Advanced Messaging Concept Development (AMCD) Project Vehicle-to-Infrastructure Program

Final Report

www.its.dot.gov/index/htm
Final Report – June 30, 2017
FHWA-JPO-18-620

U.S. Department of Transportation
Federal Highway Administration

Produced by Crash Avoidance Metrics Partners LLC in response to Cooperative Agreement Number DTFH6114H00002

U.S. Department of Transportation
Federal Highway Administration

Notice

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The U.S. Government is not endorsing any manufacturers, products, or services cited herein and any trade name that may appear in the work has been included only because it is essential to the contents of the work.

Technical Report Documentation Page

1. Report No. **FHWA-JPO-18-620**	**2. Government Accession No.** (Remove; Insert Information Here or leave blank)	**3. Recipient's Catalog No.** (Remove; Insert Information Here or leave blank)

4. Title and Subtitle

Advanced Messaging Concept Development (AMCD) Project Vehicle-to-Infrastructure Program; Final Report;

5. Report Date

June 30, 2017

6. Performing Organization Code

FHWA-AMCD-FR-02

7. Author(s)

Stowe, L., Abubakr, M., Adla, R., Ali, M., Casadei, S., Goudy, R., Kailas, A., Kumar, V., Tafish, H., Yamamoto, M., Doerzaph, Z., Song, M., Viray, R., White, E., Deering, R.

8. Performing Organization Report No.

(Remove; Insert Information Here or leave blank)

9. Performing Organization Name And Address

Crash Avoidance Metrics Partners LLC on behalf of
the Vehicle-to-Infrastructure Consortium
27220 Haggerty Road, Suite D-1
Farmington Hills, MI 48331

Virginia Tech Transportation Institute
3500 Transportation Research Plaza
Blacksburg, VA 24061

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

DTFH6114H00002

12. Sponsoring Agency Name and Address

FHWA Headquarters
1200 New Jersey Avenue, SE
West Building
Washington, DC 20590

13. Type of Report and Period Covered

Final Report: July 8, 2015 – June 30, 2017

14. Sponsoring Agency Code

(Remove; Insert Information Here or leave blank)

15. Supplementary Notes

(Remove; Insert Information Here or leave blank)

16. Abstract

The Advanced Messaging Concept Development (AMCD) Project objective was to evaluate the ability of connected vehicles to generate, and infrastructure to collect, Basic Safety messages (BSM), Probe Data Message (PDM), and Basic Mobility Message (BMM) alternatives using cellular and DSRC communications while employing message control strategies in real-world driving conditions for non-safety-critical applications. These three message schemes represented potential alternatives for transferring data from equipped vehicles to the infrastructure. Such data transfer is intended to enable a broad array of Vehicle-to-Infrastructure (V2I) applications which may be used to improve operations.

AMCD implemented the three messaging schemes on the Virginia Connected Corridor with the aim of validating efficacy and characterizing their associated behavior. The schemes were exercised in live traffic using ten instrumented vehicles and an emulated traffic operation center interface where the experimenters manipulated the various message control parameters while measuring the resulting message traffic. Results support the feasibility of advanced V2I messaging and demonstrate potential advantages of a flexible, multi-threaded message scheme. A number of recommendations are provided with the aim of further improving V2I messaging capabilities and leading to implementation of advanced messaging with infrastructure applications to assess the operational value in deployment.

17. Key Words BSM, PDM, BMM, Vehicle-to-Infrastructure	**18. Distribution Statement** (Remove; Insert Information Here or leave blank)

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
(Remove; Insert Information Here or leave blank)	(Remove; Insert Information Here or leave blank)	**102**	(Remove; Insert

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Table of Contents

List of Figures

List of Tables

Executive Summary

Overview

The United States Department of Transportation (USDOT) sponsored research has identified data requirements for Dynamic Mobility Applications (DMAs) that cannot be satisfied by the data fields in the Basic Safety Message (BSM). Furthermore, many data elements required by DMA applications do not need to be collected at the 10 Hz frequency planned for the BSM nor transmitted with the low latency enabled by dedicated short range communications (DSRC). The objectives of the Advanced Messaging Concept Development (AMCD) Project were to evaluate the ability of connected vehicles to generate, and infrastructure to collect, BSM, Probe Data Message (PDM), and Basic Mobility Message (BMM) alternatives using cellular and DSRC communications employing basic message control strategies in-real world driving conditions for non-safety-critical applications.

The AMCD Project was conducted by the Crash Avoidance Metrics Partners LLC (CAMP) Vehicle-to-Infrastructure (V2I) Consortium (Ford, GM, Honda, Hyundai-Kia, Mazda, Nissan, Subaru, VW/Audi, and Volvo Truck) and the Virginia Tech Transportation Institute (VTTI) with support from the Virginia Department of Transportation (VDOT) through a Cooperative Agreement (DTFH6114H00002) with the Federal Highway Administration (FHWA). Technical program oversight was provided by FHWA.

System Concept and Testing

To accomplish the project's objective, the systems to support the transmission, receipt, and storage of the message schemes had to be designed and implemented on an operational roadway. The system concept was to link vehicles traveling on the roadway with the infrastructure through DSRC and cellular to allow for two-way communication, where the vehicles provide information about the situational driving environment based on data requests communicated to the vehicles by the Traffic Operation Center (TOC). This information was transmitted by three different message structures: BSM, PDM and BMM. The first two message types are defined in SAE J2735 (2009). The 2009 version of J2735 was used as the 2016 version was not released until after the project was underway and compatible devices were not yet available.

The BSM utilized the standard software integrated by the manufacturer into the On-Board Unit (OBU) and Road Side Unit (RSU). The manufacturer also developed the software to generate the data messages (DMs) and control messages (CMs) for the PDM based on the published standard. Work performed as part of the preceding BSM Data Emulator Project provided the message framework for the BMM and its associated control strategy. VTTI, in collaboration with the CAMP V2I Consortium, developed the BMM structure for the OBU and RSU. Both the PDM and BMM collected snapshots of data at variable sample intervals and supported periodic and event-driven messaging. While the PDM and BMM attributes are often comparable, there are fundamental difference such as the BMM's higher reliance on CMs and its support for simultaneous data message streams relative to the PDM's single stream DM method.

The backend software to support the advanced messaging schemes was developed and integrated into the existing Virginia Connected Corridor (VCC) hardware and software platforms including the development of an experimenter control interface (provided a pseudo TOC control center for development and testing of the message schemes). The Virginia Department of Transportation assisted the project team with the installation of RSUs along a selected segment of the VCC specifically targeted for AMCD. Associated hardware and software was also installed on ten experimental vehicles including integration with the vehicle CAN data network to populate DM with representative dynamic payloads.

Testing was performed in two phases. Prototype testing was performed at the VTTI Smart Road test bed using two equipped vehicles. The primary focus of prototype testing was to validate base functionality and iteratively develop the message schemes. Full-scale testing involved 10 vehicles and took place over three days on the VCC in Northern Virginia along Route 7 where the RSUs were located.

Full-scale test scenarios exercised the messaging schemes with data from the 10 vehicles stored on the VCC Cloud for later analysis. Testing on the VCC was performed during different times of the day across light and heavy traffic conditions. During testing, an experimenter used the VCC Monitor Application to orchestrate vehicle and messaging activities from controlled testing to more natural vehicle traversals, during which time the drivers could choose their path and actions around the test bed. This allowed the collection of a controlled dataset for specific analysis while also providing an indication of how the system may operate under normal conditions. It is important to note that the work performed within AMCD was focused on assessing the feasibly of advanced message schemes and characterizing the Data Message (DM) and Control Message (CM) behavior. The project did not make conclusions regarding the relative performance of the message schemes; which will require infrastructure applications (beyond the scope of AMCD).

Results

The three primary research topics included characterizing the communication modes, message types and control schemes. The research showed that the DSRC communication range is generally good (>500 m), but that range is also significantly impacted by line-of-site obstacles that are likely to exist. These obstacles can either help or hinder the transmission of the messages via DSRC. Cellular provided sufficient coverage in the urban area to reliably transmit messages. However, in more rural settings, communication coverage diminished at times. While the drop rate was higher for DSRC, as would be expected given the technology’s limited range and protocol, both DSRC and cellular communications appear adequate for V2I messaging (testing with applications is needed to confirm suitable performance). For example, latency for the system was nearly always below 0.1 second and typically around 0.05 seconds. The key characteristic finding with regard to the communication mode is that, given reasonable coverage, both DSRC and cellular are likely capable of providing adequate data for most non-safety critical applications.

Characterizing the messages was primarily focused on the volume of messages generated by each of the three schemes, with BSM used as the baseline condition. Under normal operation, the PDM and BMM generated 6% and 3%, respectively, relative to the number of BSMs sent during the same period. While all three message types have a similar payload size, the higher level of control within in the BMM structure provides additional possibility for reduction of redundant data to minimize the bandwidth consumed. The multi-threaded, event-focused nature of the BMM also allows for additional targeting of specific information not afforded by the PDM single-threaded messaging. A multi-threaded message also provides immediate (within the normal latency of the system) access to a stream of snapshots where the content and sample interval corresponds with the triggered event. In contrast, the PDM is structured so that delivery of the single snapshot associated with a trigger event is dependent on where it is placed in the message queue. Thus, a triggered snapshot could be delayed by up to three times the sample rate before transmission if it occurs immediately after delivery of the preceding message packet. For long sample intervals associated with higher vehicle speeds, this delay could reduce the value of the information for some applications.

The final research topic involved investigating the control schemes of the PDM and BMM, which reflect fundamental differences in the message strategy. The PDM is designed to transmit DM across all driving scenarios based on a default set of parameters. Changes to these parameters with a CM are designed to be short lived, defaulting back to the nominal state after prescribed conditions. In contrast, the CM for the BMM is designed to consistently adjust the default conditions for DM generation such that message flow is explicitly controlled by the infrastructure through the CM. The BMM also supports several simultaneous vehicle event triggers via multi-threaded DM and CM support. Since there are multiple message streams, each can be focused on a specific scenario or application without sacrificing the information needs of other applications. This extra message control results in higher CM volume for the BMM relative to the PDM. However, the message size is compact and the total number of CMs broadcast is low compared to DMs. Increases in the number of CMs may not have a practical impact on data volume.

Conclusions and Recommendations

The AMCD Project successfully implemented three potential V2I messaging strategies within the context of a real-world driving environment in Northern VA. This included installing hardware and developing software for the OBU and infrastructure systems as well as creating user interfaces and characterization testing methods. Results indicate that a flexible message structure may provide an effective mechanism for infrastructure applications to request data from vehicles with the aim of improving roadway operations. Through the development of the messaging concepts, a number of enhancements to the existing messages were identified and implemented to improve functionality. In addition, the results led to a number of recommendations for future research.

The results from this research provide valuable information on the potential utility of various features associated with the V2I messaging schemes. Future efforts should consider combining the beneficial features of these the messaging alternatives into a single flexible message structure prior to additional development and testing. In addition, the primary recommendation from this work is to move toward development of infrastructure applications based on the data received from vehicles so that a performance evaluation can be executed. Without applications, this effort was limited to proving feasibility and characterizing message behavior rather than evaluating performance.

1 Introduction

The objectives of the Advanced Messaging Concept Development (AMCD) Project were to evaluate the ability of connected vehicles to generate, and infrastructure to collect, Basic Safety Message (BSM), Probe Data Message (PDM), and Basic Mobility Message (BMM) alternatives using cellular and DSRC communications under simulated Dynamic Interrogative Data Collection (DIDC) control in real-world driving conditions for non-safety-critical applications.

The project aimed to investigate three main research topics. First, the project characterized the dual mode communication path (dedicated short range communication [DSRC] and cellular) for mobility messages, which was of special interest for BMM and PDM strategies. Second, the control schemes for the PDM and BMM were investigated and characterized for concept comparison. Lastly, differences between message types (BSM, PDM, and BMM) were characterized by capturing message behaviors under various conditions.

To address the research topics, the vehicle-focused design was first refined, including the system architecture, the message structures and control schemes, and the user interfaces for experimental control. New hardware and software components were built to support dual communication modes, to support the transmission and receipt of control messages, to implement message control schemes, and to enable system characterization and evaluation through logging and user interfaces.

Characterization testing was then conducted across two phases. The first phase of the testing was conducted on the Virginia Smart Road in Blacksburg, Virginia, and included prototype testing on a small scale (e.g., two vehicles), which aimed to answer open design questions and refine the test conditions. Initial system characterization and validation of individual system components (e.g., cellular communication, DIDC emulation, etc.) was also conducted during this phase. During prototype testing, iterations were completed as needed to improve the design and implementation to support larger scale testing. The second phase, referred to as full-scale testing, utilized the fleet of 10 vehicles to perform a broader test and demonstration in Fairfax County, Virginia. Throughout field testing, researchers captured data to characterize the system to better understand capabilities and capture information to inform future standards and design activities.

This document follows the development of the project starting first with the system design, including integration of the hardware, software, and messages. It then proceeds to explain the testing phase, first describing the environment and then discussing the specific conditions tested and the procedures employed during testing. Next, there is an analysis of the data which is based on the three research topics that address the project objectives. A discussion section follows the same structure as the analysis and provides additional insights into the findings. Finally, the project conclusions are discussed and recommendations for future research are provided.

1.1 Background and Motivation

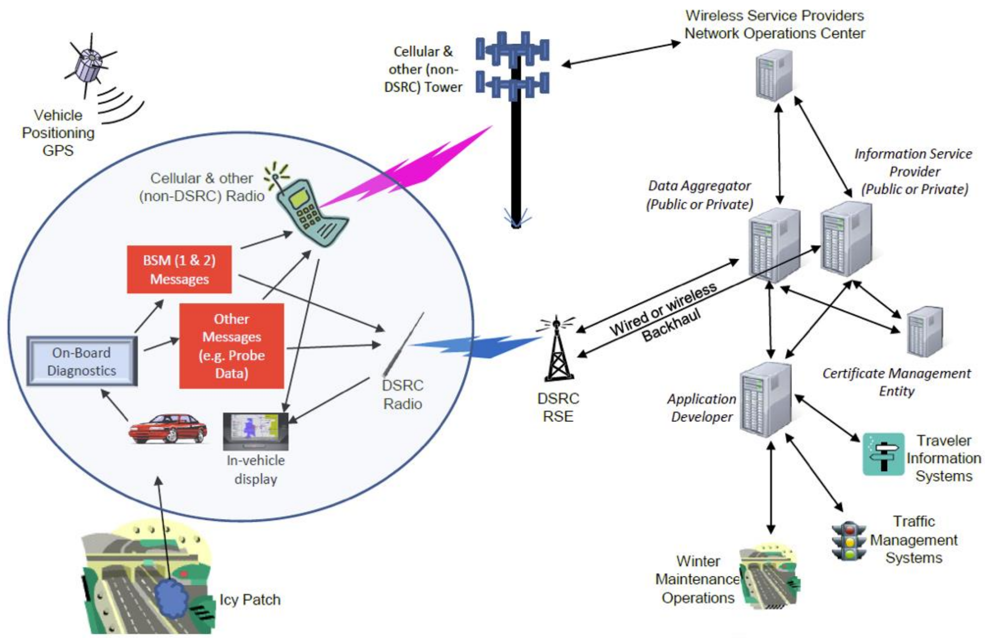
The AMCD Project is based in part on the as yet, unpublished work performed under the BSM Data Emulator Project. In this project, Noblis proposed the DIDC concept, which aimed to assist with transportation system management decisions and minimize bandwidth use by controlling message content and frequency. The BSM Data Emulator Project simulated message types (BMM and PDM as defined by J2735 2009) and message control schemes, and supplied a conceptual model for the DIDC controller and associated parameters. This provided a reference design and a set of data elements associated with example applications. However, significant gaps needed to be filled in order to implement the concept in hardware and software enabling the collection of data to address the stated AMCD objective.

The purpose of this project was to show that V2I concepts, which have primarily been evaluated in simulation, could be implemented on functional hardware and software. The reader should note that applications were not explicitly tested within the AMCD Project. Project focus was on characterizing the message strategies within the real world as a foundation on which applications may later be implemented.

The BMM was envisioned by Noblis as a possible solution to the need for a general, flexible message structure that could be used for vehicle-to-infrastructure (V2I) applications. The BMM nomenclature is retained in this document to connect the work performed here to previous research. However, in contrast to the name, AMCD focused on the characterization of the BMM as a flexible message alternative that has potential utility for a number of different application types beyond mobility. As the concept is refined and progresses toward updated standards, along with integrating the BMM features into the PDM standards, alternative nomenclature should be considered.

1.2 Operational Concept

The system created for the AMCD Project, depicted in Figure 1, emulated a real-world scenario where vehicles interact with the surrounding infrastructure by sending and receiving messages to a Traffic Operation Center (TOC). The Virginia Connected Corridors (VCC) Monitor application, created by the Virginia Tech Transportation Institute (VTTI), served as a dashboard proxy representing a TOC to allow monitoring of the messaging infrastructure in real time and to interact with the vehicles influencing the data requested from vehicles at any given time. If this system were implemented, a traffic operator would use this vehicle data to assess and respond to various operational scenarios such as incidents (e.g., congestion and accidents) and roadway conditions (e.g., weather conditions and pothole detection).



Source: Cronin, B., Vehicle Based Data and Availability, USDOT, Oct. 2012.
http://www.its.dot.gov/itspac/october2012/PDF/data_availability.pdf

Figure 1: Overall Example of an Advanced V2I Messaging System

The circled components show the portions of the system that were built and evaluated as part of the AMCD Project. These portions of the overall concept represent the research goals relating to communication mode, message types, and control schemes.

1.3 Research Goals

Three main research topics emerged from the project objective: 1) characterize dual-mode communication (DSRC and cellular), 2) evaluate message control schemes (DIDC and probe data management), and 3) message-type characterization (BSM, PDM, BMM). A short description of each topics is provided within this section.

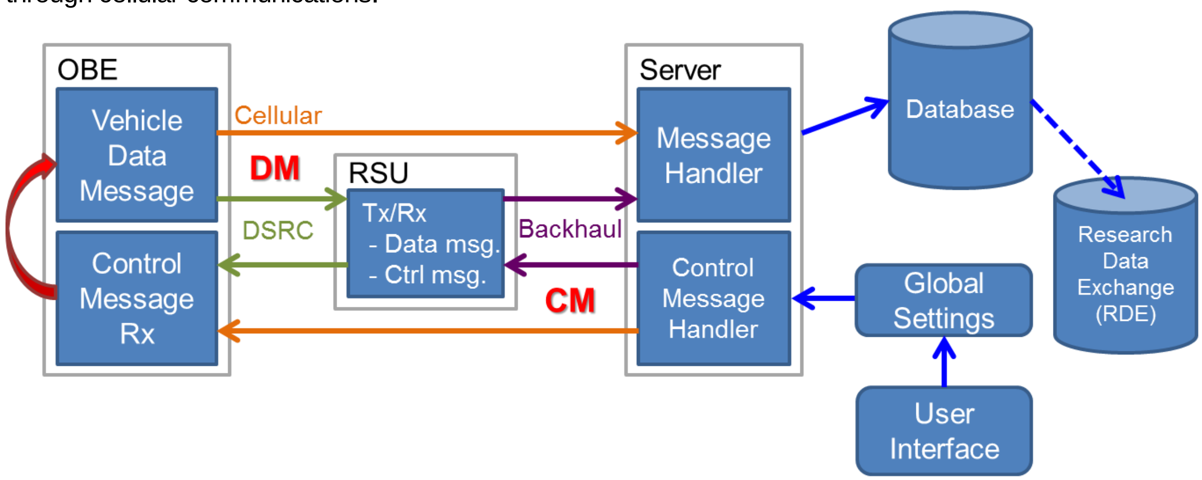
Communication mode refers to the technology used to transmit messages from the vehicle. In this case, the two modes used were DSRC and cellular. The DSRC radios installed in the vehicles and on the roadway are commercially available products that conform to applicable industry standards. Similarly, cellular communication took place on a major 4G network using a USB modem plugged into the OBU.

As the name implies, a control scheme provides a mechanism for adjusting the flow and content of the information being passed between the vehicle and the infrastructure. The level to which this is done is dependent on the intent of the scheme. The BMM scheme and supporting DIDC functionality was designed to allow increased flexibility of the information being transmitted with the aim of minimizing message congestion while maximizing the useful information from a minimal number of vehicles. To truly achieve this intelligent control of message flow, a full suite of applications informing the DIDC would be required. Since application development was outside the scope of this project, only an emulation of portions of the DIDC were implemented to show that message traffic could be controlled by dynamically changing control messages (CM) – which in turn altered the data messages (DM) returned from vehicles. In contrast, the PDM was designed to be means of collecting and storing vehicle information between communication links. The CM outlined in Annex E of J2735 are much less dynamic in nature than the DIDC, with fewer controls available for the TOC to alter DM content from the vehicle. This distinction was important when characterizing the two control schemes. Since they have different goals, it is important to evaluate with the control scheme and design considerations in mind.

Three different DM types were implemented for the study, the BSM, BMM, and PDM. As with the control scheme, each was designed with a different intent. The BSM is focused on V2V safety applications, the BMM on flexible messaging, and the PDM on the capture of probe data between communication access points. As such, descriptive measures, rather than comparative analysis, were used to characterize the three message types. The intent was to provide developers with information to aid in application design without making direct comparisons between message strategies.

2 System Design and Integration

The AMCD system architecture is shown in Figure 2 below. Three message schemes are supported by this system: BSM (DSRC only), PDM, and BMM. The system emulates specific elements of the DIDC controller rather than functioning as an implementation of full logic as laid out in the broad vision (which requires V2I applications). The experimenter interface is a web-based tool for configuring CMs and the viewing system response via returned DMs, not a full emulation of a TOC interface (which also requires applications). CMs originate at this interface as configured by an operator and are posted to a server where they are made available to the OBU through either DSRC via the RSU or through cellular communications.



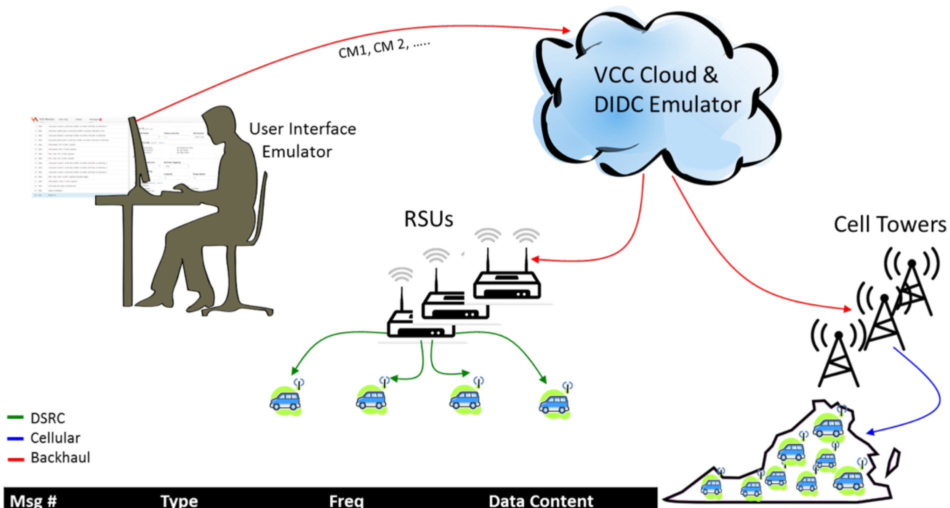
Source: CAMP V2I Consortium and VTTI

Figure 2: AMCD System Architecture

On receipt of the CM, the OBU configures message handlers and generates DMs as appropriate based on the prevailing conditions relative to the request contained in the CM. These DMs are transmitted back to the infrastructure server either over DSRC or cellular where they are stored to a database and made available to infrastructure applications. For the purpose of AMCD, data was also made available to the Research Data Exchange for archiving and future analysis. A more detailed operational example using this architecture is provided in the subsequent section.

2.1 Basic System Operation

The following graphics demonstrate the basic operation of a flexible message system (using the BMM scheme as the example) of the system and the expected flow of information. The first step (Figure 3) is for the TOC to set up a series of CMs. The CM can be thought of as a request for data from the infrastructure to the vehicles. These regulate the content, frequency, and initiation and termination of the DMs.

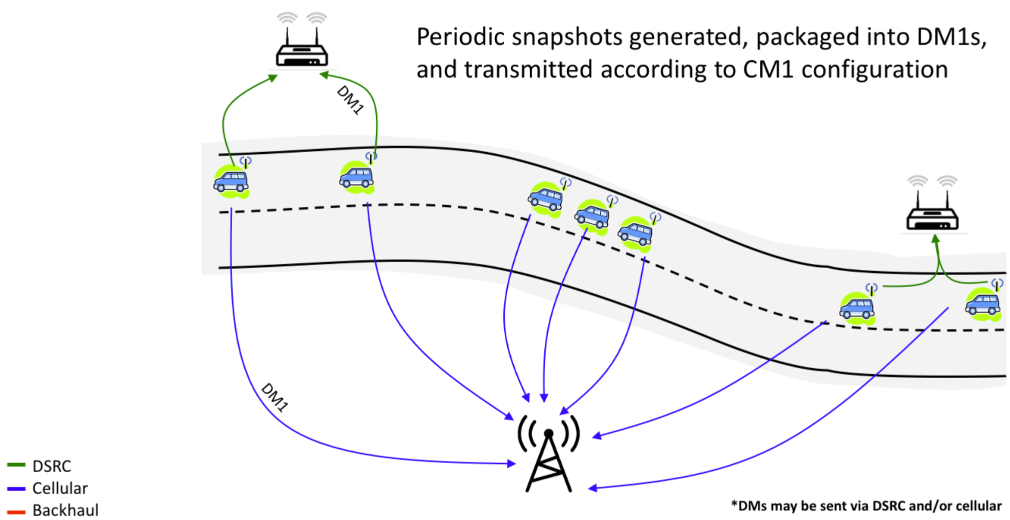


Msg #	Type	Freq	Data Content
CM1	Periodic	0.1Hz, no timeout	Part1
CM2	Event: Hard-Braking	10 Hz for 10 sec	Part 1 + ABS active, TCS, SCS

Source: CAMP V2I Consortium and VTTI

Figure 3: Set Up BMM CMs and Transmit Queue to Vehicles

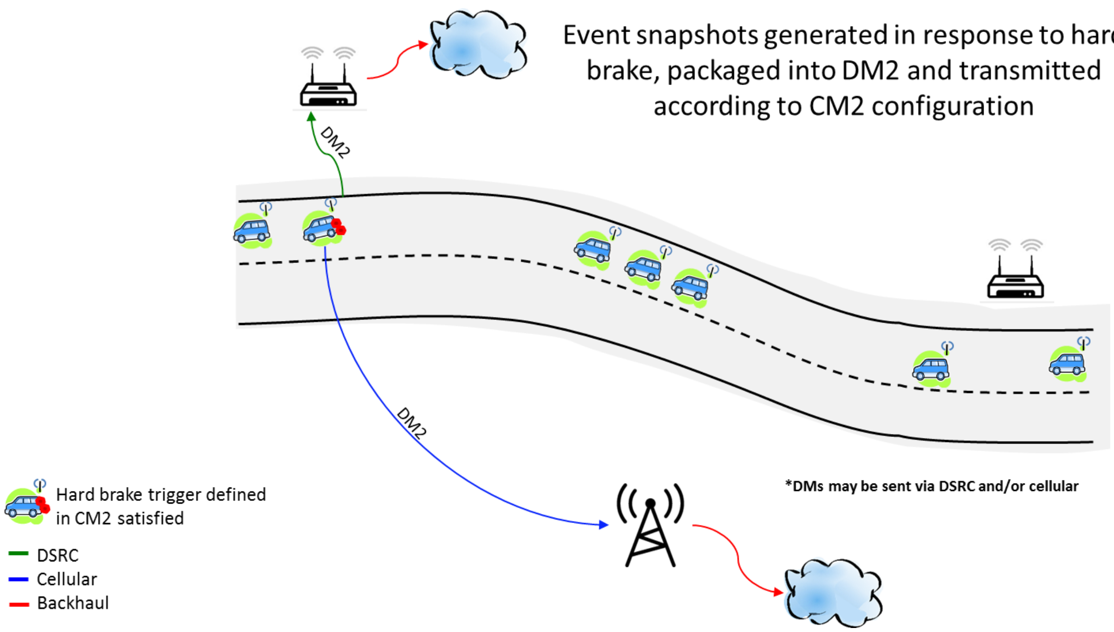
The CMs are contained in a queue which is broadcast by the cloud via DSRC and cellular. Any OBU that is set up to receive the CMs loads them and starts to transmit DMs based on the configuration parameters. In this example, there are two CMs: a baseline periodic message (CM1) and an event-driven message (CM2). CM2 transmits a burst of data when a hard-braking event occurs on the host vehicle (listed in table within each Figure). As shown in Figure 4, the vehicles that receive the CMs start broadcasting the associated DM, in this case DM1, over DSRC and/or cellular.



