AASHTO Connected Vehicle SPaT Deployment Challenge
New Hampshire Department of Transportation Response
Dover, New Hampshire

By
Sebago Technics, Inc.

University of New Hampshire, Connectivity Research Center

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University of New Hampshire
Connectivity Research Center

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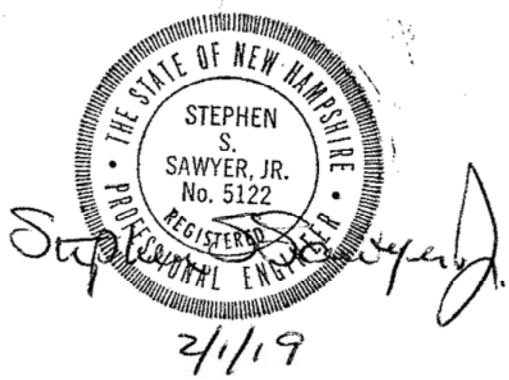

Project Manager:

Stephen S. Sawyer, Jr, PE, *Sebago Technics, Inc.*

Principal Investigator:

Dr. Nicholas Kirsch, *Electrical and Computer Engineering*

Staff:

Christina Dube, *Connectivity Research Center*

Curtis M. Thompson, PE, *Sebago Technics, Inc.*

Students:

Justin Paquette, *Connectivity Research Center*

Ethan Wamsley, *Connectivity Research Center*

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From the entire Research Team, we say a hearty Thank You.

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Section 1 – Executive Summary

Connected and autonomous vehicles use communication technologies to share information with other cars on the road, known as vehicle-to-vehicle (V2V), or to roadside infrastructure, known as vehicle-to-infrastructure (V2I). These communication technologies can be used to improve vehicle safety, as well as improve vehicle efficiency, traffic congestion, and commute times. To instigate adoption of V2I technologies, the American Association of State Highway and Transportation Officials (AASHTO) created the Signal Phasing and Timing (SPaT) Challenge.

The SPaT Challenge is a nationwide challenge to deploy Dedicated Short-Range Communications (DSRC) infrastructure with SPaT broadcasts in at least one corridor or network (approximately 20 signalized intersections) per state by January 2020. SPaT broadcasts are expected to be accompanied by a data file of the physical intersection geometry (MAP) and Radio Technical Commission for Maritime Services (RTCM) broadcasts. The primary goal of the SPaT Challenge is to deploy DSRC broadcasts of the SPaT messages, however, the long-term objective is sustained operation of connected vehicle applications that utilize the SPaT messages.

In response to the SPaT Challenge, the New Hampshire Department of Transportation (NHDOT) partnered with the City of Dover and its traffic consultant Sebago Technics, Inc., with the assistance of University of New Hampshire's Connectivity Research Center. The City of Dover is a leader in New Hampshire for transportation technology, with 14 intersections operating McCain ATC controllers in four coordinated systems all connected to a central management system. As such, the City of Dover is a natural test bed for innovative technologies such as V2I. The scope of the project was narrowed to three signalized intersections on Silver Street in Dover due to the amount of funding that was available. This scope was presented to AASHTO representatives and deemed acceptable, since they explained that the SPaT Challenge was strictly voluntary. Furthermore, the Research Team believed that the experience and lessons learned in deploying this technology at three locations would be equivalent to deploying at twenty, so the spirit of the SPaT Challenge would be met. The three intersections on Silver Street were recently upgraded with McCain ATC eX NEMA controllers, Gridsmart 360°cameras for vehicle detection and data collection, and a fiber-based network interconnect.

With the scope of the deployment reduced to three intersections, the Research Team was able to experiment with other technology options beyond just DSRC, specifically FHWA's V2I Hub and 4G LTE (cellular) connectivity. RTCM broadcast functionality was not included as the development and implementation required would be to exacting for the scope of this project.

Overall the SPaT Challenge is intended to explore the existing technology options for V2I, lay the groundwork for future deployments, and to demonstrate to the automobile industry that public infrastructure owners are committed to building the necessary infrastructure to support V2I, and entice them to move forward with these applications.

