Feasibility Study and Assessment of Communications Approaches for Real-Time Traffic Signal Applications

Final Project Report

June 9, 2020

FHWA-JPO-20-812

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FOREWORD

The Turner-Fairbank Highway Research Center (TFHRC) performs advanced research into several areas of transportation technology for the Federal Highway Administration (FHWA). The Office of Operations Research and Development (HRDO) focuses on improving operations-related technology through research, development, and testing.

This report presents the findings of the Feasibility Study and Assessment of Communications Approaches for Real-Time Traffic Signal Applications project, sponsored by the Office of Operations Research and Development, Federal Highway Administration, and the U.S. Department of Transportation Intelligent Transportation Systems (ITS) Joint Program Office (JPO). The focus of this project was to investigate if and how two representative communications approaches—dedicated short-range communication (DSRC) and cellular long-term evolution (LTE)—can support differing connectivity-based safety, mobility, and environmental applications that utilize real-time traffic signal data from the infrastructure. For this, this project assessed the feasibility of supporting several applications based on latency data gathered through DSRC and cellular LTE. Both DSRC and cellular LTE have shown strengths and weaknesses in supporting applications in terms of timing and communication range requirements. It is our intent for these results to help developers and deployers alike to improve the safety and performance of the Nation's roadways.

Brian Cronin
Director
Office of Operations Research and Development

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16. Abstract

Connected and automated vehicle (CAV) technology is expected to significantly improve transportation systems by providing benefits in mobility, safety, and environment via connectivity between vehicles and the infrastructure. This study investigates if and how two representative communications approaches—dedicated short-range communication (DSRC) and cellular (3GPP 4G/LTE)—can support various CAV applications. The Virginia Connected Corridor (VCC), operated by the Virginia Department of Transportation (VDOT) and Virginia Tech Transportation Institute (VTTI), was used as a testbed for this project. To provide a robust evaluation, signal phase and timing (SPaT) data transmitted by DSRC and cellular were collected in the field at various intersections in northern Virginia and compared based on latency and distance coverage. The latency experienced by SPaT messages over DSRC was below 5 milliseconds (ms), while the latency of cellular network was well below 100 ms. Specifically, the minimum, median, and maximum latency values for DSRC are 0.8, 1.1, and 1.5 ms, respectively; for cellular, they are 7.7, 36.4, and 68.0 ms, respectively. The minimum and maximum communication ranges for DSRC were 430 and 1,365 meters (m), respectively; for cellular, they were 1,171 and 3,751 m, respectively. An application analysis was conducted to assess the impact of latency and coverage on the feasibility of supporting various safety and non-safety applications, including Glidepath, Traffic Optimization for Signalized Corridors (TOSCo), transit signal priority (TSP), and red light violation warning (RLVW). Based on the data analysis, it was inferred that Glidepath and TOSCo could benefit from the near-ubiquitous coverage of cellular networks by receiving the data farther away from the intersection, whereas applications like TSP and RLVM, which require a low latency, may not be supported by the cellular network. Finally, opportunities for further study are suggested, which include the study of other performance metrics, such as accuracy and reliability, and the study of alternate communications methods.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

4G	4th generation
AASHTO	American Association of State Highway and Transportation Officials
ACC	adaptive cruise control
app	application
BSM	basic safety message
CACC	cooperative adaptive cruise control
CAV	connected automated vehicle
CV	connected vehicle
C-V2X	cellular-vehicle-to-everything
Dr.	Drive
DSRC	dedicated short-range communication
EPC	evolved packet core
FHWA	Federal Highway Administration
GHz	gigahertz
GPS	global positioning system
HMI	human-machine interface
Hz	hertz
ID	identifier
IQR	inter quartile range
ITS	intelligent transportation system
km	kilometer
km/h	kilometers per hour
LTE	long-term evolution
m	meter
max.	maximum
MMITSS	Multi-Modal Intelligent Traffic Signal System
mph	miles per hour
ms	millisecond
NTCIP	National Transportation Communications for Intelligent Transportation Systems Protocol
OBU	onboard unit
Q1	first quartile
Q3	third quartile
Rd.	road
REST	representational state transfer
RLVW	red light violation warning
Route 650	Virginia State Route 650
RSE	roadside equipment
RSU	roadside unit
s	second
SAE	SAE International
SOC	Signal Operations Center
SPAN	switched port analyzer
SPaT	signal phase and timing

SRM	signal request message
SSM	signal status message
STOL	Saxton Transportation Operations Lab
TFHRC	Turner-Fairbank Highway Research Center
TOSCo	Traffic Optimization for Signalized Corridor
TSC	traffic signal controller
TSP	transit signal priority
UDP	user datagram protocol
UPER	unaligned packet encoding rules
US 50	U.S. Route 50
USB	universal serial bus
USDOT	United States Department of Transportation
V2I	vehicle-to-infrastructure
VA–7	Virginia Route 7
VCC	Virginia Connected Corridor
VDOT	Virginia Department of Transportation
VTTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

BACKGROUND

Connectivity to real-time traffic signal data is a key component of vehicle-based applications that aim to improve safety, mobility, and environmental performance. For example, the red light violation warning (RLVW) application utilizes real-time signal phase and timing (SPaT) data to alert the driver of an equipped vehicle that the vehicle may be at risk of entering the intersection during the red interval. Likewise, an eco-approach and departure application can use the SPaT data to help guide the vehicle's trajectory through an intersection to reduce fuel consumption and emissions. Prior work has largely focused on the use of local (i.e., from site-based field infrastructure equipment) wireless broadcast of SPaT data using 5.9 gigahertz (GHz) dedicated short-range communications (DSRC) to provide low-latency communications with the in-vehicle system. However, other means of communicating this information exist and may be effective in the context of each application.

As an example, in northern Virginia, the Virginia Department of Transportation (VDOT) has equipped several signalized intersections with roadside equipment (RSE) that broadcasts SAE International (SAE) J2735 SPaT messages, via DSRC, as part of the Virginia Connected Corridor (VCC) effort (SAE 2016). VCC also provides alternative means of obtaining SPaT information, using cellular transmission, through the VCC Cloud via the representational state transfer (REST) interface, which may be visualized using the VCC mobile application (app) capable of accessing and displaying real-time traffic signal timing data and providing other traffic information.

VDOT currently provides real-time traffic data, including SPaT data, using three communications approaches:

- SPaT data over DSRC broadcast at several intersections[1].
- VCC Cloud/mobile app using a cellular network.
- SmarterRoads internet web portal for the wider signal data covering the northern Virginia traffic operations district.

GOAL

The goal of this project is to collect and analyze communications attributes (i.e., latency and coverage) of the SPaT data using DSRC and the cellular network, and to assess the feasibility of supporting different types of applications (safety, mobility, environmental, etc.) that use SPaT data from the infrastructure systems.

The primary outcomes of this project include:

[1] For more info on VCC test bed locations, visit https://www.vtti.vt.edu/vcc/map.html

- Characterization (including latency and coverage) of real-time traffic signal data, provided by VDOT, through DSRC and through the cellular network via the VCC Cloud data interface.
- Assessment of the feasibility of those data feeds, provided by VDOT, to support various connected and automated vehicle (CAV) applications.
- Dissemination of process and results to other agencies considering real-time traffic signal data distribution.

DOCUMENT CONTENTS

Chapter 1 defines the background and goal of the project.

Chapter 2 describes the data collection, starting with an overview of the VCC physical architecture as well as various data collection points that are available. It also describes the various components used for data collection, the methodology, and the data collected.

Chapter 3 describes the characterization of the data and the various conclusions that may be inferred based on the analyses.

Chapter 4 describes the feasibility of the various vehicle-to-infrastructure (V2I) applications over DSRC and cellular and the study conclusions.

Chapter 5 provides a summary of data and application analysis.

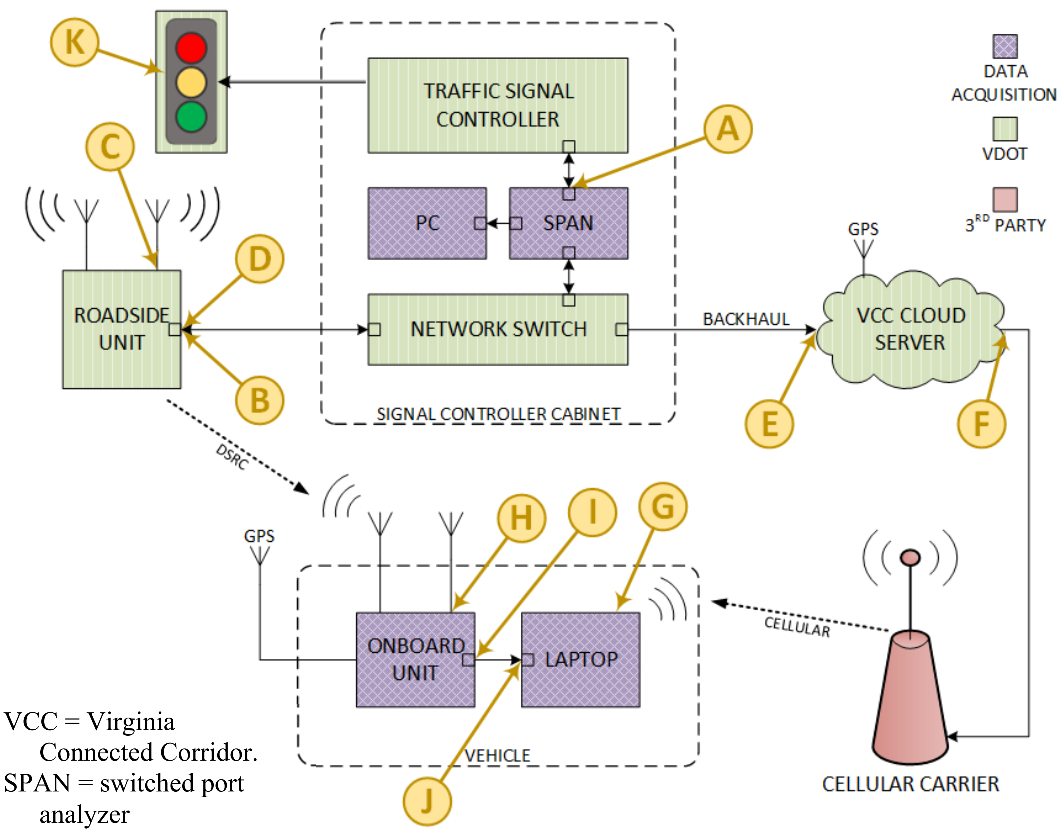
CHAPTER 2. DATA COLLECTION

SYSTEM OVERVIEW

Data Sources

While the ultimate source of the subject data is the traffic signal controller (TSC), the data sent from the controller are received, repackaged, and retransmitted by several systems before making it to the end user. This provided several opportunities for data collection throughout the system, illustrated in Figure 1.

Data collection in this study is designed to showcase the latency of SPaT messages broadcast from a capable roadside unit (RSU) and received over DSRC link or cellular connection. The goal is to analyze the latency of DSRC and cellular, and their differences, and assess the feasibility of using the two communications approaches for various connected vehicle (CV) applications. Figure 1 shows the test setup based on different data points where, if applicable, data measurements could be done.



VCC = Virginia Connected Corridor.
SPAN = switched port analyzer

Source: Federal Highway Administration.

Figure 1. Diagram. Data collection in the connected vehicle system.

Data primarily move between components using data packets to contain the relevant information. By logging these packets with a timestamp from a common time source, the overall transit time between the source and the consumer can be measured. Two data delivery paths are explored:

- Cellular RSU → VCC Cloud → laptop
- DSRC RSU → OBU

An important consideration of the data collection effort is the time source for each data collection device. Since a key focus of the analysis is latency, a common accurate time source is required for each device. To measure timing differences on the order of tens of milliseconds (ms), it is expected that time sources would be synchronized with a difference on the order of ms or better. The global positioning system (GPS) provides a common time source accessible across the test area, and synchronization is done using GPS.

In this case, data available were from RSUs at the intersections, onboard units (OBU), and laptops equipped in the test vehicles. These are summarized in Table 1 along with the importance of each data source, keeping in mind that it was not practical or feasible to collect data from some sources because of VDOT security policies, and the resources available at the time of data collection. The team had direct access to points G, H, I, and J, and access to data point C was made available through the Virginia Tech Transportation Institute (VTTI) team. Essential data collection points available for this project and devices used are presented in the sections that follow.

Table 1. Summary of data sources.

Source	Essential	Desirable	Collection Point
Traffic signal controller		x	A
Roadside unit	x		B, C, D
VCC Monitor/VCC Cloud		x	E, F
Laptop	x		G, J
Onboard unit	x		H, I
Signal Head		x	K

VCC = Virginia Connected Corridor.

Measurement activity included defining an ad hoc vehicle system of multiple wireless radios capable of DSRC and cellular communications. The vehicle system consisted of the following devices:

- Laptop with web socket application capable of logging data from VCC Cloud services.
- OBU capable of logging DSRC messages with GPS transceiver for location and time synchronization.
- Cellular modem with universal serial bus (USB) interface to provide the laptop access to the mobile data network.

Measurement studies consisted of two vehicles: a stationary vehicle and a mobile vehicle. The stationary vehicle was parked in various locations around the intersection while the mobile vehicle made multiple test passes back and forth through the intersection, and extending throughout the range of the RSU's DSRC coverage. This general setup and measurement procedure was the same for both vehicles.

Roadside Unit

The RSU was previously set up to receive SPaT data from a TSC. The RSU had a modified firmware to forward messages to VCC Cloud servers over the Ethernet interface using the network backhaul for broadcast over cellular in addition to broadcast over DSRC on channel 172. The DSRC interface of the RSU was logged as the initial data collection point using the RSU's built-in functionality to log packets passing through each interface.

Packets were recorded into a standard .pcap format for later analysis. Each packet was timestamped with the RSU system time, which was synchronized to a GPS-based time source over VDOT's network. As the last common point for data being sent out to consumers, the RSU log files were instrumental to the completion of the project.

Laptop

VCC Cloud provides SPaT data via a web service interface to its clients. To collect these data, a Python script running on a laptop is used to open a web socket connection with the VCC Cloud server and receive data from the subject intersections. A Verizon® air card is used to provide mobile internet access to the Ubuntu®-based laptop. The contents of each packet are recorded into a text file for later analysis. Each packet is timestamped with the laptop's system time. The system time is synchronized to GPS time provided over Ethernet by the OBU using chrony, a time-keeping application available on Unix®-like operating systems, such as Ubuntu. At the end of each collection day, the data from the OBU are copied onto the computer.

Onboard Unit

The OBU, which is installed in the vehicle, receives the SPaT data over DSRC on channel 172. The OBU is configured to log all received packets to a packet capture (.pcap) file. The OBU is also set up as a timeserver to enable time synchronization with the other system components over Ethernet. Each packet is timestamped with the OBU system time, which is synchronized to GPS time. The received messages are not processed by the OBU during this data collection activity.

Data Types

Various intelligent transportation system (ITS) components generate data in different formats. These data are then processed and converted into a standardized format based on the communication methods implemented. The SAE J2735 standard defines the SPaT message, which contains much of the information of interest for this project, and basic safety message (BSM).

Signal Phase and Timing

The SPaT messages indicate the current state of the signals along with the time remaining for the next change in state. This message is required for various vehicular applications, such as RLVW, Traffic Optimization for Signalized Corridor (TOSCo), and transit signal priority (TSP). This message is typically paired with a MAP message to provide the receiver with a full description of the intersection status.

- The J2735 data type has defined how the SPaT message should be encoded. The structure of the message includes the (frame + SPaT message). The message encoding follows unaligned packet encoding rules (UPER).

- The message frame includes the MessageID, which contains the type of message. For this study, the SPaT MessageType is of primary interest, which is identified by signalPhaseAndTimingMessage id.

- The SPaT message is used to convey the status of the signalized intersection. The SPaT message includes the current movement state of each active phase in the system. This includes the values of what states are active, the time when a state has begun, the earliest time the next state begins, when it is expected to most likely begin, and the latest time the current state will end. This message type may also include the current signal preemption and priority status values (when present or active). The ASN.1 representation of the SPaT message includes: timestamp (MinuteOfTheYear), name (DescriptiveName), and intersections (IntersectionStateList).

- The messages received through the web socket are encoded in base64 and had to be decoded to obtain the UPER-encoded hex data. The same messages received over Ethernet-based connections are logged as user datagram protocol (UDP) packets with the data. The messages obtained over the Ethernet interface are logged as UDP packets, which contained the UPER-encoded data.

Basic Safety Message

Though not directly related to latency measurements, the basic safety message provides a convenient means to collect the current location of the vehicle with a common timestamp. The latitude and longitude are available from the OBU's GPS receiver and populated in the appropriate fields of the BSM. The location enables an assessment of the coverage of the communication technologies under consideration.

DATA COLLECTION METHODOLOGY

Locations

Sites were chosen for data measurement that satisfied the following requirements:

- The intersection is equipped with an RSU that is constantly broadcasting SPaT messages over DSRC.
- The intersection is able to push SPaT messages over the backhaul network to VCC Cloud services.
- Time synchronization within milliseconds is achievable between different observation points.