Source: CAMP V2I Consortium and VTTI

Figure 4: Provide BMM DMs to Infrastructure – Periodic

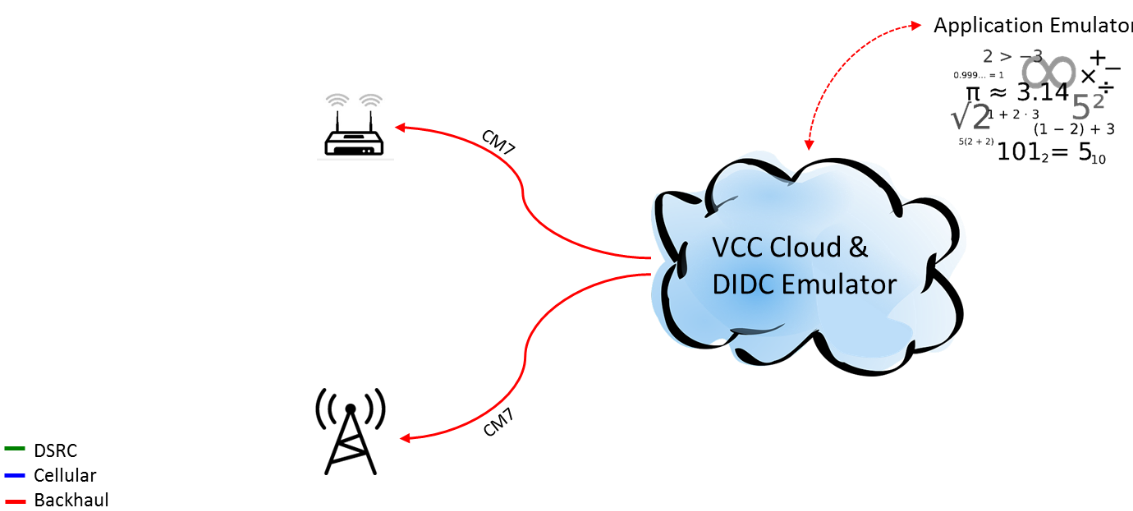
When a vehicle experiences an event of interest (as depicted in Figure 5, a hard-braking event [greater than 0.4g lateral deceleration]), the OBU sends out a short burst of data (DM2 as shown in Figure 5) to the server as depicted in Figure 5.



Source: CAMP V2I Consortium and VTTI

Figure 5: Provide BMM DMs to Infrastructure – Event Driven

The data is then reviewed and acted upon at the TOC (Figure 6), either by a server application or a human operator. In this case, the server has been configured to add another CM unique to hard-braking events (CM7) to the active list and broadcast it to vehicles on the roadway.

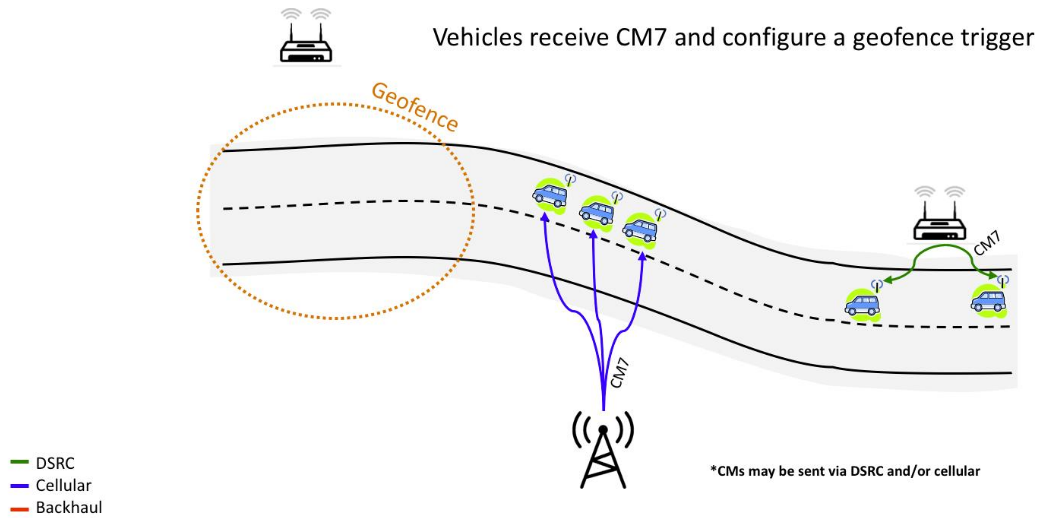


Msg #	Type	Freq	Data Content
CM1	Periodic	0.1Hz, not timeout	Part1
CM2	Event: Hard-Braking	10 Hz, 10 sec	Part 1 + ABS active, TCS, SCS
CM7	Event: Geo-Ref to CM2 event	5 Hz, 60 sec	Part 1 + wiper, air temp, atm press

Source: CAMP V2I Consortium and VTTI

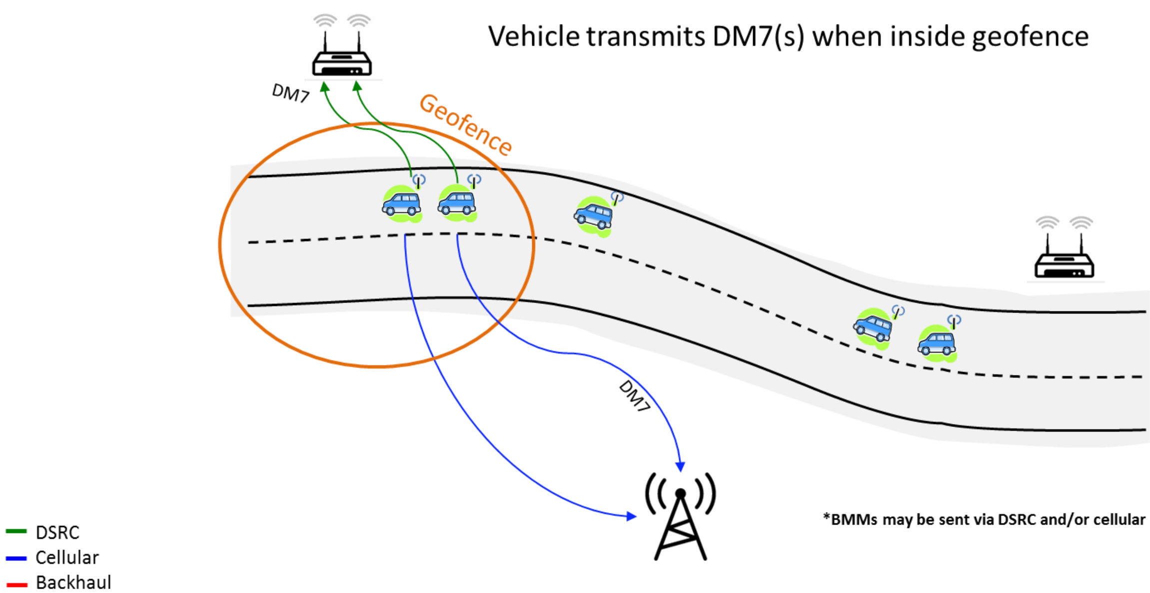
Figure 6: Revise BMM CMs and Transmit Queue to Vehicles

The CM sets up a geofence region around the location where the event occurred (Figure 7) to gather pertinent information from other vehicles entering the region (Figure 8).



Source: CAMP V2I Consortium and VTTI

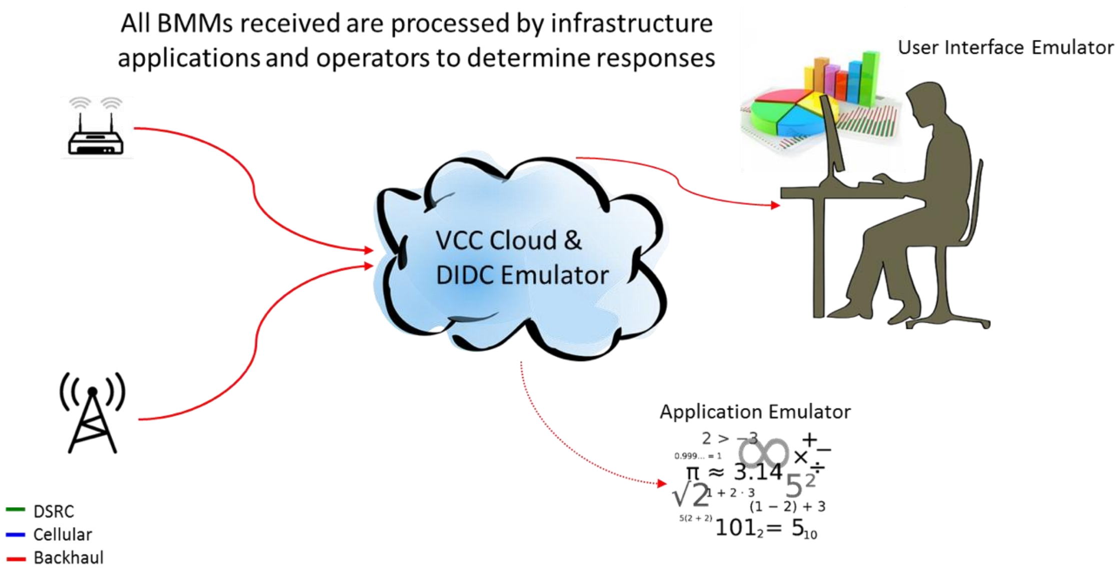
Figure 7: Vehicles Receive Revised CM List



Source: CAMP V2I Consortium and VTTI

Figure 8: Respond to Revised BMM CMs

Once a vehicle enters the geofenced region, it broadcasts the DM associated with the hard-braking event (DM7), in addition to the baseline DM (DM1), back to the server (Figure 9). The TOC can then use this data to determine if any additional actions are required and, if so, what those actions should be.



Source: CAMP V2I Consortium and VTTI

Figure 9: Analyze BMM Data to Support Infrastructure Operations

2.2 Message Architecture

The AMCD messaging consists of three types of messages: the BSM, PDM, and BMM. A brief comparison of the three types of messages is shown in Table 1 below. A thorough explanation of each type of message and its control scheme is presented in the following sections.

Table 1: AMCD Message Comparison

	BSM	PDM	BMM
Basis	SAE J2735	SAE J2735-2009 Annex E	Designed for mobility applications
Use	Vehicle-to-vehicle (V2V) safety applications	Provide information on road, weather and traffic	Support mobility applications
Content	Fixed based on SAE J2945/1	Variable: Part 1 and Part 2 elements	Variable: Part 1 and Part 2 elements Supports non-standard elements

	BSM	PDM	BMM
Message collection frequency	10 Hz	Variable: single message contains snapshots generated from multiple sources - Periodically - Event triggered - Stop/start conditions	Variable: multiple messages generated from multiple sources - Periodically - Event triggered - Stop/start condition Message can contain multiple snapshots. Snapshots can be multithreaded
Transmission frequency	10 Hz	Variable: based on time or distance and receiver availability	Multiple message sent based on configuration of each message thread
Transmission mode	DSRC	Designed around DSRC and inconsistent connectivity	Intended to be multi-modal with expectation of frequent connectivity
Buffering	No buffering	Buffering designed to allow for limited uplink points	Limited buffering
Control scheme	None	Temporarily changes the snapshot generation characteristics	DIDC model provides extensive control for snapshot generation

Source: CAMP V2I Consortium and VTTI

2.2.1 BSM

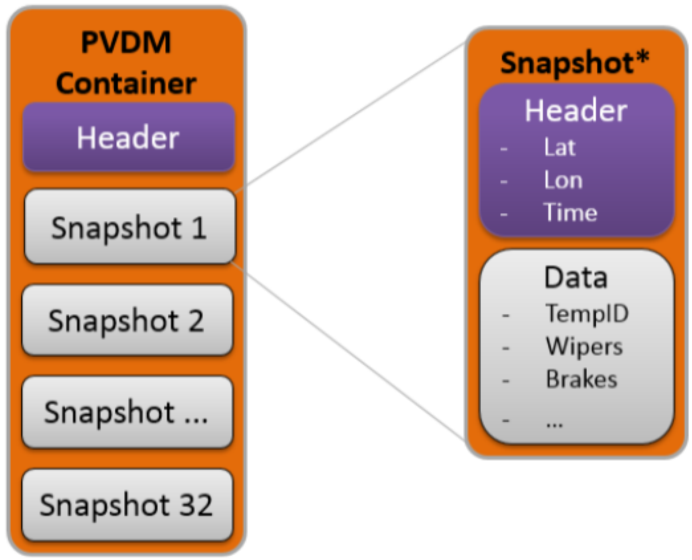
The BSM is implemented according to the SAE J2735 standard. For this project, only Part 1 elements were populated rather than the Part 1 and Part 2 elements prescribed in J2945/1. The BSM is transmitted over the air in a standard 10 Hz format using DSRC technology and provides a baseline for comparison to BMMs and PDMs.

2.2.2 PDM

Probe data is comprised of vehicle attributes and sensor data that is collected and sent from the OBU of a connected vehicle to a local RSU, or by other modes (i.e., cellular). This data may be used to ascertain real-time road, weather, and traffic conditions and is collected as vehicles are traveling along the connected roadways.

The PDM sampling strategy consists of three parts: the DM, the control scheme, and the CM. The DM, called the Probe Vehicle Data Message (PVDM), is the message between the connected vehicle and the infrastructure. The control scheme utilized is Probe Message Management (PMM), which changes the snapshot generation characteristics of the OBU. The CM, called the Probe Data Management Message (PDMM), is sent from the infrastructure to the vehicles.

A PVDM consists of probe data snapshots taken autonomously as the vehicle travels along the connected roadway. In the absence of any overriding PMMs, snapshots are generated periodically (at intervals based on vehicle movement between RSUs) via event triggers (based on vehicle conditions and triggered by the OBU or server application) or from start/stop conditions (based on vehicle motion). These snapshots consist of all probe data elements that are available for the vehicle, along with the time and location when each snapshot was taken. An illustration of the PVDM framework is shown in Figure 10 below.



Source: CAMP V2I Consortium and VTTI

Figure 10: PVDM Framework

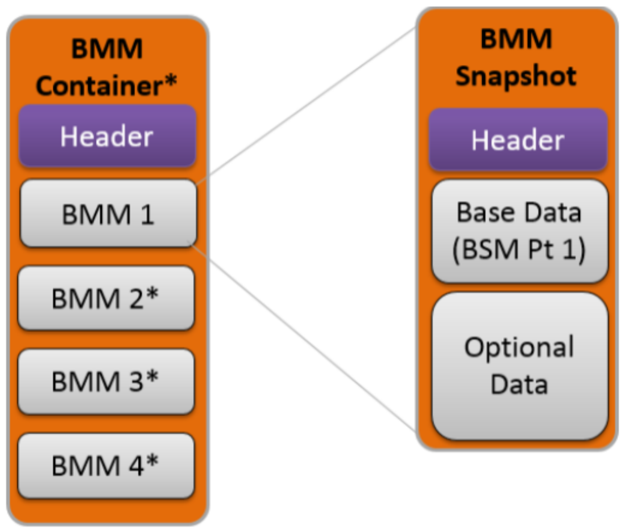
The purpose of the PDMM is to change the snapshot generation by performing one or more of the following functions:

- Control the production of snapshots by either distance or time
- Direct the management message to vehicles moving in specified directions
- Control how often snapshots are transmitted
- Be applied only to a random sample of vehicles
- Modify the thresholds of when event snapshots are triggered
- Modify the thresholds of start/stop snapshots

2.2.3 BMM

Like the PDM, the BMM sampling strategy includes three parts: the DM, the control scheme, and the CM. The DM, called the BMM, is the message sent by the connected vehicle to the infrastructure. The control scheme utilized is the DIDC, which provides logic that controls content and flow of information from vehicles based on the information received. The CM, called the Basic Mobility Control Message (BMCM), is sent from the infrastructure to the vehicles and controls the frequency and content of vehicle information.

As stated, the purpose of the BMM is to provide the infrastructure with data while minimizing message congestion. In order to reduce the load, up to four message snapshots can be bundled together and sent in a single message container. Multiple message streams can be sent at the same time via DSRC, cellular, or both, with different content and frequency. Message streams can be initiated periodically (sending continuous baseline data) via event triggers (based on vehicle conditions and triggered by the OBU or server application) or from start/stop conditions (based on vehicle motion). While all BMMs contain a minimum set of base data (based on Part 1 of J2735 BSM), variable optional elements (e.g., wiper status, ambient temperature, ambient pressure, brake status) can be sent based on the data requested by the BMCM. Thus, the DM sizes are variable based on the data requested by the BMCM and the available vehicle data. An illustration of the BMM framework is shown in Figure 11 below.



*Up to 4 BMMs can be packaged together and sent in a single container

Source: CAMP V2I Consortium and VTTI

Figure 11: BMM Framework

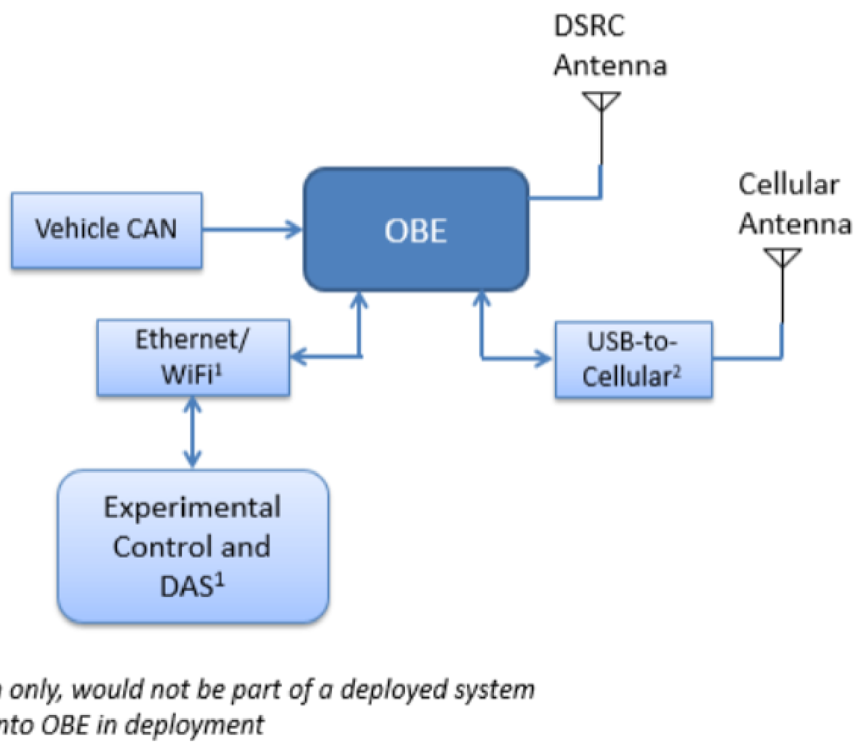
The purpose of the BMCM is to define what data is sent by the vehicle and under what conditions that data should be sent. Multiple BMCMs can be activated at the same time, allowing the dynamic content and frequency of the messages to react to various driving conditions while minimizing channel loading. BMCMs can be created manually via the VCC Monitor interface or automatically via the DIDC in response to needs from infrastructure-based applications. BMCMs can request that data be sent when the vehicles satisfy specified trigger conditions, which can be based on vehicle parameters, geolocation, or a combination thereof.

2.3 Hardware Integration

Base equipment was modified as part of AMCD to enable the message type testing. VTTI, with assistance from the radio manufacturer, updated both the OBU's and the RSU's software development kits, enabled a cellular link and verified functionality, and opened interfaces to support vehicle controller area network (CAN) data.

VTTI enhanced an existing server to construct, manage, and post the CMs, receive DMs, log message traffic, and enable cellular transmit/receive for DMs and CMs. A database was developed to store DMs and CMs. This was used for evaluation purposes with the expectation that applications would also use the content in the future. To facilitate the transmission of the three message types, the OBU and RSU hardware utilized contained two radios. One of these was used for the transmission of BSM and the other was used for the transmission and receipt of BMM and PDM DM using the WAVE (wireless access in vehicular environments) service announcement (WSA) advertising method. Cellular communication was not designed into the factory OBU, so a USB cellular modem was added to the system to enable dual mode communications. Messages were transmitted and received via UDP (DMs) and TCP (CMs) protocols over the cellular connection.

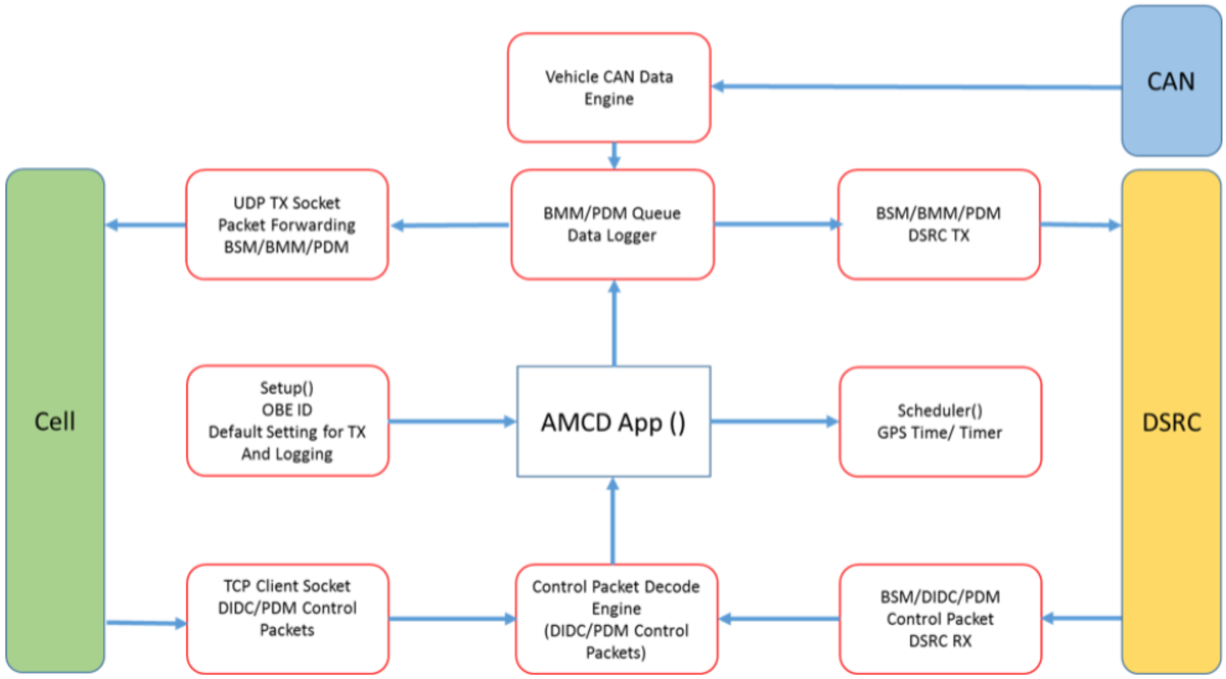
VTTI configured and set up a test bench for testing purposes and installed hardware in the AMCD vehicles according to the AMCD vehicle architecture shown in Figure 12.



Source: CAMP V2I Consortium and VTTI

Figure 12: AMCD Vehicle Architecture

Software was developed using the BSM Data Emulator project as a guide, with alterations made to support integration onto physical hardware. Figure 13 details the OBU software architecture, which implemented the DIDC control message Rx/parser, setup a buffer to store PDM and BMM snapshots, implemented the trigger engine for snapshot capture, implemented communication mode switching logic (cellular vs. DSRC), and defined a buffer to store messages when no communication channel was available.

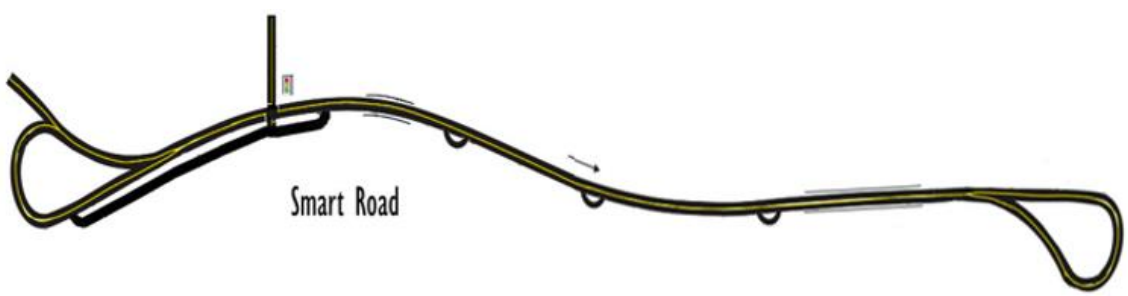


Source: CAMP V2I Consortium and VTTI

Figure 13: OBU Software General Diagram

2.4 VCC Testing Environments

The VCC is an open test and development environment that facilitates real-world development and deployment of connected-vehicle technology using more than 60 RSUs, which are connected to a low-latency backhaul network. The RSUs are positioned along two corridors: 1) the Virginia Smart Road in Blacksburg, Virginia (Figure 14), and 2) freeway and arterial roadway sections in Northern Virginia (Figure 15). The Virginia Smart Road is a 2.2 mile, controlled-access, testbed built to FHWA standards. The Northern Virginia testbed, which includes sections of Interstate 66, Interstate 495, U.S. 29, and U.S. 50, is located in Fairfax County and is one of the nation's most congested corridors.



Source: VTTI

Figure 14: Virginia Smart Road

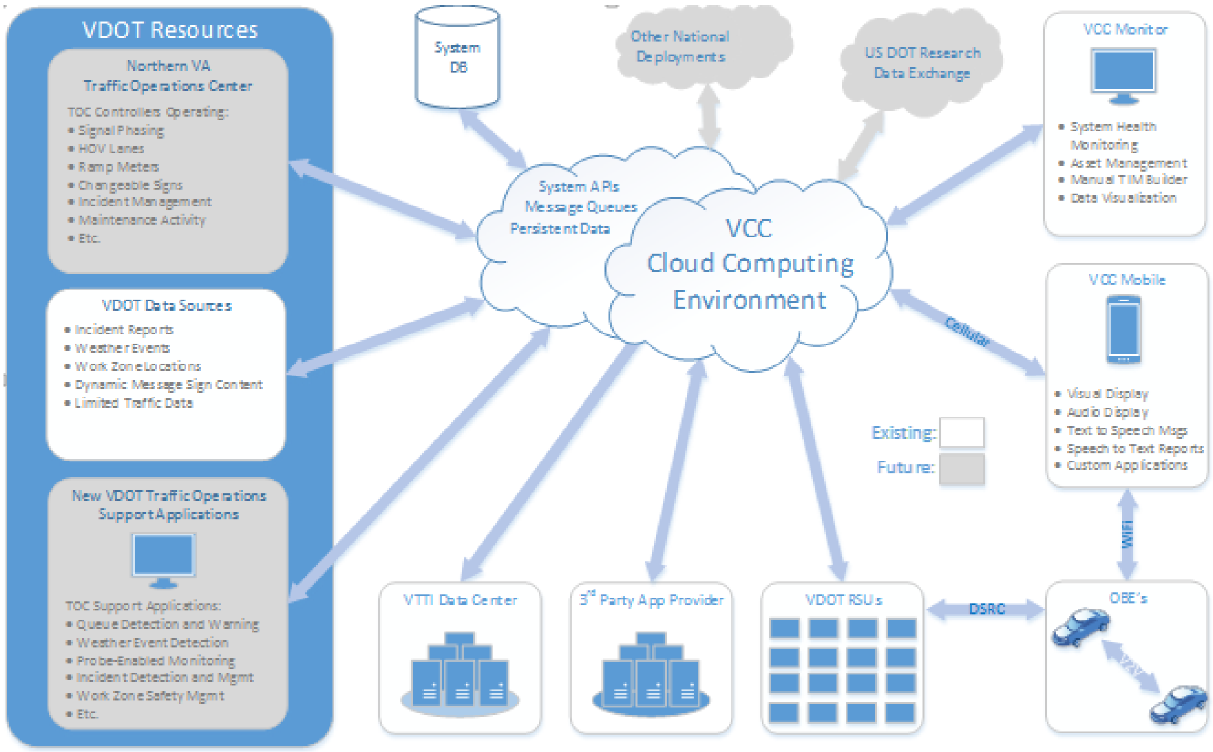
Source: VTTI

Figure 15: Map of Fairfax County, Virginia

The VCC supports the implementation of connected-vehicle applications using real-world roadway environments that feature multiple transportation challenges. Along with the VCC application deployment platform, this existing environment provided the foundation for integrating the AMCD functionality. The platform included data exchange services, including data warehouse and clearinghouse implementations, application program interfaces, user interfaces, and reference applications to simplify the enabling of AMCD features.