There were several outcomes of this project:

- Configured and tested the DSRC radios, the V2I Hub software, and receiving DSRC radio in a lab environment using emulated MAP and SPaT messages.
- Developed an application to decode SAE J2735 SPaT messages.
- Deployed three DSRC radios and V2I Hub platforms in the City of Dover, NH.
- Gained experience with the licensing requirements and process.
- Verified reception of SPaT and MAP data through both DSRC and LTE connectivity.
- Collected data to examine and compare latency over DSRC and LTE connectivity.
- Measured the maximum signal range for the DSRC radios that were deployed.

Section 2 – Infrastructure Build Out

Prior to the installation of the equipment in the City of Dover, the equipment was pre-staged and demonstrated in the lab at the University of New Hampshire's Connectivity Research Center.

DSRC Communication Path

The initial pre-stage testing was focused on the DSRC technology as the SPaT Challenge's main intention is the deployment of DSRC technology. Equipment in this communication path includes a McCain Controller, a Minix Computer running the V2I Hub software, a Denso DSRC Road Side Unit (RSU) and a Denso DSRC On-Board Unit (OBU), as described in Figure 1.

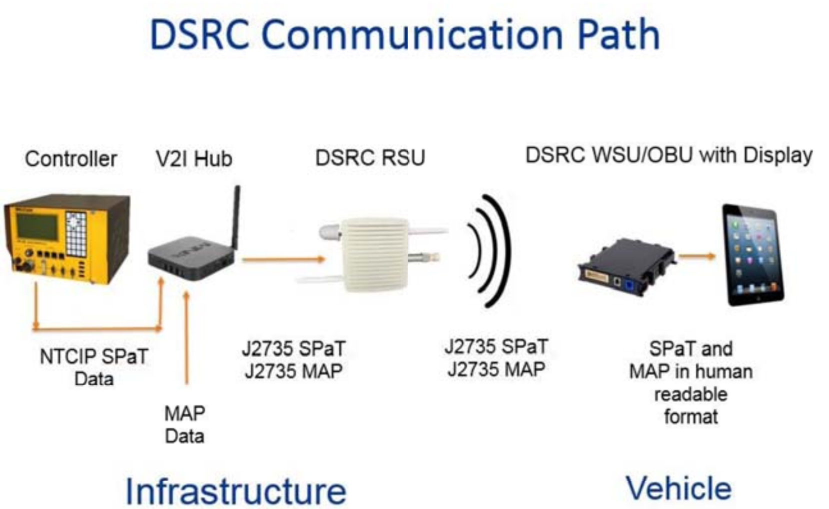

Figure 1: DSRC Communication Path which includes McCain Controller, V2I Hub, DSRC Road Side Unit, DSRC On-Board Unit with Tablet.

The communication path throughout the system is Internet Protocol version 4 (IPv4) based. It begins at the McCain Controller which is configured to send NTCIP 1202 formatted data messages to a demo traffic light (not shown in Figure 1) and the V2I Hub. The V2I Hub converts the received data message to SAE J2735 format and sends it to the DSRC RSU. The RSU broadcasts the messages received from the V2I Hub; SPaT messages are broadcast 10 times per second and MAP messages are broadcast once per second.

The vehicle is represented by a Wireless Safety Unit (WSU) and On-Board Unit (OBU). In a vehicle built with this technology, the WSU/OBU would connect to the car through BroadR Reach/Automotive Ethernet. In the demonstration, and for Dover's future use, a Rad-Moon media converter is used to convert Automotive Ethernet to traditional Ethernet in order access the data that the radio is receiving and display it on the tablet display.

For the lab demonstration and ease of understanding, a small demo traffic light was built using an Arduino programmable controller and three multi-color LEDs. A SAE J2735 parser was developed and implemented on the Arduino controller. The Arduino was connected to the network with the McCain Controller via an Ethernet. The parser script running on the Arduino listens for the appropriate lane information, then deciphers the state of the light from the SPaT data and lights up the appropriate LED with the appropriate color. For example, when the McCain controller transmits data to turn the light green, the parser would light the lowest LED green. Simultaneously, the OBU receives the data and displays it in an application on the tablet, as shown in Figure 2.

Figure 2: Traffic light and Tablet display data received from the McCain Controller simultaneously.

McCain ATC eX NEMA Controller

Sebago Technics assisted with the use of the McCain controller donated by Electric Light Company. The signal timings were programmed to represent an existing controller at a signalized intersection on Silver Street in Dover. The McCain Controller sends SPaT data in an NTCIP format. However, DSRC radios expect the format of the data to be SAE J2735. To address this incompatibility the McCain controller was connected through its Ethernet port to a Minix computer running the V2I Hub software, which is capable of converting NTCIP 1202 to SAE J2735.