Test sites in proximity to an RSU allow for a study of latency in DSRC in addition to latency related to the cellular networks. For this reason, sites with existing RSUs are considered. Based on the available RSUs set up by VDOT under the VCC program, six locations were proposed for the measurement of the data. Three of these sites are selected for study and presented below, with the remaining three sites in reserve for future study.

The first location is Virginia Route 7 (VA–7) and Springhill Road (Rd.), shown in Figure 2. This location is very close to Tysons Corner Center, providing an area of dense infrastructure development and a Metrorail line running along the median. The higher density is expected to bring increased traffic on the cellular network during business hours, which may affect latency. The intersection type is a four-way intersection with protected left turns and an elevated Metrorail and station. The traffic patterns are 180 seconds (s) cycle length, six-vehicle phases.

RSU #156 is located at the southeast corner of VA–7/Springhill Rd. The stationary vehicle is parked around the four corners of the intersection while the mobile vehicle made between three and five passes along each direction, as shown in Figure 6.

Source: screenshot created by FHWA using VCC Cloud software. VCC is the intellectual property of Virginia Tech Transportation Institute and is used herein under license. Original photo source: Google Earth™ (see Acknowledgments section). (VCC 2018)

Figure 2. Screenshot. Virginia Route 7 and Springhill Road.[2]

[2] Virginia Tech Transportation Institute (VTTI), VCC Cloud, (2020).

The second location is Virginia State Route 650 (Route 650) and Yorktowne Center, shown in Figure 3. This location has two RSUs in close proximity, which see traffic from a small shopping center, a major arterial, and a nearby interstate. This test environment may include inconsistencies due to proximity to another RSU and traffic from a range of sources. This intersection is a T-type intersection with protected left turns and a three-lane bidirectional arterial. The traffic patterns are 120 s cycle length, four-vehicle phases.

Since this particular intersection has a side street serving a shopping center, the testing is done in one path, as shown in Figure 7. The test run length was chosen such that the mobile vehicle would move in and out of DSRC coverage from the intersection RSU in each set of passes.

Source: screenshot created by FHWA using VCC Cloud software. VCC is the intellectual property of Virginia Tech Transportation Institute and is used herein under license. Original photo: Google Earth™ (see Acknowledgments section). (VCC 2018)

Figure 3. Screenshot. Virginia State Route 650 (Gallows Road and Yorktowne Shopping Center entrance).[3]

The third location is U.S. Route 50 (US 50) corridor, shown in Figure 4. This location runs through a tree-lined residential area over rolling hills. This provides a test environment with RSUs in close proximity to each other and with interference from hills and foliage. The intersection type is a multiple T and four-way intersections with protected left turns and a two-lane arterial. The traffic patterns are 150–200 s cycle length, three- or four-vehicle phases.

Figure 4 also shows the topographical layout of US 50 and the relative position of the RSUs from which data were collected. The elevation profile is relevant to identify the various line-of-sight and non-line-of-sight conditions experienced during testing.

[3] VCC Cloud, 2020.

Source: screenshot created by FHWA using VCC Cloud software. VCC is the intellectual property of Virginia Tech Transportation Institute and is used herein under license. Original photo: Google Earth™ (see Acknowledgments section). (VCC 2018)

Figure 4. Screenshot. U.S. Route 50 corridor.[4]

Data Collection Effort

Duration

Data were collected over the course of 1 day at each site. The data collection was broken up into a morning session and an afternoon session, wherever possible. The collection of data includes the following:

- Stationary vehicle. The stationary vehicle is parked within DSRC range at several points along the route during testing for constant data collection using an OBU and a laptop with access to the VCC Cloud.

- Moving vehicle. The moving vehicle makes multiple passes through the intersection from multiple directions while collecting data packets using an OBU and a laptop with access to the VCC Cloud.

- RSU. The data from the RSU were logged on the device and timestamped using the network time, which is synchronized with GPS time. These data were retrieved at the end of the day. Initially, the time synchronization between RSU and OBU was found to be incorrect. Therefore, chrony was used to keep the time synchronized in the background

[4] VCC Cloud, 2020.

while the test was running, which reduced time synchronization error down to microseconds.

In addition to the CV data collected from these sites, the additional companion field data collected, when possible, include the following:

- GPS position of the RSU and the moving vehicle.
- Estimated traffic patterns, categorized into light, medium, and heavy, based on general observation.
- Time of start and end of each run.
- Photos of the positioning of the various components, including the signal cabinet, RSU, traffic signal head, etc.
- Weather during the time of data collection.
- Any other notable incidents during data collection.

Number of Runs

The test runs are conducted in the following manner:

- Data collection is broken up into two sessions—one during the morning hours and one during the afternoon hours—to cover different levels of traffic demand.

- Data are collected over 60–90 minute runs, allowing between one and two runs during each session. The collected data are checked for any inconsistencies with collection and storage between subsequent runs. The moving vehicle makes between three and five passes through the intersection in each direction per run.

- A stationary vehicle collected data at different locations during each run. Logs are checked for collection-based inconsistencies between each session, such as appropriate file size.

- Data are logged from the RSU by VTTI and delivered at the conclusion of the test.

Logistics

To allow for analysis of data under various conditions of cell network and DSRC usage, data are collected at the following different times of day to get a diverse data set for measurements:

- Peak-hour data measurement. Any data captured between 7 a.m. and 10 a.m. and between 3 p.m. and 7 p.m. on business days are classified as peak-hour data. The RSU data output over DSRC should be constant throughout the day. Cellular network data during peak hours are particularly analyzed for any possible network saturation that could lead to poorer network performance.

- Non-peak data measurement. Any data captured between 10 a.m. and 3 p.m. on business days are classified as non-peak-hour data. These data are compared to the peak-hour data to check for any possible improvements in the latency of the cellular network data.

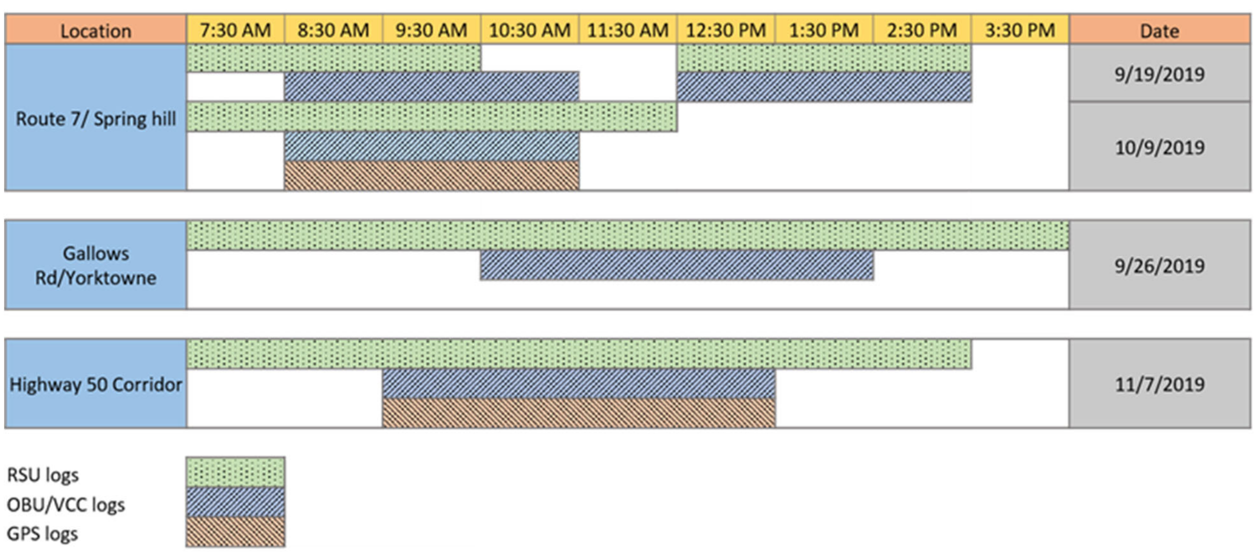
Two types of vehicular measurement are at each test site:

- Normal speed. The vehicle is traveling at traffic speed, or maximum allowable speed based on the conditions governed by peak traffic movement. This covers the real-world use case.

- Standstill. A vehicle is parked along the test route throughout the day to collect data from the RSU and from the mobile network. This allows test personnel to observe any change in the data unrelated to the movement of the vehicle (e.g., network usage).

The data collection is done over two data paths in each test run. As illustrated in Figure 1**Error! Reference source not found.**, one flow of messages logged followed data points A→B→C→H, where the team collected messages and timestamps at point C (with VTTI assistance) and H. This was the path of DSRC messages. Another flow of messages logged consisted of A→B→D→E→F→G, where the team collected messages and timestamps at G. This was the path of cellular messages. One way of comparing the latency over the two paths is to simply compare the time difference between data points C, H and C, G.

Figure 5 shows the details on test locations, timing, and data availability. Two sessions are conducted—a morning and an afternoon session—with each run consisting of multiple passes. The OBU log times matched that of the data logged from VCC Cloud services. Not all dates and locations had RSU logs or GPS positioning logs available. This limited the number of results obtained but the analysis remains homogenous across different tests.



Source: Federal Highway Administration.

Figure 5. Illustration. Test details based on locations, date, time, and available data.

The data collection team coordinated with VDOT's Signal Operations Center (SOC) during test days. The SOC staff monitored traffic conditions using cameras at the subject intersections and adjacent intersections for any incidents that may affect the results of the experiment or the safety of the data collection team. No incidents were observed during the study.

COLLECTED DATA

The collected data consist of records from each vehicle and from the RSU. The routes driven during each data collection activity are presented in Figure 6, Figure 7, and Figure 8. A summary of the collected data is presented in Table 2, Table 3, and Table 4. The following are notes on the data presented in these tables:

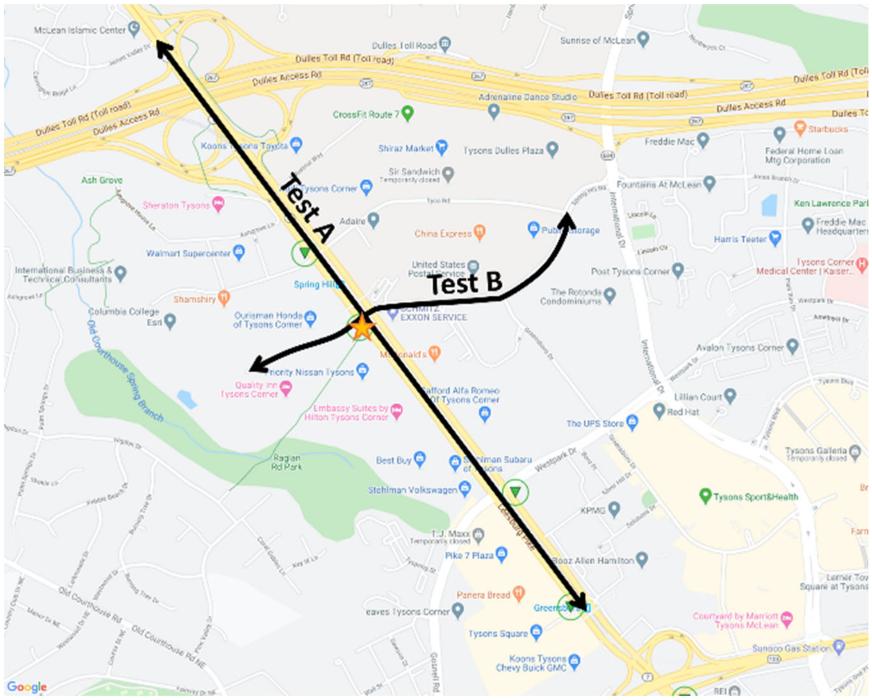
- In both data sets, the RSU logs are separated into multiple log files per day. The duration is significantly longer than the other data files because it contains data for multiple runs. The RSU logging service was running continuously in the background and recorded data even when the test was not being conducted.

- In both data sets, the duration of the cellular data files is much shorter than that of the DSRC. This is because the socket connection to VCC Cloud occasionally broke and had to be restarted, which led to multiple files with data from a single run. These files were combined during post-processing, and due to the low frequency of data coming through the cellular path, data loss is not expected.

- In both data sets, a small message was occasionally received from VCC Cloud that was recognized as a valid SPaT message but did not contain the expected data, so they are not used in the analysis; these are reported as 0.6 bytes.

- For the VA–7/Springhill Rd. intersection, the moving vehicle logs contain significantly more entries than the stationary vehicle because they included SPaT data being broadcast by other RSUs along the route.

- For the Gallows Rd. and Yorktowne intersection, the moving vehicle contains slightly fewer records than the stationary vehicle. This is due to the path of the moving vehicle, which regularly took the OBU out of range of the RSU.

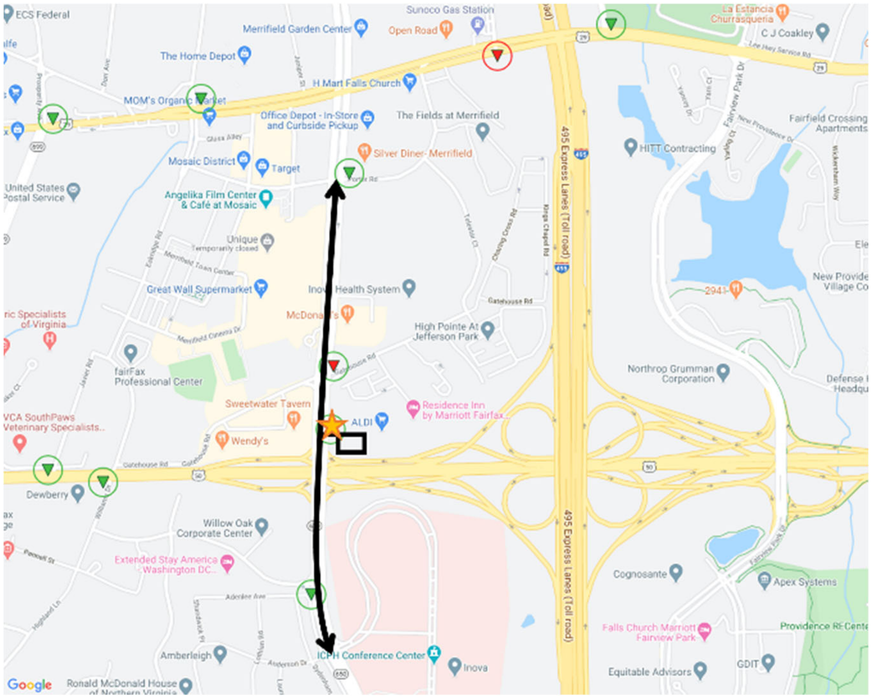


Source: Google, with overlay by VCC and test routes.

Figure 6. Map. Test routes at Virginia Route 7 and Springhill Road.

Table 2. Summary of data collected from Virginia Route 7 and Springhill Road intersection.

	Roadside Unit	Moving Vehicle Onboard Unit	Moving Vehicle Cellular	Stationary Vehicle Onboard Unit	Stationary Vehicle Cellular
Number of records	171,104	316,726	3,755	238,228	3,582
Average data entry size (bytes)	718.09	605.87	558	735.32	558
Maximum data entry size (bytes)	2309	2847	558	2847	558
Minimum data entry size (bytes)	558	129	558	566	558
Average file size (kilobytes)	39,936	24,576	160.90	29,499.52	168.81
Maximum file size (kilobytes)	39,936	45,056	252.78	44,703.34	343.25
Minimum file size (kilobytes)	39,936	14,336	2.86	8,792.88	0.60
Average duration of data files (minutes)	129.60	25.43	17.49	25.96	18.43

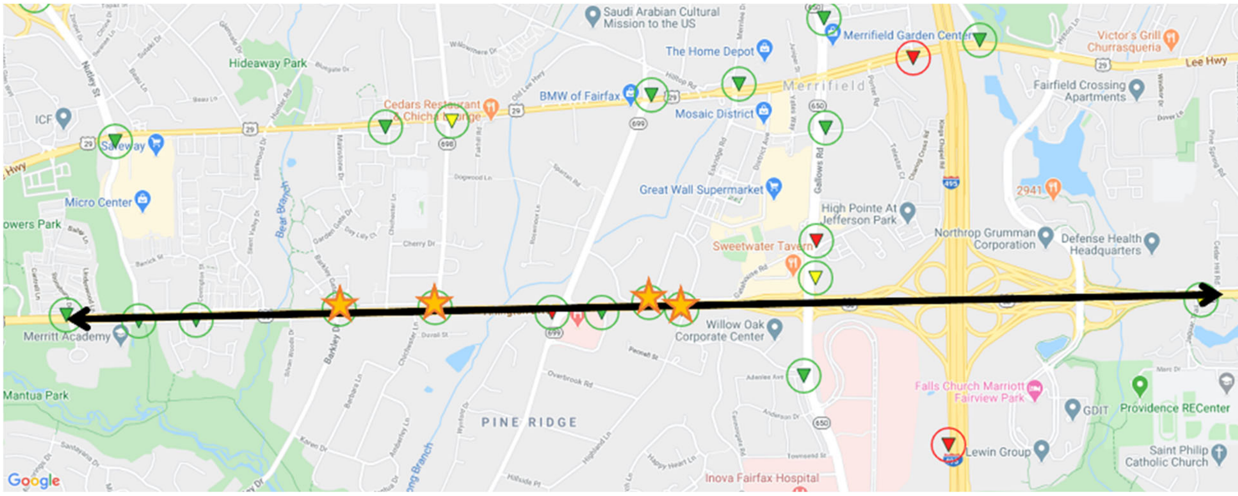


Source: Google, with overlay by VCC and test routes.