2.4.1 VCC Cloud

The VCC Cloud is a centralized data and communications hub where a variety of applications and third-party systems can exchange information and support real-time system interactions. The cloud architecture (see Figure 16 below) provides both cellular and DSRC communications capabilities and has existing interfaces to real-time data provided through the VDOT data sharing site. The public application program interface was leveraged during AMCD to send and receive DMs and CMs through the existing cloud services.



Source: VTTI

Figure 16: VCC Cloud

2.4.2 Vehicles and OBUs

The vehicle fleet used in testing consisted of up to 10 vehicles, listed in Table 2 below, which were all decommissioned, integrated vehicles from the Safety Pilot Model Deployment Program. Each vehicle had a commercially available OBU installed and was configured by VTTI to support the specific requirement for AMCD. The OBU contained custom software for the generation and transmission of PDMs and BMMs. As designed, PDM and BMM generation (e.g., frequency, triggering, data content, etc.) was configured on the VCC Monitor interface and transmitted to the vehicles through the associated CM. The OBUs were also connected to the factory vehicle network where representative data elements were extracted and transmitted within the DM payload. The completed vehicles were run through a system shakedown test and operational performance was verified. Table 2 provides additional information about each vehicle and its OBU unit. The particular radio platform was chosen due the availability of a software development environment necessary for the novel message format and handling.

Table 2: Vehicle and OBU Information

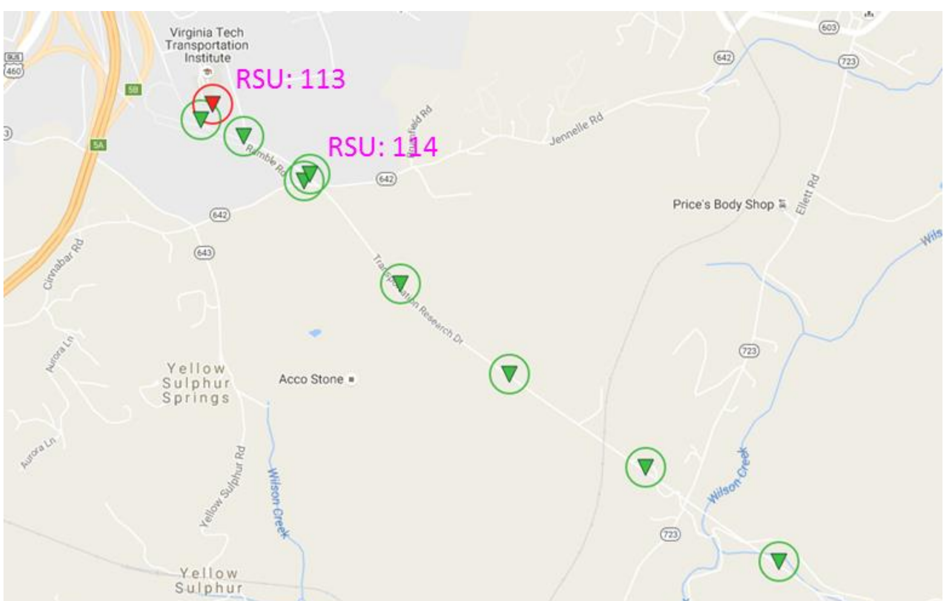
OBU/Vehicle ID	Vehicle Year	Vehicle Make	Vehicle Model
0014	2012	A	A1
0015	2012	A	A1
0020	2010	B	B1
0021	2010	B	B1
0026	2011	C	C1
0027	2011	C	C1
0032	2012	D	D1
0036	2012	D	D1
0037	2012	D	D1
0087	2012	E	E1

Source: CAMP V2I Consortium and VTTI

2.4.3 RSUs

Of the approximately 60 units available, eight RSUs were specifically configured to support the unique messaging requirements for AMCD. All RSUs were connected via a combination of fiber or commercial cable connection to the VCC Cloud backend infrastructure.

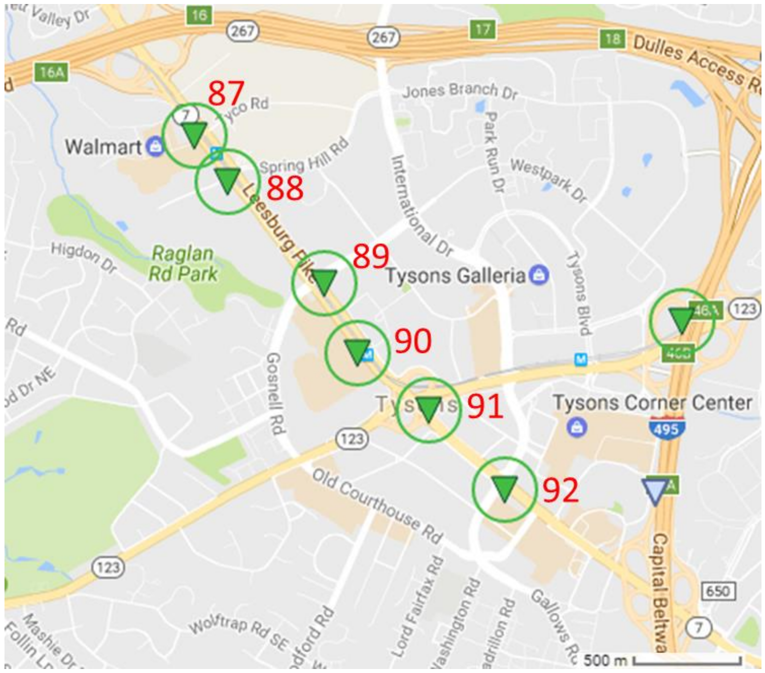
Two of these RSUs were installed on the Virginia Smart Road to support prototype testing, as shown in Figure 17 (labeled as RSU 113 and 114). Each RSU on the Smart Road was connected to the VCC Cloud via fiber connection. During Phase I data collection, only RSU 114 was active. RSU 113 was shut down as indicated by the red color on the figure below. This configuration allowed edge effects of DSRC to be evaluated from two directions towards a single radio and created a clean dataset for initial investigation. The remaining seven RSUs shown on the map below are pre-existing radios which were not configured to support this specific testing effort.



Source: CAMP V2I Consortium, VTTI and Map data – Google

Figure 17: RSUs Located on Virginia Smart Road in Blacksburg, VA

The remaining six RSUs were installed along Leesburg Pike (Hwy. 7) between Tyco Road and Gallows Road in Fairfax County, Virginia as shown in Figure 18. Each of these RSUs were connected to the VCC Cloud via a commercial cable internet provider and were routed through the VDOT network into the VCC Cloud. These RSUs were installed in locations suitable to support the Phase II testing and demonstration activities.



Source: CAMP V2I Consortium, VTTI and Map data – Google

Figure 18: RSUs Located in Fairfax County, Virginia

APPENDIX B contains images showing the mounting locations of the RSUs in Northern Virginia. Final mounting was selected by a knowledgeable VDOT contractor based on installation feasibility, suitability of mounting locations and connectivity. The locations are representative of anticipated equipment installation at scale rather than being optimized for maximum communication performance (i.e., line of site obstructions were present).

The VCC Monitor application was originally developed to provide situational awareness to VCC operations staff to monitor the general health and activity of systems engaged on the VCC. Various pages of information provide a listing of assets, asset health, message volume, real-time message scheduling, end-user application events, calls for help, traffic-flow volumes, etc. The VCC Monitor was extended to support a variety of functions within AMCD to control and monitor the real-time message activity and reaction sequences throughout prototype and full-scale testing.

The VCC Monitor provides an example information display that could reside within a TOC. The added functionality to support the AMCD Project objectives was designed primarily as a research tool. The information that would be provided to a TOC in deployment would likely be distilled down into actionable information rather than raw messages. However, the current version provided a reference implementation to demonstrate the level of control available with the BMM scheme and the subsequent DM that is returned. APPENDIX E shows the interface of the VCC Monitor in the context of the project and walks through the setup of the CMs and interpretation of the returned data.

3 Testing Method

3.1 Conditions

As introduced previously, three main research topics emerged from the project objective: 1) characterize dual-mode communication (DSRC and cellular), 2) evaluate general performance of message control schemes, and 3) message-type characterization (BSM, PDM, BMM). Because specific applications were not developed in this project, the primary task was to validate and characterize the implementation according to the research topics. For example, one performance metric under communication mode captures how each method performs at the edge of its respective service range. Similarly, different control schemes can be characterized by how they generate snapshots, including but not limited to, the frequency, what initiates the generation, and the length of time it takes for the information to arrive at the server. Research topics and the different areas in which their performance was tested are shown in Table 3 and are subsequently described in more detail.

Table 3: Applicable Tests for Each Research Topic

Topic	Research Topic	Applicable Tests					
A	Communication Mode	Baseline	Switch-over	Quality of Service	Edge Performance	End-to-End	Demo
B	Control Scheme	Baseline	Snapshot Generation	CS Mode Sensitivity	Controller Sensitivity		Demo
C	Message Type	Baseline	Snapshot Generation			Application Evaluation	Demo

Source: CAMP V2I Consortium and VTTI

Each of the three research topics had a baseline set of data collected under a defined set of conditions which afforded a rich dataset for analysis. This baseline dataset served as a basis for comparison to the other conditions. Similarly, during the demonstration, data were collected with a defined set of conditions which were closer to how the system might work under more normal operating conditions. Thus, four primary areas were considered for characterization of Communication Mode performance.

1. Switch-over: How the system performed as communication went on and off in range
2. Quality of Service: How good the service was for the two modes
3. Edge Performance: How each mode performed at the edge of the service range
4. End-to-End: What impact the different messaging schemes might have on the full transmit/receive cycle.

The primary measures of interest used in characterizing Communication Mode included latency, round-trip time, message count and size, packet error rate (PER) (i.e., the number of packets not correctly received / total packets sent), dropped messages, and message throughput.

In addition to the baseline and demo conditions, the following three areas were used to characterize the control schemes:

1. Snapshot Generation: Inherently, how the CS for the different message strategies allowed the content of the message to be modified. This included things such as content, the conditions

that initiated a snapshot (both vehicle and geographic), and the frequency and duration of the snapshots.

2. Control Scheme Mode Sensitivity: Does the control scheme perform differently over cellular vs DSRC?
3. Controller Sensitivity: How quickly can the control scheme affect the information being returned from the vehicle?

The main measures of interest used in characterizing the control schemes included latency, message frequency and size, PER, dropped messages, and message throughput.

Message Type was primarily evaluated on the baseline and demo conditions with regard to how each scheme generated snapshots. The emulated application evaluation was limited to a hypothetical scenario for which different triggering conditions would be useful to provide targeted data. No actual application was implemented, only the actions that created a complete end-to-end message flow similar to that shown in the figures within section 2.1. The main measures of interest relating to Message Type included message frequency and size, throughput, applicability of message type, and redundant data element count and size.

It should be noted that since neither of the two new message types (PDM and BMM) had been implemented before, the evaluation discussed above was based on expectations of how each scheme would operate based on the descriptions provided in SAE J2737 (2009) and the work performed during the BSM Emulator Project. In addition, the PDM was implemented by the radio original equipment manufacturer (OEM) and relied on their interpretation of the information contained in the standard. Thus, prototype testing of the PDM focused on verifying that the expected outputs were obtained. Beyond adding cellular capability, the PDM was not enhanced during development. The BMM was implemented by VTTI, as such additional design improvements were identified and implemented during the iterative testing phase with validation as the last step in the process.

3.2 Protocols

Testing was conducted in two phases: Phase I – Prototype Testing and Phase II – Full Scale Testing. During each phase, various tests were run in order to address the three main research topics, as shown in Table 4. Each of the five rows represents a set of conditions that were used to collect data for each test identified in Table 3 in order to address the three research topics.

Table 4. Tests Exercised in Each Phase

Research Topic	Test Name	Comm. Mode	Message Type	Snapshot Type	Control Parameters	Environ-ment	Cellular Tech
A, B, C	1. Baseline	1. DSRC 2. Cellular	BSM	n/a	n/a	1. rural 2. urban	1. 4G
			1. PDM 2. BMM	1. periodic	1. default		
A, B, C	6. Snapshot Generation 7. CS Mode Sensitivity 8. Controller Sensitivity 9. Application Evaluation 5. End-to-end	1. DSRC 2. Cellular	1. PDM 2. BMM	1. periodic 2. triggered	1. default 2. set1 3. set2	1. rural 2. urban	1. 4G
A	2. Mode Switch-over 3. Quality of Service	1. DSRC 2. Cellular	BSM	n/a	n/a	1. rural 2. urban	1. 4G 2. 3G
			1. PDM 2. BMM	1. periodic	1. default		

Research Topic	Test Name	Comm. Mode	Message Type	Snapshot Type	Control Parameters	Environ-ment	Cellular Tech
A	4. Edge Performance	1. DSRC 2. Cellular	BSM	n/a	n/a	1. rural 2. urban	1. 4G 2. 3G
			1. PDM 2. BMM	1. periodic	1. default		
A, B, C	10. Demo	1. DSRC 2. Cellular	BSM	n/a	n/a	1. urban	1. 4G
			1. PDM 2. BMM	1. periodic 2. triggered	variable		

Source: CAMP V2I Consortium and VTTI

3.2.1 Phase I – Prototype Testing

The first phase of the data collection included prototype testing on a small scale (i.e., two vehicles) which aimed to answer open design decisions and refine the test space. Prototype testing was conducted around Blacksburg, Virginia, primarily on the Virginia Smart Road, shown in Figure 14.

Under Phase I, initial system characterization and validation of individual system components were conducted (e.g., cellular communication, infrastructure performance, etc.). Testing protocols were developed and drivers were trained on the test scenarios, which included movements choreographed between drivers over two-way radios. Researchers utilized the VCC Monitor (explained in detail in Section 3.2.2) to observe the transmission of the various message types in real time. The vehicles listed in Table 5 were used during the prototype testing.

Table 5: Prototype Vehicle Information

Vehicle ID	Vehicle Year	Vehicle Make	Vehicle Model
0021	2010	B	B1
0026	2011	C	C1

Source: CAMP V2I Consortium and VTTI

During prototype testing, the BMM CMs listed in Table 6 were utilized. The CMs were set and controlled by an experimenter emulating the TOC and experiment from a remote location via the VCC Monitor. The CMs were transmitted to the vehicles' OBEs where they affected how and when BMMs were generated.

The messages were set up to balance the needs of the current and future research. Vehicle parameters were selected based on data previously identified during the Road Weather Management Project (waiting for publication), conducted by CAMP and VTTI that were applicable to the scenarios used to generate event-driven snapshots. For example, vehicle data relevant to a hard-braking event would more likely be associated with control parameters (e.g., antilock braking system, traction control, etc.) than weather-related parameters (e.g., wipers). A high sampling frequency was selected to allow for down sampling during future development and evaluation. This was particularly true for the baseline periodic message of 0.2 Hz. For a normal application, this would likely be collected in tens of seconds rather than tenths of seconds. However, for a dynamic event like hard-braking, 10 Hz is a reasonable frequency to try to capture the source of the behavior.

Table 6: BMM CMs Utilized in Prototype Testing

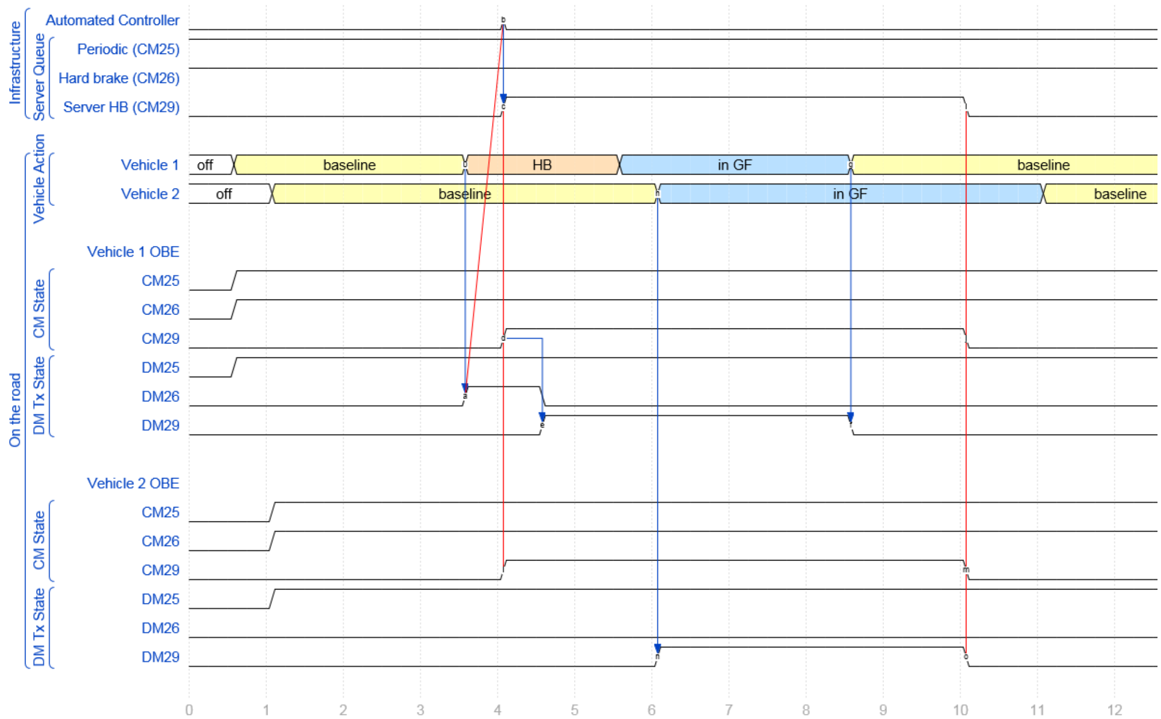
Msg ID	Type	Freq (Hz)	Content	Duration
25	Periodic	0.2	Part1	Until power off
26	Event: Hard braking (long_acc >0.4g)	10	Part 1 + ABS active, TCS, SCS*	Burst mode: 10 samples
27	Event: wipers (wiper state = on)	10	Part 1 + wiper, air temp, atm pressure, precipitation	Burst mode: 10 samples
29	Cloud-based trigger: wiper state = on	5	Part 1 + wiper, air temp, atm pressure, precipitation	Geofence around triggered event
31	Cloud-based trigger: Hard braking (>0.4g)	10	Part 1 + ABS active, TCS, SCS	Geofence around triggered event

*Antilock braking system, traction control system, stability control system

Source: CAMP V2I Consortium and VTTI

BMM CM 25, 26, and 27 were always active during the prototype testing. CMs 29 and 31 were issued based on a simple DIDC emulation that was implemented on the server as part of the VCC Monitor. This allowed the experimenter to set up infrastructure triggers based on the DM received on the server. In the prototype test scenario, the server monitored the trigger events generated by the vehicle(s) (e.g., hard-braking and wipers) and activated a new BMM CM associated with these events. These new CMs were limited to a geographic area centered at the location where the vehicle triggered the event (see figures in Section 2.1). As vehicles entered the geofenced region, they transmitted the associated DM until exiting the region or until the CM active time expired.

Figure 19 provides an example timing diagram of the prototype test scenario, including system startup and a hard-braking event. The CMs correspond to those in Table 6. Note that the horizontal time scale is arbitrary and provides relative timing between state changes. Since the server is always active, the active CMs are available at *t=0* and are loaded onto the OBU when the two vehicles start at *t=0.5* and *t=1*. While both CM25 and CM26 are on the OBU, only DM25 is broadcast by the OBU since CM26 is for a triggered event. At *t=3.5*, Vehicle 1 performs a hard-brake. This immediately activates the transmission of 10 snapshots (DM26) from Vehicle 1. When the server receives the DM associated with the hard-brake event, it activates the cloud-based trigger which activates CM29 and broadcasts the updated CM queue list to the vehicles (*t=4)*. Upon receipt of the new CM queue, the OBUs activate CM29 which has a geofence centered around the location where Vehicle 1's hard-brake event occurred. Since Vehicle 1 is still in the geofenced region, it begins transmitting DM29 (*t=4.5)* and continues to do so until it leaves the geofenced region (*t=8.5)*. When Vehicle 2 enters the geofenced area (*t=6*), it begins to broadcast DM29. CM29 is a limited duration CM and before Vehicle 2 exits the geofenced region, the sever removes CM29 from the active CM queue and broadcasts the updated CMs to the vehicles (*t=10*). Since the OBUs no longer have CM29 loaded, Vehicle 2 ceases to generate and transmit DM29.



Source: CAMP V2I Consortium and VTTI

Figure 19: Timing Diagram for Hard-braking Event

In addition, PDM testing was also completed under Phase I. Unlike the BMM, which was designed to be multithreaded and allow multiple CMs and DMs to be active at any given time, the PDM was designed to have a single control scheme and message at any given time. Any changes to the default CM are temporary, existing for only a limited life based on time or distance before returning to the default parameters. For testing, the parameters listed in Table 7 were used as the default for the PDM messages. Refer to J2735 (2009) – Annex E for more information on the PDM control scheme.

Table 7: PDM CM Utilized in Prototype Testing

Msg ID	Type	Tx Interval	Content (vehicle dependent)	Duration
4	Variable Periodic Speed slow = 1 m/s Speed fast = 15 m/s	12 sec	Part 1 + wiper, air temp, atm pressure, precip sensor, ABS active, TCS, SCS	Till power off

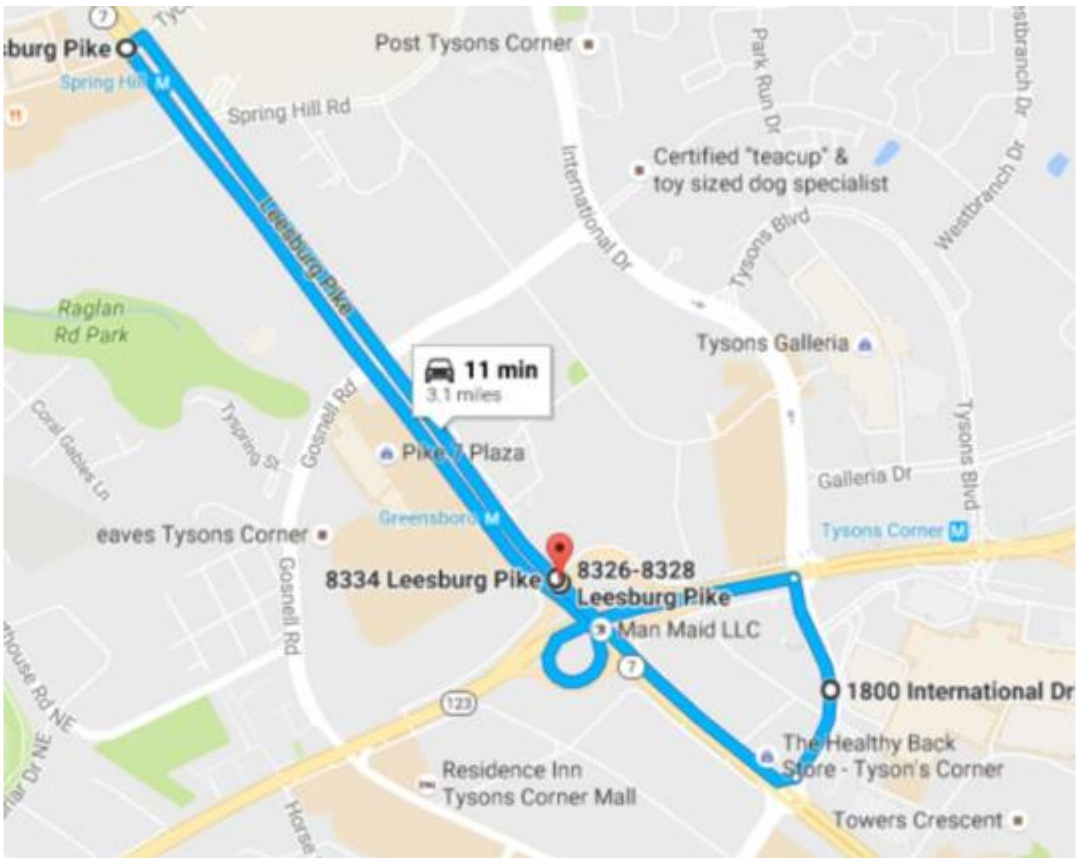
Source: CAMP V2I Consortium and VTTI

Some prototype testing was also performed on the Northern Virginia Test Bed to validate system performance in advance of full-scale testing. This testing focused on finalizing the most efficient testing routes in range of the desired RSUs as well as executing the designed, full-scale testing procedures, including interaction with the TOC and two prototype testing vehicles.

3.2.2 Phase II – Full Scale Testing

The second phase consisted of full-scale testing utilizing the entire 10-vehicle fleet on the Northern Virginia Test Bed environment near Tysons Corner in Fairfax County, Virginia. The testing was conducted during different times of the day to allow for varied levels of traffic congestion. Since the roads were not closed, timing and location of trigger events (i.e., the hard-braking event) were adjusted to generate a good distribution of events while ensuring the safety of all drivers on the roadway. All drivers were in constant communication with each other, as well as an experimenter at the control center, via a conference call and hands-free devices.

During full-scale testing, the fleet vehicles were driven on multiple predetermined routes following three different test scenarios with each test run lasting one to two hours. The first test scenario involved the entire vehicle fleet platooning together (as traffic allowed) along the route shown in Figure 20 below. This 3.1-mile route included VA-7/Leesburg Pike, Chain Bridge Road, and International Drive and took approximately 11 minutes to complete, depending on traffic. This route facilitated communication with all six RSUs in the area (see Figure 18). The vehicle fleet completed 10 laps of this testing route while maintaining formation and order as much as possible.



