic control versus adaptive traffic control. Fixed time signal control give a preset green time to each movement in the intersection. This makes it is easy to predict the signal state for SPaT application. On the other hand, an adaptive signal control based on detection of approaching vehicles can alter the green time for each movement either within a fixed cycle length or with a changing cycle length. Hence, dependent on the traffic signal management philosophy, the SPAT information will be definitive with fixed time systems but only indicative with adaptive systems as is the case with most Mahan corridor signalized intersections.

Advised Speed

According to the OBU vendor, the advised speed is supposed to replicate the MUTCD's Traffic Signal Speed Sign. The MUTCD says a sign reading "SIGNALS SET FOR XX MPH" may be used to indicate a section of street or highway on which the traffic control signals are coordinated into a progressive system timed for a specified speed at all hours during which they are operated in a coordinated mode. During the runs conducted on Mahan corridor it was observed that the advised speed changes with the change of vehicle speed. Sometimes the advised speed was lower than the vehicle speed and sometimes it was higher than the vehicle speed.

Vehicle Speed

The vehicle speed is calculated using the GPS coordinates and time lapse. The check of the displayed vehicle speed against the vehicle's own speedometer and a speed app in a smart phone showed that the difference was just within 1 mph. Thus, the displayed vehicle speed reflects the actual vehicle speed.

Speed Limit

The speed limit of 45 MPH is a static value that does not change regardless of the roadway section a vehicle is in. It should be noted that while the majority of the outlying sections in this corridor have 45 MPH speed limit, there are many other sections in the downtown area whose speed limit is 35 MPH as seen in Table 2.2. It is recommended that the displayed speed limit should change according to the prevailing speed limit in the section prior to driver observational studies slated to be conducted under Task 3 of this project.

Table 2.2 Speed Limit in the Study Corridor.

SN	Intersection	Number of through lanes	Number of left turn lanes	Number of right turn lanes	Posted speed limit (mph)
1	Tennessee St. & Duval St.	3	1	0	35
2	Tennessee St. & Adam St.	3	1	0	35
3	Tennessee St. & Monroe St.	2	1	0	35
4	Tennessee St. & Calhoun St.	2	1	0	35
5	Tennessee St. & Gadsden St.	2	1	0	35
6	Tennessee St. & Meridian St.	2	1	0	35
7	Tennessee St. & Franklin Blvd.	2	2	1	35
8	Tennessee St. & Hillcrest St.	2	1	0	35
9	Tennessee St. & Magnolia Dr.	2	2	1	45
10	Mahan Dr. & Blair Stone Rd.	2	2	1	45
11	Mahan Dr. & Hi Lo Way	2	1	0	45
12	Mahan Dr. & Riggins Rd.	2	1	0	45
13	Mahan Dr .& Capital Circle	2	2	1	45
14	Mahan Dr. & Automotive way	3	1	0	45
15	Mahan Dr. & Weems Rd.	3	1	0	45
16	Mahan Dr. & Lagniapple Way	3	1	0	45
17	Mahan Dr. & Buck Lake Rd.	3	1	2	45
18	Mahan Dr. & Dempsey Mayo Rd.	2	1	1	45

Table 2.2, continued

19	**Mahan Dr. & Edenfield Road**	**2**	**1**	**1**	**45**
20	Mahan Dr. & Champagne/Pedrick Rd.	2	1	1	45
21	Mahan Dr. & Vineland Dr.	2	1	1	45
22	Mahan Dr. & Walden Rd.	2	1	0	45

2.3.3 Positional Accuracy

In addition to determining how SPaT information is displayed as discussed in Section 3.2 above, positional accuracy of the vehicle displayed on the screen was also analyzed. Vehicle display utilizes MAP data, i.e., roadway geometric description, broadcasted by the RSUs. Unlike SPaT data, which originates from the traffic signal controller, the MAP data resides in the RSU. The MAP message is not created in real-time, but rather is a static description of the geometries of the intersection and vectors describing approaches. The vehicle systems will compare GPS location readings on the vehicle against the MAP message and determine the vehicle's approach lane. The MAP data were created using a graphical user interface (GUI) tool developed by the US Department of Transportation (USDOT), namely J2735 MAP Creator tool. This is an open-source, web-based platform available at https://webapp2.connectedvcs.com/.

The tool has three main components: ISD Message Creator (Intersection MAP and SPaT), Message Validator (for SDC/SDW messages), and TIM Message Creator (Traveler Information). These tools are designed to create and validate SPAT and MAP messages that are set to follow the SAE J2735-2016 standards. The following bullets describe these three main components:

- ISD Message Creator (Intersection MAP and SPaT): This tool is used to create MAP data by drawing lanes, approaches, and adding other data such as lane groups and connections between lanes using a graphical interface. Figure 2.7 shows this interface for Mahan Dr. and Dempsey Mayo Rd. intersection. Once the map is created, the user can encode an ISD, MAP, or SPaT message as an Abstract Syntax Notation (ASN.1) UPER Hex string.
- Message Validator (for SDC/SDW messages): This tool is used to check versions of messages for accuracy against the specifications and standards prior to depositing into a warehouse.
- TIM Message Creator (Traveler Information): This tool allows users to build traveler information messages regarding sign and work zone details using a graphical interface. Once designed, the user can encode a TIM message as an ASN.1 UPER Hex string and deposit it to the SDW warehouse.

Figure 2.7 MAP data creation for Mahan Dr. @ Dempsey Mayo Rd Intersection

Field evaluation of vehicle positional accuracy on the screen was conducted through numerous test runs on the corridor. As seen in Figure 2.8, as the vehicle moves the vehicle symbol is superimposed on Google static maps resident in the OBU. The vehicle lane position on the Google map is supposed to match the vehicle position in the approach lanes shown on the left side of the screen. However, as can be seen in this illustrative case, both displays miss the mark. This phenomenon frequently resulted in display of traffic signal status of an adjacent lane, i.e., the vehicle might be in the through lane but the signal status displayed is for the left lane.

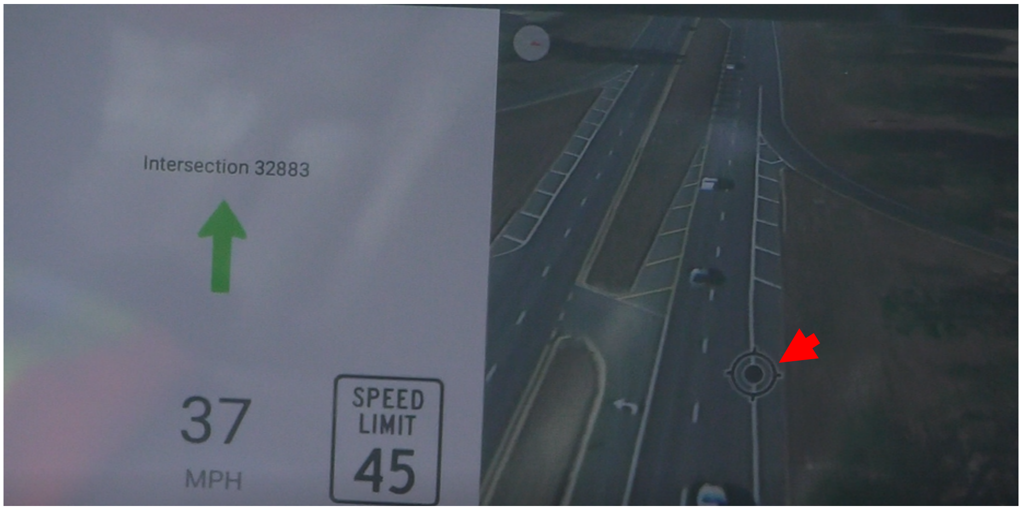


Figure 2.8 Vehicle Display on the Screen

It has long been recognized that continuous, reliable, and accurate vehicle positioning at intersections can only be achieved by broadcasting of GPS corrections via the DSRC RSUs. Currently in this corridor, GPS corrections data are not broadcast by the RSUs. Thus, the inaccurate positioning of vehicles in this corridor is the manifestation of lack of correct GPS data therefore this location accuracy problem is likely to continue until such time that the correction data is provided to the OBUs. In addition, the MAP data currently resident in the RSUs may require refinement as well.

2.4 Exploration of Two-way Communication

As discussed in Section 3, the benefits of the implementation of the connected vehicles program can be realized only when basic safety messages (BSMs) are collected from the vehicles and used to build BSM applications for the purpose of improving safety and operations. The V2I and V2V information exchange will allow for 360^0 awareness of the position of other road users (vehicles, pedestrians, bicyclists, etc.) as well as the threat or hazard posed, calculate risk, issue driver advisories or warnings, and take pre-emptive actions to avoid and mitigate crashes.

The SAE J2735 identifies high-priority data elements to be collected from vehicles as timestamp, position (lat/long/elev), speed and heading, acceleration, brake system status, and vehicle size. The collection of these vehicular data coupled with the collection of non-motorized data (e.g., bike-ped) would lead to the building of BSM safety applications, mobility applications and environmental/weather applications. The most touted BSM safety applications include speed harmonization, end of queue warning, incident/work zone/school zone warning, blind spot warning, curve speed warning, forward collision warning, transit signal priority, and red light violation warning.

As discussed in Section 3, the RSUs in the Mahan SPaT corridor are broadcasting SPaT/MAP data to OBUs but are not yet configured to receive the BSM data narrated above. With the requirement that the BSM data should be transmitted to the RSUs on Mahan corridor approximately 10 times per second and should be tailored for low latency, the major issue that arose was where should the data be stored. The Principal Investigator explored a couple of alternatives with the city and FDOT regarding BSM data storage. A server would be needed for data storage. The first alternative explored was to install a server at one of the intersections and establish a two-way communication with the local RSU. A second alternative explored was to install the server at the City of Tallahassee Advanced Traffic Management Center (TATMS) and establish two-way communication between the field RSUs and the server through the backhaul (i.e., fiber-optic system) that exists in the corridor.

Considering the fact that both alternatives would involve online testing of the system, it was suggested that the two-way communication can first be experimented with offline utilizing the connected vehicle set-up at the FDOT Traffic Engineering Research Laboratory (TERL) located on Springhill Road. A server would be purchased and installed in the lab and connected to the two RSUs that are installed in the test track.

2.5 Preliminary Evaluation of ATSPM/CV Data Fusion

As mentioned in Section 1 – Purpose and Scope, Task 2 was also aimed at performing Automated Traffic Signal Performance Measure (ATSPM) system test, identifying enhancements, and developing dashboard concepts as they relate to the V2I and ATSPM data, The City of Tallahassee has implemented ATSPM since 2017, and now, the monitoring extends to over 350 signalized intersections within the Mahan SPaT corridor and beyond. ATSPM provides, among other functions, continuous monitoring of vehicles, bikes and pedestrians entering an intersection. The ATSPM can also be configured to provide real-time and historical data of vehicle delay, volume, speed, and travel time. While the city can use ATSPM to evaluate existing signal infrastructure on a regular basis and to proactively manage the maintenance of signal assets, the main benefits may accrue if ATSPM is extended to support other emerging technologies such as SPaT data broadcasting, future V2I applications, and connected vehicle applications.