Figure 7. Map. Test route at Gallows Road and Yorktowne.

Table 3. Summary of data collected from Gallows Road and Yorktowne intersection.

	Roadside Unit	Moving Vehicle Onboard Unit	Moving Vehicle Cellular	Stationary Vehicle Onboard Unit	Stationary Vehicle Cellular
Number of records	184,100	373,653	2,540	390,496	2,522
Average data entry size (bytes)	652.08	728.04	558	595.77	558
Maximum data entry size (bytes)	1583	2727	558	2727	558
Minimum data entry size (bytes)	558	347	558	128	558
Average file size (kilobytes)	60,326	68,149.24	95.21	58,610.44	101.32
Maximum file size (kilobytes)	60,326	83,635.30	350	103,878.87	346.64
Minimum file size (kilobytes)	60,326	51,462	0.60	12,141.37	0.60
Average duration of data files (minutes)	139.47	50.04	14.86	49.46	15.80



Source: Google, with overlay by VCC and test routes.

Figure 8. Map. Test route for U.S. Route 50 Corridor.

Table 4. Summary of data collected from U.S. Route 50 corridor.

	Roadside Units*	Moving Vehicle Onboard Unit	Moving Vehicle Cellular	Stationary Vehicle Onboard Unit	Stationary Vehicle Cellular
Number of records	938,918	123,382	2,666	153,475	2,855
Average data entry size (bytes)	590.56	706.24	558	646.23	558
Maximum data entry size (bytes)	1906	2634	558	2634	558
Minimum data entry size (bytes)	558	240	558	189	558
Average file size (kilobytes)	60,100	33,006.50	136.36	36,073.50	140.78
Maximum file size (kilobytes)	75,331	34,669	1502	57,253	1609
Minimum file size (kilobytes)	39,063	31,017	0.60	22,171	0.60
Average duration of data files (minutes)	238.71	78.04	16.38	79.46	17.36

* Roadside unit numbers consider data files from all four intersections involved in this test.

CHAPTER 3. DATA CHARACTERIZATION

This chapter describes the analysis of the collected data set during the tests. The results are grouped based on observations and metrics. The metrics are defined based on observed latency over DSRC and cellular networks. In addition to the analysis, data were pre-processed to identify values that deviated further away from the median, considering them outliers. The outliers were eliminated by first finding the interquartile range (IQR) based on first quartiles (Q1) and third quartiles (Q3). The outliers were removed using the following method:

$IQR = Q3 - Q1$

Outliers lower cutoff = $Q1 - 1.5 \times IQR$

Outliers upper cutoff = $Q3 + 1.5 \times IQR$

The algorithm will give more weight to the values closer to the median and potentially remove data points further from the median value. The actual value of the cutoff range depends on the spread of the collected data and the interquartile range. A more detailed explanation of this approach is provided in appendix A.

LATENCY ANALYSIS RESULTS

Latency in wireless communication is defined as the amount of time for a transmitted packet to reach a receiver. Latency is also analogous to delay. For example, the amount of time it takes for a data packet from an OBU to reach an RSU is the latency of that data transfer. In this study, data were collected at three points, as shown in Figure 1: SPaT messages are broadcast from the RSU antenna interface via DSRC, SPaT message received on OBU via DSRC, and SPaT message received on laptop via VCC Cloud (cellular networks). The latency of the data collected was analyzed through three methods: 1) SPaT message transmitted from RSU and received at OBU via DSRC, 2) SPaT message transmitted from RSU and received on the laptop via cellular, and 3) difference in time when the same SPaT message was received at OBU with DSRC and on a laptop with cellular.

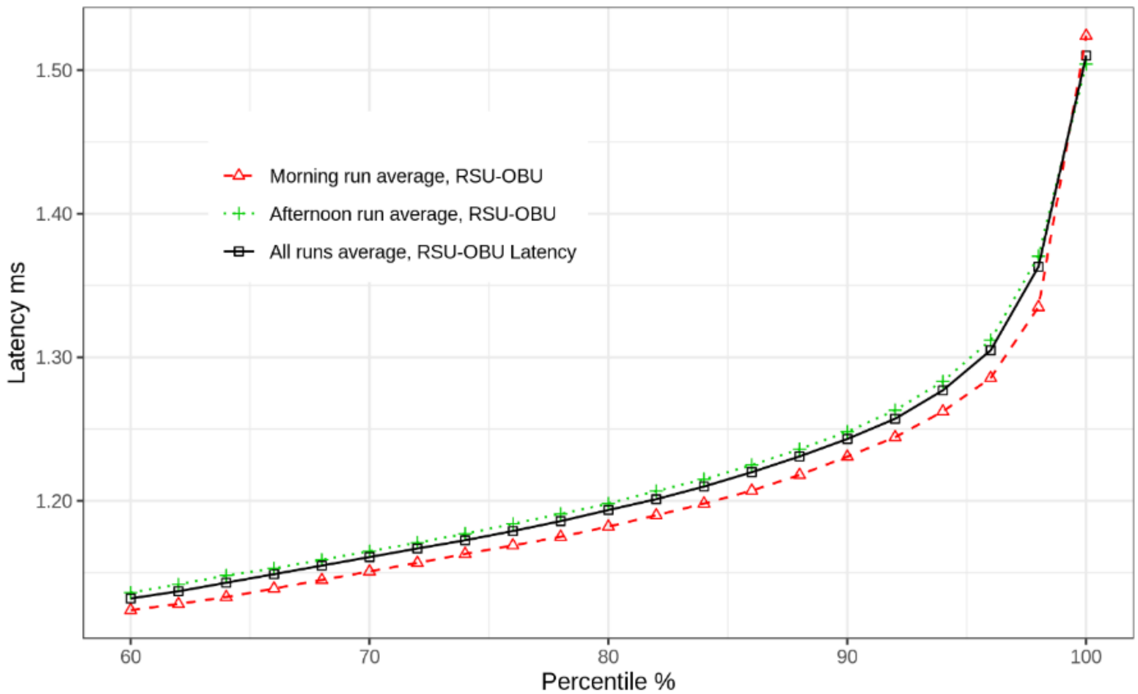
For the latency to be valid, the two events must be time-synchronized with a reliable time source. In this case, the time sync was maintained using GPS. With consistent timing, the timestamps of messages within different device logs can be compared. Matching of messages between log files was done by taking the entire J2735 encoded payload from an entry in the sparser cellular data log and searching for an identical payload in the denser DSRC data logs. Once a match is made, the difference in timestamps for the two entries gives the difference in latency between the two.

Here we present latency observed over different wireless networks at different locations when the tests were run at various times of the day in the morning and afternoon. A set of tests were run in the morning (9:30–11:30 a.m.) and another set was run in the afternoon (1:30–3:30 p.m.). In this case, the latency observed over the test runs is presented in terms of percentile analysis, which will show the variability of data over confidence percentages. Outliers embedded in the data were removed before analyzing and plotting the observations. The confidence levels are divided from 60 percent to 100 percent and show how the latency varies over that span. The starting range was selected to be 60 percent because the values above the median (50 percentile) carry more information about the confidence of the analysis. Also, the variation in latency below 60 percentile was found to be much smaller than variation in latency above 60 percentile (e.g., 21.27 percent for below 60 percentile and 78.73 percent for above 60 percentile for cellular latency at VA–7/Springhill Rd. location, and 18.82 percent for below 60 percentile and 81.18 percent for above 60 percentile for DSRC latency at the same location). The latency observations at the various locations are presented next.

Virginia Route 7 and Springhill Road

DSRC Latency between Roadside Unit and Onboard Unit

The latency data collected between RSU installed at VA–7/Springhill Rd. and an OBU was used in this analysis. Figure **9** shows the latency data observed between the DSRC broadcast interface of RSU and the DSRC interface of the OBU. The data are plotted by grouping morning runs and afternoon runs separately, as well as all runs into one data structure separately for analysis. The change in latency for morning and afternoon data collection is found to be less significant for this location, e.g., at 90 percentile the variation in latency for morning and afternoon data collection is about 0.02 ms. The solid line in Figure **9** shows the average percentile latency plot observed with both morning and afternoon sessions accumulated together. The average latency at this location varies from 1.13 ms to 1.25 ms over the range of 60–90 percent, while it varies from 1.25 ms to 1.51 ms from the range of 90–100 percent.

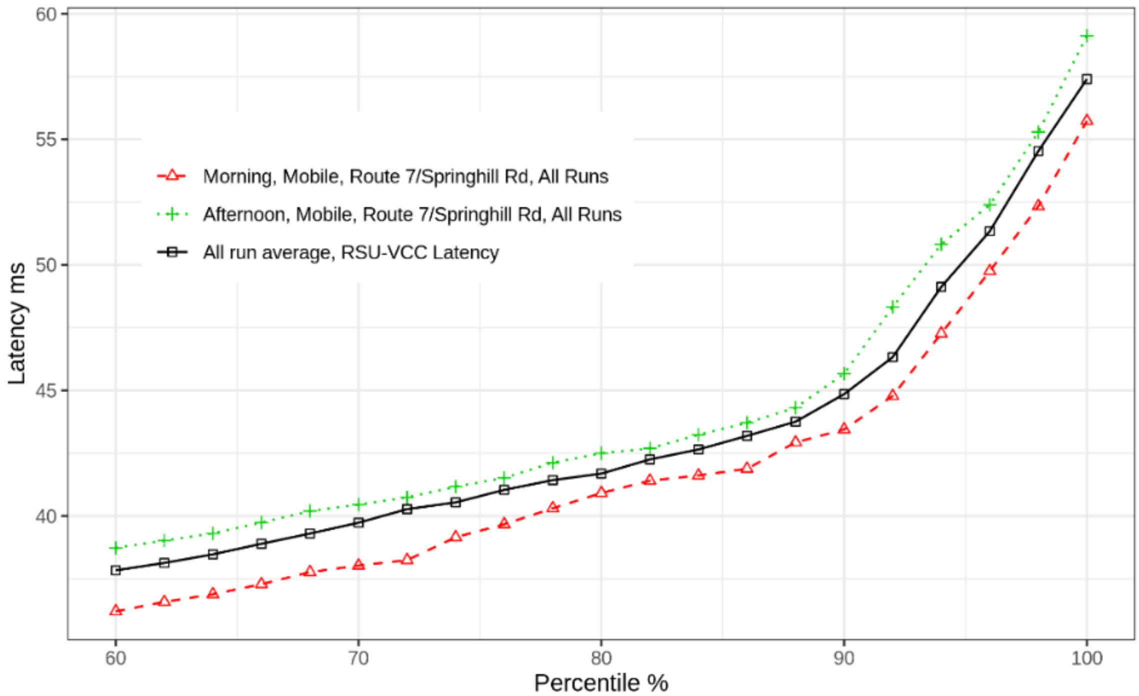


Source: Federal Highway Administration.

Figure 9**. Chart. Dedicated short-range communication latency at Virginia Route 7 and Springhill Road.**

Cellular Latency between Roadside Unit and Laptop

The latency data collected between RSU and the laptop with cellular service is shown in Figure **10**. The data were collected at points C and G, based on Figure 1**Error! Reference source not found.**. For plotting these results, the data were gathered into two groups: morning session and afternoon session. As seen in Figure **10**, a noticeable difference is observed between morning and afternoon sessions; e.g., at 90 percentile the difference in morning and afternoon session latency observed at this location is 3 ms. It can also be seen that between 60 and 90 percent, the average latency (the solid line in Figure **10**) varies from 36 ms to 45 ms, whereas the average latency varies from 45 ms to 55 ms from 90 to 100 percent.

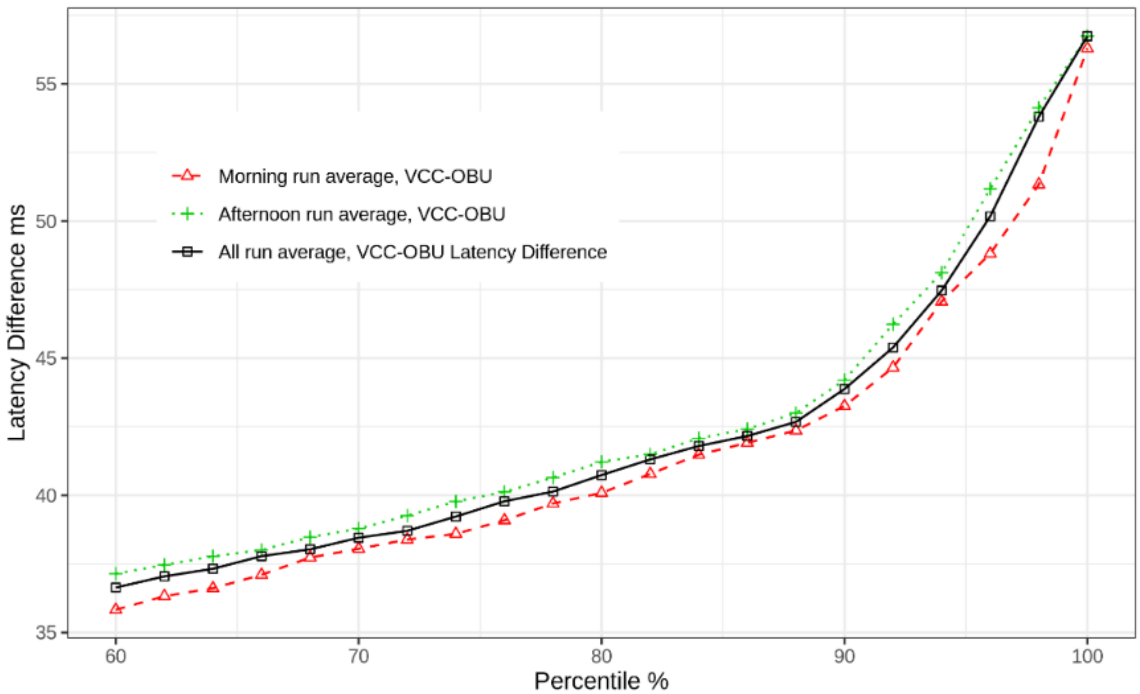


Source: Federal Highway Administration.

Figure 10**. Chart. Cellular latency at Virginia Route 7 and Springhill Road.**

Latency Difference between DSRC and Cellular

The latency difference is calculated between points G and H, based on Figure 1. The latency difference between DSRC and cellular data for morning and afternoon sessions with the average for the morning, afternoon, and the overall test is shown in Figure **11**. The values are calculated based on the observation made at the OBU and laptop simultaneously. It is interesting to note that morning sessions had smaller latency differences compared to the afternoon, however, the tests were not conducted for redundancy so this property could not be verified for correlation. The latency difference values change from 37 ms to 44 ms over the range of 60 to 90 percent, while it changed from 44 ms to 57 ms from 90 to 100 percent.

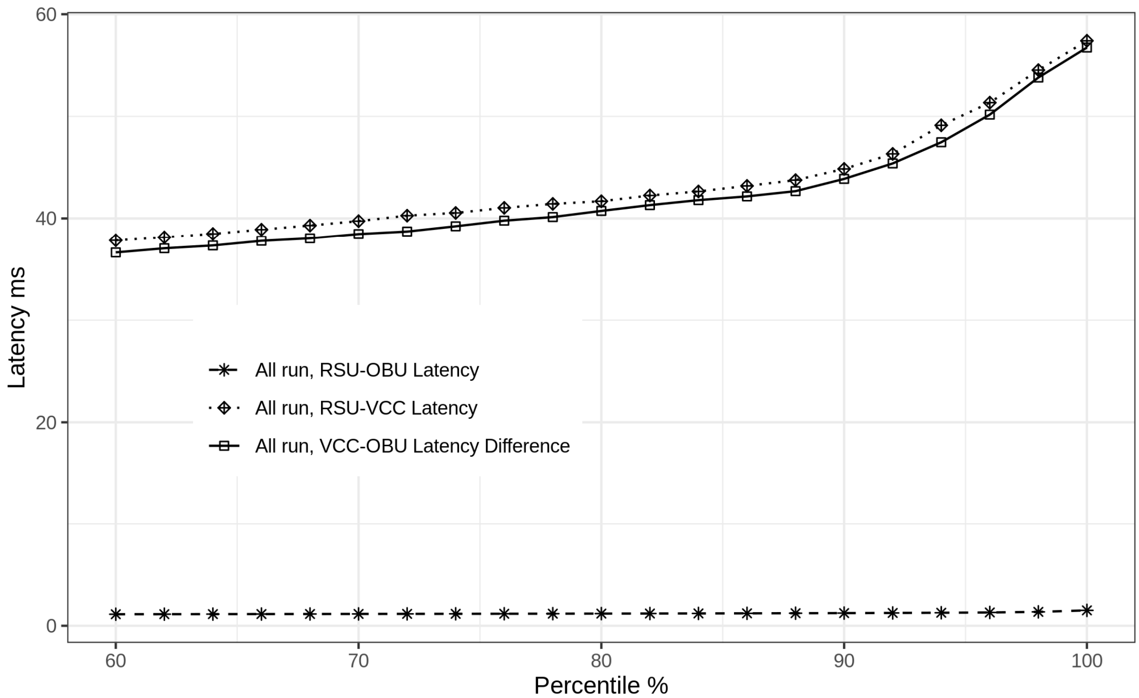


Source: Federal Highway Administration.