Source: Map data – Google

Figure 20: Full-Scale Testing Route – Scenario #1

During this scenario, the lead vehicle (Buick #26) completed multiple events as instructed by the control room experimenter in order to trigger various messages. All the BMM CMs that were utilized during full-scale testing are shown in Table 8 below. Vehicle #26 completed hard-braking maneuvers when instructed by the control room experimenter and when traffic allowed (and the following driver had confirmed readiness via the conference call). The control room experimenter also instructed the lead vehicle when to activate their windshield wipers as a trigger for a cloud-based response from CM

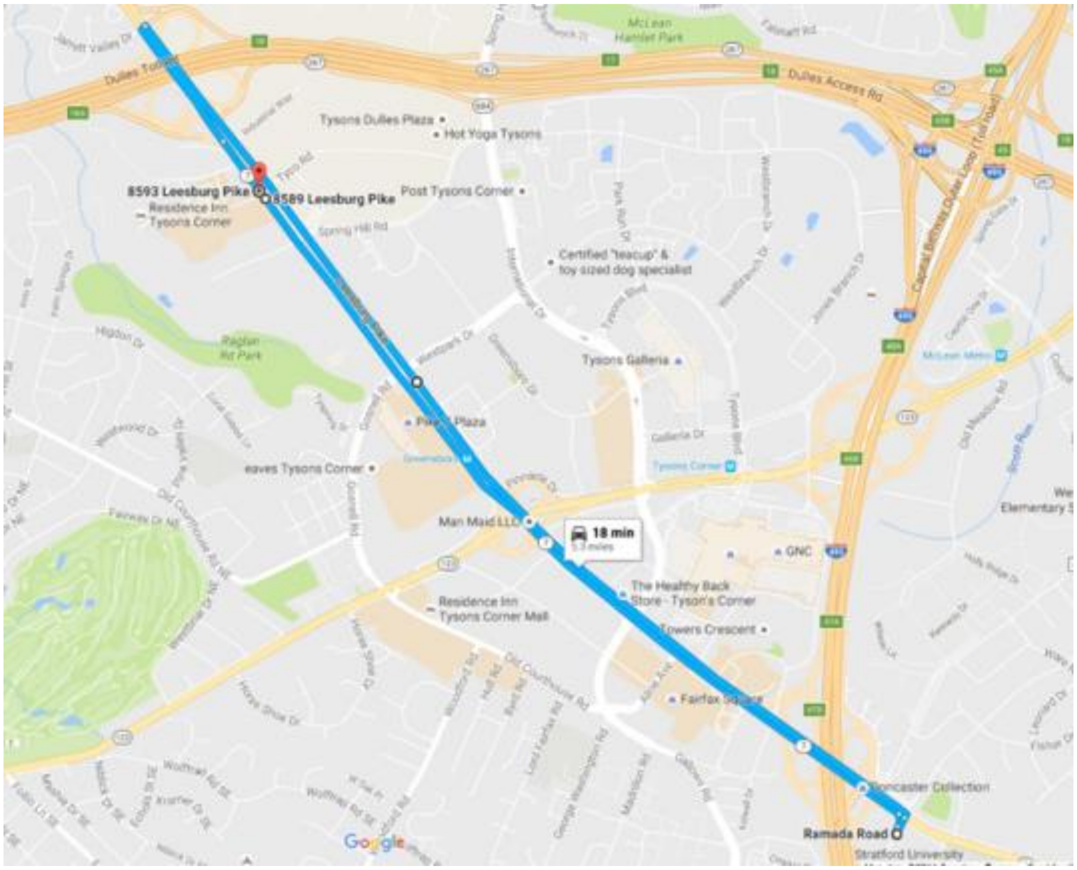
#29. Over the course of natural driving, all drivers activated their turn signals, thus triggering a cloud-based response from CM #52.

Table 8: Full Scale Testing BMM CMs

Msg ID	Description	Type	Interval (sec)	Content	Duration
1	Baseline	Periodic	0.2	Part1	Till power off
25	Baseline	Periodic	15	Part1	Till power off
29	Wiper response	Cloud-based: hard-braking (long_acc >0.4g)	0.2	Part 1 + ABS active, TCS, SCS	Burst mode: 10 samples
31	Hard brake response	Cloud-based: wipers (wiper state = on)	0.1	Part 1 + wiper, air temp, atm pressure, precipitation	Burst mode: 10 samples
37	Hard brake	Cloud-based - lights	0.1	Part 1 + light status	Burst mode: 10 samples
38	Wipers	Event trigger: wiper state = on	0.2	Part 1 + wiper, air temp, atm pressure, precipitation	Geofence around triggered event
39	External Lights	Event trigger: hard-braking (>0.4g)	0.1	Part 1 + ABS active, TCS, SCS	Geofence around triggered event
52	External light response	Event trigger: light state change	0.5	Part 1 + light status	Geofence around triggered event

Source: CAMP V2I Consortium and VTTI

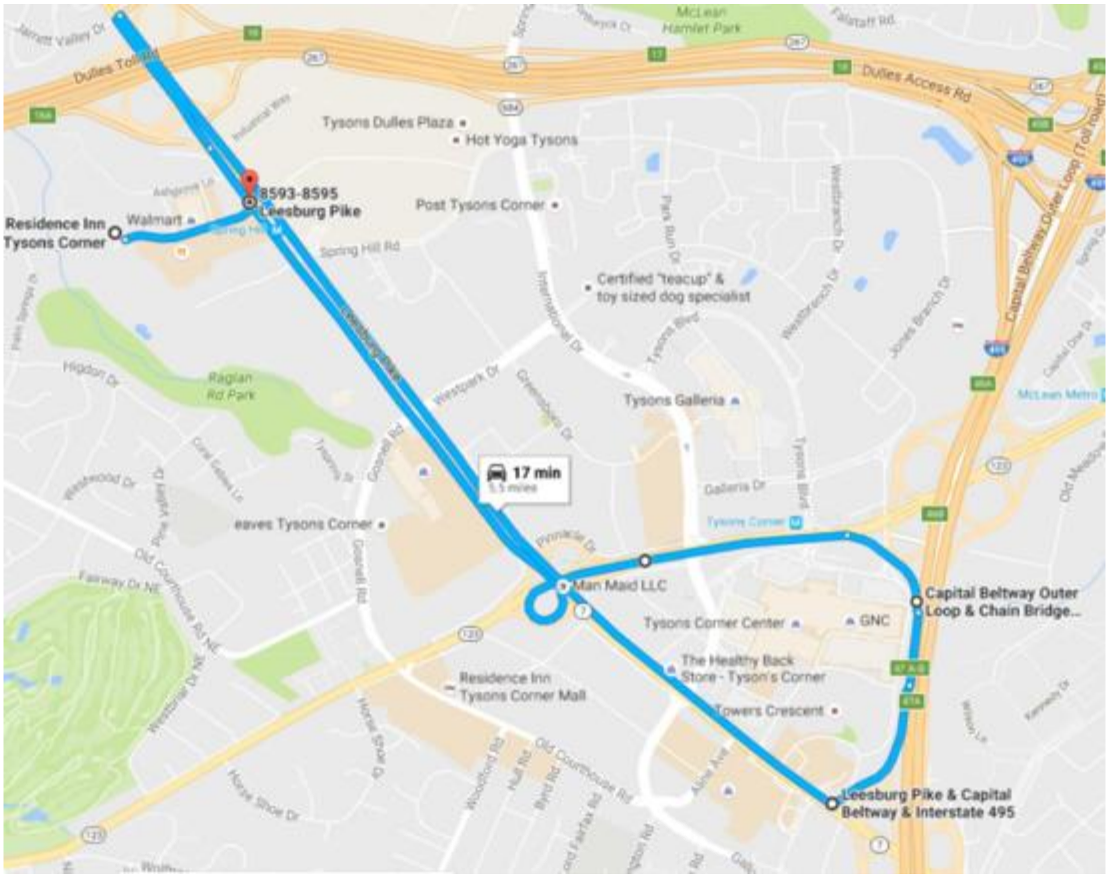
A second test scenario involved the vehicle fleet driving along another predetermined route, shown in Figure 21 below. This approximate five-mile route consisted mainly of VA-7/Leesburg Pike. This scenario was intended to be naturalistic in nature so the drivers of the vehicles were not required to maintain a certain order or formation while driving the route. Instead, the vehicles were intentionally spaced out along the route. The experimenter at the control center instructed the drivers of certain vehicles when to activate their wipers and complete hard-braking events (when the drivers deemed it safe) based on the activated CMs. External lights were again activated by the drivers during natural turn-signal activation, which also acted as triggers for CM #53.



Source: Map data – Google

Figure 21: Full Scale Testing Route – Scenario #2 (Map data: Google)

A third test scenario, shown in Figure 22 below, was completed that included arterial roads as well as the freeway. This test scenario was also naturalistic in nature and the vehicle drivers were asked to drive along the route shown in Figure 22 as well as the routes used in the first and second test scenarios, in no particular order. The experimenter at the control center again instructed the drivers of certain vehicles when to activate their wipers and complete hard-braking events (when the drivers deemed it safe) based on the activated CMs. External lights were again activated by the drivers during natural turn-signal activation, which also acted as triggers for CM #52.



Source: Map data – Google

Figure 22: Full Scale Testing Route – Scenario #3 (Map data: Google)

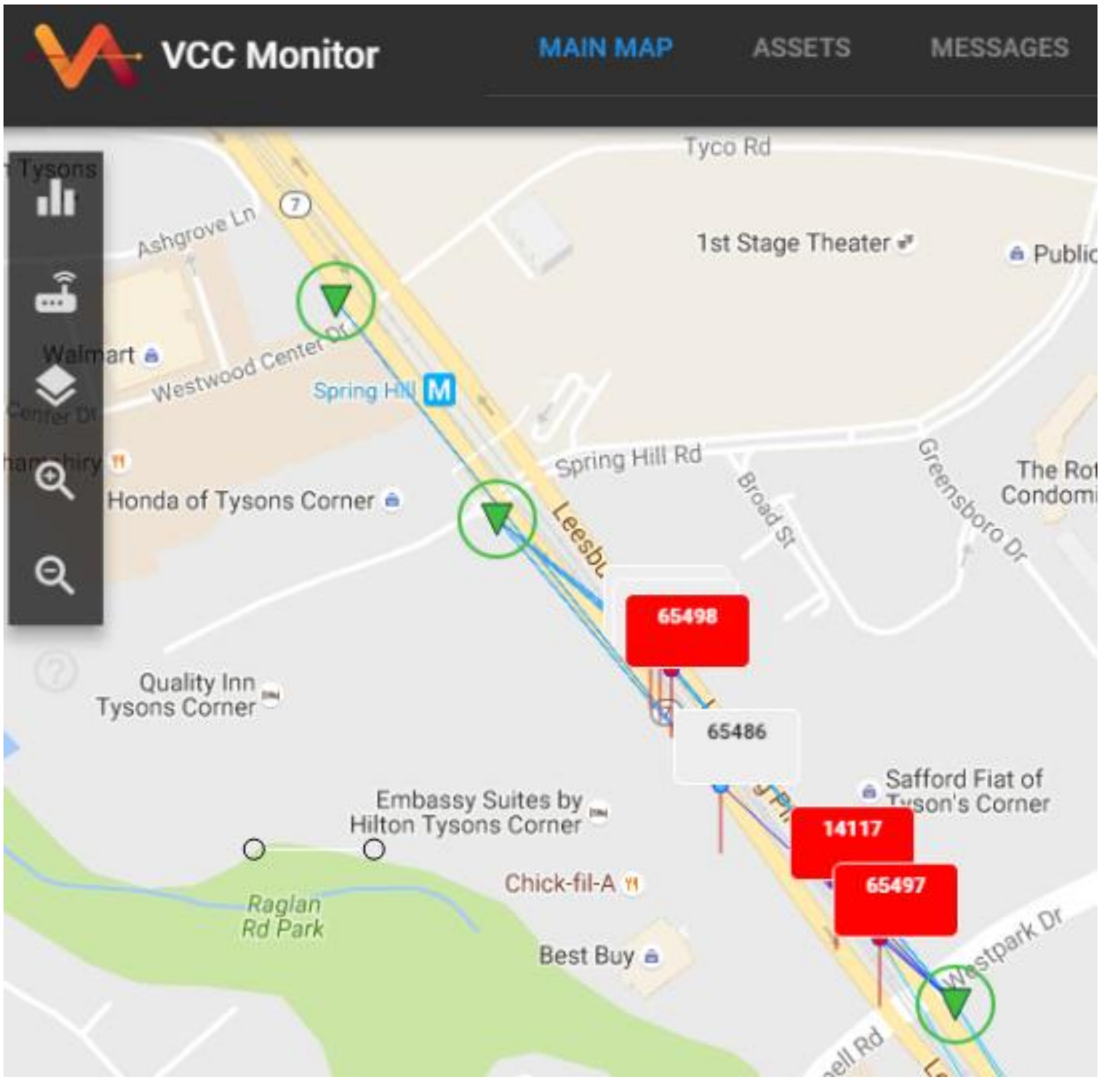
In addition, PDM testing was also completed under the second phase of testing. For full-scale testing, a single PDM CM was used, as detailed in Table 9 below.

Table 9: PDMM Utilized in Full Scale Testing

Msg ID	Type	Tx Interval	Content (vehicle dependent)	Duration
5	Variable Periodic Speed slow = 1 m/s Speed fast = 15 m/s	6 sec	Part 1 + wiper, air temp, atm pressure, precip sensor, ABS active, TCS, SCS	Until power off

Source: CAMP V2I Consortium and VTTI

Throughout full scale testing, the control center experimenter utilized VCC Monitor to monitor the vehicle fleet and initiate geofenced Cloud triggers for various events of interest. The VCC Monitor included a map of the Northern Virginia testbed showing a view of the system as a whole. A screenshot taken during the full-scale testing in Northern Virginia is shown in Figure 23 below. Using this map, the control center experimenter was able to monitor the location of the vehicles within the fleet as they were communicating with the surrounding RSUs. In this map view, each vehicle's location was indicated by a rectangle that displayed the corresponding vehicle ID. The rectangle was shaded gray when the vehicle was in motion and red when the vehicle's brake lights were activated. Each RSU is depicted by a green triangle with a circle around it. As seen in Figure 23, blue lines are drawn from each vehicle to the RSUs in its communication range at the time. Here, vehicle 65498 (northbound in red) is communicating with both RSU 88 at Spring Hill Road and RSU 89 at Westpark Drive. Vehicle 65486 (southbound in grey) is communicating with RSU 87 at Westwood Center Drive as well as RSUs 88 and 89.



Source: VTTI and Map data – Google

Figure 23: Main Map View in VCC Monitor

Figure 24 shows a view of the messages received by the server from each of the vehicles. The six charts shown in the "Messages" screen depict the flow of the three different types of messages: BSMs, PDMs, and BMMs.

Source: VTTI

Figure 24: VCC Monitor Dashboard of Messages Received

The “Basic Safety Messages” chart in the top left-hand portion of the view indicates that BSMs were being received via DSRC (as shown by the blue line) but not cellular (as shown by the absence of a red line). During the 10-minute timespan shown in this view, all 10 vehicles were driving around the testbed while sending and receiving a 10 Hz BSM. Fluctuations in the graph exist when vehicles exit and enter the range of the various RSUs in the testbed. With 10 vehicles, the theoretical maximum number of BSMs/sec should be 100. However, we see between 100 and 190 in the chart. This is because the tool does not report unique messages but rather the total number of messages received. Therefore, if a vehicle is in range of more than one RSU, the system receives a duplicate message from each RSU. In the case of vehicle 65498, which is communicating with two RSUs (Figure 23), the system receives 20 BSMs/sec. Since vehicle 65496 is communicating with 3 RSUs, the server would receive a total of 50 BSMs/sec for these two vehicles rather than the 20 BSMs/sec they are transmitting.

The “Probe Vehicle Data Messages” chart in the upper middle portion of the view indicates the total PDM DMs received by all vehicles via cellular and DSRC communications throughout the 10-minute timespan shown. This DM included horizontal acceleration, wiper status, and brake status. The “Probe Vehicle Data Messages by Vehicle ID” chart in the upper right-hand corner shows the total DMs received from each vehicle. The experimenter has the ability to toggle the individual vehicles on and off to isolate certain vehicles within the graph, if so desired.

The “Basic Mobility Messages” chart in the lower left-hand corner depicts the BMM DMs received via cellular (in red) and DSRC (in blue) by all the vehicles in the fleet that were within range of RSUs (applicable only to DSRC) during the 10-minute timespan shown. As multiple BMM CMs can be activated at any given time, this graph shows the total messages received from all active BMM CMs. The “Basic Mobility Messages by BMCM ID” graph in the lower middle portion of the view provides the transmission rate based on messages being requested by each CM. During this particular 10-minute timespan, the four CMs that are detailed in Table 10 below were active (display of the baseline BMCM #1 was toggled off by the experimenter).

Table 10: BMM CMs Associated with Figure 24

Msg ID	Type	Freq (Hz)	Content	Duration
31	Cloud-based trigger: hard braking (long_acc >0.4g)	10	Part 1 + ABS active, TCS, SCS	Geofence around triggered event
37	Event: hard braking (long_acc >0.4g)	10	Part 1 + ABS active, TCS, SCS	Burst mode = 0.1 sec
39	Event: lights changed	10	Part 1 + light status	Burst mode = 0.1 sec
52	Cloud-based trigger: lights changed	2	Part 1 + light status	Geofence around triggered event

Source: CAMP V2I Consortium and VTTI

BMM DMs from CM #39 (the light event) show up most frequently in the 10-minute timespan when the vehicles were naturally changing their light status (i.e., activating and deactivating turn signals) throughout testing. BMM DM peaks originating from CM #37 appear infrequently, as individual vehicles were limited as to when they could safely perform a hard-braking maneuver within the testing area.

There were two cloud-based triggers (DIDC emulation) that were activated on the server side during the time frame shown in Figure 24. Both set up geofenced regions around where the event occurred and were active for a limited time (5 minutes) as defined by the experimenter. The graph shows that before 15:05 the cloud-based trigger was not armed since the hard-braking events at 15:02 and 15:04 did not result in messages from surrounding vehicles. The hard-braking event at 15:06 caused the system to activate BMM CM #31. Subsequently, all the vehicles in the geofenced region around the event began transmitting the associated DM (light blue). As vehicles proceeded through that region, the number of DMs received for that CM fluctuated until the CM was automatically deactivated after 5 minutes (15:11).

Similar behavior is seen for the cloud-based server trigger for lights (#52). Since light changes (turn signals) were common, the triggers on the server were armed judiciously based on the location of the vehicles. The light event that occurred at ~15:09 set off the cloud-based trigger which then activated CM #52. This was defined as a 2 Hz BMM DM since the total number of messages received was much smaller than for the hard-braking response message (#31).

Lastly, the “Basic Mobility Messages by Vehicle ID” graph in the bottom right-hand corner shows the total BMM DMs received from each vehicle. The experimenter has the ability to toggle the individual vehicles on and off to isolate certain vehicles within the graph, if so desired.

4 Data Analysis

4.1 Overall

Analysis focused on broad data exploration as a means to characterize performance globally as well as locally around specific regions or events of interest. Consequently, the analysis performed is descriptive in nature to show the operational behavior of the V2I messaging alternatives and reveal areas that need to be considered when building applications, implementing the messaging systems, and identifying potential areas of improvement or clarification.

As described in the previous section, there were six test runs completed at different times of day with different levels of control and experimenter interaction. Early runs were more choreographed than the later runs, with the final data collection occurring during the demo at FHWA where the vehicle drivers were free to drive whatever route they chose without any direction from the experimenter. There were three test runs in particular that provided unique conditions for analysis and are the focus of the results described herein:

1. Test Run 1 was highly choreographed by the experimenter with the goal of keeping all 10 vehicles in a relatively tight platoon formation. This particular run was referred to as “The Dance.”

2. Test Run 4 did not try to keep the vehicles in a platoon but still had experimenter-requested triggered events for specific vehicles based on their location and the location of other vehicles. During this time, the experimenter was also exercising the different parameters of the control schemes (particularly the PDM) to confirm operation. This specific goal of this run was for “Lever Pulling” (i.e., changing parameters frequently to see what operational differences arise as a result).

3. Test Run 6 occurred in conjunction with a demonstration at FHWA. This test run was set up to mimic a more normal (i.e., naturalistic) system operation. The periodic baseline messages were scaled back to every 15 seconds (from 0.2 seconds) and the experimenter’s only role was to occasionally arm the cloud-based triggers, as these were intentionally designed not to automatically re-arm.

Each of the three research topics, Communication Mode, Message Type, and Control Scheme, had associated characterization research questions that drove the measures of interest and subsequent analysis. For each research topic, these questions and measures of interest are stated and followed up with the associated results.

4.2 Communication Mode

For this study, the communication mode refers to whether the messages were sent between the server and the OBU via DSRC or via cellular connections. The BMM was used for this analysis since a transmission log that recorded all transmitted BMMs was created on the OBU. Furthermore, only the periodic message was used in the analysis as it provided a heartbeat of messages that was consistent across all vehicles.

To quantify the performance of the communication modes (DSRC and cellular) across the test bed for the system, the following measures of interest were investigated. For each measure of interest, the related research question is provided.

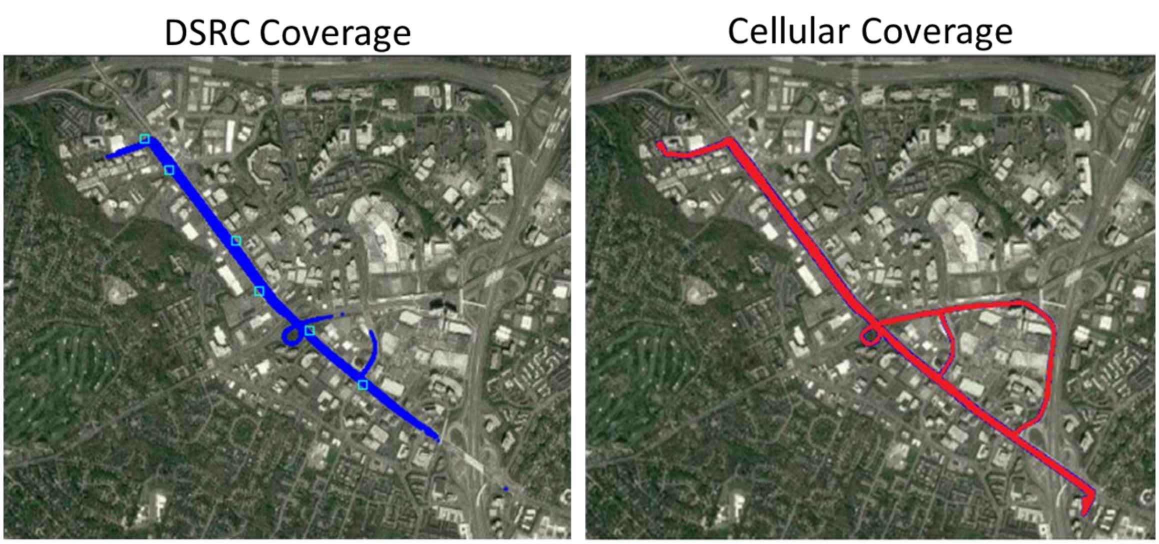
Table 11: Research Questions to Evaluate Differences in Communication Modes

Measure of Interest	Research Question
Coverage area	What is the coverage across the test bed for each mode?
Dropped messages	How often are messages dropped for DSRC and cellular in and out of communication range?
Latency	How long does it take for messages to arrive at the server from the vehicle?
Cellular quality of service across variable network coverage	What is the impact of different levels of cellular service on the transmission of messages?

Source: CAMP V2I Consortium and VTTI

4.2.1 Coverage Area

Figure 25 shows the coverage area for DSRC and cellular along the test bed. Each respective map shows the GPS location of all received messages during test 5 (478,577 DSCR messages and 187,117 cellular). DSRC received more messages since the BSM was only transmitted via DSRC.

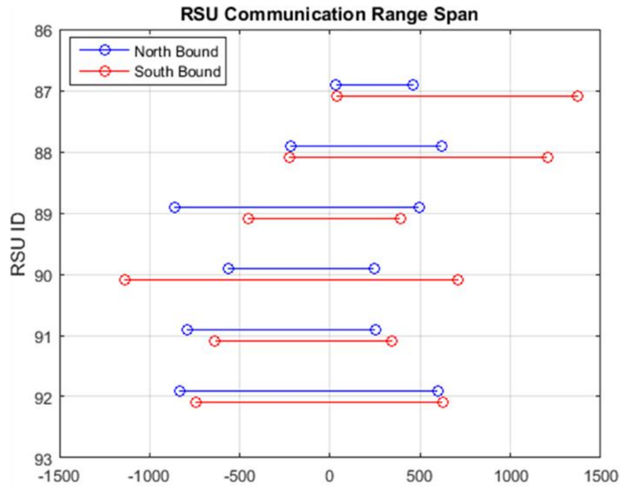


Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 25: Routes and Coverage Areas

The teal squares in Figure 25 (left side) indicate the locations of the RSUs. Note that the northern end of the route ended at RSU 87. Initially, the route was designed to proceed north past this RSU. However, due to road construction at the planned turn around area, the route was modified to incorporate a turnaround at the intersection with the last RSU. Thus, the communication range appears lower than actual at these specific RSUs such that results must be carefully interpreted.

Figure 26 shows the effective range of each of the RSUs on the test bed based on the messages received from vehicles during the full-scale test. The end points were determined by the message that was received at the furthest point from the RSU. For each RSU, the two directions of travel are indicated with north representing a negative range.



Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 26: Maximum Communication Range for Each RSU

The hypothesis was that, all things being equal, the ranges should be nearly the same across the RSU installations and, for each RSU, the ranges should be symmetric (negative and positive ranges have the same magnitude) and equal for both directions (northbound lanes are equal to southbound lanes). It quickly became apparent that this was not the case.

For RSU 87 and 88, the negative range was artificially truncated due to the test route. RSU 87 had no coverage to its north and RSU 88 had a relatively short negative range, which corresponded to the distance between RSU 87 and the end of the route (RSU 86 at Tyco Road). Therefore, no conclusions about the operational range in that direction should be drawn from the information available in the plot.

In addition, for both of these RSUs (87 and 88) along with RSU 90, the southbound direction had over twice the range for southbound traffic compared to northbound. For RSU 89, which is installed on the opposite northbound side of Leesburg Pike, this trend was reversed and the maximum range was approximately 50% greater for northbound travel compared to southbound travel.

This stretch of roadway on Route 7 was selected in part due to the challenging urban environment. In addition to heavy traffic, the metro line runs between the north and south lanes on elevated tracks between RSU 87 and RSU 90 (Figure 27and Figure 28). Relating these back to Figure 26, the explanation for reduced range in some instances becomes obvious. For RSU 87, the Spring Hill Metro Station sits between Tyco and Spring Hill Roads, creating a concrete obstruction between the northbound and southbound lanes. As the distance from the RSU increases, the concrete support pillars for the track form a line, creating a continuous obstruction as well. The maximum range for RSUs 87 and 88 demonstrate the effect of these obstructions on the communication range.

Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 27: Aerial View of RSU 87 and 88 Installation

Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 28: Aerial View of RSU 89–91 Installations

Figure 29 shows a relatively obstruction-free roadway for RSUs 91 and 92. The effect of this is reflected in Figure 26, which shows that the ranges are relatively symmetric (north to south).

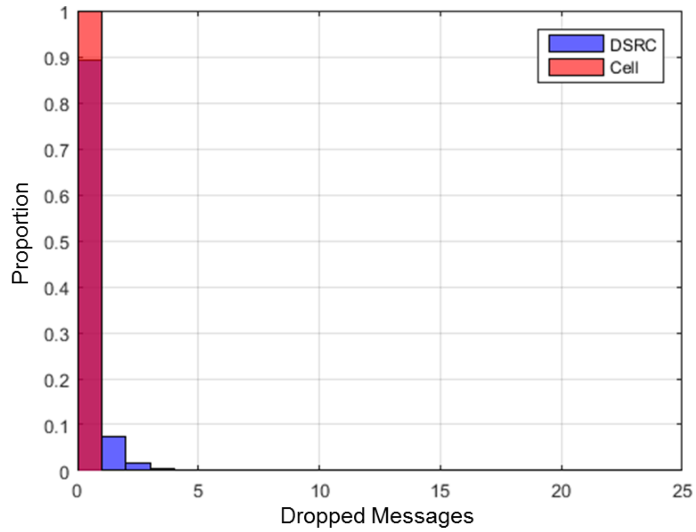
Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 29: Aerial View of RSU 91 and 92 Installation

4.2.2 Dropped Messages

While the maximum range is useful to determine the limits of the radios, evaluating the dropped messages provides further insight into the useful range of RSUs with different obstructions and expected overall message transmission rates. This analysis was performed for the BMM by comparing the detailed transmission log for all the OBUs to the messages received on the server. Since dropped messages are independent of the message content for messages of similar size, results are generalizable to the BSM and PDM as well.