Initial work conducted by the research team at the City offices involved reviewing the ATSPM system to determine what types of data are collected and how they are collected. The ATSPM database contained, among others, the following important data:

- approach volume at each intersection measured using upstream detectors,
- number of vehicles arriving at an intersection during a given phase interval (green/yellow/red),
- occupancy ratio which provides the percentage of phase cycle time a stop bar detector is actuated during the red and green intervals,
- simple delay which is the time between detector actuation during the red phase and when the phase turns green,

- pedestrian delay which is the time between pedestrian detector actuation (push button or detector) during the Don't Walk phase and when the phase turns to Walk, and
- split failures in a phase due to max-outs and force-offs.

With the help of the City, a research assistant working in the project was able to download and analyze some of the data above for the purposes of creating visualization tools. At the time of writing this report, the City has entered a contract with a private vendor to work on their ATSPM system. It is anticipated that the data and other necessary tools will be made available to the research team in the coming months.

2.6 Evaluation of Cloud-based Data Communication

One of the tasks that was to be undertaken in this project is to identify how V2I and SPaT/MAP data can be collected and disseminated to/from cloud using City's central system software for the third party use. The implementation of connected vehicle applications makes the transportation system a cyber-physical system in nature requiring continuous and area wide collection and dissemination of data. This can only be achieved through cloud-based strategies that go beyond localized information exchange between vehicles and RSUs installed at intersections. The SPaT/MAP broadcasting through RSUs has the advantage of localizing and targeting a geofenced area but leaves other areas of the transportation network uncovered.

The cloud-based dissemination of SPaT/MAP data is fairly straightforward as it poses low cyber-security risk to the City's computer and communication system. The preliminary discussion with the City indicated their willingness to provide SPaT data to the public through the cloud. The data can be accessed by OBUs or mobile devices. However, the collection of BSM from vehicles through the cloud poses significant challenges to the City as was discussed in Section 4. At this point in time, it is the preference of the City that such processes be evaluated offline utilizing FDOT TERL facilities at Springhill Road using a dedicated server and cloud communication with OBUs, smartphones, and other mobile devices. Offline evaluation of BSM data collection will lead to the understanding of how BSM data can be acquired, secured, and stored in a secure system; how the data can be normalized to a consistent format for building BSM applications; and how the data can be structured to meet user privacy preferences and expectations.

2.7 Evaluation of a Pedestrian Application

Two-way communication between RSUs and OBUs will allow for various applications based on Basic Safety Messages (BSMs) to be developed for the purpose of improving operations and safety along the corridor for both vehicular traffic and non-motorized traffic, i.e., pedestrians, bicyclists, and other micromobility travel modes. One of the most important BSM application aimed for evaluation in the corridor involves pedestrians. The evaluation would involve demonstrating and experimenting with vehicle-to-pedestrian (V2P) communication through the RSUs installed on Mahan SPaT Corridor.

The development of pedestrian application for use in the corridor logically would require to first install an active detection system for detecting pedestrians in the crosswalk. To this end, the research team contacted the University of Florida regarding previous work they conducted on the bike-ped safety systems. The review of this work indicated that technologies for bike-ped detection are vision-based, infrared-based, and thermal imaging-based. Efforts were made to find companies that can partner with the City to install an active ped-detection system at one intersection in the corridor. Incidentally, during SCMS negotiations, one company indicated that they have a vision-based pedestrian detection system currently in evaluation in Michigan and they were willing to provide the City with the system. At the time of writing this report, negotiations were underway to acquire the system for the purposes of demonstrating smartphone-based pedestrian safety application in the corridor.

2.8 Evaluation of Security Credentials Management System

Security and privacy of information exchange among entities in a connected vehicle environment is of paramount importance. While there are no national standards that have been proposed in this domain, the Mahan SPaT Corridor testbed provided an excellent testbed for testing of security credentials management system (SCMS) that are being touted by various vendors.

A request for quote (RFQ) was prepared and advertised by the Florida State University. Responding companies were expected to demonstrate operational and deployment-ready Security Certificate Management System that provides digital certificates to devices for authentication purposes. The certificate of the device was anticipated to expire after a stipulated time to protect user privacy and preventing tracking. Also, the installed system was to be able to identify anomalies and revoke digital certificates from untrusted sources. A total of four companies responded to the RFQ and provided their quotes. A follow-up phone interview was set up with the four companies using a predefined rubric. Based on the quotes and the results from the phone interviews, two companies were selected to demonstrate their credentialing systems on the corridor.

2.8.1 Preparatory Work for SCMS Implementation

Following contractual agreement with two companies to install and test their SCMS in the corridor, the RSU, OBU, and DSRC vendors, i.e., Wave Mobile Solutions and Control Technologies, were consulted to assess the readiness of the installed system and assist the SCMS vendors in implementing their credentialing systems. The City of Tallahassee was also contacted on the infrastructure-readiness question. In order for the system security to work properly, the end devices – roadside units and onboard units – should be compliant with the IEEE 1609.2 standard. The IEEE 1609.2 security standard describes such things as message signing, message verification, cryptographic algorithms, and so on. The joint review of equipment and infrastructure readiness revealed that the following preparatory work had to be performed:

- Even though it was expected that the RSUs for this project were to support an Internet Protocol (IP) IPv4 connection to the USDOT Proof of Concept SCMS, the radio firmware vendor indicated that there was a need to upgrade their 1609.2 stack in the radio firmware to bring it up to the standards used by the two SCMS companies hired for the project. This required allocation of resources (in time and funding).
- According to Wave Mobile Solutions, the current version of Intelight's MAXTIME CV software was not security-ready and needed to be upgraded.
- A software patch was to be sent to the City to upgrade the RSU and OBUs firmware.

- Since it was not known how the system will perform following security patch upgrades, it was decided that RSUs at three intersections only will be upgraded (out of 22), and only two OBUs out of four will be upgraded.
- One SCMS vendor will host the SCMS at their out-of-state headquarters and will communicate with the DSRC RSUs over the City's network through a designated TLS 443 port. This brought up firewall concerns by the City that were to be resolved at a later date.

2.8.2 Status of SCMS Implementation in the Corridor

Significant progress has been made in readying the testbed for security credentials implementation. The process started by Wave Mobile Solutions developing a SCMS security module that would enable signed Basic Safety Messages and communicate between RSU and OBU through the DSRC radio. This security module was installed on RSUs at three intersections. These intersections are Mahan Drive @ Walden Road, Mahan Drive @ Vineland Drive, and Mahan Drive @ Pedrick Road. These intersections, which are in the outskirts of the city, were chosen to ensure minimal impacts if things were to go wrong during the SCMS deployment exercise. The plan was to extend the SCMS to all other intersections in the corridor if trials were successful at the three chosen intersections.

At the same time, the SCMS vendor who chose to host the system at their out-of-state headquarters created a public SCMS server for the DSRC radio vendor, i.e., Wave Mobile Solutions, to experiment with in terms of testing OBU/RSU enrolment process. It is the understanding of the Principal Investigator that Wave Mobile Solutions accessed the server a number of times to test communications and certificate chain provided by the server. A meeting involving the City of Tallahassee, Wave Mobile Solutions, the SCMS vendor, and the Principal Investigator was called in late 2018 to determine how the City network can be extended to include SCMS hosted out-of-state. During the meeting a number of issues were discussed including a list of ports and protocols needed by the SCMS vendor to access the City's network and whether the established VPN communication will be outbound only or two-way. The questions Wave Mobile Solutions had for the SCMS vendor were related to certificate revocation endpoints, pseudonym certificate tests, and expected error codes. The lessons learned through SCMS field deployment efforts in the Mahan corridor were used by FDOT to establish requirements for SCMS vendor for the statewide implementation.

2.9 Conclusions & Recommendations

The research task reported herein was aimed at the overall performance evaluation of SPaT/MAP broadcasting and the other underlying potential applications brought about by the DSRC implementation in the Mahan corridor. The period under review, approximately two years, is long enough to have robust conclusions and recommendations on a number of operational and technical issues that were experienced as was discussed in the body of the report. Overall, the project has demonstrated and continue to demonstrate that V2I connectivity through DSRC is viable and operationally long lasting. The project was commissioned back in November 2017 and two years later the installed systems are still working and all stakeholders – i.e., FDOT, City, and private technology integrators/vendors are still displaying a high level of cooperation and willingness to ensure the project's durability and success. However, like any other trailblazing project, this project faced a number of operational, technical, equipment, and resource problems that need to be addressed. The following sections summarize the issues faced and offers recommendations for corrective actions.

2.9.1 SPaT/MAP Data Broadcasting and Display

When all RSUs were operating at full capacity, the SPaT data was being received in the vehicles equipped with OBUs at various distances from the downstream intersections. This is the case whether traveling in the inbound or outbound direction. However, it was difficult to deduce which downstream intersection's SPaT data was being displayed. This was particularly the case for closely spaced intersections in the downtown area. To minimize the possibility of driver confusion during the upcoming volunteer drivers study, it is recommended that instead of displaying the Intersection ID, the actual intersection name should be displayed, e.g. Mahan Drive @ Blairstone Road.

Furthermore, the display of minimum, average, and maximum phase times is confusing particularly since the values are frequently the same. It is recommended that only one value be displayed. In addition, the numerical countdown can be supplemented with symbolic display such as a "signal head" display with the proper color of green, yellow, or red. Studies show that symbolic displays generally elicit quick perception to reaction times. Other incorrect displays of speed limit and advised speed observed in the field test runs can be easily corrected or removed from the screen entirely.

The incorrect positioning of a vehicle on the Google maps while driving is contributed by imprecise GPS positioning and imprecise MAP data. Studies show that it is possible to broadcast differential GPS corrections via DSRC in real time to improve reliability and accuracy. As discussed previously, the amount of data and effort needed to fully encode one intersection in the MAP message is enormous. The MAP data of all intersections in this corridor were created using a graphical user interface (GUI) tool developed by the US Department of Transportation (USDOT). It is recommended that the MAP data need to be verified and corrected accordingly to enable a vehicle to be displayed properly in the left, through, or right turn lane.

2.9.2 Equipment, Software, System Maintenance and Upgrades

One of the challenges faced during the project evaluation was the upgrading of software in critical systems necessary for communication and security credentials. For example, experimenting with security credentials management system (SCMS) at just only three intersections required upgrading of the RSUs, Intelight controllers, and OBUs with software patches that took months to develop and deploy in the field. Also, the repair of malfunctioning systems and equipment was very slow as it required a technician from out of the city to travel to Tallahassee to undertake repairs and in most cases it required malfunctioning equipment to be sent out for repairs resulting in very long turn around times. Procurement of equipment was also slow because of slow production times; for example, one OBU ordered by FSU took five months to deliver.