Figure 11. Chart. Latency difference between dedicated short-range communication and cellular at Virginia Route 7 and Springhill Road.

Average Latency: DSRC, Cellular, and Difference

The plot in Figure **12** shows the latency and latency difference observed at this location. These are calculated using all available data for the location. As expected, the latency between RSU and VCC and latency difference between VCC and OBU have similar trends.



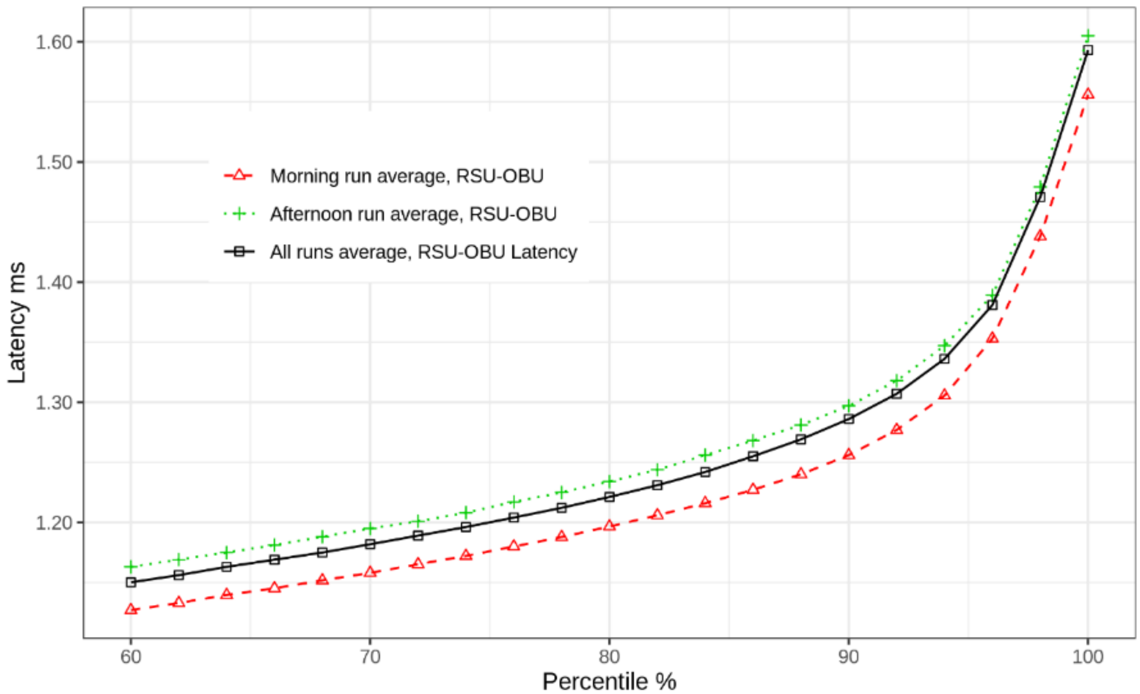
Source: Federal Highway Administration.

Figure 12. Chart. Average latency and difference at Virginia Route 7 and Springhill Road.

Gallows Road and Yorktowne

DSRC Latency between Roadside Unit and Onboard Unit

The test was conducted at the Gallows Rd. and Yorktowne intersection without considering any arterial direction because of the location. Figure 13 shows the percentile latency, in ms, between RSU and OBU along with the average latency observed overall. Like the VA–7/Springhill Rd. intersection, the latency at this intersection was found to be slightly smaller in the morning session compared to the afternoon. In the same way, the difference of 0.04 ms is not significant, and within the measurement error. On average, the latency varied from 1.15 ms to 1.28 ms from 60 to 90 percent, and from 1.28 ms to 1.60 ms from 90 to 100 percent.

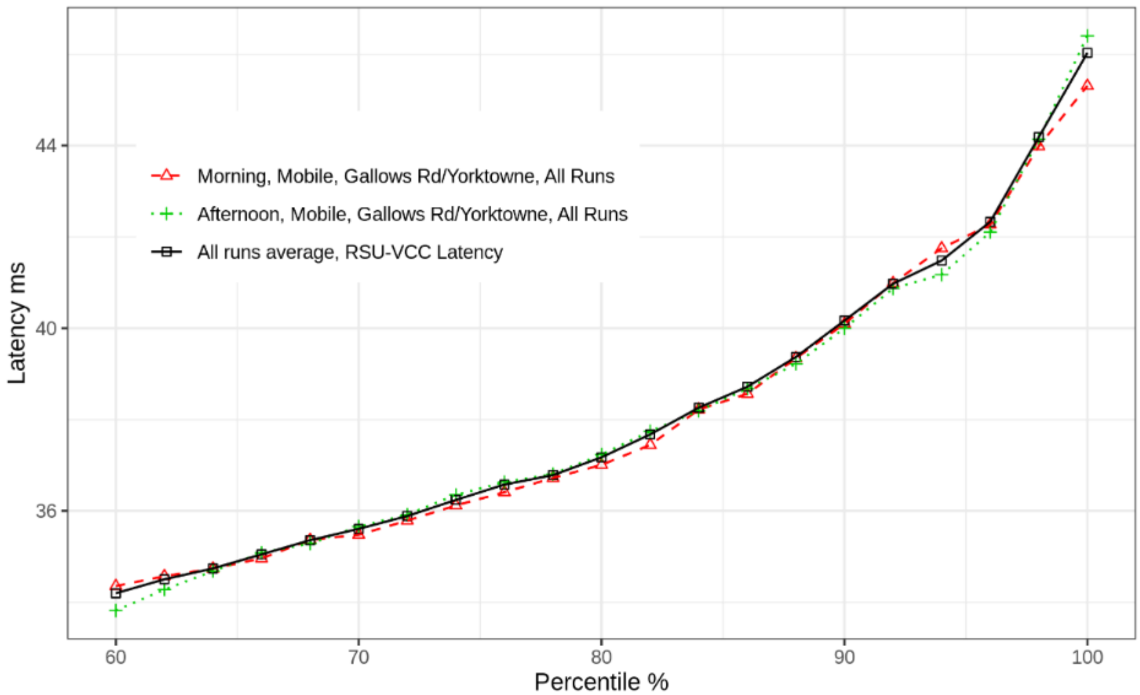


Source: Federal Highway Administration.

Figure 13. Chart. Dedicated short-range communication latency at Gallows Road and Yorktowne.

Cellular Latency between Roadside Unit and Laptop

The data collected over cellular was used to plot the latency between RSU and VCC, as shown in Figure 14. Interestingly, the location had little effect on cellular data latency with respect to time of day. Overall, the latency varied from 34 ms to 40 ms from 60 to 90 percent, and from 40 ms to 46 ms from 90 to 100 percent.

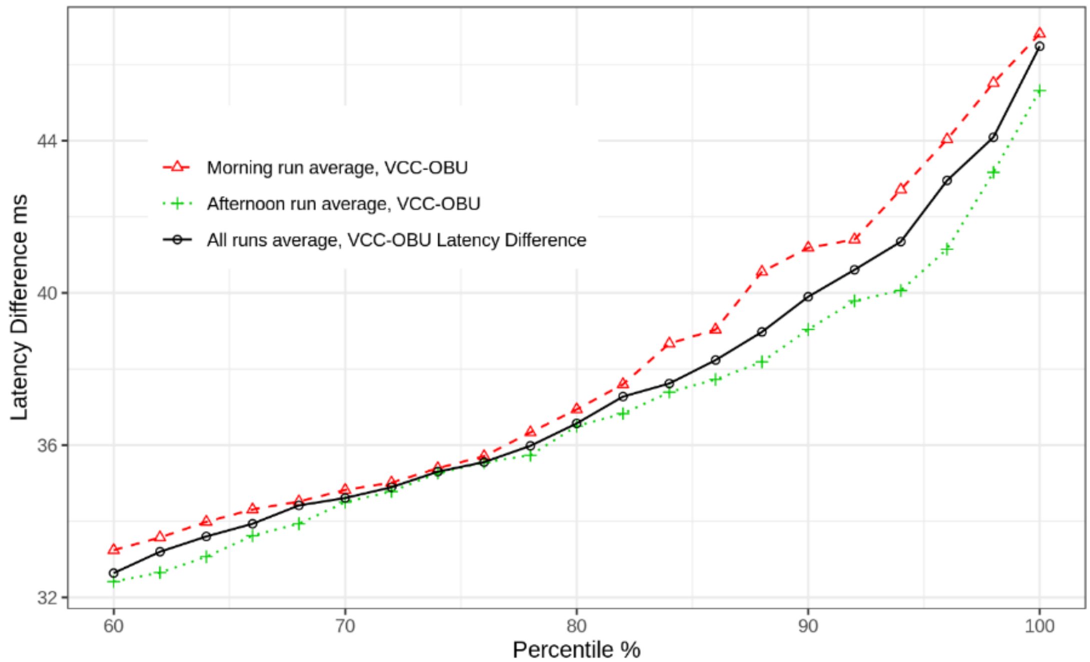


Source: Federal Highway Administration.

Figure 14**. Chart. Cellular latency at Gallows Road and Yorktowne.**

Latency Difference between DSRC and Cellular

The latency difference at this location is plotted in Figure **15**. As before, the data are grouped between morning and afternoon sessions and into one overall collection. It is interesting to note the latency difference increased from morning to afternoon session, and this trend was different from that of the previous location.

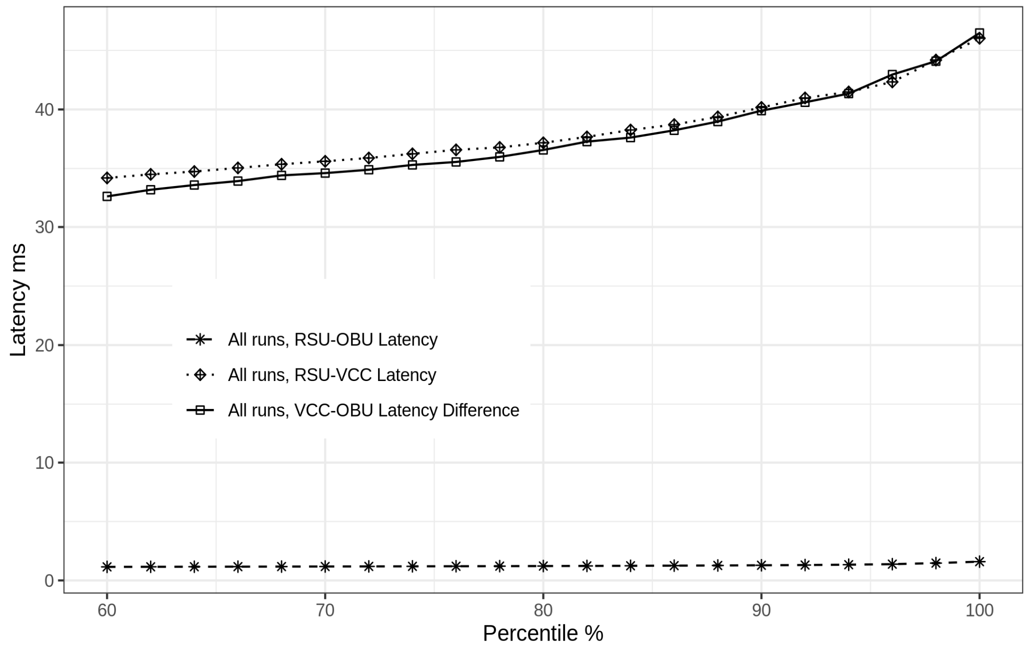


Source: Federal Highway Administration.

Figure 15**. Chart. Latency difference between dedicated short-range communication and cellular at Gallows Road and Yorktowne.**

Average Latency: DSRC, Cellular, and Difference

Finally, the average latency and latency differences observed at this location are plotted in Figure **16**. The plot shows a similar trend to what was observed in the earlier analysis. However, at the 96th percentile, the latency difference is found to be larger than the cellular latency. This may appear as an anomaly, but as explained in chapter 2, the plots were created using three separate data sets that were processed separately. The analysis seems to imply a relation between the three, but while the test was being conducted, the data were collected at three points independent of each other. This plot is done using all the data that were collected at three separate data collection points: OBU, RSU, and the laptop. The three data sets were then used to calculate the values of latencies and latency differences. The data were then processed for removing outliers and analyzed in percentile statistical observation. The plot we see in Figure **16** shows statistical distribution rather than the absolute values, and hence are used to observe the trends of the latency values given percentage confidence.



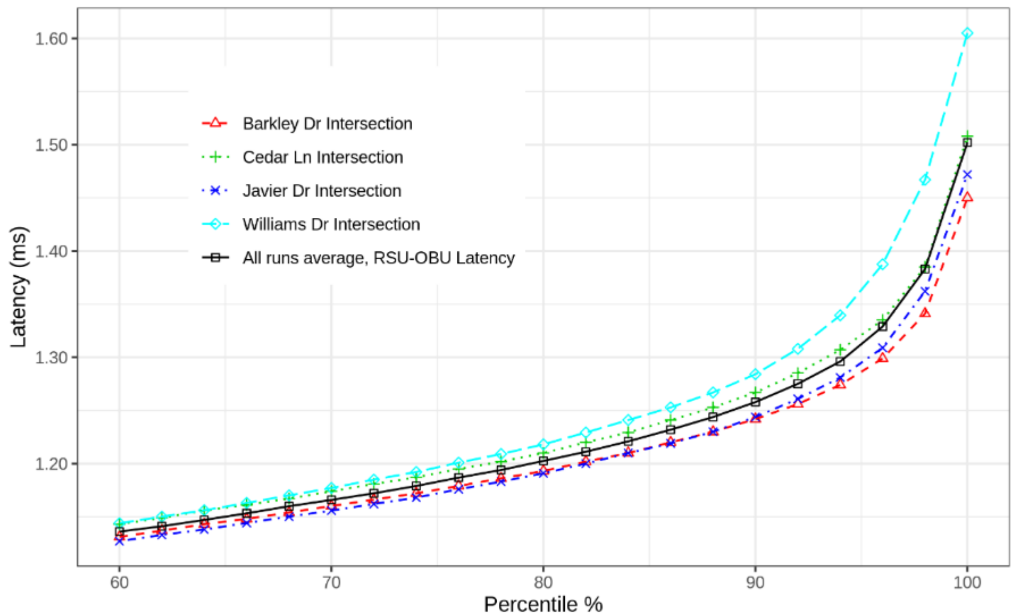
Source: Federal Highway Administration.

Figure 16**. Chart. Average latency and difference at Gallows Road and Yorktowne.**

U.S. Route 50 Corridor

DSRC Latency between Roadside Unit and Onboard Unit

The latency observed between RSU and OBU is plotted in Figure **17**. It is noted that there were no RSU logs available for Javier Drive (Dr.) during the afternoon session. There were two runs made during the test period and these data show both runs aggregated together. Figure **17** shows the latency percentile for each intersection and the overall average latency. The latency varies 1.14–1.25 ms from 60 to 90 percent, and 1.25–1.5 ms from 90 to 100 percent. It is interesting to note that Williams Dr. had a higher latency among the intersections, but the difference is relatively small and well within the margin of error.

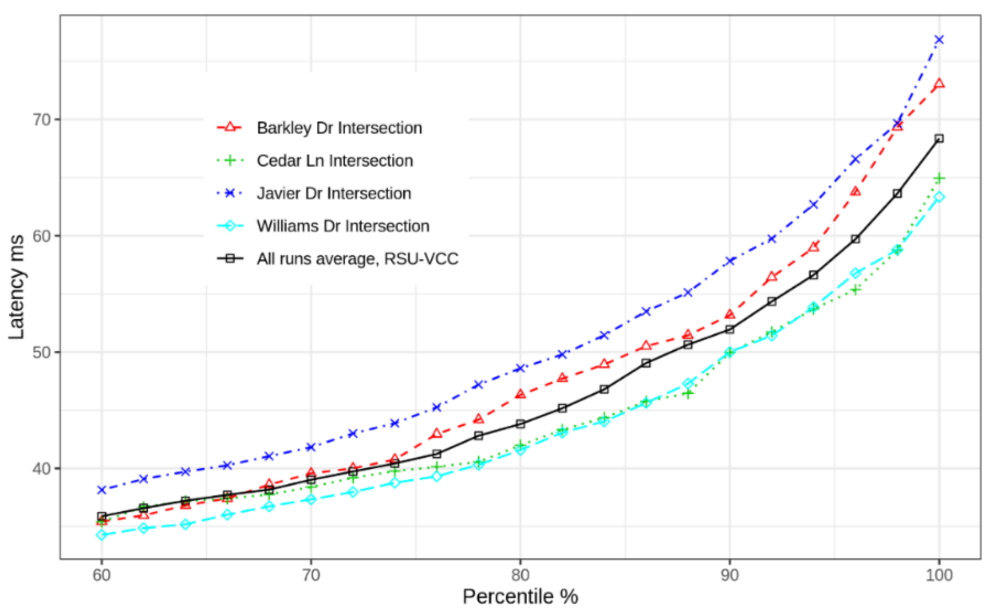


Source: Federal Highway Administration.