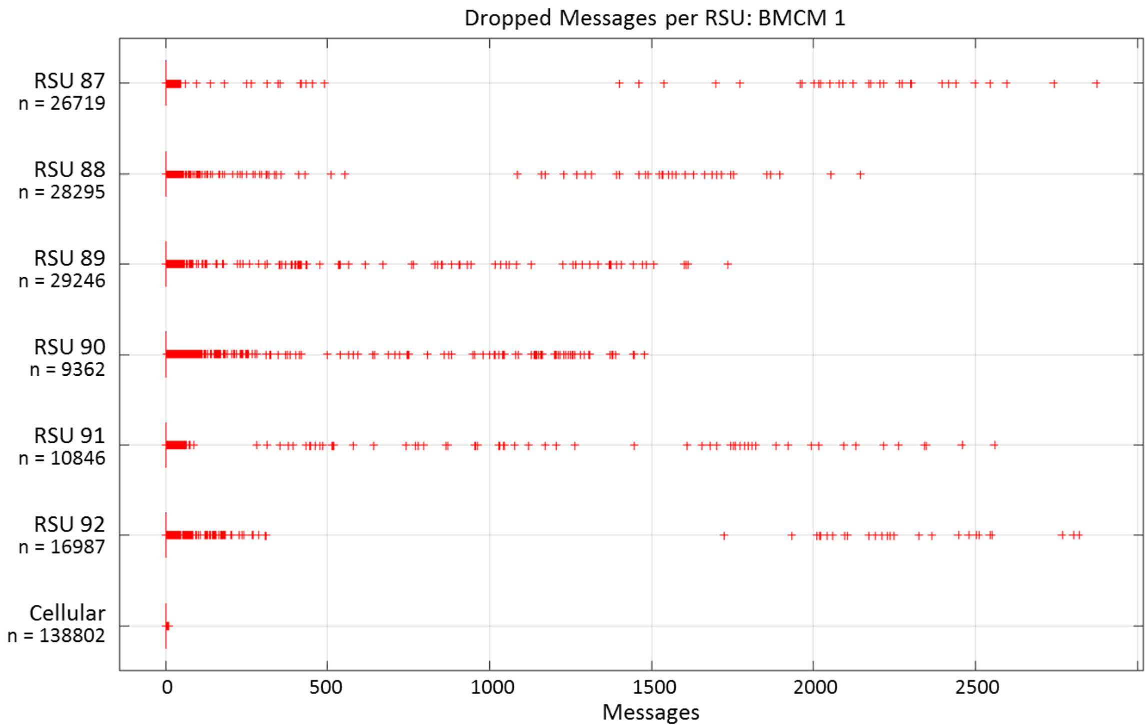
The following figures provide different perspectives regarding dropped messages. Figure 30 is a histogram of the consecutive dropped messages. Here we see that single dropped messages account for 90% of drops via DSRC and that nearly all dropped messages occur in groups of three or less. This confirms that within operational range of an RSU, the likelihood of the messages being successfully transmitted is extremely high.



Source: CAMP V2I Consortium and VTTI

Figure 30: Consecutive Dropped Messages Histogram

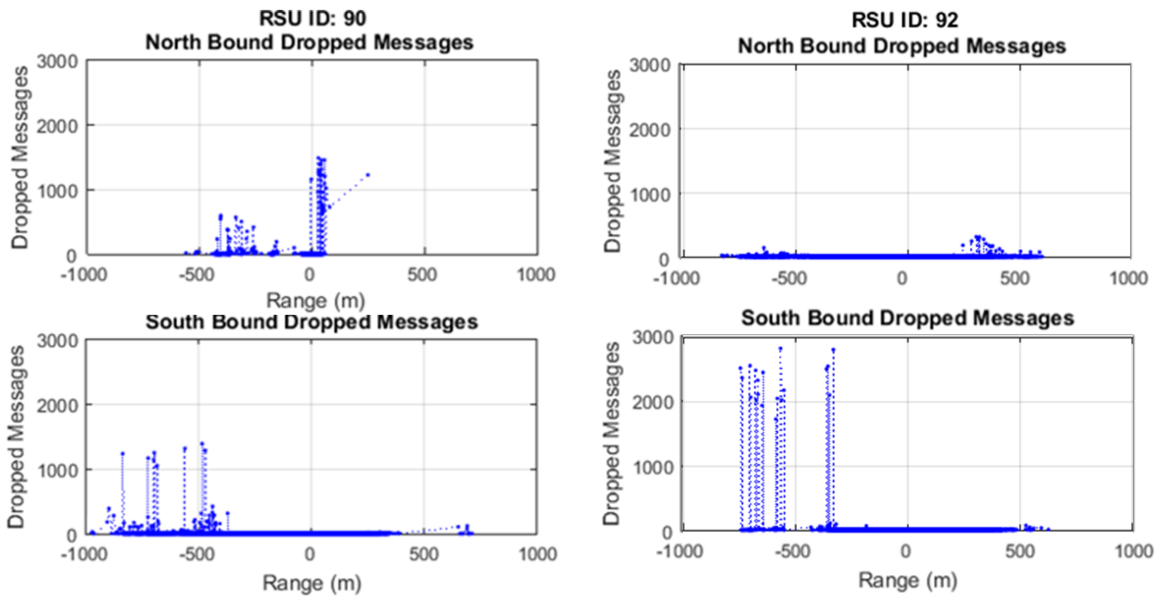
To investigate outliers, Figure 31 shows a box plot of the number of message dropped for all vehicles for each individual RSU as well as cellular. The horizontal axis is the count of consecutive messages dropped where the range is based on the maximum distance that a message was received from the RSU. Note that dropped messages are rare. The figures are zoomed out such that the boxes are compressed and the focus is out the outliers (which represent long communication outages). Under ideal conditions, when moving out of range, the number of consecutive messages should gradually increase until no messages are received. The gaps indicate a sudden degradation in signal that is likely due to the geography surrounding a given RSU, as discussed in the previous section. This sudden loss in coverage is not observed for cellular given the ubiquitous coverage in the area.



Source: CAMP V2I Consortium and VTTI

Figure 31: Consecutive Dropped Messages per Reception Point

It is important to investigate dropped messages as a function of distance from the RSUs to find out where these dropped messages occurred. For RSU 90 and 92, Figure 32 shows two extremes on the previous box plot in terms of gaps in the distribution. RSU 90 is the unit with the metro station between the north and south lanes, whereas RSU 92 exhibits a more open line of sight. As expected, RSU 92 has a more consistent transmission rate until the edge of its range is reached. Both of these correlate with the box plots, where obstructions cause more random distribution of dropped messages and more open sky conditions result in more predictable transmission.

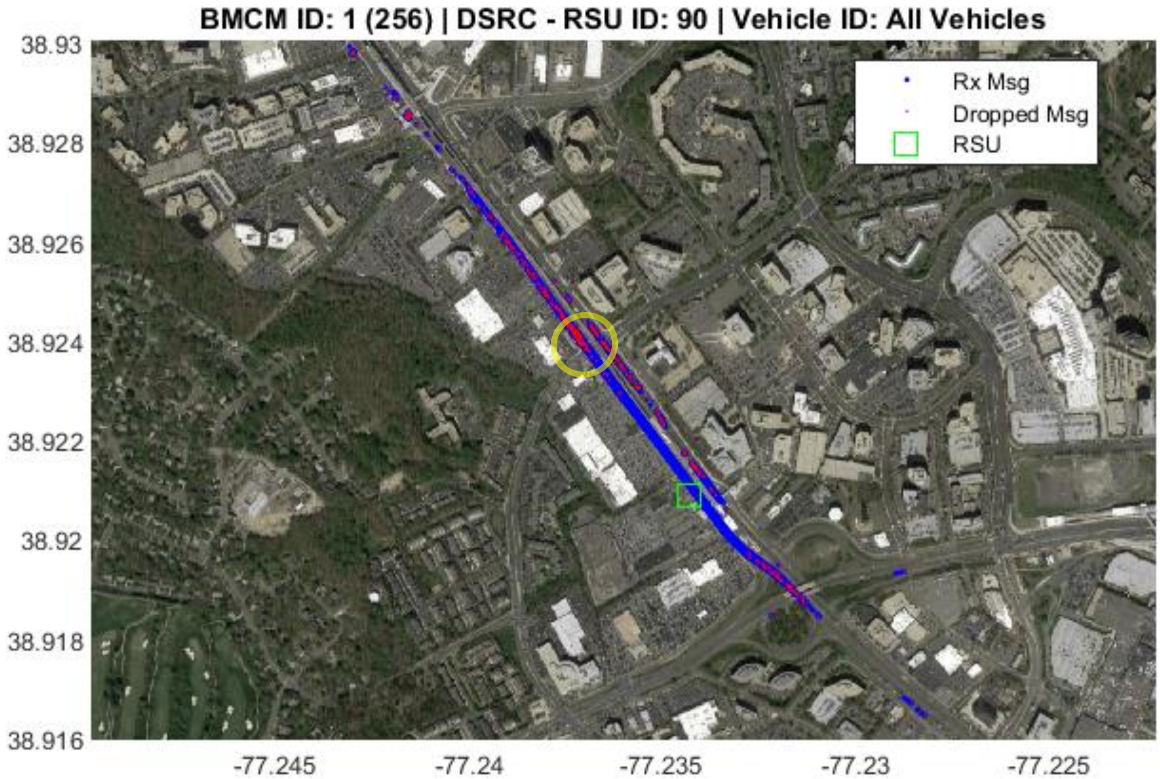


Source: CAMP V2I Consortium and VTTI

Figure 32: Dropped Messages vs Range – RSU 90 and 92

It is important in reviewing this data to recall that the RSUs are placed in such a way that coverage overlaps to ensure that messages are delivered to the server. Looking more closely at RSU 90, we can see that the messages dropped also are highly dependent on the direction of travel. As noted in the discussion of coverage, the metro line obstructs RSU communication with northbound traffic, resulting in much poorer coverage and reduced likelihood of successful transmission.

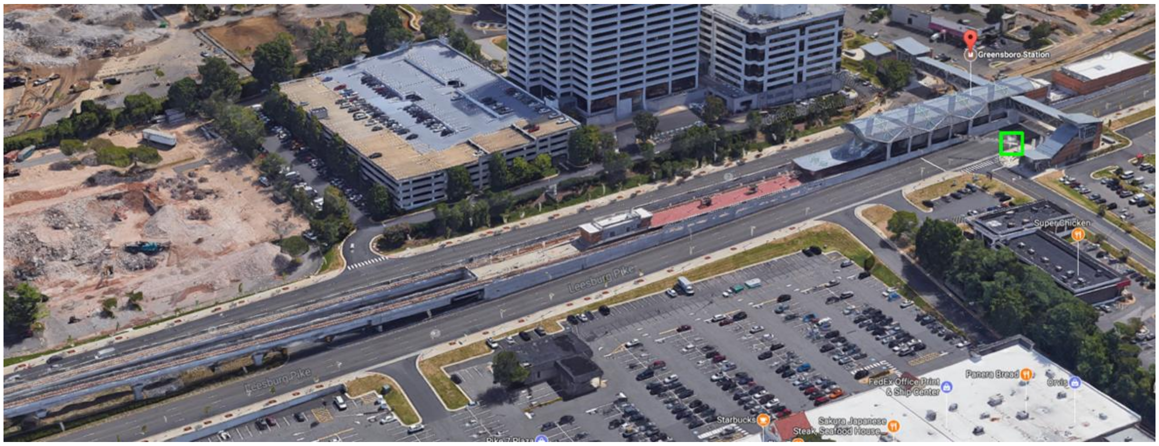
Figure 33 shows the message obstruction graphically overlaid on a map of the area. As before, blue indicates the GPS location of a received message, while red indicates the position of a message that was transmitted but not received at the server. Where the southbound lanes easily transmit more than a block away, the northbound lane has spotty service at a relatively short distance from the RSU, particularly on the south side of the intersection where the metro station building sits above the area that the metro drops underground (Figure 34).



Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 33: RSU 90 Received and Dropped Messages

Another interesting observation is the apparent impact that stopped traffic has on dropped messages. For RSU 90, we see a high concentration of dropped messages at the next major intersection north of the RSU installation, identified by the yellow circle in Figure 33. This corresponds to the spike in dropped messages at around -500 m. There are no natural obstructions at that point, the road is straight and flat with a gradual uphill (~1.7%). The increase in dropped messages could be due to the extra time spent at the light (i.e., the drop rate is the same, but there was more time to collect dropped messages while at the red light), or it could be that the surrounding vehicles increase the probability of dropped messages when they are in a tighter, at rest, configuration. All of the vehicles in this test were small to midsize cars, and as such, it is likely that in a large group of stopped vehicles some of the surrounding vehicles would block the line of sight between the car's antenna and the RSU, resulting in degraded performance.



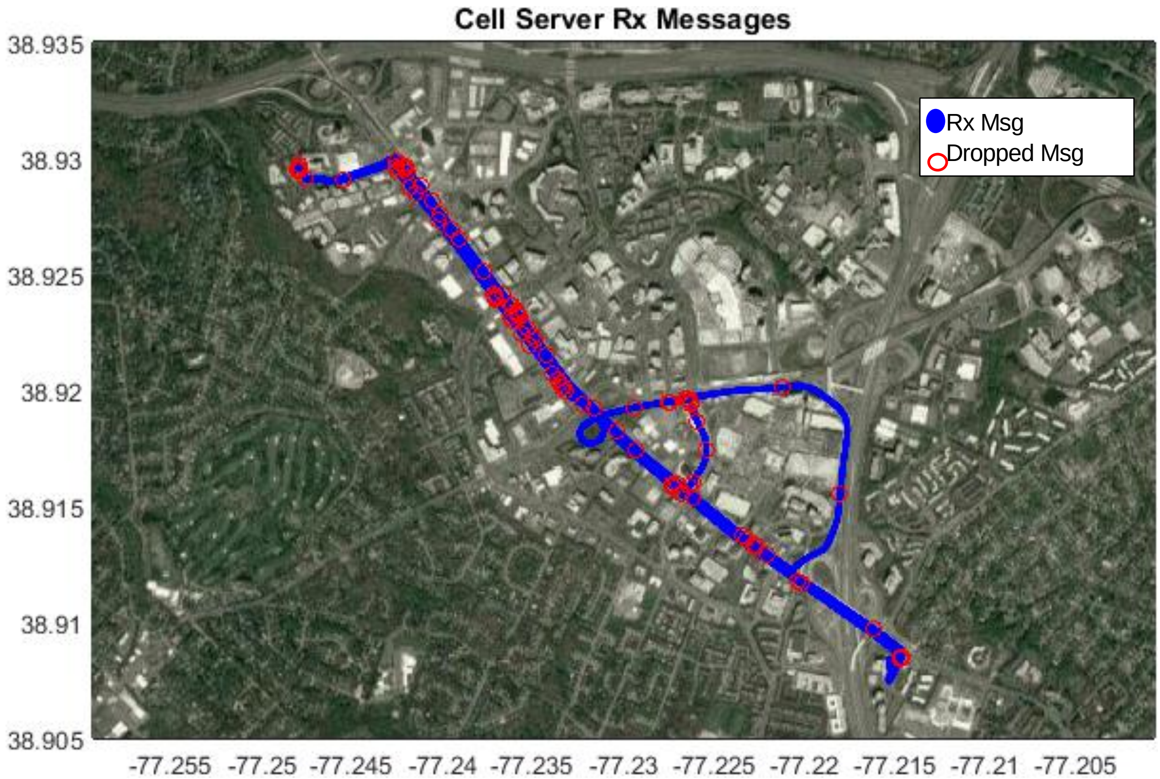
Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 34: RSU 90 Bird's-eye View

4.2.2.1 Dropped messages on the cellular network

There is generally good cellular coverage in the Northern Virginia area, which resulted in reliable communicators and a low drop rate. Packets were sent over cellular via User Datagram Protocol (UDP), which has the advantage of not having any end-to-end connections. This reduces the overhead cost but eliminates the guarantee of delivery afforded by other protocols, allowing for the possibility of information loss. This raises the question of whether the loss is of an acceptable size. While this question is application dependent, it is expected that the overall measured drop rate of 0.9% should be adequate for non-time-critical application.

The next question is whether there are any areas that resulted in more dropped message than others, and if so, why. Figure 35 shows a map of the messages received (blue) with an overlay of the location where messages were dropped (red).

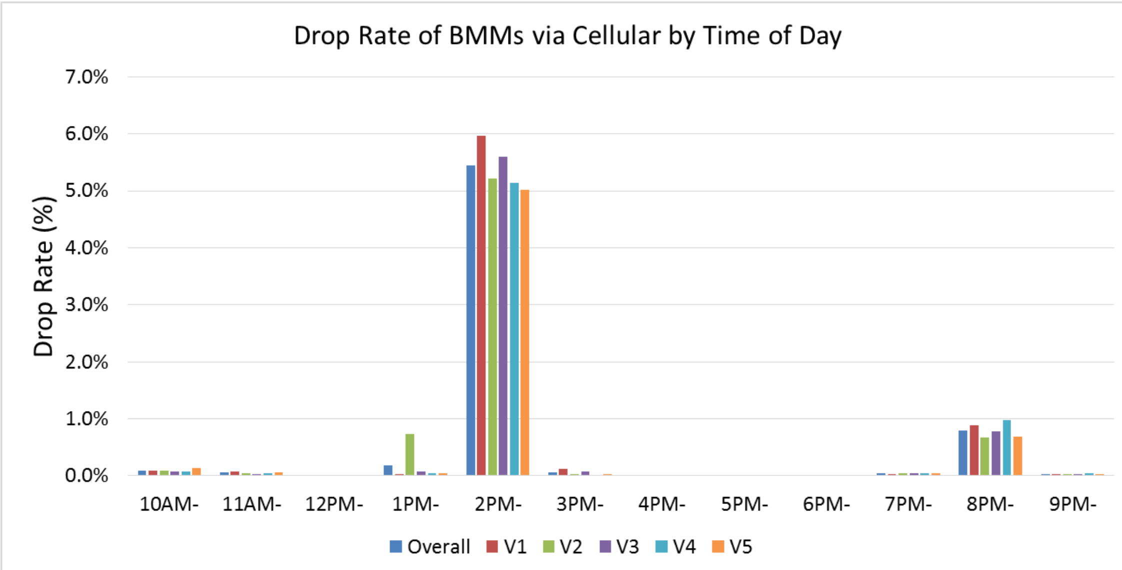


Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 35: Map of Messages Received and Dropped on Cellular Network

As with the DSRC maps, we see a concentration of dropped messages around intersections. Further analysis would be required to determine the cause, but it is likely at least in part due to the additional time spent stopped at intersections. The control scheme for the BMM has the ability to cease transmission under stop conditions. These parameters were not turned on during testing so that all data would be available for analysis. With the featured switched on, DMs would cease transmission while stopped, likely reducing this observed concentration of dropped messages around intersections.

Since the cellular network is open to all users and controlled by an external entity, the performance of the message transmission was evaluated at different times of the day. The hypothesis here was that cellular network load would vary as a function of time of day and that the network provider would likely throttle connections, either of which could result in more dropped messages. While we do not have access to the data showing cellular network load as a function of time of day, it seems reasonable that the early afternoon (after lunch) hours and after work hours may have higher usage. Thus, test runs spanned mid-morning through evening. The following figure (Figure 36) shows the results of the analysis supporting the network load assumption.



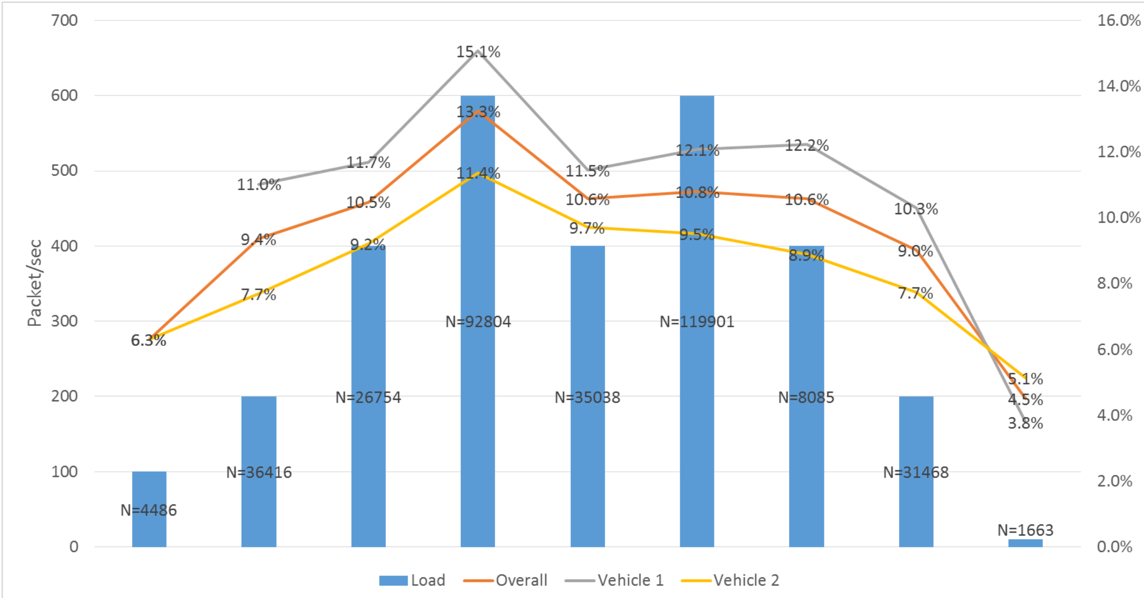
Source: CAMP V2I Consortium and VTTI

Figure 36: Cellular Drop Rate as a Function of Time of Day

We see that early afternoon, around 2:00 p.m., had a higher than normal drop rate (5%–6% vs < 1%). In the evening, around 8:00 p.m., there was again a slight increase in the average drop rates that were observed across all tests. While this limited sample (six tests over three days) showed that there may be a dependency of dropped messages to time of day, more data collection would be required to determine if these trends are stable. However, if they are, and the rate is representative, a 5% drop rate and a periodic message sampled every 15 seconds would indicate that five messages would be lost in a 25-minute period (i.e., one message would be lost every 5 minutes), which should be more than adequate for non-time critical applications.

4.2.2.2 Dropped Messages under Simulated Message Loading

The following chart shows the effect of message volume on drop rate to simulate a high traffic density condition. Data were collected with two vehicles parked within close proximity to the RSU (< 50 m). The sampling frequency started at 50 Hz and was then increased to 300 Hz by increments of 100 Hz. This yielded a total message transmission rate of 600 Hz. A final 10 Hz collection was performed to establish a baseline.

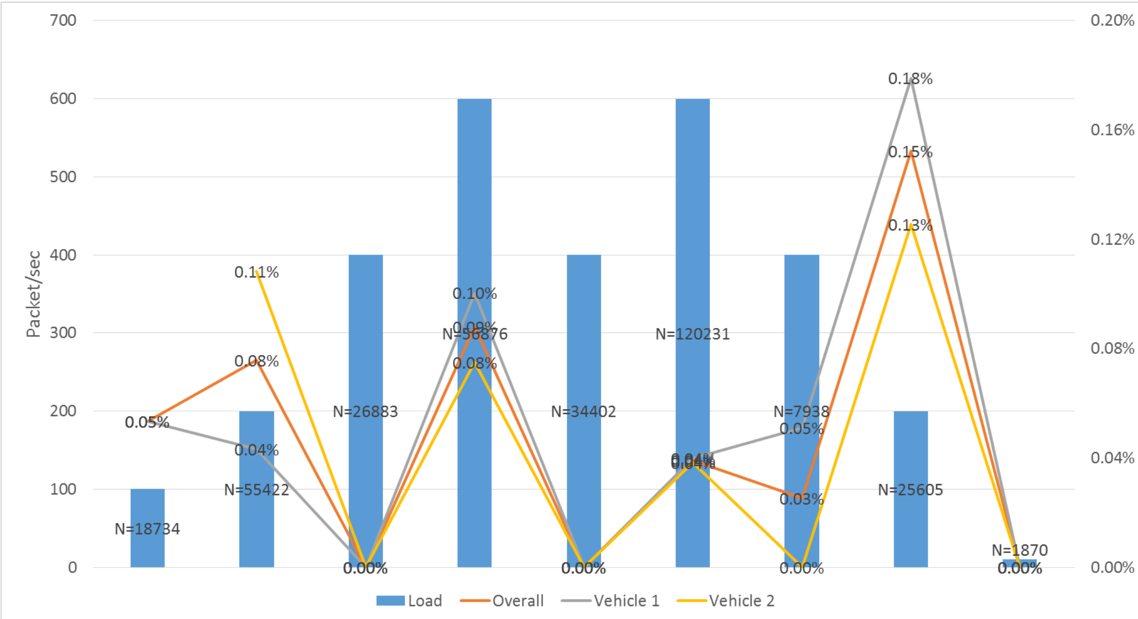


Source: CAMP V2I Consortium and VTTI

Figure 37: Static Stress Test – Drop Rate by Load – DSRC

The left axis of Figure 37 shows packet rate, which corresponds to the blue bars. The right axis indicates drop rate, which is shown by line graphs for each vehicle along with the average. The drop rate increases in line with the message load, with the maximum drop rate being 15% at 600 packets/sec. The average overall drop rate at 600 packets/sec is 12.0%. As message volume decreases, so does the percentage of dropped packets.

Cellular (Figure 38) does not appear to be impacted by the loads exerted during the tests. The first thing to note is that the max drop rate, which occurred at 200 packets/sec, is 0.18%. The second observation is that there does not appear to be any correlation between load and drop rate. This can be confirmed by doing a simple regression between drop rate and load. For DSRC, approximately 90% of the variability in drop rate is accounted for by the number of messages being sent. For cellular, less than 10% of the variability is accounted for by message volume. This would indicate that the variability is most likely unrelated and that the volume of messages being transmitted does not adversely impact the performance of the cellular network.



Source: CAMP V2I Consortium and VTTI

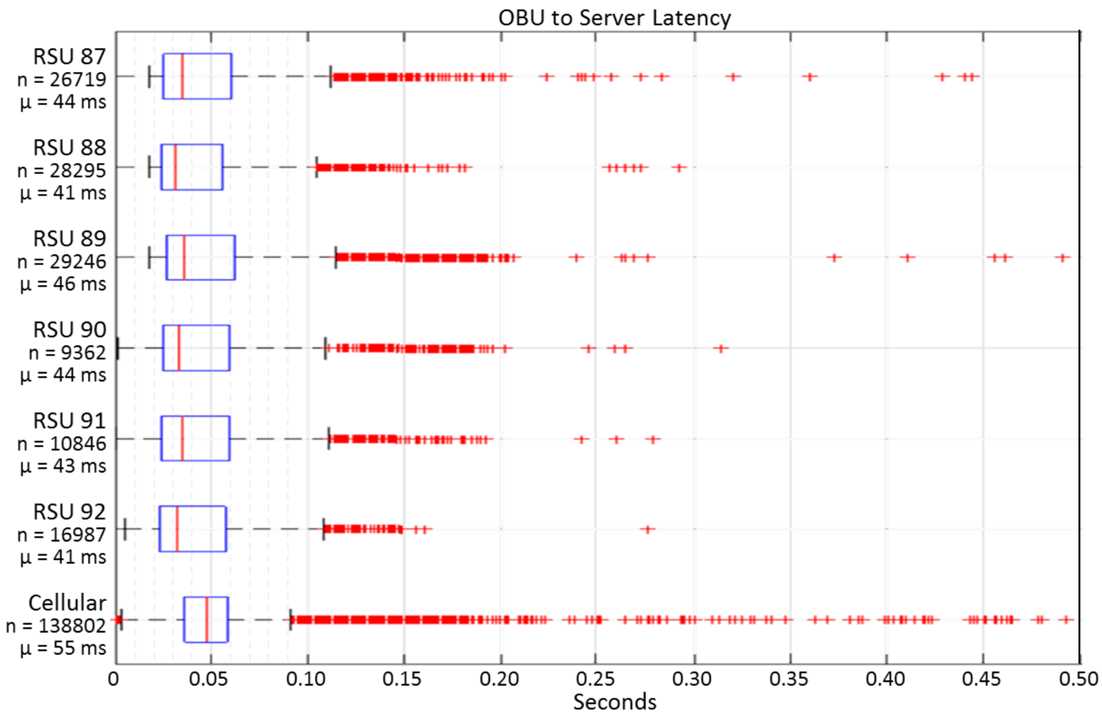
Figure 38: Static Stress Test – Drop Rate by Load – Cellular

While DSRC's dependence on load may at first seem problematic, given the constraint that a vehicle should be in motion before it starts sending messages, and that the nominal sampling interval is relatively large, it is likely that these load levels will not be experienced in deployment. For example, assuming eight lanes of traffic with one vehicle every 10 m (a little more than car length between each vehicle) and an RSU operational range of ±500 meters, there will be 800 vehicles in range of the RSU. If these are sampled every 15 seconds, that puts the RSU load at ~53 messages/sec which, based on this initial evaluation, should not cause a degradation in the throughput of DMs.