Some of these challenges can be resolved by devising creative technical support for local agencies hosting connected vehicle pilot projects such as the City of Tallahassee as discussed in the next section. However, the implementation of interoperable equipment and systems might cut down on the technical difficulties that were faced in the project evaluation process. In this scenario, a malfunctioning OBU or RSU can be replaced or upgraded vertically (with a newer version from the same vendor) or horizontally (with state of the art equipment/component/system from another vendor). Local agencies such as the City of Tallahassee should be empowered and given flexibility to effect upgrades on their own. For example, with C-V2X equipment becoming technically viable and affordable, can upgrades to the existing RSUs be made to allow for duo-mode operation of C-V2X and DSRC while being interoperable with existing and future OBUs? The answer to such questions need to be in the affirmative.

2.9.3 Technical Support and Resource Allocation

The hosting of connected vehicle pilot projects by local agencies presents opportunities and challenges for the local agencies. The opportunities include showcasing of technological advancements and features that are aimed at improving mobility, safety, and environment. This is good for public relations and for garnering community and management support. It has been learned from this project that the success and longevity of connected vehicles testbeds such as this can be achieved by empowering local agencies with technical know-how and resources to undertake procurement, installation, maintenance and upgrades of the majority of the equipment, software, and systems being deployed. The current contractual agreements seem to require original equipment vendors and system installers to play a major role in the maintenance and upgrading issues. Most local agencies today repair and upgrade traffic signal controllers on their own without deep involvement of suppliers. Going forward, the same paradigm should be utilized with RSUs, OBUs and other connected vehicle equipment. Local agencies need guidance and wherewithal to do so.

TASK 3: STUDY OF OPERATONS AND DRIVER BEHAVIOR

3.1 Purpose and Scope

The Signal Phase and Timing (SPaT) demonstration project has been in existence in the City of Tallahassee since early 2017. In this project, dedicated short range radio communication (DSRC) is being used to broadcast SPaT and Geographic Intersection Description (GID/MAP) data from traffic signal controllers through Roadside Units (RSUs) installed at 22 signalized intersections along the US 90 corridor in the City of Tallahassee. Through a customized on-board unit (OBU), the SPaT/MAP data is picked up by the OBU inside the vehicle and displayed on a tablet screen. The SPaT information displayed is in essence the status of the traffic signal upstream of the vehicle in the direction of travel.

The main purpose of this task was to conduct driver observational and operational studies in relation to the provision of SPaT/MAP data into the vehicle. A number of driving subjects were recruited to drive on the corridor under a scenario in which SPaT is turned on and under another scenario in which SPaT is turned off. Several project evaluation criteria were developed and used in the evaluation and observational studies. Given that there have been recent advances in connected vehicle applications and deployments in Florida, a comparative analysis between the SPaT deployment in the City of Tallahassee and the SPaT deployment in the City of Gainesville was conducted. To this end, the same subjects drove in both corridors to evaluate the efficacy of the SPaT deployments. The following section describes the study elements.

3.2 Study Elements

As noted above, the main goal of this task was to assess the efficacy of the SPaT/MAP availability inside a vehicle by using recruited subjects to drive in two active SPaT corridors in the State of Florida. Thus, the subjects interacted with individual signalized intersections through the OBUs installed in the test vehicles. The following sections describe the study corridors, the differences between the Tallahassee and Gainesville OBUs, and the profile of the participants that were recruited to conduct the driving runs. The RSUs in Tallahassee and Gainesville as well as the backhaul systems that provide SPaT/MAP data are not detailed in this report but can be found in other documents.

3.2.1 Description of the Study Corridors

In Tallahassee, the participants drove the 7.7 miles SPaT corridor comprising of 22 signalized intersections from Duval Street in the west to Walden Road in the east along the US 90 corridor. Each intersection is equipped with at least one RSU with omnidirectional capabilities allowing SPaT/MAP data to be picked in either approach as the drivers drive towards the intersection. It is worth noting that some intersections were equipped with two RSUs to increase the signal strength and signal reach due to topographical challenges at those intersections. In Task 2 of this research project, it was found that on average SPaT data was first picked up around 1,000 feet from the center of the upcoming intersection. While some intersections exhibited pick-up distances of more than 1,750 feet, other intersections particularly the closely-spaced intersections in the downtown area exhibited pick-up distances of less than 300 feet. Figure 3.1 shows the Mahan study corridor located in the City of Tallahassee.

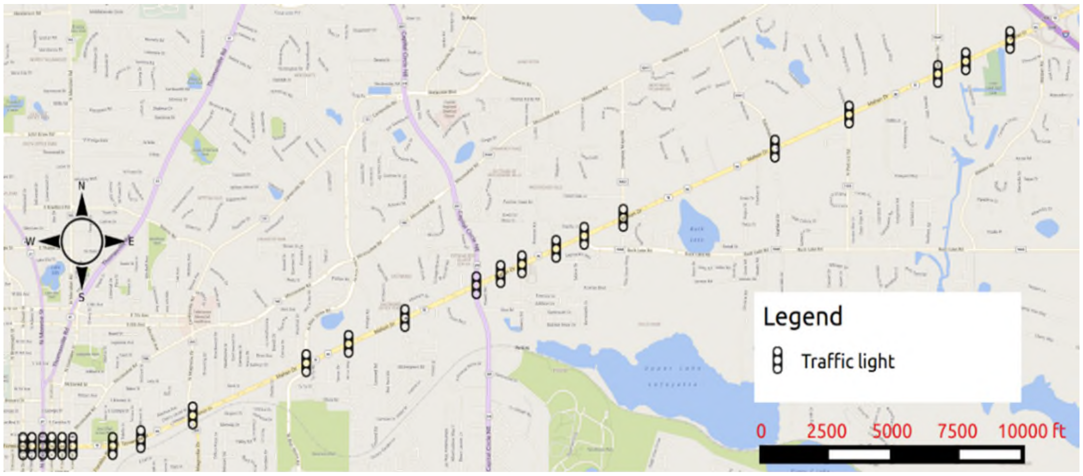


Figure 3.1 Tallahassee Study Corridor

The City of Gainesville SPaT corridor is shown in Figure 3.2. However, besides SPaT deployment for vehicular traffic, the project is also aimed at testing non-motorized connected vehicle applications for pedestrians and bicyclists with the aim of improving capacity, safety, and reliability of travel time in a connected multi-modal ecosystem. The connected vehicle technologies and applications are deployed along four highways forming a loop (nicknamed trapezium) as seen in Figure 3.2. The four highways are State Route (SR) 121 (locally known as SW. 34th Street), SR 26 (W. University Avenue), US 441 (SW 13th Street), and SR 24 (SW Archer Road). There are 27 traffic signalized intersections each equipped with one RSU. The project became operational in September 2019.

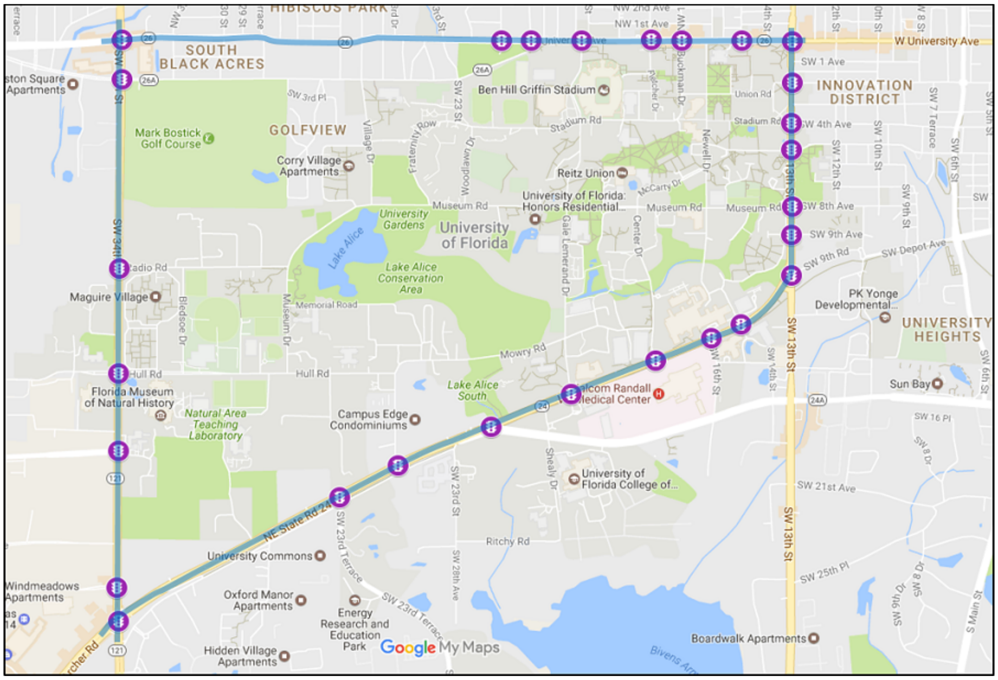


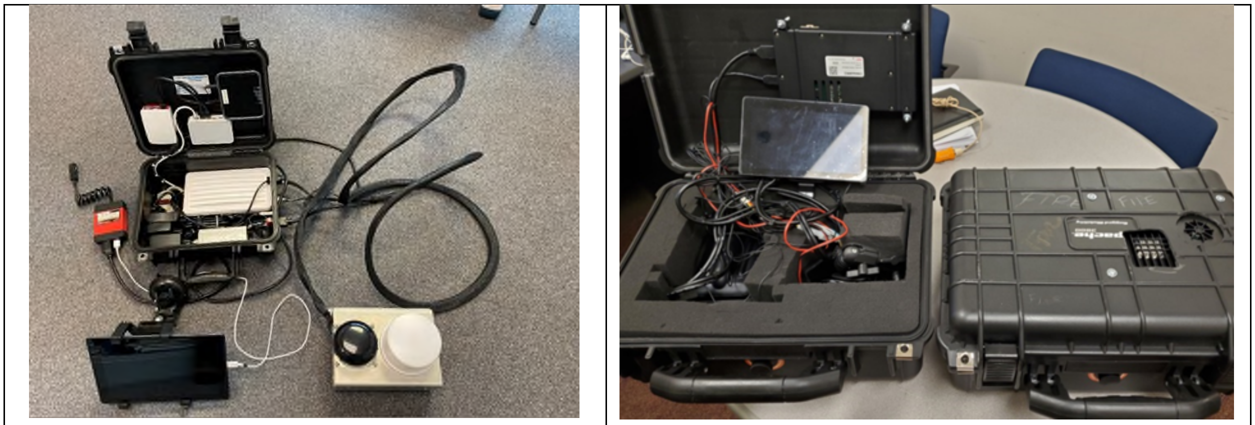
Figure 3.2 City of Gainesville Study Corridor

3.2.2 Description of the OBUs

Figure 3.3 shows the on-board units that were used in the driving runs in both corridors. An On-Board Unit (OBU) is a hardware device mounted on the vehicle. The main purpose of OBU is to communicate with RSUs and other OBUs. The OBUs being used in the Mahan SPaT project were supplied by the Control Technologies Company. The OBUs being used in the Gainesville SPaT project were supplied by the Siemens Corporation. The architecture and key components of OBUs used in Tallahassee and Gainesville are essentially the same and comprise of:

a. Radio antenna – to access the wireless channel in order to communicate with RSUs and other OBUs.
b. GPS antenna – to obtain location information, which is useful for several operations including MAP data geolocation, speed, etc.
c. Processor - raspberry PI.
d. Wi-fi modem[2].
e. Display unit.
f. Cigarette lighter adapter for power supply.