Figure 17**. Chart. Dedicated short-range communication latency along U.S. Route 50 corridor.**

Cellular Latency between Roadside Unit and Laptop

The latency between RSU and VCC is shown in Figure **18**. The data are presented for all intersections separately and together on average. On average the latency varied 42.5–51 ms from 60 to 90 percent, and 51–69 ms from 90 to 100 percent.

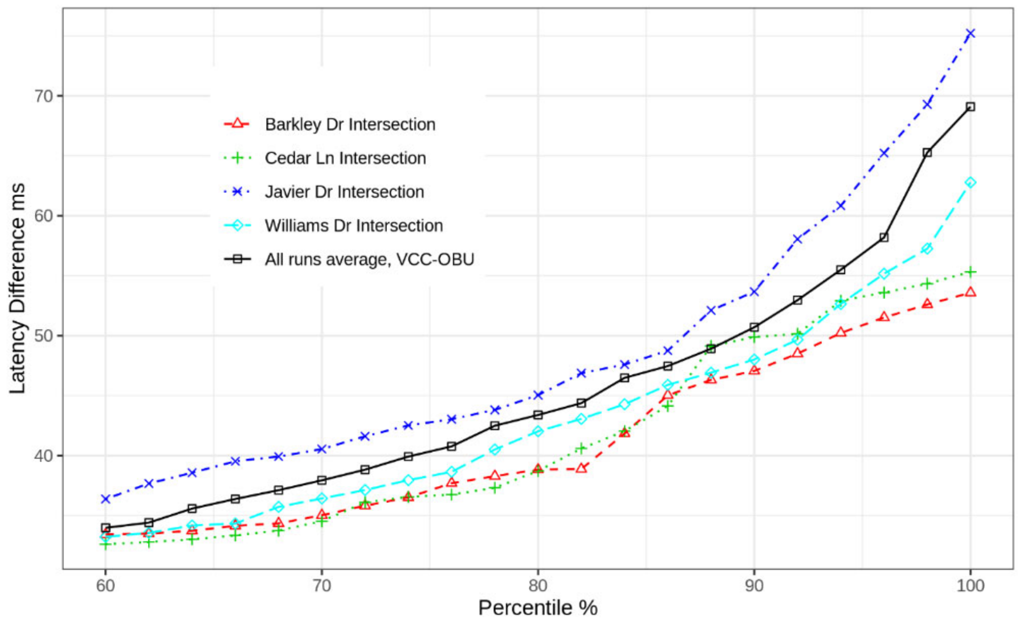


Source: Federal Highway Administration.

Figure 18**. Chart. Cellular latency along U.S. Route 50 corridor.**

Latency Difference between DSRC and Cellular

The latency difference observed between VCC and OBU is plotted in Figure **19**. As expected, the trend follows a similar pattern as Figure **18**, since the latency between RSU and OBU is much smaller compared to that between RSU and VCC.

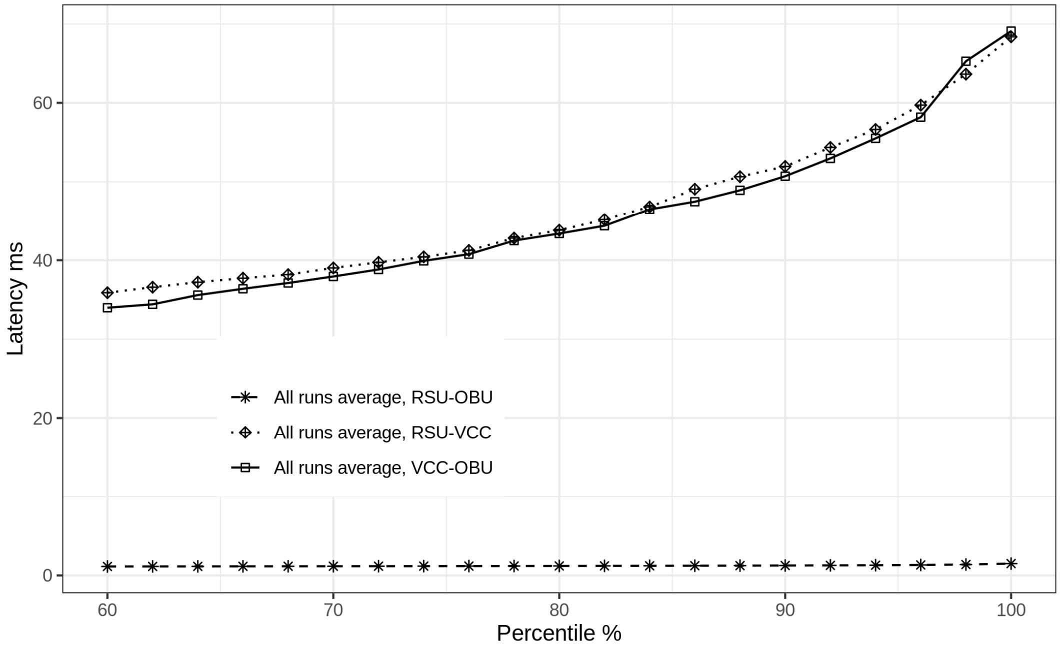


Source: Federal Highway Administration.

Figure 19**. Chart. Latency difference between dedicated short-range communication and cellular along U.S. Route 50 corridor.**

Average Latency: DSRC, Cellular, and Difference

Figure 20 shows the average latency and latency difference over the percentile observed in the corridor. All data collected for different intersections were put together for this analysis. As expected, the overall latency difference and latency between RSU and VCC followed a similar pattern, except for a few percentile values where the latency difference was larger than the cellular latency. Because Figure 20 was created with three different data sets processed separately, they may not have direct correlation as expected. This manifests, specifically, in Figure 20 as the difference between the VCC–OBU trace and what would be expected by taking the difference between the other two traces. The observation in Figure 20 is used to understand the trends of latency values.



Source: Federal Highway Administration.

Figure 20. Chart. Average latency and difference along U.S. Route 50 corridor.

SPATIAL COVERAGE ANALYSIS RESULTS

Latency data logged at various locations and GPS locations logged during the test can be used to plot a spatial observation over longitudinal distance. This helps understand the latency as the vehicle moves along the test route. The origin of the *x*-axis is placed at the Williams Dr. intersection along with the locations of three other intersections, as presented in **Error! Reference source not found.**. Table 5 shows the longitudinal distance of each intersection from Williams Dr. intersection.

Original map: ©2019 Google Earth™ (see Acknowledgments section).

Figure 21. Screenshot. Site location at U.S. Route 50 corridor with multiple intersections and elevation profile.

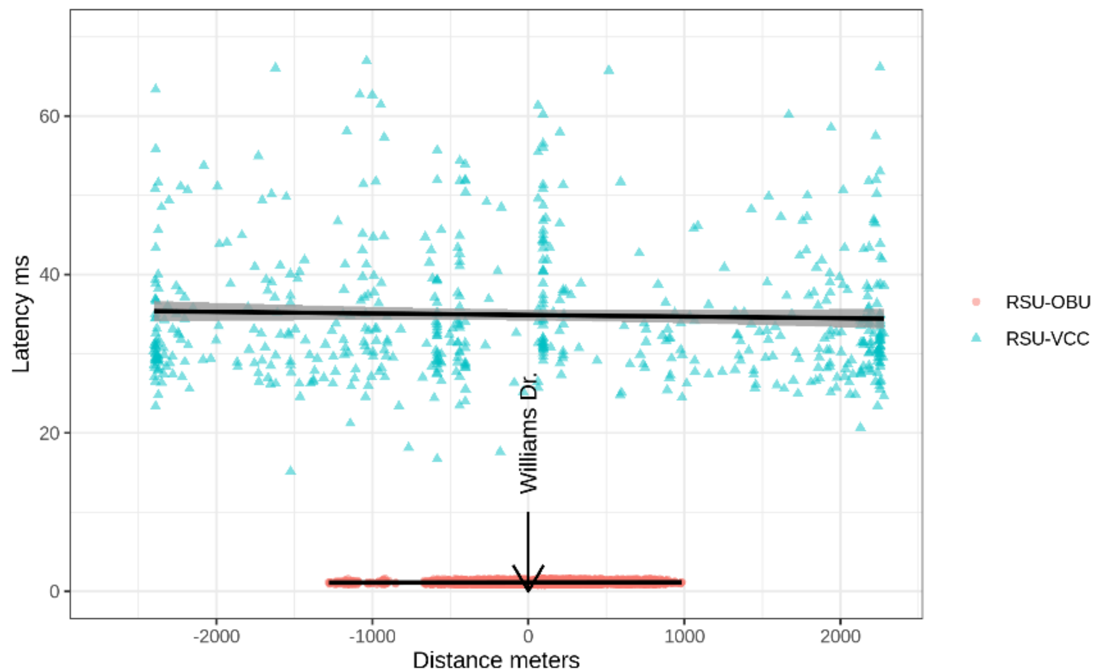
Table 5. Intersection information at U.S. Route 50 corridor.

Intersection Name	Distance from Williams Drive (meters)	Direction from Williams Drive
Javier Drive	147.34	Toward west
Cedar Lane	1,087.50	Toward west
Barkley Drive	1,510.35	Toward west

The latency over longitudinal distance is plotted for analysis. In Figure 22, Figure 23, Figure 24, and Figure 25, the *x*-axis range shows the length of the test drive. The plots also show the locations of individual intersections with respect to the Williams Dr. intersection, which is the origin of the *x*-axis. It is worth noting that the shorter range of DSRC at Cedar Lane intersection is due to the topographical location of the RSU in a dip (see Figure 21**Error! Reference source not found.**).

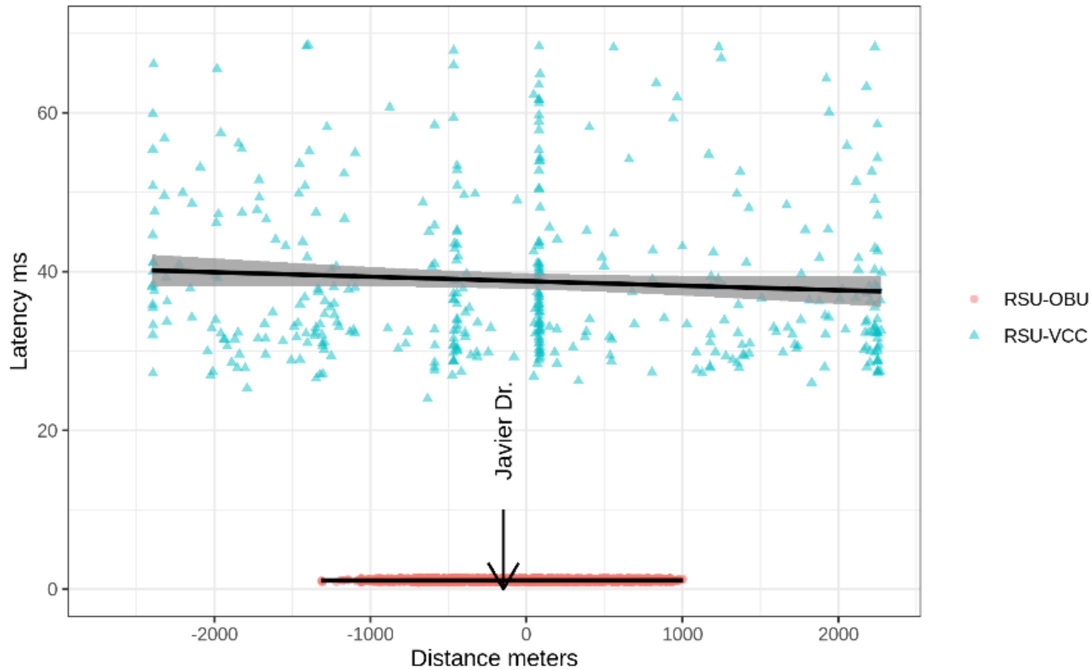
Figures 22–25 show the latency observed from RSU to OBU over DSRC and RSU to the laptop over cellular plotted along the *x*-axis, which is the longitudinal distance from Williams Dr. intersection over the length of the test. It is interesting to observe that cellular data had a much wider range, as expected, irrespective of the intersection; the latency is about 40 ms. However, DSRC is highly affected by range and it cuts off at different distances from the respective intersections based on intersection geometry and location topography.

The solid lines on the plots show a linear estimation line based on the observations of the latency. The shaded portion over the solid line is a representation of error during the linear estimation. If there are more data points available for estimation, the shaded region becomes smaller because more data points render higher confidence in estimation. Since there is a large difference in the number of data points collected through DSRC and cellular, at the rate of 10 messages per second for DSRC against only signal status change updates for cellular, the shaded regions look thicker for cellular compared to DSRC.



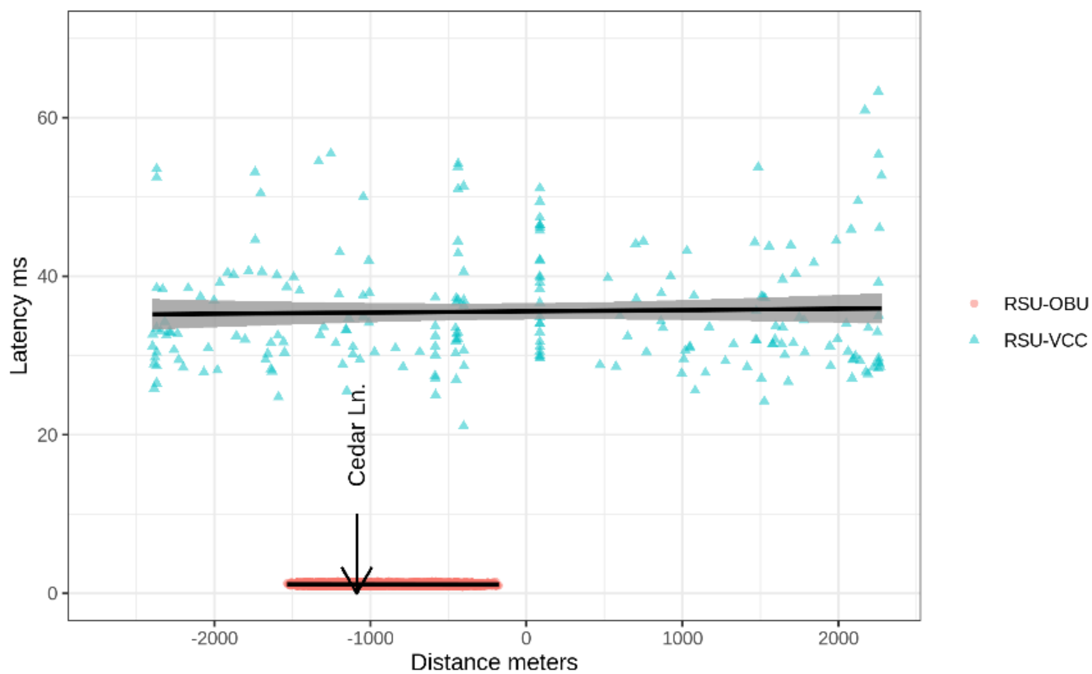
Source: Federal Highway Administration.

Figure 22. Chart. Latency versus distance at Williams Drive intersection.



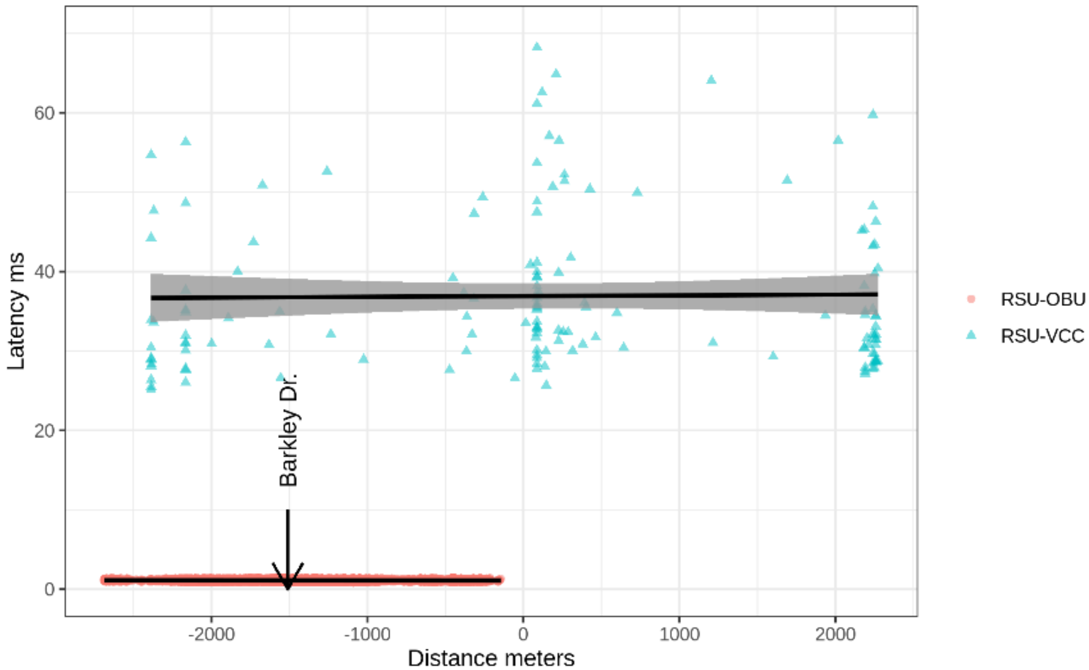
Source: Federal Highway Administration.