V2I Hub

The V2I Hub is a software platform that enables connected vehicles to talk to traffic management infrastructure, such as the McCain traffic signal controller. It can also communicate with pedestrian sensors, road weather sensors, and dynamic message signs. The V2I Hub software translates communication between different standards and protocols which enables interoperability between the various infrastructure components. The software is open source and modular in nature, allowing for rapid expansion using plugins. For this project the DSRC Message manager, SPaT, and MAP plugins were installed. In the initial installation of the V2I Hub, version 2.5.1, the SPaT plugin was not converting the NTCIP data from the McCain into a SAE J2735 message that the Denso Road Side Unit could understand. Upon reporting this issue to FHWA, it was quickly addressed and integrated into version 3.1 of the software.

The MAP file is expected to reside on the V2I Hub, which converts it into a J2735 MAP message and sends it to the RSU for broadcast. While testing version 3.1 of the V2I Hub, it was discovered that the translation of the MAP file was incorrect. Without a proper MAP file, the Denso RSU does not broadcast MAP or SPaT data. To overcome this issue for demonstration purposes, the MAP was placed in the local memory of the RSU and the MAP plugin of the V2I Hub was disabled. In this configuration, both MAP and SPaT are broadcast by the RSU. While this configuration works, it is not an ideal installation scenario. Having the MAP file reside on the V2I Hub makes it available to other plugins for a more robust support of the infrastructure.

V2I Hub version 3.2 was made available before the field deployment and is the version that is currently installed at the test intersections in Dover. With version 3.2 MAP files are translated correctly, but the MAP files must be manually installed in the plugin. However, this is a minor issue.

Currently the V2I Hub is being redeveloped into the Cooperative Automation Research Mobility Applications (CARMA) Hub. The current plans for the CARMA Hub include all the functionality of the V2I Hub along with pedestrian connectivity, MODE compatibility, and integration of the Multi-Modal Intelligent Transportation Signal System (MMITSS) software.

DSRC Road Side Unit and On-Board Unit

Both the DSRC RSU and OBU used in the testing are manufactured by Denso. The specific models were RSU-5910A and WSU-5900A. The Denso RSU is designed with its own V2I functionality, which was utilized when the MAP file was not being properly converted by the V2I Hub software. Additionally, the RSU is capable of converting the SPaT message from NTCIP 1202 to SAE J2735 without assistance of the V2I Hub software.

During our initial testing it was found that both devices are highly dependent on GPS location services. The RSU requires a GPS lock to determine the time and date which is needed to transmit any information it receives. In the initial pre-stage, it was determined that the GPS signal in the Connectivity Research Center facilities at UNH was not strong enough to enable a continuous lock and therefore a workaround by Denso was provided. The workaround involved hard coding the date and time on the RSU and the OBU, as well as providing simulated GPS coordinates to place the OBU in range of the RSU so that the OBU would display the state of the light. The workaround enabled an indoor demonstration of the equipment, but once deployed in the field this workaround was no longer necessary.

MAP SAE J2735 Message Creation

A MAP file was required for each intersection before the equipment could be deployed to the field. The MAP message contains simplified information, including the rough centerlines of each approach lane for the intersection along with basic approach phase information to tie the approaches to signal phases in the SPaT message. The MAP files were created using the FHWA's online Connected Vehicles Tool Library, specifically the ISD Message Creator tool. The ISD Message Creator tool is a browser-based application that allows for the creation of MAP messages utilizing aerial imagery supplied by Bing Maps. The centerline of the approaches is mapped using nodes and then each approach can be configured with the appropriate phase information. Once the intersection is fully mapped, the ISD Message Creator tool can then produce the MAP file for the intersection. The tool is capable of producing the MAP file in many various formats to accommodate different applications.

DSRC Radio Licensing

The DSRC Radios operate in the 5.9 GHz band, which is similar in nature to the 5.8 GHz band typically used for public WiFi. However, the 5.9 GHz band is a restricted band that requires licensing with the Federal Communications Commission. The license is a two-stage license requiring that the municipality or other controlling entity apply for both a county-wide operational license and for individual RSU radio licenses filed under the operational license. DSRC licensing can be filed under radio codes IQ Public Safety and QQ Non-Public Safety. All government agencies are required to file under IQ Public Safety.