The OBUs are designed to be vehicle-mounted. OBUs have a module, an antenna box, low-loss cabling connecting antenna to the main unit, tablet, and a bracket mount with suction cup to hold the tablet on the vehicle's windshield inside the vehicle.



(a) Tallahassee OBU

(b) Gainesville OBU

Figure 3.3 Description of the OBUs

3.2.3 Description of the Study Participants

Five participants were recruited to conduct this research activity. Because of the complications resulting from the COVID pandemic, availability of subjects, and tight project timeframe, no rigorous efforts were put into subject selection to ensure demographic and social-economic diversity of age groups, gender, educational level, or experience related to driving. All five participants were university students pursuing Ph.D. studies at the FAMU-FSU College of

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[2] In the Tallahassee project, the OBU communicates with the tablet (display unit) through wi-fi while in the Gainesville project the tablet is connected to the OBU using HDMI cable.

Engineering located in Tallahassee. All participants were licensed drivers, own vehicles, and drove regularly in the City of Tallahassee. They all indicated that they were familiar with the Mahan corridor but were not familiar with the Gainesville SPaT corridor.

3.3 Data Collection

This study applied an experimental setup in a non-contrived setting to capture the experience of a ride with signal status information displayed inside the vehicle. The study took advantage of the existence of two SPaT projects utilizing different SPaT display configurations. The following sections describe the status of the equipment operations at the time of the study and detailed description of the experimental design of the study runs.

3.3.1 Status of Equipment Operation

Prior to conducting runs with the study participants the principal investigator conducted numerous runs both in Tallahassee and Gainesville to determine the status of equipment operation, to increase familiarity with the corridors, and to iron out any issues that might arise prior to test runs. The pre-test runs revealed the status of communication between the central servers with the local intersection controllers and the status of the communication between the RSUs and the onboard units. In some intersections, the city personnel had to reset connections to bring the RSUs online. Overall, the majority of intersections were broadcasting SPaT data as intended thus enabling the study to be scheduled for a later date.

3.3.2 Description of the Study Runs

At the beginning of the study runs, participants were given background information about the study purpose and what was expected of them. Five subjects were recruited to drive the two corridors under observation of the principal investigator. This field experiment was designed as follows:

(a) five participants were recruited for the study runs,
(b) each participant drove both Tallahassee and Gainesville corridors in both directions twice,
(c) the first ride was conducted with SPaT display turned off while the second ride was conducted with SPaT turned on, and
(d) the principal investigator sat in the passenger sit observing the driver and taking notes.

3.4 Analysis of Results

The wireless communication between RSU and OBU based on DSRC has to be highly reliable with low latency if the benefits of connectivity for mobility and safety applications are to be realized. In addition, the distance coverage has to be suitable for the intended results such as warning drivers and road users way ahead of intersection on the upstream side. Latency in wireless communications is defined as the amount of time taken for a transmitted packet to reach a receiver (analogous to delay). However, in this study the delay analyzed was the difference in time from the change in signal indication (on the signal head) to the time the signal change is replicated on the OBU display inside the vehicle.

The metrics used to assess the efficacy of SPaT/MAP data availability inside a vehicle were how far from the intersection the data was picked up, the delay between actual signal indication and displayed indication in the car, how SPaT data is displayed to the driver, and the desirability of having the information at all inside the vehicle considering a number of factors. The following sections describe the participants' views on these metrics.

3.4.1 Subject's View of Signal Reach and Latency

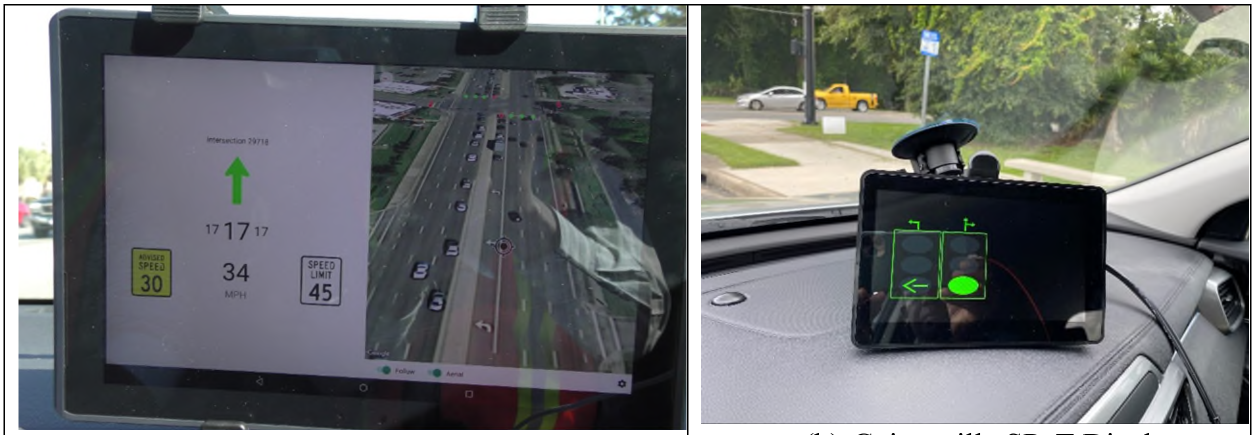
The SPaT/MAP application is supposed to enable a vehicle approaching a signalized intersection to receive information on signal timing status and geometry of the intersection way ahead so that a driver can make correct decisions on lane assignment and decision to proceed or stop. Subjects were encouraged to note at what point did the SPaT information appear on the heads-up display unit and what was the signal latency, if observed.

Overall, the subjects were satisfied with the signal reach and latency for the Gainesville project. This is probably because in Tallahassee, the SPaT information can be received at longer distances from the intersection while in Gainesville the RSU's are tuned to broadcast SPaT information only close to the intersection of interest. Some subjects reported that receiving information 4 to 5 car lengths from the intersection would be useful particularly for the green countdown time to avoid the urge to speed up to beat the light if the signal is received far ahead of the intersection.

Signal latency between the two deployments was deemed to be operationally okay. In Gainesville, the SPaT latency was minimal compared to Tallahassee. This probably was caused by, among other factors, the communication between OBU and display unit. In Tallahassee, the communication is through Wi-Fi, while in Gainesville the display unit is connected to OBU with a HDMI cable. There were some situations in Gainesville in which the start of the signal indication on the in-vehicle display was not in sync with the physical signal head indication. However, all subjects expressed satisfaction with the low latency on both SPaT projects in general.

3.4.2 Subject's View of Display of SPaT Information

Although both SPaT demonstration projects were aimed at providing signal status information to drivers, the information was displayed differently on the tablet screen, as seen in Figure 3.4. For the Tallahassee SPaT project, the display was configured such that on the left side of the screen, the Intersection ID number is displayed on top. The Intersection ID number represents the intersection whose signal status is being relayed to the driver. The display also shows a green arrow pointing upward which changes to yellow and red depending on the signal phase status. The arrow shown is for through lane, but left turn arrow and right turn arrow are also displayed, depending on which approach lane the vehicle is in.



(a) Tallahassee SPaT Display (b) Gainesville SPaT Display

Figure 3.4 SPaT Displays on Tablet Screen

Below the arrow are three values. The left value is supposed to be the minimum green time left. The middle value is the average while the right value is the maximum value. In the last row on the left, there are three speed values in miles per hour. The speed highlighted in yellow is supposed to be progression speed suggested by the device. The middle speed value is the vehicle speed as calculated through GPS coordinates. The speed on the right is supposed to be the prevailing speed limit in the section.

The Gainesville SPaT display has a more simplified design as shown in Figure 3.4b. The status of the signal is displayed and counted down similar to Tallahassee's SPaT demonstration project. In displaying the signal indication, the signal head is replicated in which the green, yellow, and red color are displayed in an arrangement similar to the actual physical signal head, i.e., red on top, yellow in the middle, and green at the bottom. When the left-turn arrow flashes in yellow to signify permissive LT, it is properly displayed as well. During the ride in the corridor, it was observed that when a vehicle is in the outside through (TH) lane, after the start of the green, a pedestrian warning sign is displayed when the ped-signal is counting down to warn the driver that there might be a pedestrian in the crosswalk. So, the driver is warned to be careful before you make a right turn.

The Gainesville SPaT project's display design elicited better responses from the subjects due to it's simple design which replicates the actual signal heads. Subjects indicated that the countdown of how much time is left before red turns to green at both projects were accurate and appropriate. However, the countdown of green indication were jumping up and down as observed in Tallahassee and Gainesville. The jumping up and down of the countdown might be a manifestation of fixed traffic control versus adaptive traffic control. Fixed time signal control give a preset green time to each movement in the intersection. This makes it is easy to predict the signal state for SPaT application. On the other hand, an adaptive signal control based on detection of approaching vehicles can alter the green time for each movement either within a fixed cycle length or with a changing cycle length. Hence, dependent on the traffic signal management philosophy, the SPAT information will be definitive with fixed time systems but only indicative with adaptive systems as is the case with most Mahan corridor signalized intersections.

3.4.3 Subject's View of Significance, Benefits, and Hazards of SPaT/MAP Messages

It has been argued that providing SPaT/MAP data to drivers (and road users in general) can reduce stress to drivers by having knowledge of when the signal indication will change and can also increase situational awareness thus improving safety and operations. The test drivers also expressed the same sentiment after conducting driving runs on both corridors. Some subjects indicated that the benefits were not apparent when they first started driving with SPaT turned on. It took a number of runs to get habituated with the paradigm of having SPaT data inside the vehicle. The subjects were knowledgeable enough to deduce that provision of SPaT/MAP messages on the screen in the vehicle is just the first step in vehicle-to-infrastructure connectivity as in the future as automation advances, there is the likelihood that SPAT/MAP messages could feed directly into the vehicle's Intelligent Speed Adaptation system. In this case the driver needs no display at all.

The subjects indicated that one of the hazards to be mindful of is the likelihood of yellow light running and red light running when a driver is faced with green indication countdown. A driver who would have otherwise chosen to stop because they are far from the intersection could easily be enticed to speed up to beat the yellow and red light when he or she judges that they can make it with the green time that is left, if they could just speed up. This phenomenon has the potential to cause safety problems that may or may not currently exist. Other potential hazards mentioned by the subjects are:

- the information load brought about by extensiveness of connected vehicle information beamed into OBU is of concern,
- display of pedestrian warning message (Gainesville project) is a bit distracting,
- a driver maybe too fixated on the display resulting in distraction from other important driving tasks, and
- if drivers are focused on the light being green, they may be distracted from the possibility of a long queue and could be caught off guard by the long queue resulting in hard braking or rear-end crash,

3.5 Conclusions and Recommendations

Provision of SPaT/MAP messages inside a vehicle has the potential to increase situational awareness and reduce driving stress, resulting in improved operations and safety. However, this move could have a potentially significant effect on driver behavior, and therefore on the effective benefits of the system. Thus, undertaking research on driver behavior and attitudes towards SPaT/MAP deployment is of utmost importance. Critical factors related to the provision of SPaT/MAP data to the driver include distance from the center of an intersection at which signal status is picked up, signal latency, and how the information should be displayed to the driver. A complex SPaT/MAP display might lead to driver distraction or lead to driver ignoring the information as too confusing or irrelevant.