Figure 23. Chart. Latency versus distance at Javier Drive intersection.



Source: Federal Highway Administration.

Figure 24. Chart. Latency versus distance at Cedar Lane intersection.



Source: Federal Highway Administration.

Figure 25. Chart. Latency versus distance at Barkley Drive intersection.

RESULTS SUMMARY

The scope was to collect and analyze SPaT messages using two separate wireless network technologies: DSRC and cellular LTE. The DSRC network broadcasts SPaT locally in 5.9 GHz spectrum band where the SPaT messages are generated at the RSU after receiving National Transportation Communications for Intelligent Transportation Systems Protocol (NTCIP) 1202 messages (AASHTO 2018) from the traffic signal controller.

The flow of messages started at the traffic signal controller and included local network switches, the RSU, and an OBU in the vehicle. In comparison, the cellular long-term evolution (LTE) network includes, in general, base stations, the evolved packet core (EPC) network, and end-user devices along with a series of network switches and routers, which route the packets to their destination. The flow of messages starts at the signal controller and is routed to the VCC Cloud using a high-speed connection where it is then routed through different cellular network components before finally reaching the laptop. The analysis demonstrates the distribution of latency of the two different wireless technologies. Table 6 shows the summary of findings.

Table 6. Summary of latencies and ranges using dedicated short-range communication and cellular.

Type	Latency (milliseconds)			Range (meters)	
	Minimum	Median	Maximum	Minimum	Maximum
Dedicated short-range communication	0.80	1.10	1.50	430.53	1,365.50
Cellular	7.70	36.46	68.00	1,171.00	3,751.00

In addition to testing for latency, reliability was also assessed. Based on general observations of the data, no data losses occurred while cellular and DSRC channels were in use. However, obtaining SPaT data through cellular required a WebSocket connection to be initiated with the VCC servers. The WebSocket connection broke multiple times and needed to be reinitiated. This caused data loss if any SPaT packets were generated during the downtime. The reliability-based observations are specific to this implementation of the VCC-sourced SPaT data stream and may be improved by building robust applications and increasing the WebSocket idle closeout interval.

CHAPTER 4. ASSESSMENT OF SUPPORT FOR APPLICATIONS

The feasibility of selected ITS applications under DSRC and cellular network services are investigated in this section by evaluating applications for which V2I communications play a major role.

Upon discussion with stakeholders and investigation of the various applications that can be supported by the data collected, the following applications were selected:

- TOSCo.
- Glidepath.
- RLVW.
- TSP.

TRAFFIC OPTIMIZATION FOR SIGNALIZED CORRIDOR

TOSCo is an infrastructure-based application where a CV equipped with the TOSCo capability can make an intelligent decision about its trajectory as it approaches an intersection. The vehicle must have wireless communication equipment and should include a processor that can support the TOSCo mobility application. TOSCo-capable intersections are equipped with an RSU that can broadcast J2735 SPaT messages, MAP messages, and information about the presence of traffic queues at the intersection. The TOSCo-capable vehicles receive the SPaT, MAP, and queue information from the intersection and calculate their approach policy and speed profile toward the intersection. The approach policy is such that the TOSCo vehicle can either pass the intersection within the bounds of the green state or slow down to a stop because it is unable to safely cross the intersection. The approach speed profile is calculated to either cruise at the same speed, speed up, or slow down to safely pass the intersection or to slow down smoothly and come to a safe stop.

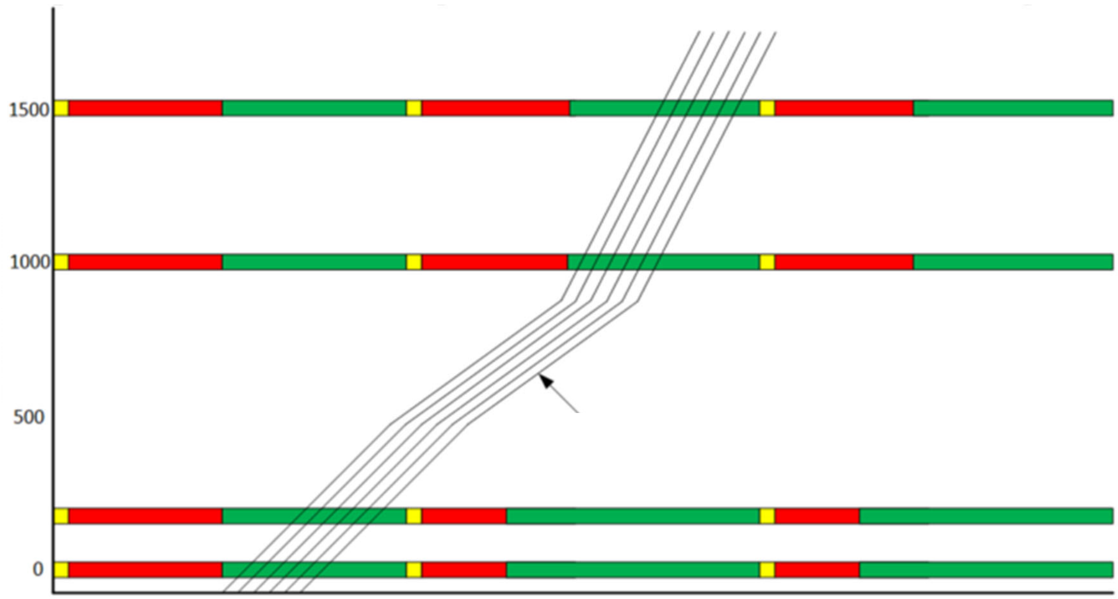
A key feature of the TOSCo application is that it handles vehicles operating in a cooperative adaptive cruise control (CACC) string. TOSCo vehicles form a CACC string as they approach the intersection. There is a lead vehicle in the string and several followers. Each follower's driving control is dependent on inputs from its radar, which measures BSM, distance, and relative velocity from the vehicle immediately in front. A leader would use CACC or adaptive cruise control (ACC), depending if there is a vehicle traveling ahead of it and if that vehicle has CACC availability. When the platoon enters DSRC range from an intersection broadcasting SPaT and queue information, TOSCo optimization takes priority over CACC. Therefore, based on the rated speed, length of the queue, and inter-vehicle gap within the string, each vehicle recalculates its speed profile and may react differently to the intersection information. An interesting scenario occurs when the string splits because of inadequate time and space at the intersection for the full length of the string to pass safely. If such a scenario occurs, then a new string is formed with the first stopped vehicle at the intersection assuming the role of string leader. The TOSCo application allows for a coordinated starting maneuver of the vehicles so that energy consumption and delay are minimized as the vehicles leave the intersection at the start of the next green phase.

TOSCo has been simulated for corridors with more than one intersection in a series with a spacing of 100 meters (m) to more than 1 kilometer (km). The results presented so far indicate that execution of TOSCo on a corridor with lower speed limits (35 miles per hour [mph] to 50 mph) improves stop and delay time with increasing DSRC range (FHWA 2019). The overall intersection delay and vehicles per second improve if the TOSCo-equipped vehicles can receive SPaT much earlier compared to the typical DSRC range. From the results in task 3 of this project, the following observations can be made about DSRC range and cellular range:

- DSRC range = 400–1,400 m.
- Cellular range = 1,200–3,800 m (based on the range of the test run).

The cellular network is ubiquitous, and the longer range of communication can provide support for SPaT messages to be delivered to the vehicles much farther upstream on a corridor. The VCC mobile app running within the vehicle may determine vehicle location and trajectory using GPS data, and obtain SPaT data for multiple signalized intersections in its path from the VCC Cloud. If there are several intersections in a row along a corridor, sharing information about all of them can improve coordination among the vehicles, and can safely allow a string to pass through with minimum acceleration or deceleration. This includes speeding up in time to reach the next intersection (or series of intersections) in a planned manner so that energy consumption and delay are minimized and the string is not broken. It can be ascertained that when a string breaks and vehicles are forced to stop, it consumes more energy than if its speed remained constant because of the idle period at the intersection and subsequent acceleration phase.

Hence, assuming that cellular service is used to transmit intersection plans to vehicles farther upstream at a much larger distance compared to DSRC communication range, the use of cellular service can improve the performance of TOSCo vehicles, especially for fixed-time intersections where timing is predictable. If the intersections are actuated, then TOSCo provides a mechanism to calculate timings based on the latest SPaT message. This allows for multiple actuated intersections to benefit from cellular services as the maximum latency is found to be 68 ms, which is negligible for the TOSCo application. To further validate and investigate this analysis, a thorough simulation of TOSCo over longer communication ranges is needed. In addition, the algorithm for TOSCo needs to be updated so that it can coordinate speed profiles based on multiple intersections and not just one. Figure 26 shows an example use case for the TOSCo vehicles with longer communication coverage provided by pervasive networking, such as cellular services. It can be inferred that with information available about downstream intersections, the TOSCo vehicles can make a better judgment on coordination and speed profile for optimized path planning. This aspect of TOSCo can be tested in the future.



Source: Federal Highway Administration.

Figure 26. Chart. Time-space diagram showing potential use case of cellular network for Traffic Optimization for Signalized Corridor systems. The distance is based on that of the four Virginia Connected Corridor intersections along U.S. Route 50.

GLIDEPATH

Glidepath (FHWA, 2016) is a mobility application designed to optimize the energy consumption caused by frequent acceleration or deceleration of a vehicle when approaching an intersection, and to improve safety. The motivation lies in developing an algorithm to either cruise, speed up, or slow down a vehicle as it approaches an intersection based on the intersection signal state. The components required for Glidepath to function properly include: 1) a traffic signal controller that can generate SPaT messages, 2) a DSRC RSU that can broadcast the messages, and 3) a vehicle equipped with a DSRC OBU, GPS, computer processor, graphical display, and longitudinal control capabilities. The SPaT messages received by the vehicle from a nearby intersection are used to determine its trajectory. The prototype Glidepath application under study relies on the signal controller to be operating on a fixed time mode. The SPaT messages were broadcast at 10 hertz (Hz) (period = 100 ms) from an intersection.

From the results in task 3 of this project, it was observed that latency for DSRC communication is less than 2 ms, while the maximum latency for the cellular network is 68 ms. Although the cellular latency is significantly higher than DSRC latency, the data suggest that a SPaT message using the cellular network can reach an intended vehicle within the bounds of the 100-ms period that is widely used for SPaT message broadcast and required by the prototype Glidepath application. Therefore, the cellular network can be a feasible alternative mode of communication for Glidepath. In fact, the use of the cellular network was demonstrated on VDOT roads in a similar application that provides signal timing information to drivers of Audi vehicles[5]. An important feature of this application is that, to counter the effect of errors introduced by latency and position inaccuracies, the timing is not shown within 4 seconds of an expected signal state change.

Currently, the Glidepath application uses DSRC as the only mode of communication; hence, the limited range of DSRC played a vital role in developing the algorithm that selected the speed profile for the vehicles. When a vehicle enters the DSRC range of the RSU (typically 300–1,000 m), the SPaT messages received from the nearby intersection are used to find the set of green window periods, as shown in

(1) ***and***

(*2*).

$$\begin{cases} \left[t_0, g_e^{\{curr\}}\right] \cup \left[g_s^{\{next\}}, g_e^{\{next\}}\right], \ \textit{if Green at } t_0 \\ \left[g_s^{\{next\}}, g_e^{\{next\}}\right], \ \textit{if "Red" at } t_0 \end{cases} \qquad \textbf{(1)}$$

$$t^{cr} = \frac{d_0}{v_c} \qquad \textbf{(2)}$$

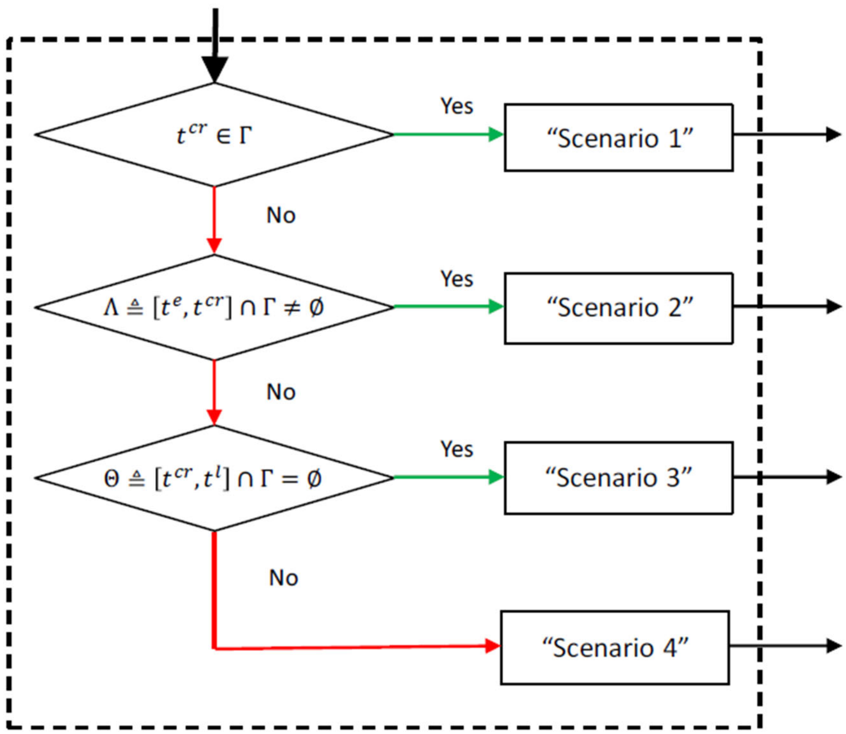
Where,

Γ = set of available green windows.
t_0= time at which the vehicle enters the DSRC range and receives SPaT update
$g_e^{\{curr\}}$ = end of current green window.
$g_s^{\{next\}}$= start of next green window $g_e^{\{next\}}$ = end of next green window.
t^{cr} = time to reach the stop bar in the nearest intersection.
d_0 = distance to the stop bar.
v_c = instantaneous speed of the vehicle.

Figure 27 shows a decision tree for the Glidepath trajectory planning algorithm. The algorithm moves through multiple decision points to select one from four scenarios. In scenario 1, the vehicle will arrive at a green light at its cruise speed and pass the green window safely within its cruise time, t^{cr}, so no speed adjustment is necessary. If scenario 1 is not applicable, then the earliest time to arrival, t^e ($t^e < t^{cr}$), is calculated, and whether speeding up would allow the vehicle to pass the intersection during the green time is estimated. Scenario 2 demonstrates the

[5] https://www.virginiadot.org/newsroom/statewide/2019/vdot-audi-and-tts-bring-traffic-light-information-technology-to-virginia2-21-2019.asp

vehicle approaching the intersection at a speed higher than cruising speed. If the vehicle is estimated to not have enough time to pass the green window, even with increased speed, then scenario 3 comes into play, in which the vehicle has to stop at the stop bar right before the intersection. However, scenario 4 defines an environmentally friendly way to glide through the intersection by slowing down to reach the intersection as the state changes from red to green, and easily pushing forward without a significant energy expense.



Source: Federal Highway Administration.

Figure 27. Diagram. Decision tree for Glidepath trajectory planning.

It is assumed that for the limited range of DSRC, the updates about current and next green window phases are sufficient to make the trajectory decisions. However, with the cellular networks, the distance at which the SPaT is received, (d_0), is much larger than that supported by DSRC, and the Glidepath algorithm can be updated to incorporate the larger scope of intersection information. A path planning optimization can be designed in such a way that it takes into account the available green windows at multiple intersections and plans the speed trajectory based on energy consumption or other priorities. This path planning optimization is similar to the improvement to TOSCo by using cellular networks.

RED LIGHT VIOLATION WARNING

The RLVW application enables a CV approaching an intersection to receive information from the infrastructure about the intersection's signal timing and geometry using the SAE J2735 SPaT and MAP message over the wireless interface. The OBU will consume this information and combine it with the speed, acceleration, and heading of the vehicle to determine if there could be a potential red light violation. If the OBU algorithm determines that the vehicle may enter the intersection while the phase is red for the particular lane the vehicle is traveling, it would send a warning to the driver of an imminent red light violation. The logic for providing the RLVW resides on the OBU and relies on the SPaT and MAP message broadcast from the intersection to compute the warnings.