4.2.3 Latency

As with dropped message analysis, the BMM was used to evaluate the time it took for a message to travel from the vehicle to the server. This transmission time is the latency. A series of boxplots were created to examine the time between when a message was sent by the vehicle to when it was received at the server. Figure 39 shows a boxplot of the time between messages for each vehicle's OBU and each RSU (for DSRC), as well as for each vehicle's OBU via cellular communication, in the Northern Virginia test bed for the Baseline BMM CM (#1). For the box plot,

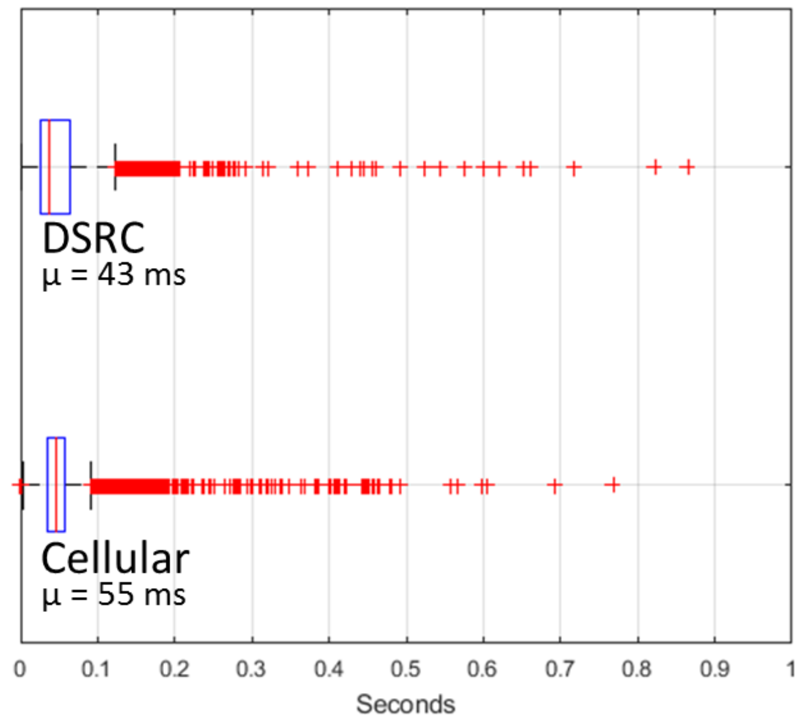
- Red line = median
- Box size = ± quartile
- Whisker length = Interquartile range ± 1.5 quartile



Source: CAMP V2I Consortium and VTTI

Figure 39: System Latency per RSU

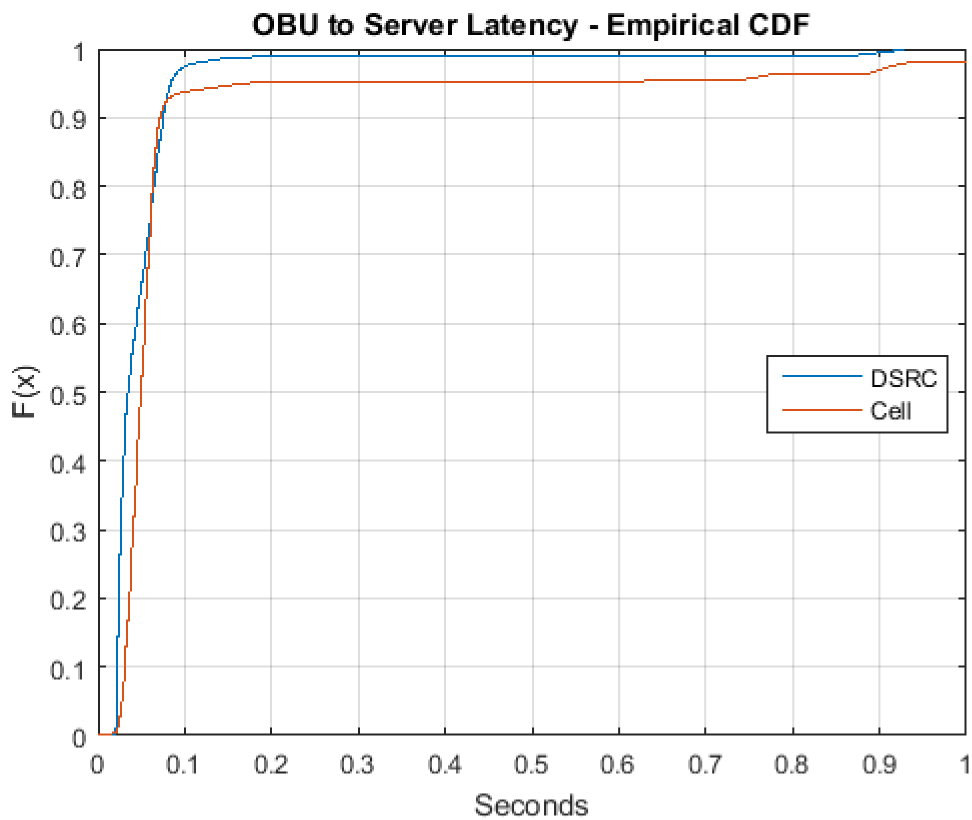
Compressing this further, we see that the messages were received, on average, 12 msec sooner via DSRC.



Source: CAMP V2I Consortium and VTTI

Figure 40: Overall System Latency for DSRC and Cellular

For DSRC, a positive skew is observed where the median value (red line in the box) is less than the mean (center of the box). This is reflected in the Cumulative Distribution Function (CDF) of OBU-to-server latency (Figure 41), where the rise of the DSRC slope is steeper (up to ~50%) and then flattens out, whereas the slope for cellular is relatively constant. This indicates that it took less time for the majority of messages to be received via DSRC. However, for both DSRC and cellular, we see that over 90% of the messages were received within 0.1 seconds of transmission.



Source: CAMP V2I Consortium and VTTI

Figure 41: CDF of OBU to Server Latency

4.2.3.1 Time Between Messages

Another way to look at the messages' transmission time is to compare the time between received messages. Since the baseline BMM was sent at 5 Hz (0.2 seconds between messages), comparing the time stamp of sequential messages should result in a mean value of 5 Hz.

Source: CAMP V2I Consortium and VTTI

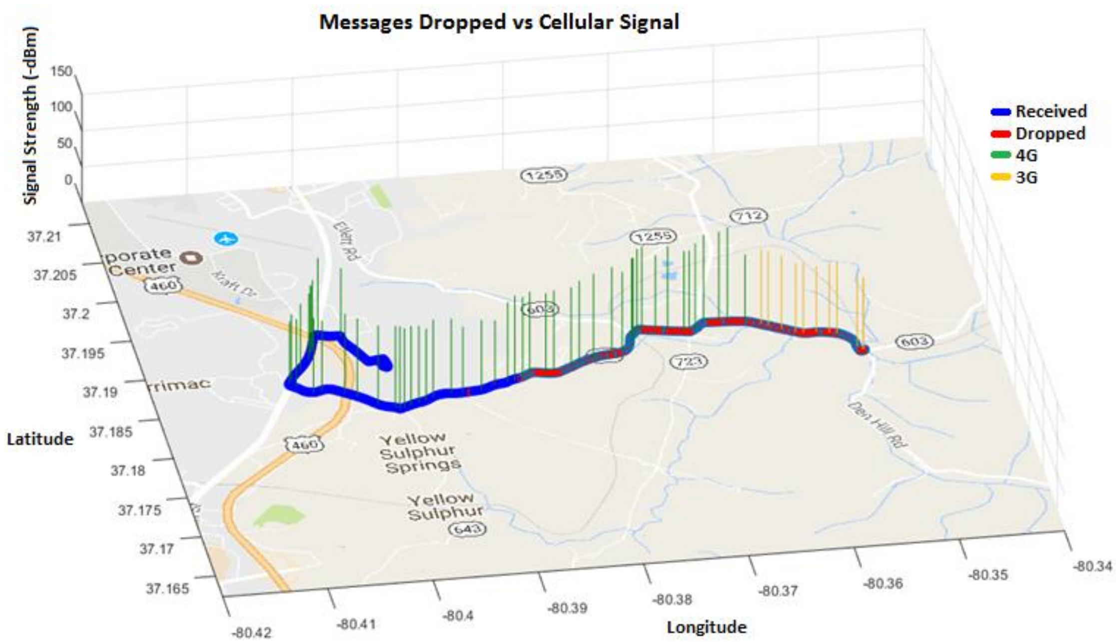
Figure 42: Time Between Received Messages on Server

What we see in the figure above is that most messages were received at the same rate that they were transmitted — within 5% of the 0.2 second transmission period. The exception to this is the messages received from RSU 90, which, as we saw in the previous section, had a high number of dropped messages. Dropped messages appear to be accompanied by delayed messages.

4.2.4 Quality of Service

While cellular coverage in Northern Virginia is generally very good, there is a wide variation of coverage in rural areas around Blacksburg, Virginia. Quality of service tests were performed in Blacksburg to determine the level of coverage and any effects on message transmission. Since signal strength was not available through the OBU, a separate cellular device was operated concurrently to obtain an approximation of signal type and strength. These data were then correlated to relate message transmission with coverage. The hypothesis was that service type and signal strength would impact dropped messages and latency.

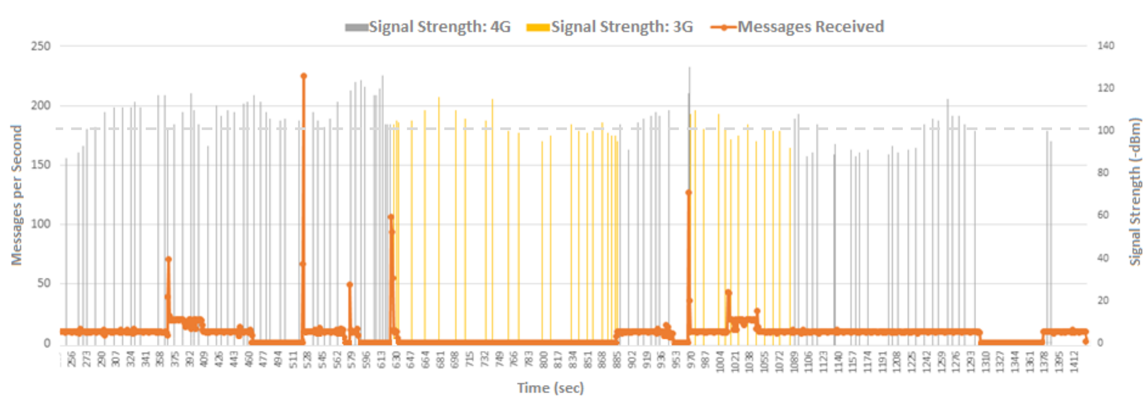
Figure 43 shows a plot of the GPS positions of messages that were received by the server from a vehicle traveling along the shown route. Service type and signal strength are also displayed. Along this route, there was a mixture of 4G, 3G, and no service available with most signal strengths recorded between -90 dBm to -120 dBm. Regarding signal strength, less negative numbers (i.e., closer to 0) indicate a stronger signal. Signal strength is also measured on a logarithmic scale, so an increase of 3 dB doubles the power and an increase of 10 dB increases the power by 10. In addition, 4G performs better than 3G for a similar signal strength.



Source: CAMP V2I Consortium and VTTI

Figure 43: Dropped Messages vs Cellular Signal Along Test Route

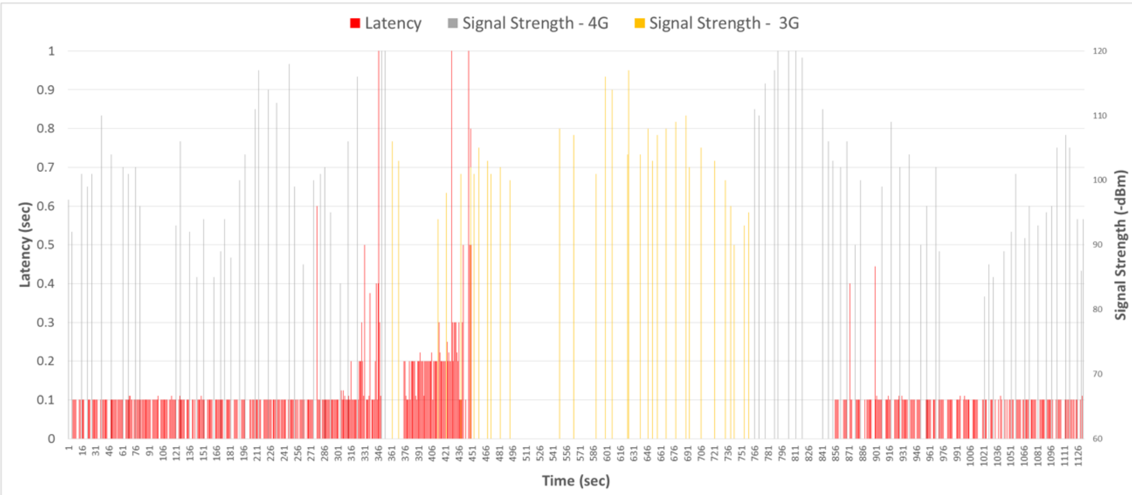
From Figure 43 we see that, along this route, messages received does not directly correlate with signal strength. In the early portion of the run, messages were consistently received with signal strengths around -115 dBm. A little later, with similar signal strength, messages were not received by the server. In addition, while in the latter 3G service region where more readings were recorded, with similar signal strength, messages were successfully transmitted to the server.



Source: CAMP V2I Consortium and VTTI

Figure 44: Comparison of Message Receipt Frequency and Cellular Signal Strength

It was expected to see the latency increase with lower signal strength and with a lower grade of service (3G vs 4G) which is observed in Figure 45. The nominal latency for 3G is twice what it is for 4G with latencies increasing as signal strength diminishes.



Source: CAMP V2I Consortium and VTTI

Figure 45: Comparison of Latency to Cellular Signal Strength

Evidence suggests that cellular communication is related to, but not determined by, fluctuations in service quality. Even if the device shows connectivity, messages may or may not be received at the server side. It does appear that the stronger the signal, the more certain the message will be successfully received. This is consistent with most cell users' experience in sending text messages, meaning that most successfully make it to the recipient in a timely manner. However, sometimes messages are delayed or never make it to the recipient, even with what appears to be reasonable service.

4.3 Message Type

As discussed previously, three message types were implemented in the system: the BSM, the PDM and the BMM. Each message type was designed with a particular purpose in mind and, therefore, has unique characteristics. The primary purpose of this project was not to evaluate one message type as better than another (which would require applications), but rather to qualify the operational characteristics of each in order to evaluate what characteristics should be kept, refined, or merged to create a more functional message structure(s). The BSM was carried over from the BSM Emulator Project as a baseline to compare the performance of other message types for different mobility applications. AMCD collected this data to include in the Research Data Exchange collection for future research and development. However, lacking applications, the comparison value for this analysis was limited and, therefore, focuses primarily on the PDM and BMM. It is useful to review the purpose of each of these message types as well as provide some specific features of each.

One of the stated purposes of the PDM according to J2735, Annex E, is to

> …ascertain real-time road, weather, and traffic conditions. The post-processed data will be used to advise vehicles approaching the area of current conditions and suggest appropriate

action. This data is collected autonomously as vehicles are traveling along the roadway system and sent to an RSU when applicable. [1]

This is supported by a set of rules for the storage and up-loading of data, which include the following:

- Snapshots are generated that include a time stamp, vehicle position, speed, acceleration, vehicle system status, and temporary vehicle identifier (Probe Segment Number [PSN]). These can be generated for any of the following three conditions.
  - Periodic (every 4–20 seconds depending on vehicle speed)
  - Start/Stop (Stop: no movement for 5 seconds and no other stops for past 15 seconds; Start: speed exceeds 10 mph after a stop)
  - Event Triggered (change in vehicle status)
- Protects vehicle anonymity (privacy gaps; rollover of PSNs)
- At least 32 snapshots are to be saved on the OBU based on a well-defined buffering scheme. The messages that are saved and removed are a function of age, snapshot type, and the number of snapshots currently stored.
- Snapshots are packaged and transmitted to an RSU when in range
- Changes to some of the collection parameters are temporary and revert back to the default conditions after a given period or distance

There are also several privacy protocols established to help ensure the anonymity of the vehicle:

- The first snapshot is generated only after 500 m or 120 seconds, whichever occurs first
- The PSN changes every 120 seconds or 1 km, whichever comes later
- After the PSN changes, no snapshots are generated for 3 to 13 seconds, or 50 to 250 m, whichever comes first
- After a vehicle sends snapshots to an RSU, all remaining snapshots with the PSN are purged and the vehicle does not communicate with that RSU for 6 minutes or 4 km, whichever comes first

These provide a robust way to maintain privacy and keep a historic record of the most relevant information but do not facilitate a targeted transmission of data based on current conditions or events. The BMM expanded the application of the PDM to support additional real-time applications and provide more control of the message flow and content from the vehicle. The primary was that the BMM differs from the PDM as follows:

- The multi-threaded nature of the BMM message allows for multiple asynchronous messages to be generated and sent to the infrastructure
- The control infrastructure actively requests BMM information tailored to a specific scenario, geolocation, or application rather than a generic default message generation

The result of some of these inherent differences become readily apparent in the analysis of the data. To investigate the performance characteristics of the PDM and BMM, the following areas were investigated as noted in Table 12.

Table 12: Research Questions to Evaluate Difference in Message Types

Measure of Interest	Research Question
Message volume and frequency	How many messages were received and how do the different message types compare?
Redundant data	Does the flexibility of a multi-threaded message come at a cost of large amounts of information being transmitted?
Age of information	How long does it take for targeted information to get to the server?
Applicability of message type	Can the messages provide timely and targeted data for different applications?

Source: CAMP V2I Consortium and VTTI

4.3.1 Message Volume and Frequency

Assessing message volume is useful as it provides not only a means to compare message strategies for total messages sent, but also to see how messages are affected by different control strategies. We began by looking at volume rather than bandwidth, as the size of the messages is dependent on their content. The size of the BSMs and PDMs are defined in J2735. The average size for the BMM during full-scale testing was 75 bytes.

PDMs were transmitted with multiple snapshots per messages. Table 13 following provides a breakdown of the number of snapshots collected.

Table 13: Total Data Messages (DM) Received During FullScale Testing

	Test Run	1	2	3	4	5	6	Total	Msg /min
	Duration (min)	129	73	96	106	55	126	**585**	
DSRC	BSM	384983	332891	457368	524637	321793	571441	**2593113**	4433
DSRC	BMM	239063	320618	260451	327664	154267	34817	**1336880**	2285
DSRC	PDM (msg)	28486	22417	1837	18707	2497	19314	**93258**	159
DSRC	PDM (snp)	100095	81080	3023	63073	3068	67527	**317866**	543
Cellular	BSM	n/a	n/a	n/a	n/a	n/a	n/a	**-**	-
Cellular	BMM	285653	774296	385938	355281	183779	40908	**2025855**	3463
Cellular	PDM	27124	30229	4835	21121	3338	23839	**110486**	142
Cellular	PDM (snp)	96528	108838	12697	70041	4056	82653	**374813**	641

Source: CAMP V2I Consortium and VTTI

As expected, the BSM produced the highest number of DM. The BMM generated the next largest number of messages. This will be discussed further in the analysis of the communication mode and message types. As discussed earlier, each test run was performed with a particular intent. Table 14 shows a comparison of test runs 1 and 6, illustrating the contrast between a choreographed test run and a more naturalistic scenario.

Table 14: Test Conditions for Test Run 1 and Test Run 6

Description	Test Run 1: "The Dance"	Test Run 6: "Demo"
Periodic Interval	0.2 sec (5 Hz)	15 sec
Conditions	• Controlled test run (~2 hrs.) • Scripted triggered events • Light traffic conditions (evening)	• Demo run (~2 hrs.) • Triggered events due to normal driving • Intermittent rain during demo

Description	Test Run 1: "The Dance"	Test Run 6: "Demo"
		• Moderate to heavy traffic (lunch hours)

Source: CAMP V2I Consortium and VTTI

Since each run was of nearly the same length, we can compare the two to see how the volume of messages compared for the two scenarios (Table 15). In addition to the messages received, the difference between the two provides a comparison of the two test runs.

Table 15: Comparison Between Test Run 1 and Test Run 6

		Data Messages Received			Percent of BSM		
Test Run		Dance	Demo	***Delta***	Dance	Demo	***Delta***
Msg. Type	BSM	384,983	571,441	*186,458*	100%	100%	-
	BMM	239,063	34,817	*-204,246*	**62%**	**6%**	*-56%*
	PDM	28,486	19,314	*-9,172*	7%	3%	*-4%*

Source: CAMP V2I Consortium and VTTI

A few observations based on these tables:

- During the highly-choreographed Dance test run, the BSM produced the most messages. The BMM produced 62% of the messages compared to the BSM, whereas the PDM only produced 7%. During this run, in addition to messages from triggered events and the associated geofenced triggers, the periodic baseline was set at 5 Hz with the expectation that this could be subsampled at a later time to evaluate the effect of sample rate on application performance. For the Demo run, the baseline was reduced to a sampling interval of 15 seconds, which is still likely higher than in a normal operation scenario.
- Between these two tests, there was an 85% reduction in the number of BMMs received, while the number of PDMs dropped by only a third. This illustrates the level of control afforded by the BMM scheme relative to the PDM scheme. The BMM message flow could be further reduced by decreasing the periodic message below the 0.02 Hz setting, if desired, based on the application requirements and bandwidth available.
- By default, the PDM packages four snapshots per message. Due to other factors in the design of the PDM, the actual number of snapshots per messages was, on average, 3.6. The value reported in the table reflects the messages received. Therefore, the actual snapshot count is closer to 103,000 for the Dance run and 69,500 for the Demo run. BMM snapshots were sent as individual messages for these two tests. As a result, there were more PDM snapshots received by the server than BMM snapshots.
- Approximately 50% more BSMs were received during the Demo run compared to the Dance run for the same length of time. The Demo run took place starting towards the end of typical lunch hours (12:56 pm), whereas the Dance run was conducted in the evening, starting at 7:55 pm, when traffic was much lighter. Consequently, during the Dance run, much less time was spent at stoplights, where it was typical to be in range of multiple RSUs. (It was common to be

in communication with two and three RSUs, and communication with up to five RSUs occurred on a few occasions.)

Simulation results from the BSM Emulator Project showed the number of messages received for the BMM and PDM to be 3% and 1% of the BSM. While the Dance run results are not close to that ratio, the Demo run, which took place under more normal operating conditions, does show results comparable to those simulated ratios.

4.3.2 Redundant Data

One of the purposes of using a message type other than the BSM for non-time critical applications is the potential to reduce bandwidth. Using a multi-threaded messaging structure assumes that multiple independent messages will occasionally be sent at the same time providing additional opportunities to decrease bandwidth by eliminating redundant data. This was investigated in two ways. First, the source of the DMs was considered (periodic vs. triggered and which triggers were invoked) to provide an indication of where the messages volume originates and how it might be affected. Second, the content of the messages was examined to see if it could be manipulated to reduce the payload without impacting the information transmission.

Table 16 shows a breakdown of how many DMs were generated by different CMs and, if from an OBU trigger, which event triggered the message. Comparing the Dance run with the Demo run, we see the reverse proportion of periodic messages to OBU triggered messages. It is important to keep in mind that the total number of messages sent during the Demo was approximately 15% of the number sent during the Dance, but there were four times as many triggered messages sent during the Demo. Not surprisingly, the messages consuming bandwidth during “normal” operation are primarily from OBU triggered events. These were generated approximately every 4 seconds during the test. The biggest contributor to these is the light event. Since light events include turn signal light activation, they occur quite often. The same applies to the wiper triggers. Again, these events were selected for convenience (ease of initiating in live traffic) given the absence of applications within AMCD. The aim of the events was simply to exercise the message schemes; thus, event triggers should not be presumed representative of actual desired event triggers and caution should be exercised when interpreting these results.

Table 16: Source of Messages Received During Test Runs 1 and 6

	All Tests		**Test 1: Dance**		**Test 6: Demo**	
	Messages Rx	**% of Total**	**Messages Rx**	**% of Total**	**Messages Rx**	**% of Total**
Total (DSRC)	1336680		239063		34817	
Periodic	1133228	85%	183866	77%	3774	11%
Cloud based triggered	122338	9%	48222	20%	2874	8%
OBU triggered	81114	6%	6975	3%	28169	81%
OBU: Hard brake	4491	6%	624	9%	1048	4%
OBU: Wiper	9439	12%	579	8%	6941	25%
OBU: Lights	67184	83%	5772	83%	20180	72%

Source: CAMP V2I Consortium and VTTI

While modifications to event triggering would reduce the number of DMs generated, both monitoring the timing of the messages and limiting the payload to messages unique to other messages being transmitted in close temporal proximity provide another way to reduce bandwidth. Table 17 shows the results of an analysis aimed at determining the amount of redundant data that could be eliminated from triggered messages if common elements (BSM Part 1 for this analysis) were removed. Four time windows between 0.1 seconds and 15 seconds were considered. The goal was not to create an optimized solution but to rather to confirm that eliminating common data elements would be an effective method for reducing redundant data due to the BMM's multithreaded feature. For a highly choreographed setting, the savings is limited due to the low number of proximal triggered events. However, the bandwidth savings potential is pronounced when there is a large portion of triggered events as collected during the Demo,

Table 17: Potential Reduction in Data by Eliminating Redundant Data

Window Size	Test 1 "Dance"	Test 6 "Demo"
0.1 sec	9.5%	1.6%
0.2 sec	14.4%	2.2%
1 sec	16.4%	5.3%
15 sec	16.4%	52.2%

Source: CAMP V2I Consortium and VTTI

While not all messages could be lumped into a 15 second window, these results do provide a glimpse into what might be possible with an optimized message handler capable of suppressing redundant data. This, in conjunction with a more applied triggering implementation, could significantly decrease unnecessary message traffic.

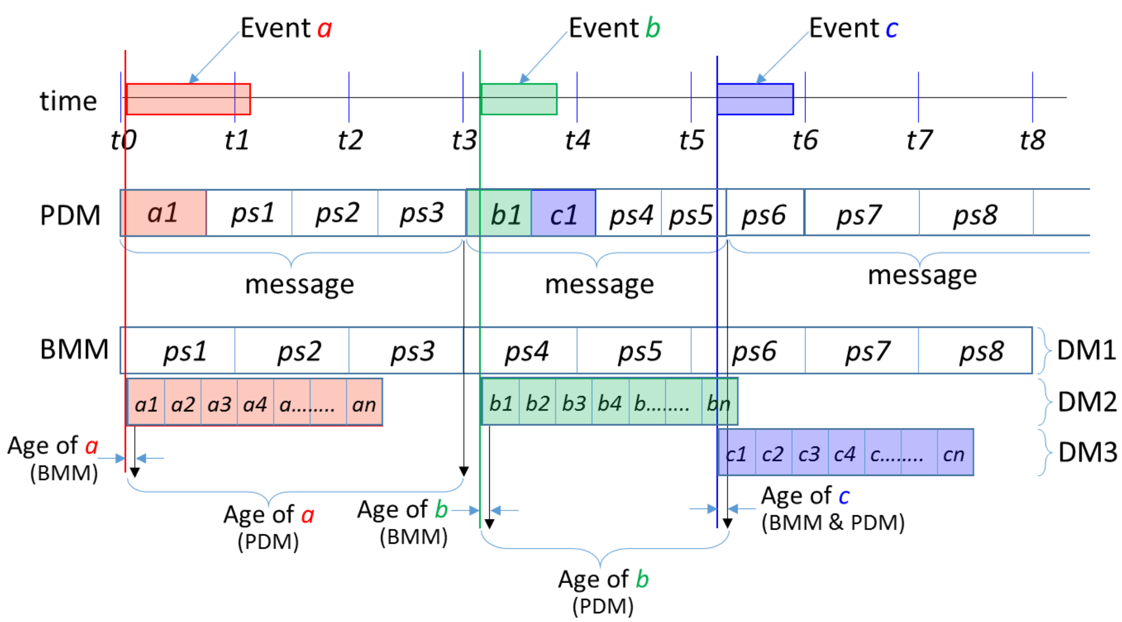
4.3.3 Age of Information

Age of information relates to the time from a snapshot's generation on the vehicle to when it is received at the server and available to infrastructure applications. The PDM, which was built by the device manufacturer according to the standard, did not locally log message transmission timing on the OBU. Consequently, the intent was to gather this information by initiating a DM via a triggered event and measuring the response time. However, since different PDM snapshots (i.e., periodic, triggered, and start/stop) are packaged together in a single message, and there is no way to distinguish the origin of the snapshot with certainty, this measurement scheme was not possible. Given that appropriate data for the age assessment was not available, we instead looked at this this question as an analytical exercise to determine a range for the time it might take to receive an event-triggered snapshot from the vehicle for all three message types. We will consider the age to be the time between the event and when the message is transmitted by the OBU.