This study applied an experimental setup in a non-contrived setting to capture the effect that the experience of a ride with SPaT/MAP provided inside a vehicle. The information gathered after the subjects rode in SPaT-equipped vehicle show that the rides had a positive and significant effect on attitudes towards provision of SPaT/MAP within a vehicle. One of the main upsides of SPaT information is to increase situational awareness at the signalized intersection particularly in relation to the countdown to the start of the green. However, concerns were expressed by the subjects regarding countdown to the end of green as they opined that this might encourage drivers to speed up to beat the light. Indeed, signal anticipation systems that were tried in the past resulted in more crashes at signalized intersections.

The subjects made positive remarks about the simplicity of display design as it made the information quite visible and readable. Some of the improvements suggested include audible warnings to complement visual displays. Also, it should be noted that SPaT/MAP services should be viewed as one of the potential day one applications in a whole slew of Connected Vehicle applications yet to come. In the future, it is likely that SPaT/MAP services will not be displayed to the driver and instead fused directly with the vehicle system allowing for the vehicle to have more control on start-stop functions, speed functions, and eco-driving functions. Subjects were aware of what the future holds for connected vehicle initiatives currently underway.

TASK 4: EXPLORATION OF C-V2X CONNECTIVITY AND USE CASES

4.1 Purpose and Scope

The automotive industry, federal and state governments, as well as scientific institutions are making significant efforts to develop and promote the Dedicated Short Range Communication (DSRC) and the cellular vehicle-to-everything (C-V2X) technologies that would sustain reliable and efficient V2X connections. Consistent with the continuing trend of research and field deployment of both DSRC and C-V2X based field equipment, the purpose of this research task was to explore the efficacy of both communication platforms in broadcasting Signal Phase and Timing (SPaT) and intersection geometric layout (MAP) data to vehicles and pedestrians on the Mahan corridor. A total of 31 DSRC-based Roadside Units (RSUs) capable of communicating with experimental Onboard Units (OBUs) were installed at the 22 signalized intersections in the corridor. The DSRC communication platform was field evaluated under Task 2 of this project. The research task reported herein involved qualitative assessment of both C-V2X and DSRC in order to demonstrate the ability of the infrastructure owners and operators (IOO) in utilizing such communication platforms to broadcast SPaT both at the RSUs field level and through the cloud. Numerous metrics were to be evaluated including latency in messaging, signal reach, reliability, and interoperability.

4.2 The Need for IOO to Support Connected Vehicle Applications

To more effectively and efficiently utilize the existing transportation system, infrastructure owners and operators (IOO) at various levels are exploring connected vehicle approach to enhance safety, alleviate congestion, increase public transit ridership, and enable faster response from emergency responders and roadway maintenance crews. According to the United States Department of Transportation (2021), connected vehicle is a multimodal initiative that aims to enable safe, interoperable networked wireless communications among vehicles, the infrastructure, and passengers' personal communications devices. Critical to the success of this initiative is the role of the IOO in enabling the transportation infrastructure to support various connected vehicle applications, i.e., vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P) and vehicle-to-infrastructure (V2I), collectively referred to as vehicle-to-everything (V2X).

Local IOO such as the City of Tallahassee are increasingly faced with challenging decisions on how they should respond to the ever changing landscape of connected vehicles ecosystem. While, for example, the City can provide roadway, traffic, signalization, and weather information collected through existing legacy infrastructure (loop detectors, signal controllers, etc.), the provision of safety-critical information needed for collision avoidance (for example, pedestrian in the crosswalk) would require building or strengthening the digital infrastructure to collect information about the trajectory of road users (particularly pedestrians), vehicle speeds, vehicle locations, arrival rates, and queue lengths. An operational cyber-physical infrastructure managed by IOO will ultimately enable two-way communication between infrastructure and various entities thus making the infrastructure the integral part of the connected vehicle ecosystem.

While two-way communication between the infrastructure and mobile units is in its infancy and various field tests are evaluating its efficacy initially, however, IOO such as the City of Tallahassee can begin providing important information that is currently being collected through legacy and non-legacy infrastructure system. An example is the Signal Phase and Timing, commonly referred to as SPaT message. Table 4.1 shows the kind of data that can flow from the infrastructure to various entities to enable them to make better travel choices.

Table 4.1 Infrastructure to Mobile Systems Data Flow

Type of Communication	Data Type	Potential applications
Infrastructure-to-vehicles	SPaT/MAP messages Traveler Information Message (TIM)	• Lane phase mapping identification • Trajectory mapping • Red light violation warning • Lane departure warning • Pedestrian in crosswalk warning • Speed limit • Progression speed
Infrastructure-to-road users	Pedestrian signal timing Traveler Information Message (TIM)	• Pedestrian in Signalized Crosswalk Warning • Mobile Accessible Pedestrian Signal System (PED-SIG) • Vulnerable Road User (VRU) assistance and alerts
Infrastructure-to-transit	SPaT/MAP messages Signal Status Message (SSM)	• Transit signal priority • Transit bus stop pedestrian warning • Bus-pedestrian intersection conflict warning • Right turn on red warning
Infrastructure-to-emergency vehicles	SPaT/MAP messages Signal Status Message (SSM)	• Pre-emptive signal timing • First responder signal priority

Other data flows involving other forms of communication such as V2V, V2P, and V2X are discussed in various literatures (National Highway Traffic Safety Administration, 2014; Tahmasbi-Sarvestani, 2017). At this point in time, the City of Tallahassee can concentrate on providing information collected through legacy systems for advisory/warning purposes only instead of for safety-critical connected vehicle applications as these will require significant building of technological capacity. For example, SPaT/MAP data provided for advisory purposes to drivers as to the signal status is easier to communicate whether through the cloud or RSU because latency issues are not critical. However, if the information is provided for drivers to take immediate action, e.g., apply brakes to avoid hitting pedestrian, then latency issues become very important. The next section discusses the importance of SPaT in connected vehicle (CV) applications. The Society of Automotive Engineers (SAE) defines the formats and information contained in all CV data types in the SAE J2735_201603 standards.

4.3 The Rise of SPaT Data Broadcasting

The Signal Phase and Timing (SPaT) data was considered by the American Association of Highway and Transportation Officials (AASHTO), the Institute of Transportation Engineers (ITE), and the ITS America (ITSA) as a low-hanging fruit that can be used by IOO such as the City of Tallahassee to demonstrate the efficacy and the benefits of DSRC-based V2I connectivity. To this end, AASHTO issued the SPaT Challenge in 2016 which urged "infrastructure owners and operators (IOO) to cooperate together to achieve the deployment of DSRC infrastructure with SPaT broadcasts in at least one corridor or network (approximately 20 signalized intersections) in each of the 50 states by January 2020". Consequently, the Florida Department of Transportation in conjunction with the City of Tallahassee and a number of private technology integrators installed 31 RSUs at 22 signalized intersections along the Mahan corridor. Figure 4.1 below shows a typical SPaT-enabling set up.

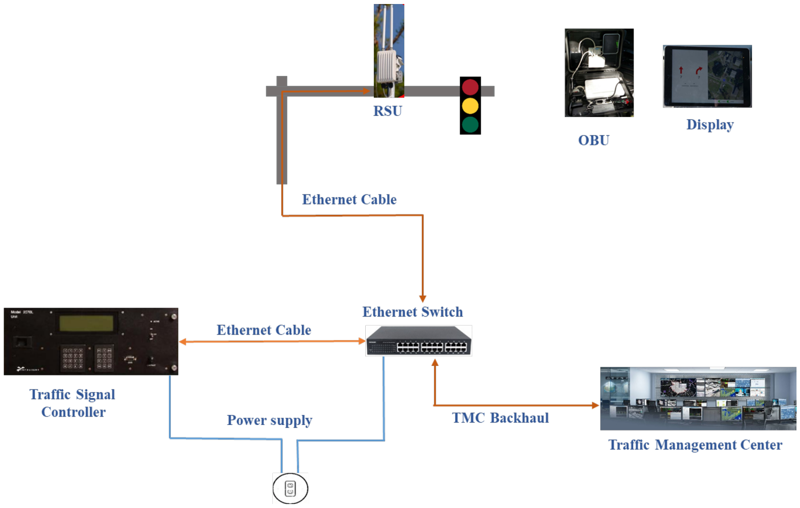


Figure 4.1 Typical SPaT enabling set up

Figure 4.1 shows that the roadside unit (RSU) and the traffic signal controller are connected using Ethernet cable, while the RSU and the On-board unit (OBU) are connected by the Dedicated Short Range Communication (DSRC). The OBU and the display unit are connected by wireless fidelity (wi-fi). An RSU broadcasts data to OBUs or exchanges data with OBUs in its communications zone. An RSU also provides channel assignments and operating instructions to OBUs in its communications zone, when required.

While the geometric layout of the intersection (MAP data) is resident in the RSU and is static, the SPaT data which is dynamic, originates from the traffic signal controller. The SPaT data is broadcast using DSRC according to the Society of Automotive Engineers (SAE) J2735 standard. The purpose of SAE J2735 standard is to support interoperability among DSRC applications through the use of a standardized message set, and its data frames and data elements, particularly for MAP/SPaT messaging. However, recent studies have indicated that the SAE J2735 standards may need to be strengthened to remove ambiguities related to specification of MAP message node points using either absolute lat/long positions or reference node points/offset values; time accuracy and synchronization of the TimeMark; and other ambiguities related to OBU applications and SPaT message content related to flashing yellow arrows (Institute of Transportation Engineers, 2019).

4.4 Infrastructure Needed to Disseminate SPaT Data

Various V2I schemes are emerging around the world to make traffic signal phasing information available wirelessly to vehicles and road users. Obviously SPaT data can be dynamically broadcasted in industry-accepted J2735 format through the cloud or through roadside units (RSUs) by DSRC and/or C-V2X communication technologies. Each of these broadcast methods poses different challenges and opportunities for small size IOO such as the City of Tallahassee. The legacy infrastructure system, represented by Figure 4.2, forms the cornerstone of the current and future SPaT data dissemination. In this figure, the signal timing plans are generally generated at the main office and uploaded to the server (i.e. master controller) which is linked with individual intersection controllers through a backhaul system, in the case of the City of Tallahassee, mainly through fiberoptic cable.