The licensing process can be done online through the FCC's Universal Licensing System. The process was somewhat cumbersome and took 4-6 weeks to complete.

LTE (Cellular) Communication Path

With less equipment involved, the LTE communication path was easier to deploy in the field compared to the DSRC communication path. The complexity lies in the architecture of the database which houses the SPaT and MAP data as it is forwarded from the V2I Hub. Similar to the DSRC communication path, LTE uses IPv4 throughout the system and begins with the McCain Controller sending NTCIP 1202 formatted messages to the V2I Hub's IP address. The V2I Hub converts this data message to SAE J2735 format and sends it to a server on the internet, where it is stored in a database. The vehicle (represented by the Tablet) accesses the server on the internet through an LTE connection utilizing the existing 4G network, looks up the appropriate data based on the vehicle's location, and downloads the data to the vehicle. For demonstration purposes there is an application on the tablet interpreting the data and displaying the state of the light. In addition, the McCain controller also sends the SPaT data to the Arduino controlled demo light, which is not shown in Figure 3.

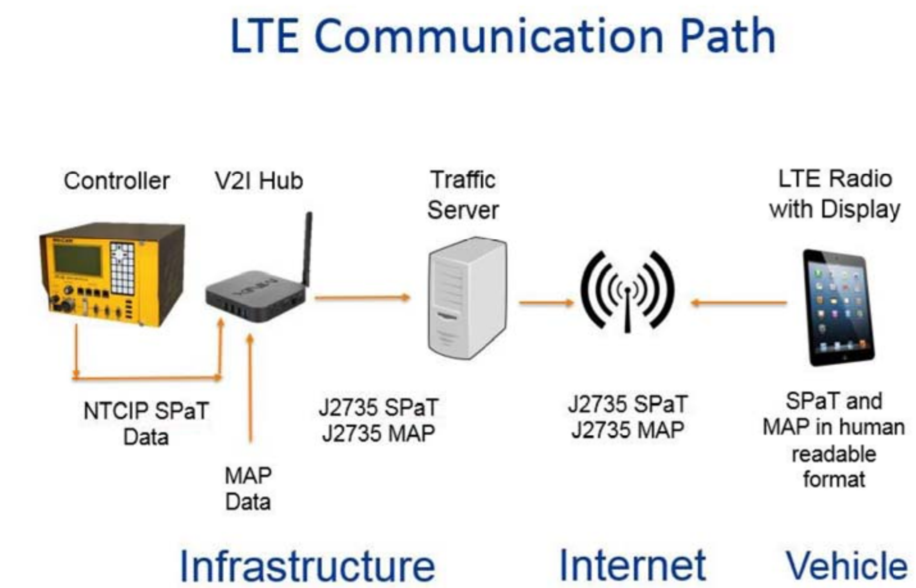

Figure 3: LTE Communication Path which includes McCain Controller, V2I Hub, Server and Tablet with LTE access.

For the demonstration in the lab of the LTE communication path the same Arduino controlled stoplight was used. However, an application was built for an Android tablet. The custom application connects to the server hosting the SPaT and MAP messages and requests data from the database based on the tablet's GPS based location. In Figure 4, the McCain controller sets the light state to green and the tablet in the car accesses the SPaT data from a database through an LTE connection and displays it.

Figure 4: LTE Data Path displaying the stop light and vehicle receiving data in sync.

LTE Server

The LTE Server can be housed anywhere that has internet connectivity. For the lab demonstration the database was hosted on a server at UNH's Connectivity Research Center. For the field deployment the database is being hosted on Dover's transportation network. The database that collects SPaT data for the LTE Communication path was created with phpMyAdmin. A MySQL table holds the SPaT data and the table consists of three columns: id, date, and data. To add data the V2I Hub sends a UDP packet containing the desired payload (with some extraneous header information) to the IP address of the server at port 4589. On the server a UDP server (run by NodeJS) listens at port 4589. When the UDP server receives the packet it strips the header information and adds the payload into the database. The database is being updated with information roughly 10 times a second. To keep the database maintainable a MySQL event runs every 2 minutes and clears all data older than 5 minutes. Another NodeJS UDP server services requests from the vehicle. When a '/light' request is received by the server from the vehicle the server will respond with the most recent entry in the MySQL table.