BSM: The BSM runs at a fixed transmission frequency of 10 Hz. Therefore, the age will be ≤ 0.1 seconds.

PDM: For the PDM, periodic snapshots are intended to be distributed at regular intervals between RSUs (assumed to be placed more closely in urban environments and further apart in rural). To accomplish this, the interval between snapshots linearly increases between a lower and upper speed. The default values are 20 mph and 60 mph, which results in a sample interval of 4 seconds and 20 seconds, respectively. In addition, there is the transmission interval, which sets how often messages are sent to the RSU. This is part of the PDM CM and is, therefore, a temporary condition. Under default settings, at highway speeds, one message will take 80 seconds to populate (where k = 4). If an event is triggered after the third snapshot in a message is taken, the messages will be transmitted after the snapshot is added to the message. Thus, the age of the event snapshot will be dependent only on the latency in the system. However, if the event is triggered immediately following transmission of a message (e.g., snapshot count = 0), then the event snapshot will remain in the message queue until three more snapshots are collected, at which time the message is transmitted. In this latter case, the age of the event snapshot will be 80 seconds for the above conditions. In this last case, if the transmission interval is greater than 80 seconds, the age of an event snapshot will be equal to the transmission interval. In addition, with the privacy measures that are in place, the message could be delayed further.

Since the BMM is multi-threaded, when a triggered event occurs, a snapshot is generated and transmitted as soon as the message is formed. Figure 46 shows a graphic of how the two message schemes would record and transmit the different events along with the periodic snapshots.



Source: CAMP V2I Consortium and VTTI

Figure 46: Comparison of Age of Event Triggered Snapshots (PDM and BMM)

The first line shows the time. For simplicity, the sampling interval for the periodic snapshots are the same for both the PDM and BMM. In addition, it is assumed that default settings are active. Just after *t0*, a triggered event occurs. This immediately gets placed at the front of the next message queue in the PDM. When the first periodic message is generated, it is placed in the next slot in the message queue. This continues until four snapshots are in the message queue, at which time the message is sent. Thus, the age of the first triggered snapshot is three times the periodic sample interval. The second one occurs shortly after the *t3.* Like snapshot *a1*, snapshot *b1* is placed at the beginning of the next message queue followed by *ps4* at time *t4*. The same occurs for *ps5.* However, before the message queue receives the snapshot at *t6*, another triggered event occurs. This is pushed into the second spot of the message queue, thus, creating a complete message which is then sent out. Since the OBU needed only one more snapshot before the message was transmitted, the age of *c1* is equal to the time it took the OBU to configure *c1*. However, since snapshot *b1* was in the queue, its age is the sum of the time between the start of event *b* and *t4,* the sample interval, and the time between *t5* and the start of event *c*. Additionally, there is no unique identifier associated with an event snapshot. Consequently, unless there is a unique set of data associated with a snapshot, looking at the available data is the only way to determine if snapshots are associated.

For the BMM, the baseline periodic data message thread is DM1. The triggered event initiates a burst of snapshots that are sent on a different data message thread (DM2) with the first one being sent immediately after it is created. Therefore, the age of the first triggered snapshot is the time it takes the OBU to configure the message. This will be the age of every subsequent event since each event initiates a new thread as shown with event *c*. Another important distinction is that more than one snapshot is associated with an event and only snapshots generated by a particular control message with a unique ID will be associated with that ID, thereby, giving immediate knowledge of what caused the trigger as well as more data to work with in assessing the scenario.

4.3.4 Applicability of Message Type

While the project did not develop applications, the results from AMCD do provide the opportunity to make a general assessment as to the applicability of the different message types. In general, the PDM scheme is more reactive and the BMM is more proactive. The PDM does well at what it was designed for, which is to provide a historical picture of roadway conditions where there is limited communication coverage. However, having a single snapshot embedded into a message stream makes it challenging to identify the applicability of the information to a specific scenario. As a multi-threaded message, the BMM scheme eliminates the age challenge by allowing a set of data to be immediately transmitted based on the identification of a particular scenario. In addition, with a more flexible triggering method, the BMM allows a TOC to actively configure the generation of data messages thus enabling the operator to mine information from the roadway in a more precise manner. Accordingly, the BMM likely requires more frequent connectivity to function appropriately whereas the PDM may experience longer periods with no connectivity.

4.4 Control Scheme

The purpose of a Control Scheme is to allow the TOC to affect the flow of information coming from the vehicles. The degree of control is directly related to the design goal of the message scheme. As we have discussed previously, one of the motivations in establishing the PDM was to allow information to be gathered from the roadway, even when no RSUs were available for transmitting the information, so that the TOC could review the historic record when it became available. It then follows that the control provided to the TOC is limited to temporary changes to the snapshot generation characteristics. The system defaults back based on a time- or distance-based criteria set by the TOC or when the vehicle is out of range of an RSU or comes in range of a new RSU. Where much of the test bed had coverage by more than one RSU, the time available to the TOC to change the defaults is limited. Thus, it is largely a hands-off control scheme with the emphasis on a default data flow.

By contrast, the BMM assumes that there will be more ubiquitous communications so that the TOC has near real-time data to act upon. Understandably, the control schemes for these two message types are quite different. The BMM is focused on optimizing the capture of relevant vehicle-based data and subsequent transmission of the information. Since the relevant information has many dependencies (e.g., traffic density, road type, geography, time of data, etc.), the BMM is highly dependent on TOC input for setting up CMs to provide the information that the particular TOC deems important. Consequently, the TOC’s options for control over the information content and transmission is quite extensive. Being multi-threaded, multiple custom DMs can be configured and set to activate and deactivate based on how the TOC sets them up in consideration of their local application/data needs.

The following table (Table 18) outlines the measures of interest for characterizing the control schemes along with the associated research question.

Table 18: Research Questions to Evaluate Difference in Control Schemes

Measure of Interest	Research Question
Message volume	How much bandwidth do the CMs consume? Does CM volume provide any indication of potential flexibility and adaptation for other vehicle-to-everything (V2X) applications?
Round Trip Time	How long does it take to get the information of interest?

Source: CAMP V2I Consortium and VTTI

4.4.1 Control Message Volume

The first question is how much bandwidth these different schemes consume and whether is it significant compared to the overall message volume. While the BMM allows for targeted messaging to be more efficient in the DM, if it comes at the cost of a large number of CMs being broadcast, then it may not be a worthwhile tradeoff. Table 19 provides a summary of the CMs sent during full-scale testing.

The number of DMs received during full-scale testing is shown in the last row for comparison. The percent of CMs compared to DMs is 0.05% for BMM and 0.03% for PDM. This includes the test runs where the intent was to manipulate the CM configuration, something that shouldn't happen often in a fully-operational environment.

The other item to note is the number of CMs sent between the tests. The three of interest are highlighted in the table. The first and sixth test runs have already been discussed. The fourth test was focused on manipulating the levers of the control schemes to see what could be affected. This is reflected in the number of CMs sent out compared to the other tests.

Table 19: Volume and Rate of Control Messages Sent During Full Scale Testing

Test Information		Number of CMs Sent		Tx Rate (msg/hr.)		Tx Interval (min.)	
Test #	Time (hr.)	BMM	PDM	BMM	PDM	BMM	PDM
1 (Dance)	2.0	204	1	102	0.5	0.6	120.0
2	1.2	7	0	6	0.0	10.4	-
3	1.6	198	1	126	0.6	0.5	94.0
4 (Levers)	1.7	218	26	131	15.6	0.5	3.8
5	1.0	13	0	13	0.0	4.6	-
6 (Demo)	2.0	25	0	13	0.0	4.8	-
Total	**9.4**	**665**	**28**	**70**	**3.0**	**0.9**	**20.2**

Test Information		Number of CMs Sent		Tx Rate (msg/hr.)		Tx Interval (min.)	
Test #	Time (hr.)	BMM	PDM	BMM	PDM	BMM	PDM
DMs received		**1336880**	**93258**				

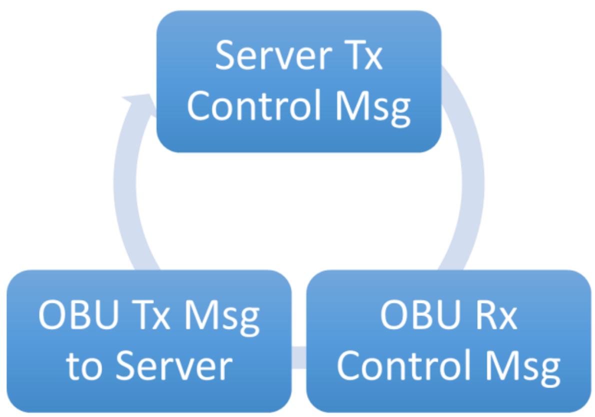
Source: CAMP V2I Consortium and VTTI

As with the DM analysis, the Dance and Demo runs provide an interesting comparison since they were similar in duration but had different operational characteristics. The Demo run reflects what might be more typical in a real TOC. Here, other than the initial broadcast of messages, the primary CMs sent out for the BMM were cloud-based triggers, which automatically activated (i.e., sent out) a new CM when certain changes in vehicle parameters were detected on the server. Thus, we see approximately 10% of the CMs sent in the Demo run compared with the Dance run. Only 0.07% of CMs were sent compared to the number of DMs sent during the Demo run.

The PDM only shows activity during the Levers run. This reflects the design of the message and subsequent control scheme, which is simply not designed for active manipulation. The differences imply that the BMM, compared to the 2009 version of the PDM, provides more flexible control of DM generation and, therefore, may be better suited to support a broader range of applications.

4.4.2 Time from Activation to Receipt at OBU

Testing results showed the possibility for a delay in a particular snapshot being transmitted from the OBU to the server. Here, we consider the time it takes for the server to receive a message back after sending out a new CM (Figure 47).



Source: CAMP V2I Consortium and VTTI

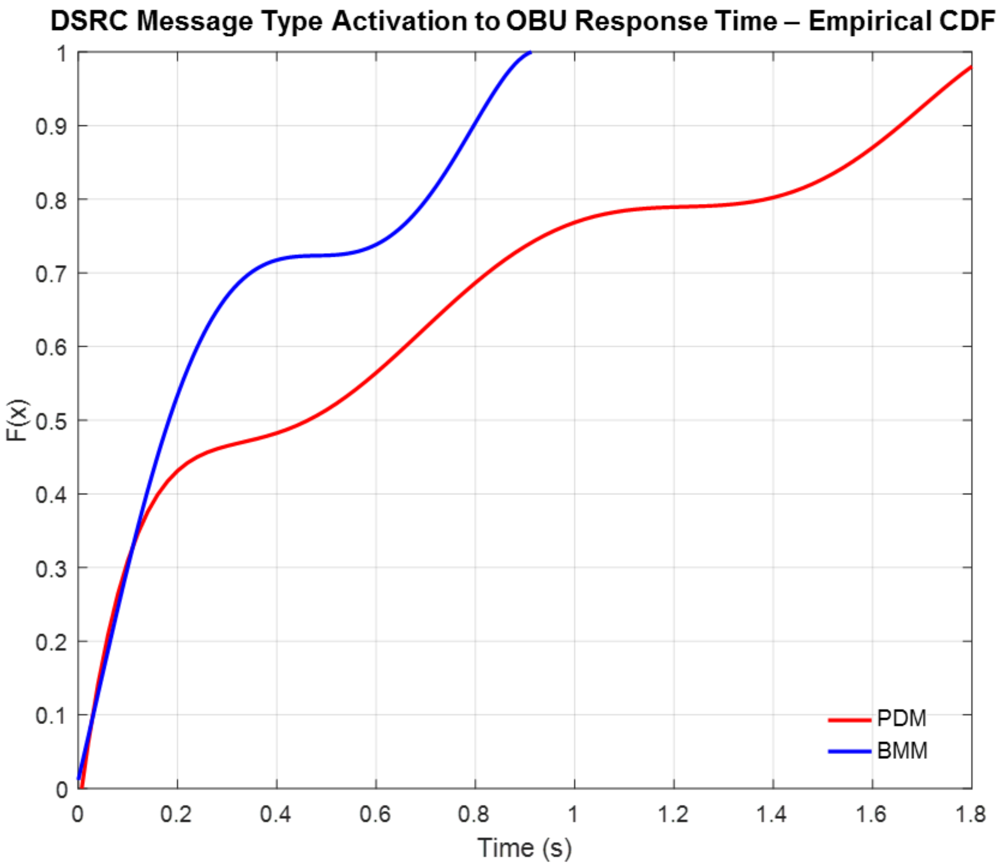
Figure 47: Message Round-trip Schema

The scenario used for this is analysis is as follows:

- A CM is activated on server
- The subsequent CM is broadcast on the entire network and the clock starts
- A vehicle recognizes and downloads the new CM and responds back to the server with the associated DM

- The first response back to the server from the OBU stops the clock

Figure 48 shows the results of the analysis in a cumulative distribution function. Here we see that for both the BMM and PDM, approximately 40% of the first DMs were received at the server in less than 0.2 seconds. For BMMs, a response was received back for 100% of the CMs within 1 second. At 1.8 seconds, the server received back 98% of the DMs for the PDM.



Source: CAMP V2I Consortium and VTTI

Figure 48: CDF of Response Time Data Message for Change in Control Message

The flattening out of the PDM behavior is likely due to how the snapshots get packaged in the messages, as discussed in Section 4.3.3 of this report. Given that round-trip response time for either message type is generally within 2 seconds, performance is likely sufficient for most envisioned non-imminent safety V2I applications.

5 Discussion and Characterization

As stated, the goal of the project was the evaluation of different messages and their associated control schemes transmitted over DSRC and cellular. In order to do this, a significant amount of time and effort was devoted to the development and implementation of the messages as well as the infrastructure to support the transmission, reception, storage, and display of the information. Data collected during testing validated the operation of the infrastructure in the Northern Virginia installation and not only allowed the characterization of the message types and modes, but also of the test bed, including the unique issues to be considered in a challenging urban environment.

The location for RSU installations was predicated on several factors, including road type, traffic density, variability in the driving environment, existing RSU installations, and future expansion, with the goal of creating a test bed that would allow for a broad array of scenarios that would aid in the development and evaluation advanced messaging strategies and applications. The two-mile stretch of Leesburg Pike (Hwy. 7) at Tyson's Corner provides light to heavy density traffic, with its four lanes each direction, obstructions which both hinder and aid in communication range, unobstructed radio line of sight, and the ability to expand to include freeways and associated interchanges at both ends of the current test bed.

More importantly than the hardware installation, the software developed demonstrated the efficacy of supporting advanced messages and an array of future applications that can be developed on top of the current architecture. In addition, the architecture implemented for the BMM allows for rapid development of modified message types should additional feature testing be desirable. The full-scale testing demonstrated successful implementation of the hardware and software and enabled the characterization of message types and control schemes over DSRC and cellular networks.

5.1 Dual Mode Communication

5.1.1 Coverage Area

The challenging obstacles along the testbed allowed for a unique opportunity to provide a qualitative assessment of obstacles on the effective range for DSRC in a field environment. The two southern RSU locations, which were relatively clear of obstructions, provided a baseline for expected performance of the vehicles along the entire length. As shown in Figure 32, with a relatively unobstructed view, the effective range is approximately 500 m. Interestingly, obstructions such as those on RSU 89 may cause reduced range in some cases (e.g., 400 m on the north lanes) but increased range in other cases (e.g., 1,200 m on the south lanes). This finding highlights the importance of considering the impact, both positive and negative, of the surrounding infrastructure on system performance. For example, within this installation and RSUs alternately mounted between the north and southbound lanes, the performance of the system range could be improved while also reducing the number of duplicated messages due to simultaneous communication with more than one RSU. As expected in a developed urban area, the cellular coverage area was more than adequate for the test bed.

5.1.2 Dropped Messages and Latency

Nearly 90% of messages broadcast via DSRC were received at the server. This is most relevant for event-driven messages since the important content may be isolated to a single vehicle. An advantage of the multi-threaded message structure is that there are multiple messages sent for triggered events. With a single message thread, if the message containing an event snapshot is dropped, that event will be lost. The BSM Emulator Project showed that high market penetration is unnecessary for most of the applications considered. Consequently, with moderate market penetration, this drop rate likely poses little concern for periodic snapshots.

The use of UDP for cellular communication requires a reduced overhead but does not provide handshaking to ensure packet transfer. However, given good coverage (e.g., strong signal strength), the results show the likelihood of missing a triggered event is very low. This is particularly true when multiple snapshots are transmitted for a given event.

For both DSRC and cellular, 90% of the messages were received within 0.1 seconds, with DSRC being slightly faster for more than 50% of the messages. With either communication option, latency should be adequate for non-imminent safety events.

5.1.3 Quality of Service

An advantage of DSRC is that the signal path is more controlled and has the possibility of being isolated from non-transportation uses. Cellular is dependent upon service providers who, while having a vested interest in maintaining coverage for their customers, do not currently provide special treatment of V2X communication. Consequently, the transmission of messages is dependent on many factors outside the control of the V2X system. This was observed in the time of day analysis, where messages sent during the early afternoon had a higher drop rate than other times of the day where the system load was likely lower.

In addition, the type of service (3G vs 4G) impacts performance. Areas with 3G appear to require stronger signal strength than 4G areas to ensure reliable message transmission. However, areas with 3G are also less likely to have DSRC coverage, so the opportunity to have less reliable information from the roadway may be acceptable for most rural applications.

5.2 Message Type

A primary advantage of the BMM that the researchers became convinced of during implementation and testing was that a multi-threaded messages structure is more effective than a single threaded message for capturing data from non-time critical events. Along with a flexible DM payload, multithreading provides the opportunity to tailor the content of the DM to the requirements and needs of the TOC and improves the likelihood of receipt of timely vehicle information.

5.2.1 Message Volume and Redundant Data

The possible costs associated with the BMM format, namely increased bandwidth consumption for both DMs and CMs compared to a single threaded message, does not appear to be a significant factor in the message performance. When comparing the number of snapshots, fewer snapshots were transmitted by the multi-threaded message under specific configurations. This could be further optimized with more appropriate deployment-oriented event triggers.

Multiple message streams provide an opportunity for redundant data to be transmitted. For example, if a periodic message with a base set of data is transmitted at the same time event messages are being sent, it is likely that some of the basic information (e.g., GPS location, accelerations, yaw, etc.) contained in each message will be repeated. For the Demo test run, where there was a high volume of triggered messages transmitted, eliminating the redundant data would have reduced the bandwidth consumed by around 50%.

5.2.2 Age of Information and Applicability of Message Types

Assuming good coverage, both message structures provide periodic information in a timely manner. For instance, where there is intermittent DSRC coverage, the PDM is designed to store the most relevant information until it can be off-loaded. Because all snapshots are placed in the message queue prior to transmission, there is the possibility for triggered events to be delayed in the PDM. For a multi-threaded message structure, this delay is removed since the snapshots are sent as soon as the message is formed. The identification of the impetus for the DM is also more easily identified since it is tied to a particular CM which was configured by the TOC and can included more complex triggering. This minimizes the need for parsing and analysis of the messages to determine cause as required for the PDM event triggers.

In addition, having more than one snapshot associated with an event provides time-based evaluation of the event as well (e.g., did the level of braking increase or decrease after the initial trigger of the hard-braking event). The ability to provide more targeted information based on specific scenarios a TOC may be interested in allows the multi-threaded message structure to be more applicable to a broader array of applications. For those applications that only require periodic monitoring, either message structure would work comparably since they both collect periodic messages in a similar fashion with a single message stream.

5.3 Control Scheme

The efficacy of the multi-threaded message is predicated on the implementation of a flexible control scheme. As discussed, CMs allow for targeted information to be sent to the TOC. However, this flow of CM increases bandwidth consumption. Results demonstrated that relative to the number of DMs sent, the volume of CMs is negligible (13 CMs/hr. compared to 13k DMs/hr. or < 0.1%). While this volume was for only 10 vehicles, the number of CMs broadcast does not directly scale with the number of vehicles, but rather based on the number of cloud-based triggers that are armed and subsequently triggered by vehicles on the roadway. Therefore, multi-threaded messages based on a queue of active CMs should not significantly increase system loading relative to the DMs.

6 Conclusions and Recommendations

The project successfully implemented the hardware and software infrastructure to perform a characterization of message schemes over DSRC and cellular communication modes. It also provides a proven testbed for future development and testing of advanced messaging and applications. While the project was successful in this regard, it was also successful in revealing possible improvements to the current message and control structures, the unique challenges to V2X communication in urban environments, and recommendations for future research to further investigate the V2I applications. The next sections outline some of the challenges that occurred in the implementation, design decisions that were made, and recommended future activities.

6.1 Constraints and Challenges

Several factors introduced constraints that had to be considered during the development. These impacted both the hardware and software development. These factors also introduced several challenges that were addressed through the project.

6.1.1 Hardware Implementation

AMCD leveraged existing infrastructure that VDOT had in place along with existing expansion plans when selecting the location for hardware. The final installation area provided a realistic environment, which allowed for a variety of driving conditions and challenging infrastructure. As previously discussed, the location selected provided a realistic roadway obstacle, with the metro line running between the north and southbound lanes. This provided an uncommon scenario and allowed for qualitative characterization of structural obstacles compared with a similar traffic flow without obstacles.

6.1.2 Software Implementation

As with the hardware, there were several constraints that presented challenges during the project. The first of these was the maturity of the message designs. The PDM was based on the 2009 version of J2735, as the 2016 version had not yet been published when the project began. In addition to the message definition, Annex E, entitled, “Traffic Probe Message Use and Operation” provides a more detailed description of how the message should work. As this was not implemented by the manufacturer previously, part of the evaluation was to gauge the difficulties an OBU OEM would experience while implementing a new message type based on the existing PDM standard. Several inconsistencies within the published standard that required interpretation and compromise in order to get the PDM to work. Following is a list of some of the specific issues that were uncovered.

- Configuring the snapshots via PDM control message
    - Some of the values contained within the probe management message do not explicitly specify allowable values (e.g., “subtype” under VehicleStatusRequest).
    - Some of the optional values appear to be necessary (e.g., “send” in VehicleStatusRequest)

- The number of snapshots in a Probe Vehicle Data message is defined as (1…32). However, it is not possible to add this many snapshots (depending on their contents) to a single message and remain within the maximum length of the MSDU specification of 2304 octets (802.11).
- The allowable combinations of event snapshots, start/stop snapshots, and periodic snapshots within a single Probe Data Message is not clearly defined.
- The snapshot contains “thePosition” (FullPositionVector) and the “dataSet” (VehicleStatus) which also includes this, therefore one of these is redundant.

For the BMM, VTTI reviewed the structure proposed and used in simulations during the BSM Data Emulator Project. While this provided a foundation for how the message was to operate, it did not contain the detail required to implement the scheme into an operational system. This both required and allowed the researchers to design the DM and CM structure, triggering, content, storage, and general operation of the BMM. While more extensive effort was required than originally anticipated, it did allow for the evolution of the message to occur. For example, the notion of a CM queue published by the infrastructure was devised during this project. Several of the recommendations for future development, discussed later, are based on outcomes of the systems development and validation testing.

Another challenge designers should be aware of is the data availability and standardization on the vehicle networks. The candidate elements were selected based on the research performed in the CAMP V2I Road Weather Project in collaboration with VTTI and FHWA. However, these elements were not necessarily present on all vehicles (e.g., wiper status), and those that were present were not standardized, so each vehicle required the OBU to be programmed for the specific vehicle model. For widespread application, data elements may need additional standardization, particularly if any data elements outside of SAE J2735 are considered for inclusion.

6.2 Design Decisions

Many design decisions were made to address the constraints and challenges discussed throughout this document. The following sections cover the primary design decisions that were made during the project. These are focused on the BMM since it is a new, non-standardized, message format. For implementation of the PDM, the reader is referred to SAE J2735 (2009), particularly Annex E.

6.2.1 Control Scheme

The CM implemented was a fixed length, as outlined in APPENDIX C. Again, this design decision was primarily based on ease of implementation and consistency with the previous BMM work. A flexible CM was considered and is proposed for future development as it would allow for the inclusion of a more flexible message scheme as described below.

First, having a variable message would make it possible for requested DM data elements to be specified as a name-value pair rather than having a predetermined set of elements to choose from based on a fixed bit in the CM. While this would increase the size of the CM, based on the results of this research, the total bandwidth consumed by the CMs is negligible in comparison to the DMs. In addition, the added flexibility has the potential to reduce the number of elements included in the DM, which may greatly reduce the total bandwidth consumed, more than compensating for the increased size of the CM.

Second, additional flexibility may also be built into the vehicle event trigger sent within the CM. To contain the project scope and maintain the fixed CM, predefined algorithms were programed into the OBU to serve as triggers. The event triggers were simply activated by selecting the associated bit in a two-byte bit vector in the CM, with support for up to 16 pre-programmed triggers. While efficient from a CM size standpoint, this approach limits the possible range of event triggers and, thus, the range of potential applications. It also means that foreseeable algorithms must be preprogramed into the hardware.

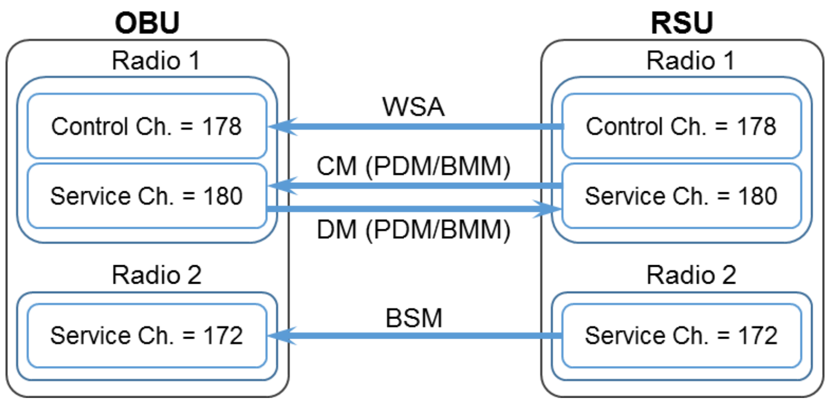
An alternative method, which was devised but not implemented, uses an equation-based triggering schema that would allow the CM to contain detailed event trigger information, thus eliminating the need to for predefining triggers. Information such as the trigger data parameters and associated operations (e.g., Boolean, time based, hysteresis, etc.) that, in combination with a threshold, would completely define a trigger condition. This method provides a flexible triggering scheme that could support a broad array of applications, improve backward compatibility, and provide a method for precisely requesting information from vehicles to better isolate scenarios of interest.

The previous BMM simulation effort distributed CM to the vehicles with a single broadcast. While implementing this scheme, the team realized this distribution method was prone to failure from a single dropped CM. It was also unclear how a vehicle would be aware of the current CMs at ignition cycle. Thus, a CM queue was devised and implemented to contain all active CMs and publish them for continuous access over both DSRC and cellular communication modes. Due to limited computational resources on the OBU, the number of active CMs in the queue was limited to six. This was done to ensure that all the messages requested could be processed even at very high sampling rates. For this project, this approach was adequate, though it did limit the number of server-triggered CMs that could be activated at one time. Future designs should investigate the more flexible methods for limiting the number of CMs. For example, make the OBU evaluate available computing resources and operate as many CMs as feasible in order of priority rather than implementing a fixed cap.

6.2.2 Message Structure

APPENDIX C provides the specification for the BMM packet protocol. The DM was configured to contain a minimum set of data (BSM Part 1 elements) with a number of optional Part 2 elements (APPENDIX C.3) based on a review of existing literature regarding data elements for mobility applications. However, this does not imply that inclusion of all Part 1 elements is necessary nor that only these Part 2 elements are required. Optimization of the message content was not the goal of the project and would be difficult without consideration for specific application needs, which did not fall within the scope of the AMCD Project.