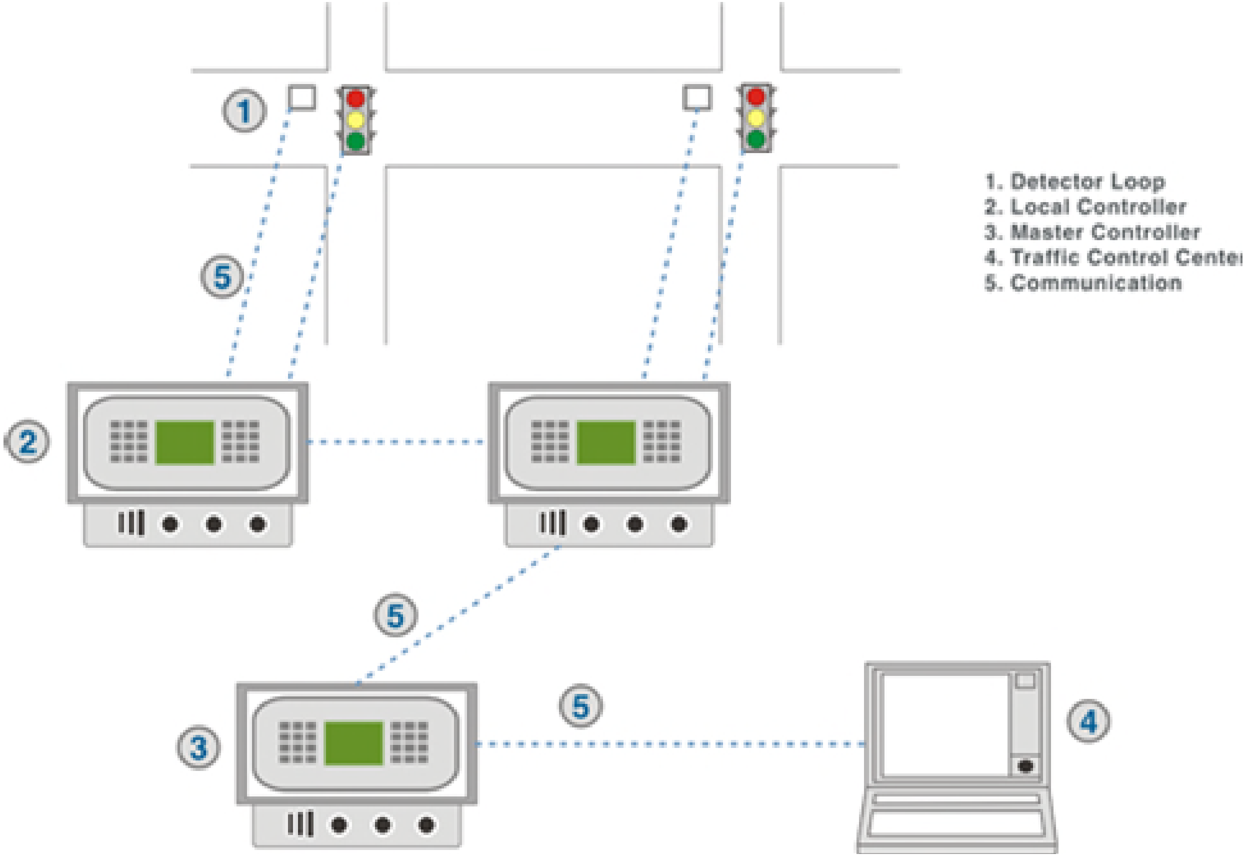


Figure 4.2 Signalization Infrastructure

With modern local traffic controllers gaining sophistication in computing power and networking, manufacturers are enabling them to be interconnected to the main central system to perform various functions such as disseminating SPaT, implementing Advanced Traffic Signal Performance Measures (ATSPM) strategies, and interfacing with connected vehicles applications. However, the master controllers resident in the Traffic Operations Center (TOC) have also been undergoing technology upgrades enabling cloud-based applications to interface with the existing databases. The following sections discuss cloud-based and RSU-based SPaT information dissemination.

4.4.1 SPaT Information Dissemination through the Cloud

The cloud-based dissemination of SPaT information in SAE J2735 format would require creation of a cloud platform that relies on the legacy infrastructure existing in many Traffic Control Centers around the country, the main feature of which is the central computer system which manages various functions including communication with field devices such as CCTV, changeable message signs, ramp metering, and incident management. The current computer and software systems used by agencies to manage traffic signals for the purposes of signal timing, adaptive signal control, transit signal priority, and emergency priority response can also be extended or scaled up to accommodate connected vehicle features and operations.

To allay concerns for network security, making SPaT and other traffic information available to the public and 3rd-party developers would require establishing a dedicated server that can be accessed without penetrating internal secure systems. With the use of Application Programming Interface (API) in the dedicated server, IOO such as the City of Tallahassee can more securely and flexibly allow applications (operated by external entities) to access SPaT data and interact with external software components, operating systems, or other microservices.

4.4.2 SPaT Broadcasting through RSUs

Roadside units (RSUs) in the connected vehicle environment are appealing to IOO because of the potential for geofencing, targeted traffic information broadcasting/communication, and distributed computing. In the current state-of-the-art found in various SPaT deployment projects around the country (including the City of Tallahassee) the RSU controller broadcasts SPaT and MAP data to vehicles equipped with On-board units (OBUs). However, in the near future the RSU controller is envisioned to be able to connect to a signal controller and periodically read the traffic signal plan which contains the information of signal state, phase separation, steps, seconds, and control strategy (Lee & Chiu, 2020). The RSU controller can then send commands to the signal controller such as extending the green period or cutting off the red period. The RSU controller will periodically broadcast the real-time signal plan via 802.11p or Bluetooth/Wi-Fi interface. OBU or smart phone App in the radio signal coverage range can receive the signal plan data and react to the signal plan. For example, vehicles can take action before the signal change and perform eco-driving or re-routing.

While the cloud center designed with a cloud platform and a central database (as discussed in Section 4.1 above) can provide management functions to all the RSUs in the field, the radio communication used by the RSUs to communicate with various entities in the vicinity is currently based on DSRC and C-V2X as seen in various literature and numerous deployments around the country. The following subsections discuss the DSRC and C-V2X communication at the RSUs level.

4.4.3 SPaT Broadcasting Through DSRC Communication

The Dedicated Short Range Communication (DSRC) utilizes a dedicated bandwidth of 75 MHz in the 5.850 to 5.925 GHz band to connect RSU transceivers and OBU transceivers. This is a short to medium range communication service restricted for use in the outdoor environment only. The 5.9 GHz band and its channel for DSRC is presented in Figure 4.3. From this figure, the SPaT infrastructure system broadcast SPaT, MAP, and Radio Technical Commission for Maritime (RTCM) messages using Channel 172 of the DSRC spectrum.

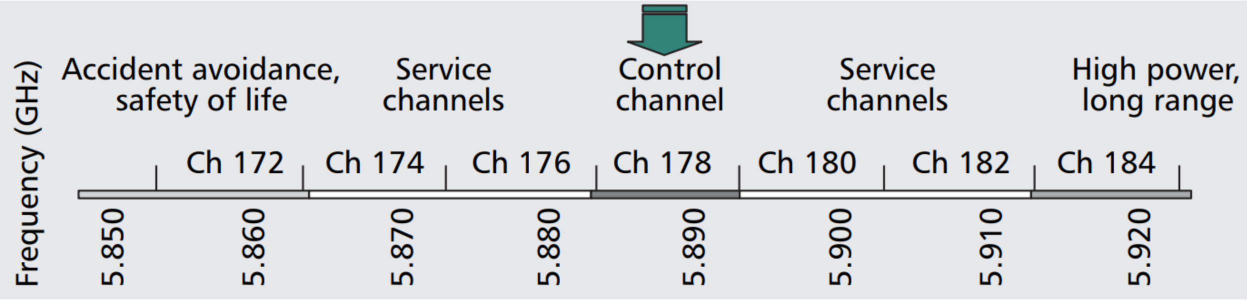


Figure 4.3 DSRC Channels

The DSRC uses a wireless standard called wireless access in vehicular environments, also known as WAVE (IEEE Standards Association, 2021). As seen in Figure 4.3, this standard allocates the 75 MHz bandwidth at the 5.850–5.925 GHz frequency band, divided into seven channels of 10 MHz, one for the control channel, and the other six reserved for service channels. Meanwhile, the 5.850–5.855 GHz band is reserved for future uses. Studies show that the range of DSRC radio is typically 1,000 feet and many installations have shown that much higher range is possible. The performance of DSRC radio at the 22 signalized intersections on Mahan SPaT corridor was evaluated in Task 2 of this project, the results of which are redisplayed in Figure 4.4 below. Figure 4.4 shows the distance at which SPaT data first appeared on the screen when driving east (Trip No. 1) and when driving west (Trip No. 2) on Mahan corridor.

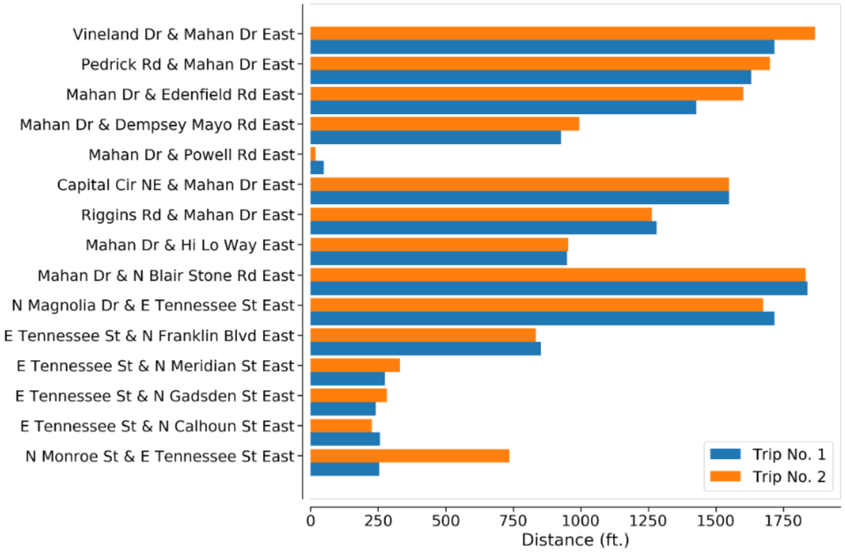


Figure 4.4 Upstream Distance of First SPaT Data Display

The results in Figure 4.4 show that on the average SPaT data is first picked up around 1,000 feet from the center of the upcoming intersection consistent with the results of other studies found in literature. While some intersections exhibited pick-up distances of more than 1,750 feet, other intersections, particularly the closely-spaced intersections in the Tallahassee downtown area exhibited pick-up distances of less than 300 feet. These results may have both positive and negative implications if Basic Safety Messages (BSMs) were to be disseminated for the purposes of queue detection and speed harmonization.

Timely delivery of the safety related information through DSRC is important as enough time is needed for the surrounding vehicles/drivers to react automatically or manually. Thus, communication and messaging latency of DSRC radio is of important consideration particularly for mission-critical vehicular communications. Miao *et al.* (2013) listed eight safety applications and their latency requirements ranging from emergency electronic brake light to traffic signal violation warning. Various field and simulation studies indicated that DSRC communication had latency and capacity that could support collision avoidance and other safety-related V2V traffic applications as discussed in Miao *et al.* study.