LTE Tablet

The LTE tablet runs a custom-built android based application. The application makes a request to the LTE Server with a "/light" command. When the application receives the database entry, it parses it based on its known lane location and then displays the data as a virtual traffic light.

Section 3 – Deployment of Equipment

The equipment was deployed in three signalized intersections along the Silver Street corridor on October 12, 2018. The locations are Arch Street at Silver Street, Locust Street at Silver Street, and Central Avenue at Silver Street. Installation of the RSU devices was performed by Electric Light Company, the City's traffic signal maintenance contractor. Sebago Technics, with assistance from UNH's Connectivity Research Center, installed the Minix computers running the V2I Hub software into the traffic cabinets and configured the McCain controllers to communicate to the V2I Hubs. The deployment was quickly verified with a later date scheduled for latency testing. In addition to the physical deployment of the equipment, a server was created on Dover's transportation network to host the LTE database. The database is accessible only through a secure VPN connection for security purposes.

Section 4 – Field Testing

The goals of the field testing were to validate the RSU deployment, determine the range of the RSU, verify the MAP data, and compare the LTE network speed with the DSRC radio speed. The initial field test proved that the RSU devices were functioning. (A video is provided as an attachment at the end of the document as verification that the deployment was successful.) However, subsequent tests revealed that the V2I Hub was not re-initializing after a power cycle event. This issue was remedied by with minor changes to the initializing sequence in the operating system of the Minix computers. Once the system was stable, multiple trips through the intersection were made to verify the accuracy of the transmitted MAP file. Finally, the DSRC measurements and LTE measurements were gathered in two separate experiments to examine the latency involved in each communication path.

Experiment One – DSRC Latency

When determining latency in a distributed system, clock synchronization is critical. In this experiment, both the On-Board Unit and the Road Side Unit have their clocks synchronized using the GPS/GNSS network as their master clock.

DSRC data was gathered at the Arch and Silver Street and at the Locust and Silver Street intersections from multiple approaches on December 3, 2018. This data was collected simultaneously at the RSU and OBU. TCPDump, a linux-based command-line data packet analyzer, was used to capture data on the RSU as it was received from the V2I Hub and at the OBU as it was received by the radio in the vehicle. After completion of the data capture, the packet traces were examined for the transition of the light state to identify a data packet frame at both devices. The arrival time of the packet at the OBU was examined in comparison to when the same packet was received from the V2I Hub at the RSU. The latency measurements on average ranged from 9 milliseconds to 20 milliseconds. One of the measurements recorded from RSU to OBU had a time difference of less than 1 milliseconds.

Table 1: Timestamps from DSRC Packets Recorded at the RSU and OBU

Location	Distance from Intersection (meters/feet)	RSU Timestamp	OBU Timestamp	Difference (ms)
Arch Street	25/82	14:26:40.204	14:26:40.213	9
Arch Street	200/656	14:25:23.987	14:25:24.007	20
Locust Street	20/66	14:39:32.534	14:39:32.534	0
Locust Street	43/141	14:38:20.954	14:38:20.964	10

Experiment Two – LTE Latency

In this experiment, clock synchronization was not possible between the server and the vehicle. A script was run between the vehicle and the infrastructure to determine the time difference. This value was relatively consistent from measurement to measurement. The script was run multiple times and the average delay between the vehicle clock and the LTE Server clock was 22.512 seconds, with the LTE Server lagging in time. This was factored into the latency calculations.

LTE data was gathered at the Locust Street and Silver Street intersection on December 18, 2018 from various distances. A laptop connected to the internet through cellular LTE was used to emulate the vehicle. This laptop was running the same application as the tablet that was used for demonstration purposes, as described in LTE Tablet section. While approaching the intersection, the laptop requested SPaT and MAP data from the LTE Server. Wireshark, a data packet analyzer, was used to capture the packet data as it was received through the LTE network on the laptop. Each packet captured has a timestamp embedded in its payload (byte 0x291 through byte 0x29f). This timestamp is added to the packet when the server receives the data from the V2I Hub. To calculate the latency, the arrival time of packet at the laptop is compared to the timestamp embedded in the payload, accounting for the clock offset. The latency measurements ranged from 128 milliseconds to 142 milliseconds.