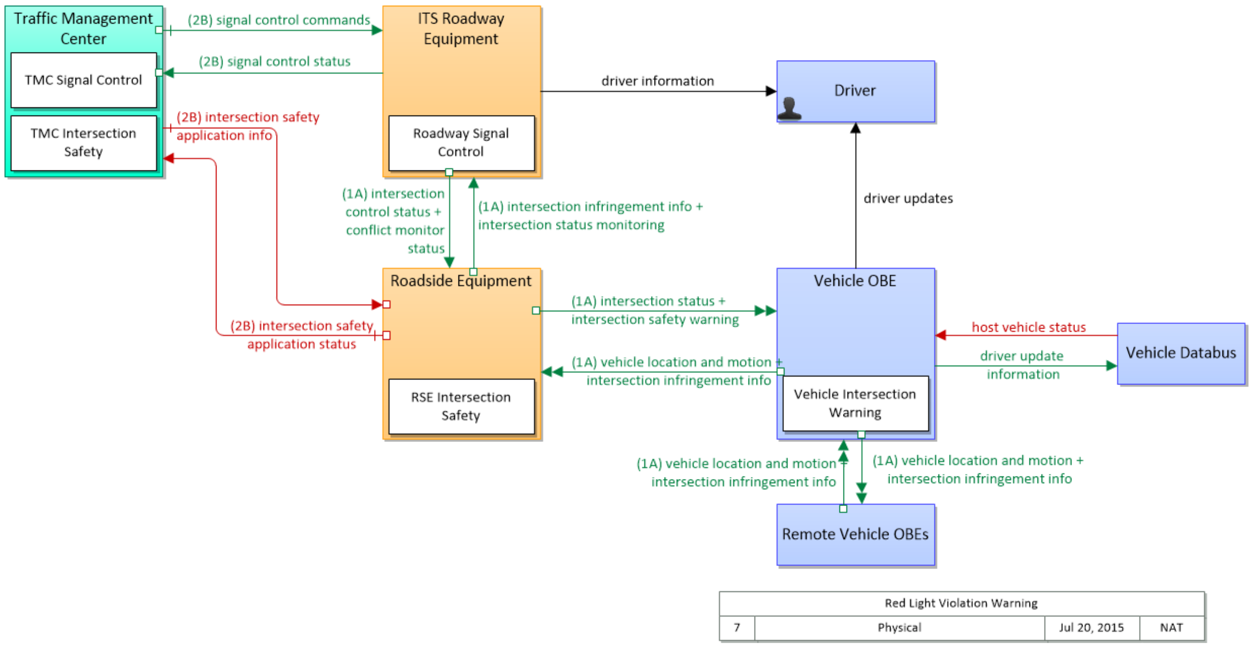
The J2735 SPaT information is generally broadcast at 10 Hz from the traffic signal controller using an RSU. The application warns potential violators of the signal status in time for the driver to take appropriate action. RLVW determines when the vehicle must begin slowing down in order to safely stop and avoid violating a signal. The average stopping distances at various speeds are mentioned in Table 7, which includes a reaction distance and a braking distance (New Jersey Motor Vehicle Commission 2019). The reaction time (0.75 seconds) is included in the calculation to provide insight into additional delays caused by driver behavior in such a scenario; reaction times may vary for individuals. The RLVW application is required to warn the driver at the total distance mentioned in the table from the stop bar (2019).

Table 7. Stopping distance and time for standard vehicle at various speeds.

Speed (km/h)	Reaction Distance (m)	Reaction Time (s)	Braking Distance (m)	Braking Time (s)	Total Stopping Distance (m)	Total Stopping Time (s)
16	3.35	0.75	2.44	1.10	5.79	1.85
32	6.71	0.75	9.45	2.13	16.16	2.88
48	10.06	0.75	21.04	3.16	31.10	3.91
64	13.41	0.75	37.50	4.22	50.91	4.97
80	16.77	0.75	58.54	5.27	75.30	6.02
96	20.12	0.75	84.45	6.33	104.57	7.08
112	23.48	0.75	114.63	7.37	138.11	8.12

km/h = kilometers per hour. m = meters. s = seconds.

The RLVW algorithm needs to know the location of stop bars at the intersection where RLVW is operating so it can calculate when it needs to notify the driver to stop. The information is made available from the J2735 MAP message, which is generally broadcast from the intersection at 1 Hz, as it is a static message, unlike the SPaT message. The RLVW algorithm also needs to know the current and short-term future signal state, which is available in the SPaT message at a signalized intersection. Finally, the RLVW algorithm needs to know the speed and acceleration of the vehicle, which are available from the vehicle itself or derived from GPS, though the timeliness of these data is not addressed in this report. Figure 28 depicts the architecture for a generic RLVW application and various data transfers that happen over the wireless interface and within the system to provide adequate warning to the driver.



Source: U.S. Department of Transportation.

Figure 28. Diagram. Architecture of red light violation warning application.

Based on the previous comparison of speed versus stopping distance, Table 8 shows the minimum time before a stopping event that is required to successfully implement RLVW by receiving SPaT and MAP information over DSRC versus cellular.

Table 8. Stopping time for standard vehicle at various speeds.

Speed (km/h)	Stopping Time (s)	DSRC Average Latency (s)	DSRC Average Total Time (s)	DSRC Max. Latency (s)	DSRC Max. Total Time (s)	Cellular Average Latency (s)	Cellular Average Total Time (s)	Cellular Max. Latency (s)	Cellular Max. Total Time (s)
16	1.848	0.001	1.849	0.002	1.850	0.050	1.898	0.068	1.916
32	2.876	0.001	2.877	0.002	2.878	0.050	2.926	0.068	2.944
48	3.906	0.001	3.907	0.002	3.908	0.050	3.956	0.068	3.974
64	4.969	0.001	4.970	0.002	4.971	0.050	5.019	0.068	5.037
80	6.019	0.001	6.020	0.002	6.021	0.050	6.069	0.068	6.087
96	7.084	0.001	7.085	0.002	7.086	0.050	7.134	0.068	7.152
112	8.119	0.001	8.120	0.002	8.121	0.050	8.169	0.068	8.187

km/h = kilometers per hour. max. = maximum. s = seconds.

The VCC system only sends SPaT data when there is an interval change event. The SPaT data contains time-to-change information in real-world time format. This means the vehicle will have to calculate a potential red light violation using an older message depending on either source. Table 9 shows the distance traveled by the vehicle if the status of the light changes at the minimum stopping distance from the stop bar. At this point, the vehicle would have crossed the minimum stopping distance, but the vehicle will likely violate the red light, because at the given speeds, the vehicle may not be able to successfully stop before the stop bar. These distances assume that the driver only relies on the RLVW to indicate when to stop the vehicle. They also ignore any processing delays associated with an actual implementation of RLVW, since those delays are not the focus of this study.

Table 9. Distance traveled after considering delay in dedicated short-range communication versus cellular.

Speed (km/h)	Stopping Distance (m)	DSRC Maximum Distance Traveled (m)	DSRC Distance Beyond Stop Bar (m)	Cellular Maximum Distance Traveled (m)	Cellular Distance Beyond Stop Bar (m)
16	5.79	5.80	0.01	5.95	0.16
32	16.16	16.18	0.02	16.49	0.33
48	31.10	31.14	0.04	31.59	0.49
64	50.91	50.94	0.03	51.54	0.63
80	75.30	75.34	0.04	76.10	0.80
96	104.57	104.59	0.02	105.45	0.88
112	138.11	138.15	0.04	139.21	1.10

km/h = kilometers per hour. m = meters.

Table 9 indicates that as vehicle speeds increase, an RLVW received over DSRC could cause the vehicle to overrun the stop bar by up to 0.04 m. However, in the case of cellular-based communications, the vehicle may end up as far as 1.10 m into the intersection. These distances are calculated solely on the basis of latency induced by the two communication technologies and reference human reaction times. There will be added processing delays, which have not been taken into account. These delays have been known to exist and would increase latency in the system causing the vehicle to overrun the stop bar farther, thus creating potentially hazardous situations.

The near-ubiquitous coverage of cellular-based V2I communications means that the vehicle could potentially receive SPaT information at distances much farther away from the stop bar. However, the RLVW application is designed to warn the driver only in the event of a potential red light violation. This requirement, along with the delay in receiving the messages immediately after an interval change event and the lack of information about the duration of the next phase in the SPaT message, would nullify the advantage of receiving the message much sooner.

It may be inferred that it is not feasible to use cellular-based communications for safety-based applications, such as RLVW, and it is recommended to use low latency wireless communications, such as DSRC. A hybrid system may also be used as long as DSRC is primarily used for receiving the SPaT messages that trigger the warnings.

TRANSIT SIGNAL PRIORITY

TSP is an infrastructure-based application that provides signal priority by calling a priority table on the TSC, if such a request is made for a particular phase at the intersection under consideration. The application consumes SAE J2735 signal request message (SRM), which is sent by the OBU in the transit vehicle. The SRM message has critical information about the trajectory of the vehicle, as well as the vehicle identifier (ID). Upon receiving the SRM, the RSU uses the information provided in the message, and the BSM identified by the vehicle ID, to request that the TSC at the intersection give priority to the approaching vehicle. Once priority is given, the controller sends out a signal status message (SSM) broadcast from the RSU to inform the approaching vehicle of the status of the request. The SPaT message further confirms the approval or rejection of priority to the transit vehicle. Figure 29 is a schematic of the Arizona implementation of the TSP application, as a part of the Arizona Multi-Modal Intelligent Traffic Signal System (MMITSS) project (University of Arizona 2016), and indicates the flow of data and the various nodes involved in the system.

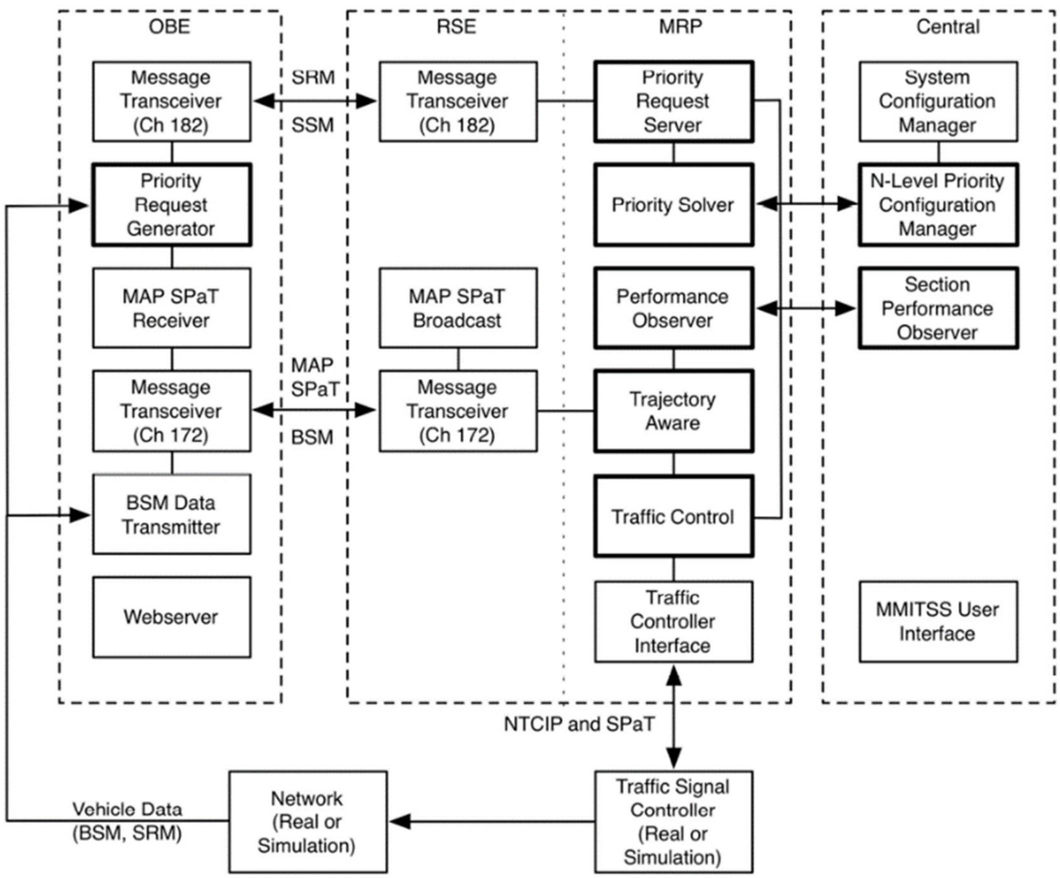


Figure 29. Diagram. Schematic of Arizona Multi-Modal Intelligent Traffic Signal System.[6]

[6] University of Arizona, University of California PATH Program, Savari Networks Inc., Econolite, Multi-Modal Intelligent Traffic Signal System—Phase II: System Development, Deployment and Field Test—Final Report (September 2016).

The following is a transit priority logic (Dion 2005) that replicates the actions of signal priority systems considering green signal extensions and early green recalls. This logic and further analysis have been adapted to fit the current CV infrastructure and the system deployed by the Arizona MMITSS (2016) deployment:

- Approaching buses are detected based on the SRMs at a user-specified distance upstream of the signal stop line. In the study, the distance was set at 100 m. This is used in the example use case.

- If a bus is to enter the intersection during the green interval, no signal alteration is made.

- If a bus is to arrive at the intersection after the end of the green, the green is extended at increments of *n* seconds until either the vehicle has left the approach or the maximum green is reached. An SSM indicating affirmative priority action is generated and sent to the RSU for broadcast. The time required for the extensions is taken from the next phases in the cycle that has not been reduced to its minimum allowed duration.

- If a bus is detected while traffic on another approach is being served, the active green phase is terminated after an increment of *n* seconds, or as soon as the minimum green time is satisfied, to allocate service to the approaching bus as quickly as possible. An SSM indicating affirmative priority action is generated and sent to the RSU for broadcast. The green is returned to the prioritized approach only after satisfying the minimum green, amber, and all-red intervals of all the intermediate phases in the phase sequence. Following the early green recall, the green time on the prioritized approach is terminated at its normal endpoint.

- If a priority request has already been granted during the signal cycle, no additional changes are made to the signal timings for the remainder of the cycle to minimize traffic disruption.

- Priority requests are granted on a first-come-first-served basis. In the highly unlikely event that two or more SRM requests are received at the same instant in time from conflicting approaches, no changes are made because there are no means to prioritize the priority requests.

This logic is further subject to the following constraints:

- Service of minimum green times assigned to each phase.
- Extensions cannot result in green phases exceeding their maximum defined duration.
- Cycle length is fixed in order to preserve coordination with adjacent intersections.
- No phase skipping while transitioning to and from a priority phase.

Based on the above constraints, (3) is used to determine the maximum allowed duration of a prioritized green phase. The maximum green is the time that remains within a signal cycle after subtracting all inter-green intervals and the specified minimum greens of all conflicting phases.

$$ge_{\max i} = \min\left(g_{\max i}\ ;\ C - a_i - \sum_{j=1}^{n} \left(g_{\min j} + a_j \right) \text{ for all } j \neq i \right) \quad (3)$$

where:

$ge_{\max i}$ = maximum allowed duration of phase i.
$g_{\max i}$ = user-defined maximum green for phase i.
$g_{\min j}$ = user-defined minimum green for phase j.
C = Cycle length.
a_j = inter-green duration at end of phase j.
n = Number of phases within signal cycle.

The Arizona MMITSS deployment (2016) implemented a similar priority logic to enable TSP at connected intersections using a combination of SAE J2735 messages, including SRM, SSM, BSM, SPaT, and MAP. Using the latency values generated in the comparative study between DSRC and cellular, the following in Table 10 may be inferred:

Table 10. 95th percentile latency of Multi-Modal Intelligent Traffic Signal System messages between roadside unit and vehicle.

DSRC SRM Latency (s)	DSRC SSM Latency (s)	DSRC Total Latency (s)	Cellular SRM Latency (s)	Cellular SSM Latency (s)	Cellular Total Latency (s)
0.002	0.002	0.004	0.068	0.068	0.136

DSRC = dedicated short-range communication. s = seconds. SRM = signal request message. SSM = signal status message.

TSP has a feedback loop using the SSM that informs the requesting entity of the status of the request. The receipt of the SSM completes the loop and enables the system to function efficiently. Based on the test scenario, at 100 m away, when the SRM is sent, the bus would have traveled the distances listed in Table 11 by the time the feedback is received.

Table 11. Distance traveled between signal request message and signal status message at various speeds.

Speed (km/h)	Distance Traveled with DSRC (m)	Distance Traveled with Cellular (m)
16	0.02	0.62
32	0.03	1.24
48	0.05	1.87
64	0.07	2.48
80	0.09	3.11
96	0.10	3.73
112	0.12	4.36

DSRC = dedicated short-range communication. km/h = kilometers per hour. m = meters.

If priority is given to the requesting vehicle, then stopping distance is not a concern. However, if priority cannot be given to the vehicle, and the vehicle must come to a stop, then an appropriate amount of time must be given to the driver. Table 12 shows the approximate stopping distance for a heavy vehicle, such as a bus, at various speeds. In the given scenario, in which the TSP request process begins 100 m from the intersection, there is little time to stop if the vehicle is traveling above 80 kilometers per hour (km/h). At speeds slightly above 80 km/h, the small difference in latency between DSRC and cellular would have an impact on the ability of the vehicle to stop. Cellular would require at least an additional 3 meters of stopping distance at or above 80 km/h. However, at speeds below 80 km/h, which is the case on most signalized corridors in the study area, the difference between DSRC and cellular would not significantly impact the ability of the vehicle to come to a stop prior to the intersection. The distance traveled between the SRM being sent and SSM being received does not include the processing time required by the infrastructure systems, as these times will be similar across DSRC and cellular. Any additional time required would reduce the performance of both systems, with the compounding effect being detrimental to the system with a larger delay.

Table 12. Stopping distance for heavy vehicles at various speeds.