4.4.4 C-V2X Communication

IoT-enabled assets such as RSUs and road sensors can communicate with mobile entities (e.g., vehicles) using cellular vehicle-to-everything (C-V2X) radio communication. The term “cellular” in C-V2X can cause some confusion. “Cellular” in this context does not refer to the use of cellular networks, but rather the use of the underlying electronics in cellular radios adapted to communicate from one radio directly to another (Gettman, 2021). However, long range communication between vehicles and distant entities is possible through the use of cellular networks. The broadcasting of SPaT from RSUs and the exchange of information between RSUs and mobile units (vehicles, smartphones, etc.) will rely on direct short range communication (the so-called peer-to-peer communication) which also operates in the 5.9 GHz band similar to DSRC.

The review of literature revealed that SPaT data can be broadcast either from dual mode RSUs (i.e., those utilizing both DSRC and C-V2X electronic chips) or from exclusive C-V2X based RSUs. A handful of OEM brokers have demonstrated that signal phase and timing (SPaT) data can be delivered to vehicles using dual mode RSUs, for example using NR C-V2X sidelink. As with DSRC radio communication, latency issues are also a subject of significant research and discussion in the literature. One study suggested that the end-to-end latency of C-V2X signaling is limited by the quality and dimensioning of the cellular infrastructure, i.e., the capacity of backhaul connections, as well as the delays introduced by both the core and transport networks (Emara *et al.,* 2018). In addition, these latency bottlenecks will be more prominent for high loads corresponding to coverage areas of high vehicular/ pedestrian densities.

4.5 City of Tallahassee Case Study

The City of Tallahassee being less urbanized (i.e., population less than 500,000 people) exhibits different opportunities and challenges in traffic control and in participating in deployment projects designed to showcase new technologies associated with the connected vehicles initiative. The connected vehicles initiative has many evolutionary phases ranging from *one-way communication* to provide roadway, traffic, signalization and weather information to vehicles/pedestrian and other mobile entities to *two-way communication* in which vehicles/pedestrians and other mobile entities provide information to the infrastructure and request various services from the infrastructure.

The current SPaT project on Mahan corridor has demonstrated that SPaT and MAP data can be broadcast at the 22 signalized intersections in the corridor using DSRC-based RSUs. The RSUs installed in this corridor can be considered to be first generation RSUs and offer the potential for upgrading to dual mode RSUs that can use both DSRC and C-V2X radios to broadcast SPaT and MAP data. While this type of upgrade might require substantial resources in manpower and equipment at each intersection, provision of SPaT data through the cloud as discussed in Section 4.1 above might be more appealing to the City of Tallahassee authorities due to low upfront cost.

The City of Tallahassee, like other transportation agencies operate a Traffic Management Center, is increasingly seeing the need to upgrade software and hardware to cope with the ever-changing technological landscape for traffic operations and connected vehicles deployments. This increase in responsibility and operational expectations creates the need for increased staffing capabilities and skill set. While provision of important data collected through legacy infrastructure (signal controllers, sensors, etc.) does not pose significant burden to small size Traffic Management Centers (TMCs) such as Tallahassee TMC, collection of connected vehicle data from mobile systems (through DSRC or C-V2X-based RSUs) will require the building of a cyber-physical infrastructure to process, distribute, and archive these data quickly, reliably, securely and in real time (Li *et al.*, 2019).

4.6 Conclusions and Recommendations

In this task, qualitative review of DSRC and C-V2X communication systems was conducted in relation to enabling infrastructure owners and operators (IOO) to broadcast roadway, traffic, weather, and signalization information, particularly SPaT and MAP data. While it is clear that these technologies can also be used by IOO to collect important traffic information from mobile systems, the review was limited to *one-way communication* only, i.e., the broadcasting of SPaT to mobile entities. The collection of traffic information from mobile systems will require significant building of a cyber-physical infrastructure, the technology of which has not yet matured.

Like DSRC, the deployment of C-V2X has to be assessed from a number of perspectives, including the maturity of the technology, cost, and scalability. The review of literature and results from C-V2X deployments show that the technology is gaining momentum but has not reached a level of significantly impacting traffic operations and safety. Thus, many agencies are asking themselves if it is prudent at this point to significantly invest in infrastructure, equipment, hardware, or software that will transmit and receive data through C-V2X-based RSUs if there aren't any vehicles yet to communicate with.

In addition, the evaluation of safety performance and capabilities of C-V2X through small-scale or large-scale deployment must consider important issues such as congestion, interoperability, and complex transportation scenarios. The Florida Department of Transportation desire to deploy field equipment for small-scale prototype/proof-of-concept testing and for high-level conceptual development in cities of various sizes is important in providing relevant metrics needed to evaluate various performance measures.

CONCLUSIONS AND RECOMMENDATIONS

The communication between Roadside Units (RSUs) and Onboard Units (OBUs) using Dedicated Short-Range Radio Communication (DSRC) was implemented across 22 intersection on Mahan corridor in the City of Tallahassee. The overall goal of this project was to evaluate the efficacy of DSRC in improving efficiency and safety of road users along a signalized corridor. There were four main tasks that were undertaken: (1) pre-ATSPM/CV operational and safety studies; (2) overall performance evaluation of SPaT/MAP broadcasting and the other underlying potential applications brought about by the DSRC implementation on the Mahan corridor; (3) evaluation of driver behavior and attitudes towards SPaT/MAP deployment; and (4) qualitative review of C-V2X communication systems in relation to enabling infrastructure owners and operators (IOO) to broadcast roadway, traffic, weather, and signalization information, particularly SPaT and MAP data.

In Task 1, HERE, BlueTOAD, and Waze crowdsourced data were used to evaluate the pre-ATSPM and connected vehicle (CV) operational and safety characteristics of the Mahan study corridor. The results of the analysis using travel time reliability, level of service, and delay performance measures indicated that segments that intersect with major highways – Monroe St. and Capital Circle – had more constrained operations during the peak hours than other segments in the study corridor. Further analysis of crashes occurring in the corridor was conducted with the aim of determining contributing causes and crash types amenable to mitigation by the implementation of ATSPM and CV applications in the corridor. The implementation of DSRC in the study corridor to enable V2I connectivity is expected to allow for the transmission of basic safety messages (BSM) and dynamic improvements in ATSPM. A number of CV safety applications were reviewed to determine their potential for mitigating the vehicle-to-vehicle crashes as well as crashes involving pedestrians and bicyclists.

Task 2 was aimed at the overall performance evaluation of SPaT/MAP broadcasting and the other underlying potential applications brought about by the DSRC implementation in the Mahan corridor. Overall, the project has demonstrated and continue to demonstrate that V2I connectivity through DSRC is viable and operationally long lasting. The project was commissioned back in November 2017 and four years later the installed systems were still working and all stakeholders – i.e., FDOT, City, and private technology integrators/vendors were still displaying a high level of cooperation and willingness to ensure the project's durability and success. However, like any other trailblazing project, this project faced a number of operational, technical, equipment, and resource problems that need to be addressed.

Provision of SPaT/MAP messages inside a vehicle has the potential to increase situational awareness and reduce driving stress, resulting in improved operations and safety. However, this move could have a potentially significant effect on driver behavior, and therefore on the effective benefits of the system. In Task 3, driver behavior and attitudes towards SPaT/MAP deployment were evaluated. This study applied an experimental setup in a non-contrived setting to capture the effect that the experience of a ride with SPaT/MAP provided inside a vehicle. The information gathered after the subjects rode in SPaT-equipped vehicle showed that the rides had a positive and significant effect on attitudes towards provision of SPaT/MAP within a vehicle. One of the main upsides of SPaT information is to increase situational awareness at the signalized intersection particularly in relation to the countdown to the start of the green. However, concerns were expressed by the subjects regarding countdown to the end of green as they opined that this might encourage drivers to speed up to beat the light. Indeed, signal anticipation systems that were tried in the past resulted in more crashes at signalized intersections.

In Task 4, qualitative review of DSRC and C-V2X communication systems was conducted in relation to enabling infrastructure owners and operators (IOO) to broadcast roadway, traffic, weather, and signalization information, particularly SPaT and MAP data. While it is clear that these technologies can also be used by IOO to collect important traffic information from mobile systems, the review was limited to *one-way communication* only, i.e., the broadcasting of SPaT to mobile entities. Like DSRC, the deployment of C-V2X has to be assessed from a number of perspectives, including the maturity of the technology, cost, and scalability. The evaluation of safety performance and capabilities of C-V2X through small-scale or large-scale deployment must consider important issues such as congestion, interoperability, and complex transportation scenarios. The Florida Department of Transportation desire to deploy field equipment for small-scale prototype/proof-of-concept testing and for high-level conceptual development in cities of various sizes is important in providing relevant metrics needed to evaluate various performance measures.

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APPENDIX A

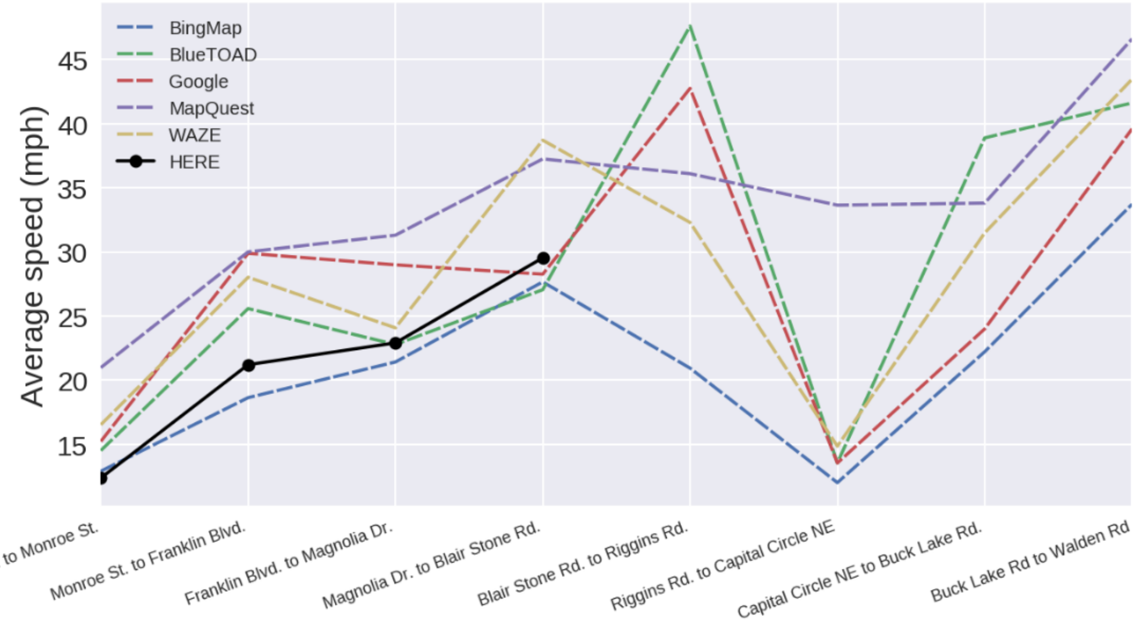
Table A1 Characteristics of BlueTOAD Segments