Table 2: Timestamps from LTE packets recorded at the LTE server and vehicle

Location	Distance (meters/feet)	LTE Server Timestamp	Laptop (vehicle) Timestamp	Clock offset	Adjusted Server Time	Difference (ms)
Locust St	25/82	12:13:57.501	12:14:20.131	22.512 s	12:14:20.013	128
Locust St	43/141	12:15:03.878	12:15:26.532	22.512 s	12:15:26.390	142
Locust St	75/246	12:17:00.917	12:17:23.571	22.512 s	12:17:23.429	142
Locust St	200/656	12:20:18.580	12:20:41.131	22.512 s	12:20:40.996	135

**Note: The clocks for these devices were not synchronized. The average clock offset was calculated and the server time was adjusted appropriately.*

Experiment Three – Field Observed DSRC Signal Range

The range of DSRC was investigated at the intersection of Locust Street and Silver Street. The "tcpdump" command was used on the on-board unit's radio interface to 'listen' for the DSRC signal. The on-board unit has an application which calculates distance from the intersection by comparing the GPS location of the on-board unit to the GPS location in the MAP file. Periodic measurements were taking at distances of 250 ft, 500 ft, 750 ft and 1000 ft. The signal was no longer 'heard' at 1000 ft. Additional measurements were then taken at intervals between 750 ft and 1000 ft. The observed field maximum signal range at the Locust and Silver Street intersection was determined to be 825 ft.

Section 5 – Additional Observations

Throughout this work, both in the laboratory demonstration of DSRC and LTE and the field deployment, it has been evident that V2I communications are a new, emerging technology. While DSRC has been used for V2V communications for many years, V2I is a new use case with ultimately the same goal, improving safety and efficiency. The deployment of V2V thus far has been vendor specific communications. For example, a BMW with DSRC can only communicate with another BMW with DSRC. V2I communications have multiple vendors as well as multiple industry standards involved in the communication path which can lead to interoperability challenges. As smart infrastructure is being built out, the V2I Hub software will become instrumental in its success as it will serve as a translator and arbiter between the various vendors and various industry standards.

Various interoperability issues were revealed during this project. Initially the SPaT message, when converted from NTCIP to J2735 was not acceptable to the Denso Road Side Unit and it would reject the message. The conversion itself was compliant to the J2735 standard, but the Denso device expected a stricter conformance and rejected the message. Later in the project, a similar issue was seen with the conversion of the MAP data. In both instances, the issues were reported and a software update to the V2I Hub enabled interoperability. As smart infrastructure is deployed further, other equipment combinations will utilize the V2I Hub to overcome similar challenges and effectively communicate.

The goal of this technology is to be 'plug and play'. Communities seeking to add in smart infrastructure should be able to install it and, with minimal configuration, it should work. This project has enabled this technology to be one step closer to that goal.

Section 6 – Recommendations

This work demonstrates the successful completion of the SPaT Challenge for the State of New Hampshire. In this project, the V2I Hub software was tested along with the DSRC Road Side Units and On-Board Units to verify MAP and SPaT messages could be transmitted and received properly. These vehicle to infrastructure systems were deployed in the City of Dover, NH. Once the deployment was complete, additional testing was performed in the field, and data was collected to examine the latency over DSRC. In addition, J2735 decoder application was created for an Android tablet. This application was used to verify LTE connectivity and SPaT and MAP data collection through LTE, which was used to examine the latency over LTE.

This work verified the use of DSRC and LTE as methods for vehicle to infrastructure communication. DSRC, with its low latency, is ideal for safety applications and time sensitive data, such as SPaT messages. LTE could be employed to transmit information that is not time sensitive, such as MAP messages. Finally, the students involved in this project will continue to research best practices for displaying and conveying SPaT data with the UNH Driving Simulator.

Overall, this project demonstrates the use of two different modalities to communicate SPaT information; SPaT information combined with other vehicular communication systems would enable future transportation technologies to improve safety, reduce traffic congestion, and improve other efficiencies. The world of wireless communications is rapidly changing as more sensors are deployed and new communication modalities are created it is important to understand how these technologies can be best implemented and how the data can be used. Further study and deployment of V2I infrastructure would make it possible to gain this knowledge and unlock the benefits of vehicular communications.