Speed (km/h)	Reaction Distance (m)	Braking Distance (m)	Stopping Distance (m)
16	3.30	2.88	6.18
32	6.00	11.28	17.28
48	10.00	25.20	35.20
64	13.40	45.00	58.40
80	16.80	70.20	87.00
96	20.10	101.28	121.38
112	23.46	137.52	160.98

km/h = kilometers per hour. m = meters.

In other scenarios in which the TSP process is initiated farther than 100 m out, the difference between DSRC and cellular would be even less apparent. DSRC should reliably work beyond 300 m, provided that line of sight exists. However, cellular provides near-ubiquitous coverage, and if the system allows for it, the TSP process could be initiated significantly farther out. However, it may not be optimal for the transit vehicle to request priority when it is too far out because of potential stops and uncertainty related to traffic conditions. Hence, the simulation model mentioned in the analysis of the application uses the 100-m range. As the vehicle speed increases, the delay induced by cellular would tend to approach 5 percent of the total distance to the stop bar. This may be significantly larger when all system delays are included.

A similar scenario may be replicated for TSP applications for freight. However, freight vehicles do not take on passengers, and so would not be expected to stop between intersections as frequently as transit vehicles. As a result, cellular based-communications to provide signal priority for freight vehicles may be worth exploring. If a wireless communications-based TSP system is in place, it is recommended to default to the lower latency system to make it applicable to use with different vehicle types. A hybrid system may also be used as long as DSRC is primarily used for sending and receiving the SRM and SSM messages, respectively.

Another potential use case for signal priority is signal preemption for emergency vehicles. This is significantly different than how the TSP application interacts with the TSC. It uses a different methodology to force a signal preemption and provide passage to the emergency vehicle. The primary advantage, in the case of emergency vehicle preemption, is to clear the intersection for the emergency vehicle. However, the emergency vehicle has the right of way through the intersection, irrespective of the state of the light. Hence, a cellular-based approach may be advantageous to the emergency vehicle due to the increased range and emphasis on the SRM over SSM. Many factors would need to be considered with this approach—most importantly, how the system would limit disruption to normal traffic operations. For instance, an emergency vehicle could send a preemption request through cellular miles ahead of the target intersection. Such a request may be useful in clearing congestion in anticipation of the emergency vehicle, and sending SRM over cellular may have certain advantages. A more detailed examination of this case would need to be conducted to observe the overall effect on the system and the benefit to emergency responders.

CHAPTER 5. CONCLUSION

This project evaluated the effects of latency and coverage over DSRC versus cellular for three non-safety applications: TOSCo, Glidepath, and TSP; one safety application, RLVW, was also evaluated.

Data were collected at three different intersections in northern Virginia by driving along the primary road of the subject intersection, and arterial roadways across the intersection, to collect SPaT messages. For time-synchronization purposes, GPS-based time sources were used. The time-synchronized logs enabled a good measurement of the latency difference between the data collected using DSRC and cellular. An initial comparison showed that DSRC has a shorter range but very low latency (less than 2 ms), whereas cellular has a longer range, but higher latency (greater than 40 ms). On average, DSRC latency was found to be 1.4 ms, and cellular latency was found to be 50 ms.

Table 13 summarizes the feasibility of the applications considered in this study, based on data collected from VCC installation. Use cases based on using DSRC, cellular, and a DSRC and cellular hybrid system are considered. In the event of a hybrid system, it is recommended that all critical communication data are primarily exchanged over DSRC.

Table 13. Feasibility of applications using dedicated short-range communication and cellular.

Applications	DSRC	Cellular	Hybrid (DSRC and Cellular)
TOSCo	Yes	Yes	Yes
Glidepath	Yes	Yes	Yes
RLVW	Yes	No	Yes
TSP	Yes	No*	Yes

DSRC = dedicated short-range communication. TOSCo = Traffic Optimization for Signalized Corridor. RLVW = red light violation warning. TSP = transit signal priority.

*Cellular may be acceptable for TSP at speeds ≤80 km/hr

Based on the findings, it may be inferred that for applications like Glidepath and TOSCo, receiving SPaT data over cellular might enhance the performance of the system, as the delay induced by cellular may be negated by the message being received over a wider distance. This will allow the algorithm to initiate trajectory planning much sooner, thus improving overall efficiency of the system. Cellular-based message broadcast for such applications is recommended.

In the case of RLVW, the driver is alerted only in the possibility of a violation. Therefore, latency becomes a highly critical factor. It was observed that latency induced by cellular, processing delays from the various computational systems, and potential variability from tuning the violation warning to avoid unnecessary nuisance alarms may cause the vehicle to end up at a considerable distance beyond the stop bar, creating potentially unsafe scenarios. This could be mitigated by receiving cellular-based messages much sooner and over longer distances. However, the VDOT system that was studied sent messages only when there was an interval change. Based on the information available in the SPaT message, the vehicle will know when the phase state is going to change to yellow, but will not have information of the yellow change interval until the interval has changed and a new SPaT message has been generated. Any delay in receiving that message will lead to a situation where the vehicle might not be able to stop, even though it is on course to violate the light. Hence, cellular is not recommended for safety applications like RLVW in a system with this behavior.

For applications like TSP, the delay would be twice the standard delay for cellular, as the application works with a send-receive loop. In the algorithm that was used to determine feasibility, the vehicle would request priority at a distance of 100 m from the stop bar. It was observed that the latency might not have a substantial impact when the vehicle requesting priority is traveling at lower speeds (≤80 km/hr). However, in high-speed scenarios, a delay in response from the infrastructure could mean that the vehicle requesting priority might have to start reducing its speed before receiving the response from the infrastructure. The reduction of speed may be necessary because of limited roadway between the position of the vehicle and the stop bar at the intersection. This will reduce system efficiency. Hence, DSRC-based communications are preferred for TSP.

This project helped to develop a better understanding of the effects of latency and coverage on several CV applications. Other aspects of the SPaT data, including accuracy and reliability of data, may have an impact on the overall function of the system. Understanding these aspects and conducting end-to-end data collection would require additional access to the data sources, including controller logs and signal head wiring. Making these available for future research will add tremendous value to the analysis. In addition to testing a separate cellular network in comparison with DSRC, it may also be desirable to research a system that provides the capabilities of an integrated, cross-platform system, such as cellular-vehicle-to-everything (C-V2X) with LTE/5G sidelink, when such a system becomes commercially available. An initial deployment of a C-V2X system is already underway in northern Virginia[7]. With respect to the research conducted, it may also add value to further study the effects of a cellular-based preemption system for emergency vehicles to understand any changes in traffic behavior.

[7] https://www.qualcomm.com/news/releases/2020/01/22/audi-america-virginia-dot-and-qualcomm-announce-initial-c-v2x-deployment

ACKNOWLEDGMENTS

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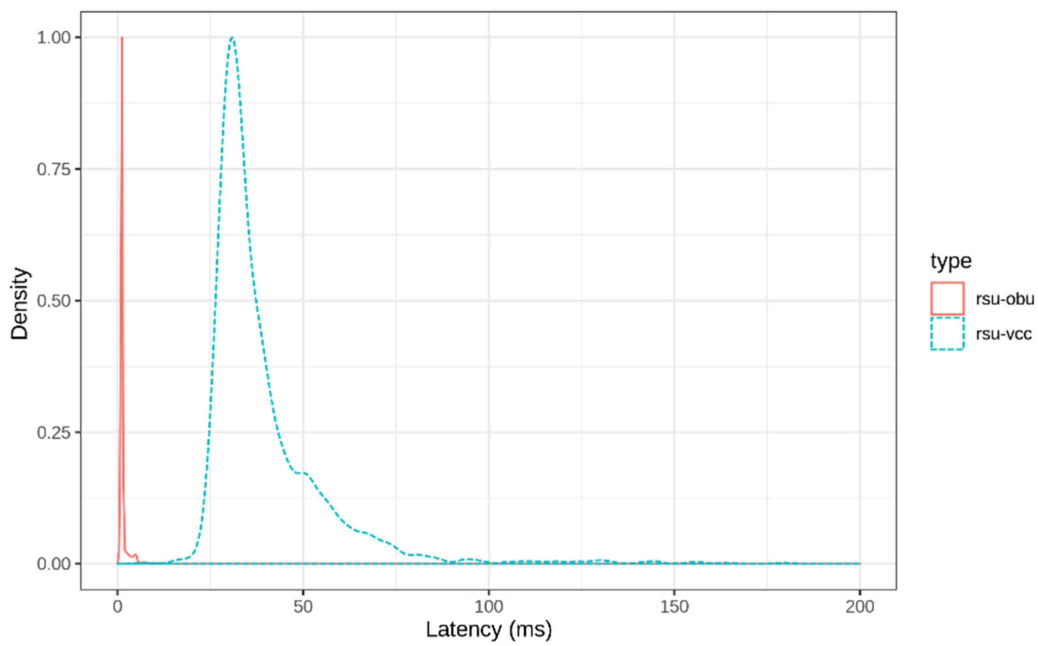
Virginia Tech Transportation Institute provided background information about the VCC Cloud network, provided a pre-configured Roadside Unit for preliminary testing, and provided the necessary data files from Roadside Units at each test site. This made a more complete analysis possible.

APPENDIX A. OUTLIERS

The methodology used to determine outliers and select them for removal from the data set is presented in this appendix. The data were collected as part of the test runs at different locations spanned over different days. The locations also presented different traffic scenarios so the correlation between the data sets was affected by the topography, traffic situation, and test run settings. Source: FHWA

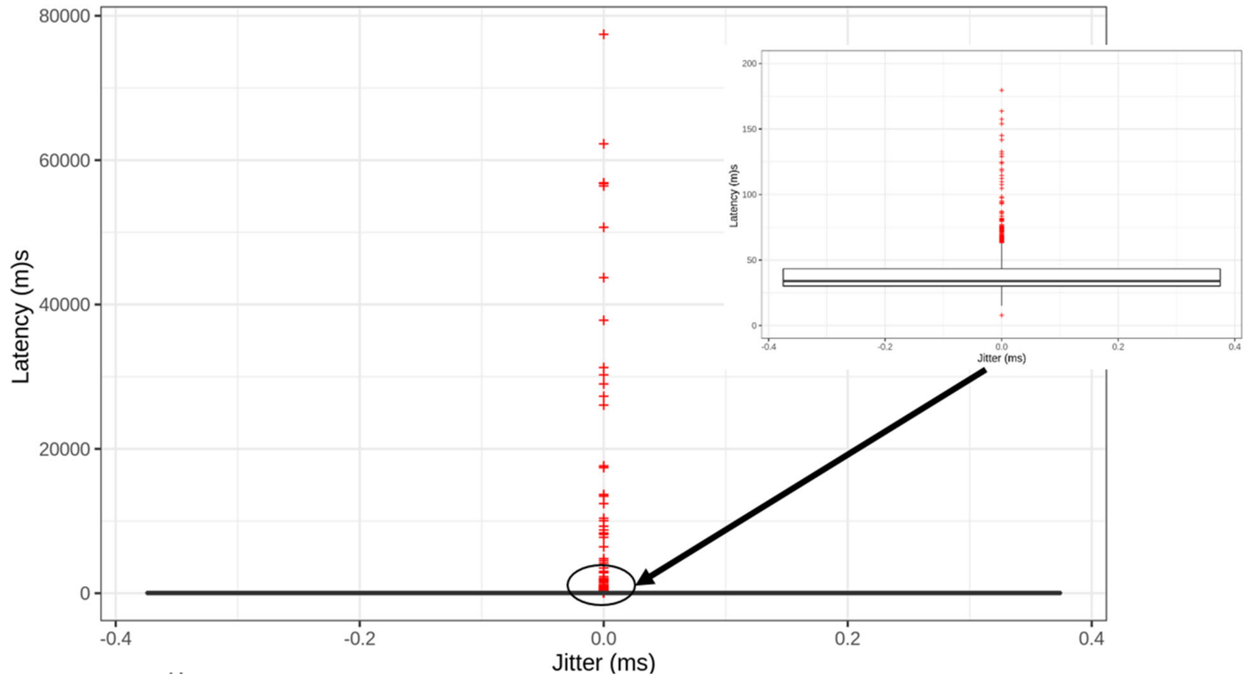
- Figure 30 shows the density plot with an emphasis on latency values between 0 and 200 ms only for all test runs conducted at US 50 corridor. It presents the density of latency data probabilistically for DSRC (rsuobu) in solid red line and cellular networks (rsuvcc) in dotted blue line. This shows that the most likely latency data occurs near the peak of the plots because as the peak is taller, higher will be the probability. The larger and smaller values of latency occur much less frequently; hence less probable.



Source: FHWA

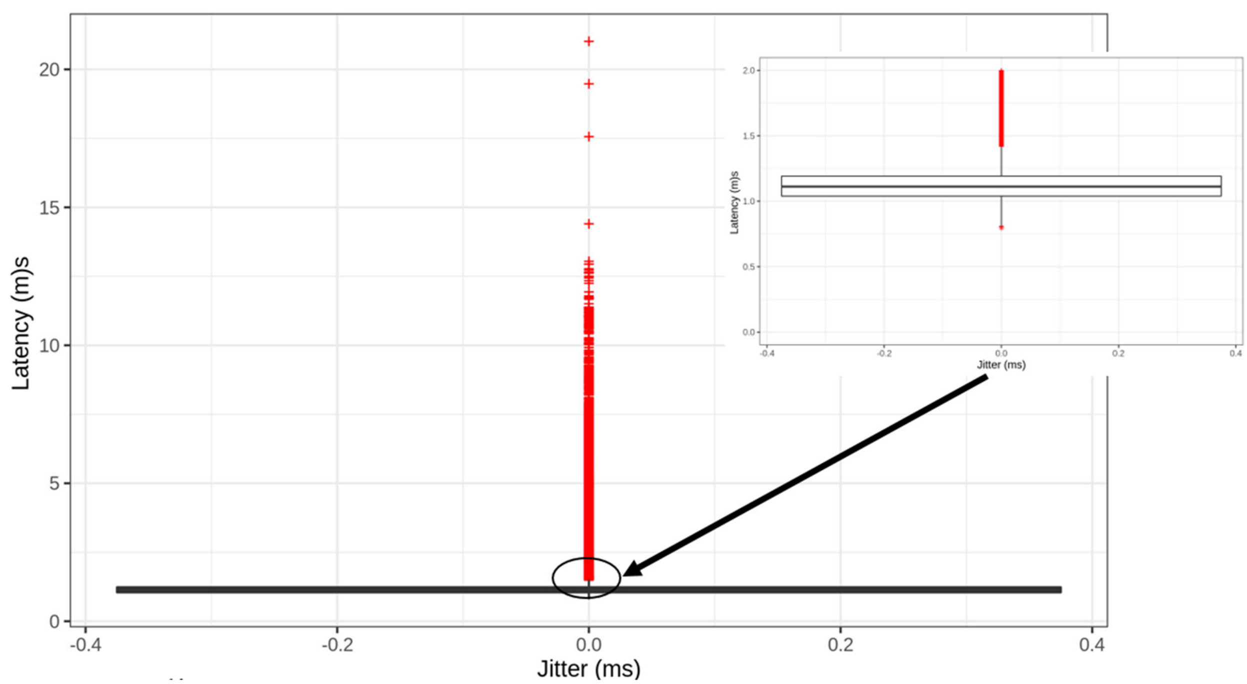
Figure 30. Chart. Density plot showing all data captured at U.S. Route 50 corridor during two test runs.

Source: FHWA
Figure 31 and Source: FHWA
Figure 32 show the boxplot of data collected at the US 50 corridor using DSRC and cellular networks. The blue dots on both figures represent the actual latency data collected during the test run. The red crosses represent the outliers detected by the boxplot. Also presented in the figures are zoomed-in sections showing a closer view of how the boxplot looks for each of the data sets. The boxplot can show the cutoff range for outliers as well as the IQR.



Source: FHWA

Figure 31. Boxplot. Latency collected using cellular network at U.S. Route 50 corridor (inset shows IQR and range).



Source: FHWA

Figure 32. Boxplot. Latency collected using dedicated short-range communication at U.S. Route 50 corridor (inset shows IQR and range).

From this observation, and also realizing the latency data did not follow a normal distribution, which prevented the use of classical outlier detection techniques (e.g., Grubbs test, Tietjen-Moore test), the IQR-based outlier detection process was used to identify and remove possible outliers from all data sets. This method is described as follows:

- Calculate the interquartile range IQR.
  IQR = 3rd quartile – 1st quartile = Q3 – Q1.
- Calculate inner walls for the outliers.
  Lower inner wall = Q1 – IQR * 1.5.
  Upper inner wall = Q3 + IQR * 1.5.

This method gives more weight to the median data points while considering data points farther away from the median less probable. Using this methodology, values obtained during the test that deviated from the median with a larger span and occurred with lesser probability were removed. For comparison purposes, the same methodology was used in all the data sets. Table 14 highlights the amount of data considered as removal from each data set.

Table 14. Percentage of data considered outliers during pre-processing step.

Data Type	Percent Removed
Route 7, Springhill Rd DSRC data	15.67
Route 7, Springhill Rd LTE data	12.56
Gallows Rd and Yorktowne DSRC data	15.76
Gallows Rd and Yorktowne LTE data	6.05
Hwy 50 Corridor DSRC data	13.45
Hwy 50 Corridor LTE data	10.59

DSRC = dedicated short-range communication. LTE = long-term evolution.

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