Direction	SN	Route ID		Segment name	Posted speed limit	Number of signalized intersection	Distance (miles)
Eastbound	1	188-226		Macomb St. to Monroe St.	35	2	0.5
	2	226-135		Monroe St. to Franklin Blvd.	35	3	0.5
	3	135-191		Franklin Blvd. to Magnolia Dr.	35	1	0.6
	4	191-294		Magnolia Dr. to Blair Stone Rd.	45	0	0.9
	5	294-197		Blair Stone Rd. to Riggins Rd.	45	1	0.8
	6	197-080		Riggins Rd. to Capital Circle	45	0	0.6
	7	080-057		Capital Circle to Buck Lake Rd.	45	3	0.8
	8	057-357		Buck Lake Rd to Walden Rd	45	5	3.3
Westbound	1	357-057		Walden Rd. to Buck Lake Rd.	45	5	3.3
	2	057-080		Buck Lake Rd. to Capital Circle	45	3	0.8
	3	080-197		Capital Circle to Riggins Rd.	45	0	0.6
	4	197-294		Riggins Rd. to Blair Stone Rd.	45	1	0.8
	5	294-191		Blair Stone Rd. to Magnolia Dr.	45	0	0.9
	6	191-135		Magnolia Dr. to Franklin Blvd.	35	1	0.6
	7	135-226		Franklin Blvd. to Monroe St.	35	3	0.5
	8	226-188		Monroe St. to Macomb St.	35	2	0.5

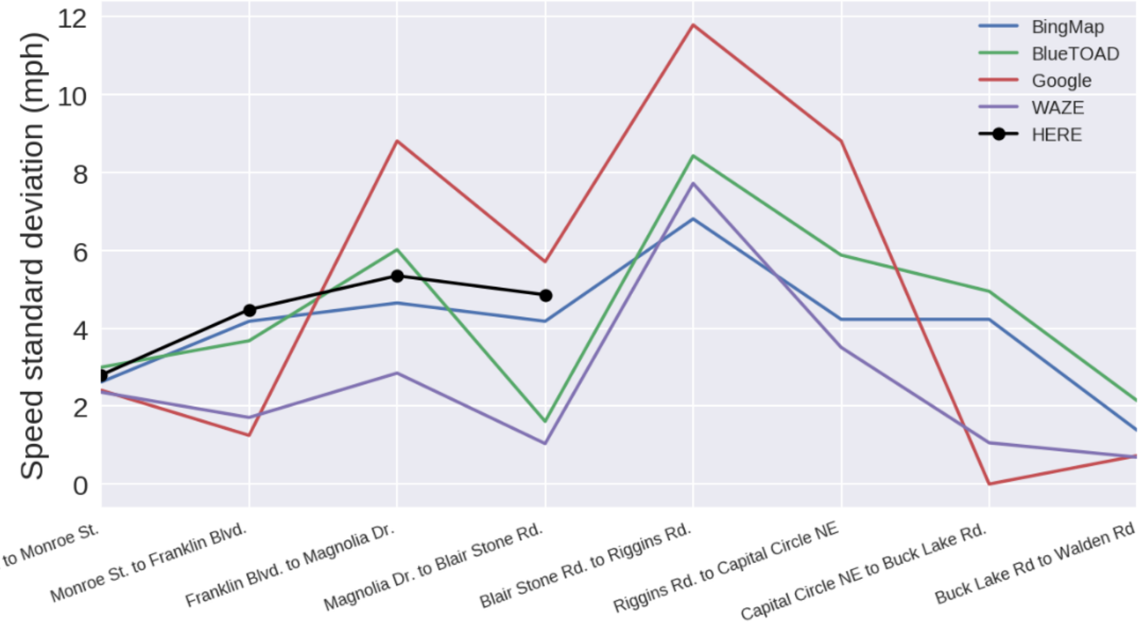
Table A2 Characteristics of TMC Segments

Direction	SN	TMC ID	Segment name	Posted speed limit	Number of signalized intersection	Distance (miles)
Eastbound	1	102+08112	Macomb St. to Monroe St.	35	2	0.47
	2	102+09616	Monroe St. to Franklin Blvd.	35	3	0.49
	3	102P09616	Franklin Inter TMC	35	0	0.03
	4	102+08113	Franklin Blvd. to Magnolia Dr.	45	1	0.62
	5	102+09617	Magnolia Dr. to Blair Stone Rd.	45	0	0.86
	6	102P09617	Blair Stone Inter TMC	45	0	0.03
	7	102+08114	Blair Stone Rd. to Capital Circle	45	2	1.32
	8	102P08114	Capital Circle Inter TMC	45	0	0.01
	9	102+09618	Capital Circle to Dempsey Mayo Rd.	45	4	1.15
	10	102+09619	Dempsey Mayo Rd. to Edenfield Rd.	45	0	1.19
	11	102+09620	Edenfield Rd. to Thornton Rd.	45	1	1.28
	12	102+08115	Thornton Rd. to I-10	45	2	0.68
Westbound	1	102-09620	I-10 to Thornton Rd.	45	2	0.72
	2	102-09619	Thornton Rd. to Edenfield Rd.	45	1	1.28
	3	102-09618	Edenfield Rd. to Dempsey Mayo Rd.	45	0	1.19
	4	102-08114	Dempsey Mayo Rd. to Capital Circle	45	4	1.13
	5	102N08114	Capital Circle Inter TMC	45	0	0.03
	6	102-09617	Capital Circle to Blair Stone Rd.	45	2	1.29
	7	102N09617	Blair Stone Inter TMC	45	0	0.04
	8	102-08113	Blair Stone Rd. to Magnolia Dr.	45	0	0.89
	9	102-09616	Magnolia Dr. to Franklin Blvd.	35	1	0.62
	10	102-08112	Franklin Blvd. to Monroe St.	35	3	0.51
	11	102-09615	Monroe St. to Macomb St.	35	2	0.47

APPENDIX B

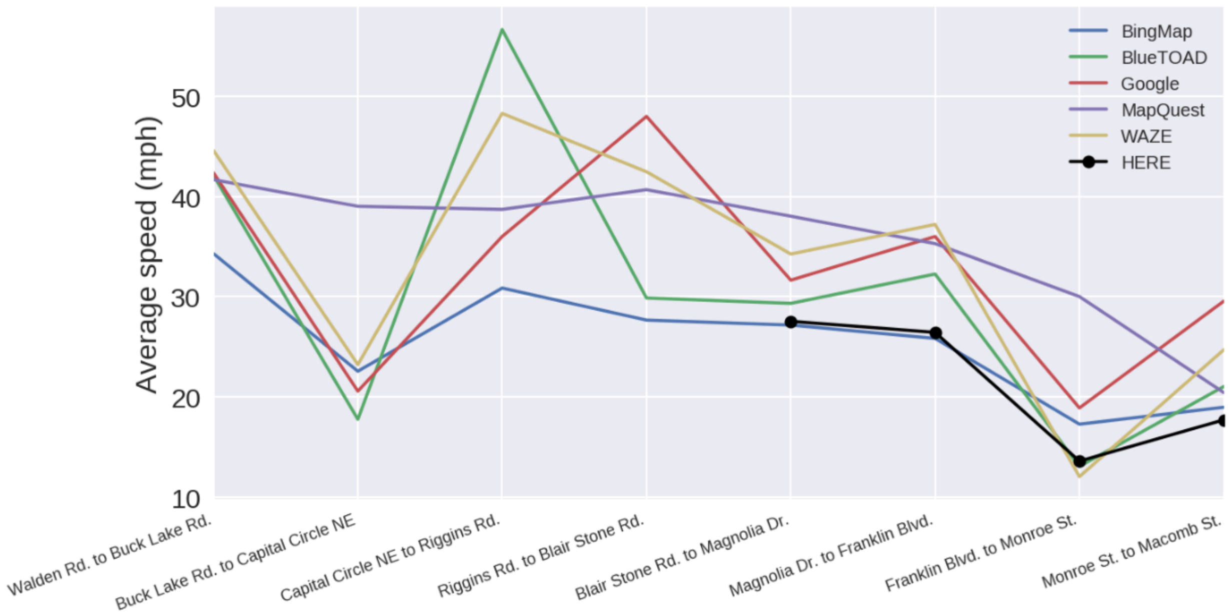


(a) Average speed

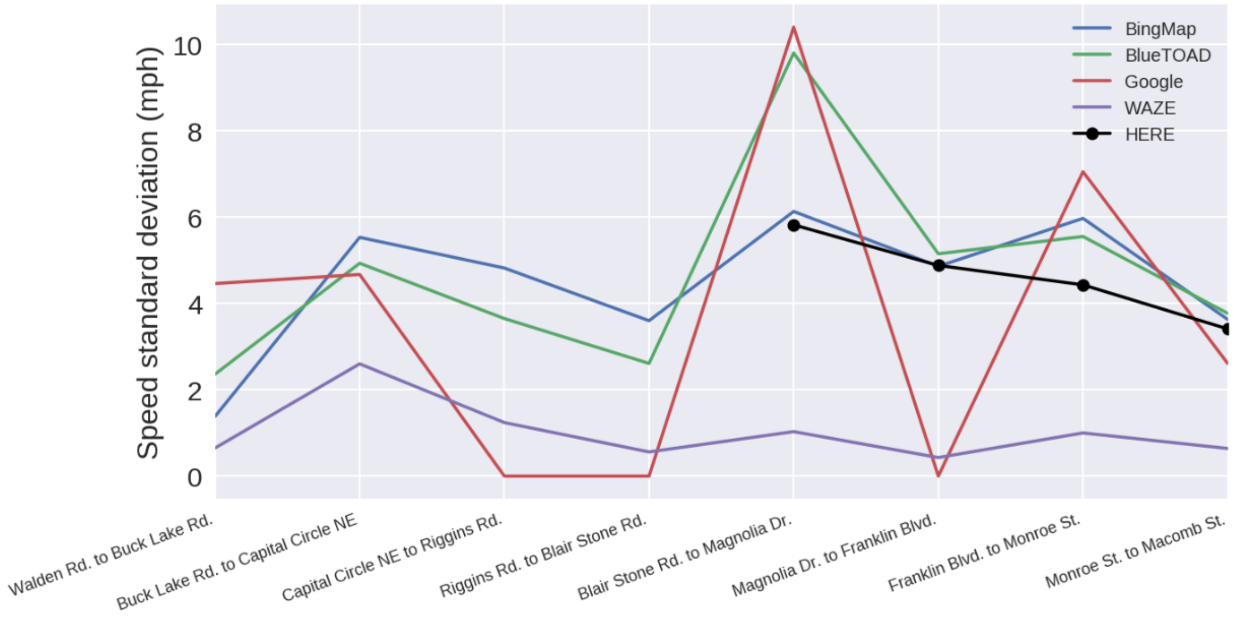


(b) Speed Standard Deviation

Figure B1 Eastbound Traffic



(a) Average speed



(b) Speed Standard Deviation

Figure B2 Westbound Traffic