The following figure (Figure 49) shows the channel allocation. The first priority was given to the current standards or proposed usage from standards discussion followed by the current implementation on the VCC to maintain compatibility with existing equipment.



Source: CAMP V2I Consortium and VTTI

Figure 49: Channel Allocation

6.2.3 Privacy and Security

The BSM Data Emulator Project outlined several features to address privacy concerns. First, it is important to remember that the project was operating in the framework of the BSM. Consequently, some of the methods outlined for the prototype BMM are in context of the BSM. AMCD started with the notion of a BMM and built the message type as its own independent entity.

The key element introduced to aid in privacy was the use of random sampling intervals. Whereas the PDM utilizes a variable sampling rate that is a function of vehicle speed, the periodic BMM was generated by random sampling of the 10 Hz BSMs. Part 1 of every n^{th} BSM is taken, where n is a random number based on a Poisson distribution with a mean of λ which is set in the CM. Rather than sampling the BSMs, AMCD allowed the target sampling interval to be directly selected. This was also the proposed method of generating snapshots for triggered messages. Finally, for termination of a collection sequence, a random number of samples was generated after the termination condition, based on a Log-Normal distribution whose median value is a configuration parameter in the CM. While the random number generation was coded into the OBU, it was not activated during data collection to simplify the analysis of the results. This feature would be activated in future research.

The control scheme used encrypted messages, though they were not digitally signed. This was based on the time constraints of the project. It is expected that digital signatures would be part of a final system design.

6.2.4 Information Display

The functionality of the VCC Monitor discussed in Section 3.2.2 was designed for research purposes rather than for TOC applications. This was a deliberate choice to maximize both the control and data monitoring capabilities during the development and testing of the systems.

One aspect that was included in the VCC Monitor was the cloud-based triggers to emulate a portion of the DIDC functionality. This feature was not explicitly part of the previous work but adds functionality that may be of use with future infrastructure applications. Unlike the trigger on the OBU, which initiates a new DM, these triggers initiate a new CM for broadcast. The cloud-based triggers are more adaptable compared to the DM triggers. Some of the functionality included in the cloud based triggers includes:

- **Geofenced activation region:** If a vehicle is outside this region, the CM is not activated on the OBU. This is intended to be a larger geographic area that a TOC might be interested in (e.g., Northern Virginia only).
- **Geofence based on triggered events:** CMs also have the ability to define a geofenced area where DMs associated with a particular CM are broadcast. This differs from the first geofenced region, which determines whether a CM is even loaded onto a vehicle's OBU. This functionality can be dynamically set in the cloud-based trigger definition. If set, the GPS location included in the DM is used to set the center of the geofenced region. This is how a new message based on a triggered event on a vehicle can be set.
- **Complex trigger definitions:** Each element has multiple operations available based on the element type, binary or value. The individual expressions can be combined together and/or nested to create complex triggering logic. For example, to trigger a CM when there is potentially poor visibility during bad weather, a logical AND could be defined to look at headlight status, wiper status and vehicle speed less than a user-defined threshold. This could also be configured as a nested operation so that the light status is evaluated only when wiper status is true and speed is less than the threshold. One feature that is not built into the expression builder is the ability to include hysteresis in the equation (e.g., if wipers are active for greater than 60 seconds, send out a new CM).
- **Activation time:** A defined activation time determines how long the CM is active. After the defined time, the CM is removed from the active list on the server and the new list is broadcast, removing the CM from the OBU.

This functionality represents a simplified TOC application with DIDC and was implemented to demonstrate the value of a multi-threaded message. It would be difficult to effectively implement this type of logic for a single threaded message such as the PDM.

6.3 Future Research and Implementation Activities

While the current research indicates a flexible, multi-threaded, message structure is likely an appropriate tool to support V2I infrastructure applications, the following recommendations outline future research that would allow for a broader evaluation of this thesis. While the specific recommendations stand alone, they are framed in the context of a potential next research phase, which should include testing of applications in an operational environment. For this to be effective, several updates to the system need to occur.

The first task is to focus on expanding the functionality of the flexible message structure to improve data selection and handling. The following describes the top four improvements to make to the current system design.

1. **Flexible trigger definition:** As described earlier, an equation-based triggering scheme is something that was examined during development. The next phase of research should include this capability if feasible as it broadens the supported range of applications and increases backward compatibility.
2. **OBU resource management:** Allowing more targeted triggering would naturally lead to the generation of more CMs. As discussed previously, due to limitations in processing

capacity, the OBUs were limited to six CMs. In order to allow the handling of more CMs, a priority scheme was developed giving precedence to DM generation. Implementing this would allow more CMs to be active on the OBU without jeopardizing the transmission of important data. Based on the priority set by the TOC, the available vehicle data, and the current processor load, the OBU would generate the key DMs while delaying generation and/or transmission of others. The stochastic snapshot generation would allow another variable to manage DM generation to manage processor load.

3. **Reduce duplicate data:** Each snapshot has data common to other snapshots. Managing this common data would reduce the amount of redundant information transmitted. There are several ways this can be accomplished that will need to be further investigated. This will impact the implementation on both the vehicle and the infrastructure. For the OBU, this functionality could also reduce the required resources if designed appropriately.
4. **More sophisticated geofencing**: The current implementation uses a simple center-radius geofence to set the region of interest. However, this can easily lead to requests for irrelevant information from other nearby roadways (e.g., underpass/overpass). A more sophisticated way to select regions so that only the information relevant to a given roadway segment or application should be implemented. Several methods are currently available (e.g., map matching, node list segmentation, path following) and need to be evaluated to determine if one is adequate or if a hybrid solution would be more effective.

Second, applications need to be developed to provide context for an evaluation of performance and to demonstrate the feasibility of the V2I message. They should address specific roadway operational challenges while showing the versatility of a flexible message structure to support a wide range of applications. To do this effectively, the applications should be developed in concert with regional operations to address their specific priorities. Based on input from VDOT, the following four applications were identified and are recommended for the next phase of research if conducted on the VCC. The type of data required (periodic vs. event driven) and purpose of the application are provided here and described in more detail in APPENDIX D.

1. Traffic Behavior Investigation Tool – *Periodic*
    a. Purpose: Evaluate traffic behavior of specific operator-selected roadway sections by requesting periodic, high-resolution, vehicle-dynamics data and comparing that to the expected behavior for use as a decision support tool.
2. Roadway Hazard Identification – *Event*
    a. Purpose: Identify transient hazards on the roadway, allowing tactical operations response and strategic infrastructure repair planning.
3. Incident Detection and Decision Support – *Event*
    a. Purpose: Permit rapid response to traffic incidents by providing operational decision support for identification, response planning, and execution.
4. Infrastructure Design Assessment – *Event*
    a. Purpose: Monitor performance across the roadway network by capturing notable vehicle dynamic events to proactively improve infrastructure design

These have intentionally been designed to cover a range of specific scenarios. For example, the BSM Data Emulator Project simulated applications for estimating travel times, queues, turning movements, and slippery conditions. The functionality to address these four scenarios exists in the first two recommended applications even though they are not explicitly mentioned by name. The Traffic Behavior Investigation Tool provides the information for travel times, queues, and turning movements, while slippery conditions can be identified with the Roadway Hazard Identification application.

Finally, once applications are developed, it is important to integrate them into an operational TOC environment to assess the value of real-time, vehicle-dynamics data in improving infrastructure operations. Specifically, the integration would provide the data to conduct the following analyses.

- Evaluate the actions executed with roadway information and determine if they enhance existing operating procedures.
- Verify compatibility of the new information and systems/displays with existing investments and infrastructure.
- Compile operational improvement data to evaluate the value proposition for both the roadside owner/operator and vehicle OEMs.

These recommendations provide a logical next step to make a thorough investigation into the efficacy of a multi-threaded message structure for V2I applications as well as determining the benefit of this information for roadway owners/operators to their daily activities and assessing the value proposition for vehicle OEMs.

7 References

[1] BSM Data Emulator Project. Unpublished report, Prepared by Noblis for U.S. DOT, 2016.

[2] Road Weather Management Program (RWMP). Unpublished report, Prepared by CAMP and VTTI for U.S. DOT, 2016.

[3] *SAE J2735 Dedicated Short Range Communications (DSRC) Message Set Dictionary, Revision 35,* Society of Automotive Engineers, DSRC Committee. October 2009.

[4] *SAE J2945/1 On-Board System Requirements for V2V Safety Communications,* Society of Automotive Engineers, DSRC Committee. March,2016.

APPENDIX A. List of Acronyms

AMCD	Advanced Messaging Concept Development
API	Application Program Interface
BMCM	Basic Mobility Control Message
BMM	Basic Mobility Message
BSM	Basic Safety Message
CDF	Cumulative Distribution Function
CM	Control Message
DIDC	Dynamic Interrogative Data Collection
DM	Data Message
DMA	Dynamic Mobility Application
DSRC	Dedicated Short Range Communication
OBE	Onboard Equipment
OBU	Onboard Unit
PDM	Probe Data Message
PDML	Probe Data Management Logic
PDMM	Probe Data Management Message
PER	Packet Error Rate
PMM	Probe Message Management
PSN	Probe Segment Number
PVDM	Probe Vehicle Data Message
RSU	Roadside Unit
Rx	Signal Receive
SDK	Software Development Kit
TIM	Traveler Information Message
TOC	Traffic Operation Center

Tx	Signal Transmit
UDP	User Datagram Protocol
USDOT	United States Department of Transportation
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything
VCC	Virginia Connected Corridors
VDOT	Virginia Department of Transportation
VTTI	Virginia Tech Transportation Institute

APPENDIX B. RSU Mounting Locations

Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 50: RSU 87

Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 51: RSU 88

Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 52: RSU 89

Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 53: RSU 90

Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 54: RSU 91

Source: CAMP V2I Consortium and VTTI; Map Data: Google

Figure 55: RSU 92

APPENDIX C. Message Format and Content

C.1 Basic Mobility Control Message (BMCM)

The following defines how the control message for the BMM is constructed.

C.1.1 Outline

Header	ID	Data	Triggering				Transmission	BMM Pack	Timeout	Checksum
VTTIBMCM	BMCM ID	Data Field Bit Vector	Periodic	Event	Location	Start and Stop	DSRC or Cell	# of BMMs per packet	Timeout	Checksum

Source: CAMP V2I Consortium and VTTI

C.1.2 Bit Description

Data Field	Description	Number of Bytes
Header	VTTIBMCM	8
ID	BMCM ID (1 – 10)	1
BMM Data	Bit0 – light status	3
	Bit1 – not used	
	Bit2 – wiper status	
	Bit3 – brake status	
	Bit4 – not used	
	Bit5 – not used	
	Bit6 – not used	
	Bit7 – precipitation sensor status	
	Bit8 – air temp	
	Bit9 – air pressure	
	Bit 10 – not used	
	Bit11 –not used	
	Bit12 – not used	
	Bit13 – not used	
	Bit14 – not used	
	Bit15 – not used	

	Bit16 – not used	
	Bit17 – not used	
	Bit18 -- not used	
	Bit19 – not used	
	Bit20 – not used	
	Bit21 – not used	
	Bit22 – not used	
	Bit23 – not used	
Triggering	**Periodic triggering** 0 = 0 sec (off) 1 = 300 sec 2 = 120 sec 3 = 90 sec 4 = 60 sec 5 = 30 sec 6 = 15 sec 10 = 1 sec (1Hz) 11 = 0.5 sec (2Hz) 12 = 0.2 sec (5Hz) 13 = 0.1 sec (10Hz) 14 = 0.01 sec (100Hz)	1
	Event Triggering Bit0 – HazardLights	2
	Bit1 = not used	
	Bit2 = ABS Activated	
	Bit3 = Traction Control Loss	
	Bit4 = Stability Control Activated	
	Bit5 = not used	
	Bit6 = not used	
	Bit7 = Hard Braking	
	Bit8 = Lights Changed	
	Bit9 = Wipers Changed	
	Bit10 = not used	
	Bit11 = not used	
	Bit12 = not used	

	Bit13 – not used	
	Bit14 – not used	
	Bit15 – not used	
	Location Triggering Int latitude 0 = none LSB = 1/10 micro degree	10
	Int longitude 0 = none LSB = 1/10 micro degree	
	Uint16 range 0 = none LSB = 1 centimeter	
	Start and Stop Triggering 0 = none 1 = start only 2 = stop only 3 = start and stop	1
Transmission	0 = none 1 = DSRC 2 = cell phone 3 = DSRC and cell phone	1
BMM Pack	# of BMMs per packet	1
Timeout	BMCM Timeout (s)	2
Checksum	Standard XOR checksum	1
Total Number of Bytes		**31**

Source: CAMP V2I Consortium and VTTI

C.2 Basic Mobility Message Packet Protocol

The following defines how the data message for the BMM is constructed.

C.2.1 Outline

Header	BMCM ID	Item Count	Packet Size	Packet UID	BMM (Item #1)				BMM (Item #2)				…	Checksum
VTTI-BMM					Item #	Item Size	Item UID	Item Data	Item #	Item Size	Item UID	Item Data	…	

Source: CAMP V2I Consortium and VTTI

C.2.2 Bit Description

Data Field	Description	Number of Bytes
Header	VTTI-BMM	8
BMCM ID	BMCM ID	4
Item Count	Item Count (BMMs)	1
Packet Size	Packet Size	2
Packet UID	Packet UID	4
Item #1 (BMM)	Item #	1
	Item Size	2
	Item UID	4
	Item Data (Dynamic)	# Bytes
Item #2 (BMM)	Item #	1
	Item Size	2
	Item UID	4
	Item Data (Dynamic)	# Bytes
Item #X (BMM)	…	…
Checksum	XOR Checksum	**2**

Source: CAMP V2I Consortium and VTTI

C.2.3 Example


```
56:54:54:49:2d:42:4d:4d:00:00:00:01:03:02:b8:00:00:00:05:01:00:da:00:00
:00:0d:30:81:d7:80:01:02:81:26:0c:00:00:00:00:00:30:39:0d:48:00:00:16:2
a:82:f2:d0:14:73:ca:19:c7:00:00:ff:ff:ff:ff:45:dc:00:00:05:00:00:8c:00:
1e:a3:81:a9:80:01:40:81:01:01:a2:0c:80:01:00:81:01:00:82:01:00:83:01:00
:83:02:00:00:84:01:00:85:01:00:86:01:00:87:01:00:88:01:00:89:01:00:aa:0
d:80:02:00:00:81:01:00:82:01:00:83:01:00:ab:0b:80:00:81:01:00:82:01:00:
83:01:00:8e:01:04:8f:01:22:90:01:04:b1:14:80:01:00:a1:06:80:01:00:81:01
:00:82:01:00:83:01:00:84:01:00:b2:09:83:04:00:00:00:00:84:01:00:b3:18:8
2:01:00:83:01:00:84:01:00:85:01:00:86:01:00:87:01:00:88:01:00:89:01:00:
b4:0f:80:01:02:81:01:00:82:01:02:83:01:00:84:01:00:95:0c:00:75:6e:61:76
:61:69:6c:61:62:6c:65:02:00:da:00:00:00:0e:30:81:d7:80:01:02:81:26:0d:0
0:00:00:00:00:30:39:0e:10:00:00:16:2a:82:f2:d0:14:73:cb:19:c8:00:00:ff:
ff:ff:ff:45:dc:00:00:05:00:00:8c:00:1e:a3:81:a9:80:01:40:81:01:01:a2:0c
:80:01:00:81:01:00:82:01:00:83:01:00:83:02:00:00:84:01:00:85:01:00:86:0
1:00:87:01:00:88:01:00:89:01:00:aa:0d:80:02:00:00:81:01:00:82:01:00:83:
```

01:00:ab:0b:80:00:81:01:00:82:01:00:83:01:00:8e:01:04:8f:01:22:90:01:04
:b1:14:80:01:00:a1:06:80:01:00:81:01:00:82:01:00:83:01:00:84:01:00:b2:0
9:83:04:00:00:00:00:84:01:00:b3:18:82:01:00:83:01:00:84:01:00:85:01:00:
86:01:00:87:01:00:88:01:00:89:01:00:b4:0f:80:01:02:81:01:00:82:01:02:83
:01:00:84:01:00:95:0c:00:75:6e:61:76:61:69:6c:61:62:6c:65:03:00:da:00:0
0:00:0f:30:81:d7:80:01:02:81:26:0e:00:00:00:00:00:30:39:0e:10:00:00:16:
2a:82:f2:d0:14:73:cb:19:c8:00:00:ff:ff:ff:ff:45:dc:00:00:05:00:00:8c:00
:1e:a3:81:a9:80:01:40:81:01:01:a2:0c:80:01:00:81:01:00:82:01:00:83:01:0
0:83:02:00:00:84:01:00:85:01:00:86:01:00:87:01:00:88:01:00:89:01:00:aa:
0d:80:02:00:00:81:01:00:82:01:00:83:01:00:ab:0b:80:00:81:01:00:82:01:00
:83:01:00:8e:01:04:8f:01:22:90:01:04:b1:14:80:01:00:a1:06:80:01:00:81:0
1:00:82:01:00:83:01:00:84:01:00:b2:09:83:04:00:00:00:00:84:01:00:b3:18:
82:01:00:83:01:00:84:01:00:85:01:00:86:01:00:87:01:00:88:01:00:89:01:00
:b4:0f:80:01:02:81:01:00:82:01:02:83:01:00:84:01:00:95:0c:00:75:6e:61:7
6:61:69:6c:61:62:6c:65:0c:74


```
Header  = VTTI-BMM
BMCM ID  = 1
Item Count = 3
Packet Size = 696
Packet UID = 5
Item # 1
  Item Size = 218
  Item UID = 13
  Item Data = 0x30 0x81 0xD7 0x80 0x01 0x02 0x81 0x26 0x0C 0x00
     0x00 0x00 0x00 0x00 0x30 0x39 0x0D 0x48 0x00 0x00
     0x16 0x2A 0x82 0xF2 0xD0 0x14 0x73 0xCA 0x19 0xC7
     0x00 0x00 0xFF 0xFF 0xFF 0xFF 0x45 0xDC 0x00 0x00
     0x05 0x00 0x00 0x8C 0x00 0x1E 0xA3 0x81 0xA9 0x80
     0x01 0x40 0x81 0x01 0x01 0xA2 0x0C 0x80 0x01 0x00
     0x81 0x01 0x00 0x82 0x01 0x00 0x83 0x01 0x00 0x83
     0x02 0x00 0x00 0x84 0x01 0x00 0x85 0x01 0x00 0x86
     0x01 0x00 0x87 0x01 0x00 0x88 0x01 0x00 0x89 0x01
     0x00 0xAA 0x0D 0x80 0x02 0x00 0x00 0x81 0x01 0x00
     0x82 0x01 0x00 0x83 0x01 0x00 0xAB 0x0B 0x80 0x00
     0x81 0x01 0x00 0x82 0x01 0x00 0x83 0x01 0x00 0x8E
     0x01 0x04 0x8F 0x01 0x22 0x90 0x01 0x04 0xB1 0x14
     0x80 0x01 0x00 0xA1 0x06 0x80 0x01 0x00 0x81 0x01
     0x00 0x82 0x01 0x00 0x83 0x01 0x00 0x84 0x01 0x00
     0xB2 0x09 0x83 0x04 0x00 0x00 0x00 0x00 0x84 0x01
     0x00 0xB3 0x18 0x82 0x01 0x00 0x83 0x01 0x00 0x84
     0x01 0x00 0x85 0x01 0x00 0x86 0x01 0x00 0x87 0x01
     0x00 0x88 0x01 0x00 0x89 0x01 0x00 0xB4 0x0F 0x80
     0x01 0x02 0x81 0x01 0x00 0x82 0x01 0x02 0x83 0x01
     0x00 0x84 0x01 0x00 0x95 0x0C 0x00 0x75 0x6E 0x61
     0x76 0x61 0x69 0x6C 0x61 0x62 0x6C 0x65
Item # 2
  Item Size = 218
  Item UID = 14
  Item Data = 0x30 0x81 0xD7 0x80 0x01 0x02 0x81 0x26 0x0D 0x00
     0x00 0x00 0x00 0x00 0x30 0x39 0x0E 0x10 0x00 0x00
     0x16 0x2A 0x82 0xF2 0xD0 0x14 0x73 0xCB 0x19 0xC8
     0x00 0x00 0xFF 0xFF 0xFF 0xFF 0x45 0xDC 0x00 0x00
     0x05 0x00 0x00 0x8C 0x00 0x1E 0xA3 0x81 0xA9 0x80
     0x01 0x40 0x81 0x01 0x01 0xA2 0x0C 0x80 0x01 0x00
```

```
      0x81 0x01 0x00 0x82 0x01 0x00 0x83 0x01 0x00 0x83
      0x02 0x00 0x00 0x84 0x01 0x00 0x85 0x01 0x00 0x86
      0x01 0x00 0x87 0x01 0x00 0x88 0x01 0x00 0x89 0x01
      0x00 0xAA 0x0D 0x80 0x02 0x00 0x00 0x81 0x01 0x00
      0x82 0x01 0x00 0x83 0x01 0x00 0xAB 0x0B 0x80 0x00
      0x81 0x01 0x00 0x82 0x01 0x00 0x83 0x01 0x00 0x8E
      0x01 0x04 0x8F 0x01 0x22 0x90 0x01 0x04 0xB1 0x14
      0x80 0x01 0x00 0xA1 0x06 0x80 0x01 0x00 0x81 0x01
      0x00 0x82 0x01 0x00 0x83 0x01 0x00 0x84 0x01 0x00
      0xB2 0x09 0x83 0x04 0x00 0x00 0x00 0x00 0x84 0x01
      0x00 0xB3 0x18 0x82 0x01 0x00 0x83 0x01 0x00 0x84
      0x01 0x00 0x85 0x01 0x00 0x86 0x01 0x00 0x87 0x01
      0x00 0x88 0x01 0x00 0x89 0x01 0x00 0xB4 0x0F 0x80
      0x01 0x02 0x81 0x01 0x00 0x82 0x01 0x02 0x83 0x01
      0x00 0x84 0x01 0x00 0x95 0x0C 0x00 0x75 0x6E 0x61
      0x76 0x61 0x69 0x6C 0x61 0x62 0x6C 0x65
Item # 3
  Item Size = 218
  Item UID = 15
  Item Data = 0x30 0x81 0xD7 0x80 0x01 0x02 0x81 0x26 0x0E 0x00
      0x00 0x00 0x00 0x00 0x30 0x39 0x0E 0x10 0x00 0x00
      0x16 0x2A 0x82 0xF2 0xD0 0x14 0x73 0xCB 0x19 0xC8
      0x00 0x00 0xFF 0xFF 0xFF 0xFF 0x45 0xDC 0x00 0x00
      0x05 0x00 0x00 0x8C 0x00 0x1E 0xA3 0x81 0xA9 0x80
      0x01 0x40 0x81 0x01 0x01 0xA2 0x0C 0x80 0x01 0x00
      0x81 0x01 0x00 0x82 0x01 0x00 0x83 0x01 0x00 0x83
      0x02 0x00 0x00 0x84 0x01 0x00 0x85 0x01 0x00 0x86
      0x01 0x00 0x87 0x01 0x00 0x88 0x01 0x00 0x89 0x01
      0x00 0xAA 0x0D 0x80 0x02 0x00 0x00 0x81 0x01 0x00
      0x82 0x01 0x00 0x83 0x01 0x00 0xAB 0x0B 0x80 0x00
      0x81 0x01 0x00 0x82 0x01 0x00 0x83 0x01 0x00 0x8E
      0x01 0x04 0x8F 0x01 0x22 0x90 0x01 0x04 0xB1 0x14
      0x80 0x01 0x00 0xA1 0x06 0x80 0x01 0x00 0x81 0x01
      0x00 0x82 0x01 0x00 0x83 0x01 0x00 0x84 0x01 0x00
      0xB2 0x09 0x83 0x04 0x00 0x00 0x00 0x00 0x84 0x01
      0x00 0xB3 0x18 0x82 0x01 0x00 0x83 0x01 0x00 0x84
      0x01 0x00 0x85 0x01 0x00 0x86 0x01 0x00 0x87 0x01
      0x00 0x88 0x01 0x00 0x89 0x01 0x00 0xB4 0x0F 0x80
      0x01 0x02 0x81 0x01 0x00 0x82 0x01 0x02 0x83 0x01
      0x00 0x84 0x01 0x00 0x95 0x0C 0x00 0x75 0x6E 0x61
      0x76 0x61 0x69 0x6C 0x61 0x62 0x6C 0x65
Checksum = 0x0C74
```

C.3 Basic Mobility Message Element Available for AMCD

The following J2735 data elements were included as candidates for AMCD. These were elements identified in the Road Weather Project performed by CAMP and VTTI for FHWA. Since most variables on the vehicle network are proprietary, using elements that had already been identified in previous work expedited the approval for use by the manufacturers as well as delivery of the PID definitions or code for the network gateways. Also included in the table is the availability of the elements on the vehicle network. Except for vehicle size, the elements were not populated if a vehicle network did not support a given element.

BSM	Element	A1	B1	C1	D1	E1
Part 1	ID (temp)	yes	yes	yes	yes	yes
	Vehicle Size/Type	no	no	no	size	no
	GPS Long	yes	yes	yes	yes	yes
	GPS Lat	yes	yes	yes	yes	yes
	GPS Elevation	yes	yes	yes	yes	yes
	GPS Positional Accuracy	yes	yes	yes	yes	yes
	GPS Heading	yes	yes	yes	yes	yes
	Transmission state	yes	yes	yes	yes	yes
	Acceleration Long (X)	yes	no	yes	yes	yes
	Acceleration Lat (Y)	no	yes	yes	yes	yes
	Acceleration vertical (Z)	no	no	no	no	no
	Brake system status	yes	yes	yes	yes	yes
	Steering angle	no	yes	yes	yes	yes
	Yaw Rate	yes	yes	yes	yes	yes
Part 2	ABS Active (> 100 msec)	yes	no	yes	yes	yes
	Ambient air temp	no	no	no	yes	yes
	Ambient atmospheric pressure	no	no	no	no	no
	Precipitation sensor	no	no	no	no	no
	Wiper status and mode change	no	yes	yes	yes	yes
	Light status and mode change	High beams	High beams	High beams	no	High beams
		Blinkers	Blinkers	Blinkers	Blinkers	no
		no	no	Auto light control	no	Auto light control
		Head lights	no	no	no	no
	Traction Control active	yes	no	yes	yes	yes
	Stability Control active	yes	no	yes	no	yes

Source: CAMP V2I Consortium and VTTI

APPENDIX D. Recommended Applications for Future Research

The following provides an outline of the four recommended applications. Included are the type of type of message required (periodic/event), the purpose, and then information about the infrastructure (metrics and operational responses) and the vehicles (data surrogates for metrics and trigger algorithms).

1. Traffic Behavior Investigation Tool – *Periodic*
   a. Purpose: Evaluate traffic behavior of specific operator-selected roadway sections by requesting periodic high-resolution vehicle dynamics data and comparing to the expected behavior for use as a decision support tool
   b. Infrastructure Metrics
      i. Speed relative to design intent
      ii. Acceleration relative to design intent
   c. Operational Responses
      i. Monitoring by TOC operations when making operational decisions
      ii. Provision of data to traffic engineering for evaluation
   d. Vehicle Data Surrogates for Metrics
      i. Speed
      ii. Acceleration
      iii. Location
   e. Vehicle Algorithms (triggers)
      i. Periodic or distance based sampling of vehicle dynamics data within a specified region
2. Roadway Hazard Identification – *Event*
   a. Purpose: Identify transient hazards on the roadway allowing tactical operations response and strategic infrastructure repair planning
   b. Infrastructure Metrics
      i. Object in roadway
      ii. Poor visibility
      iii. Low traction
      iv. High wind or heavy precipitation
      v. Pothole/rough surface/cracking/rutting/ shoving
      vi. etc.

c. Operational Responses
    i. Display event on geospatial situational awareness interface
    ii. Initiate update to traveler information systems (e.g. TIM, DMS, etc.)
    iii. Initiate SSP dispatch workflow
    iv. Initiate ticket to maintenance system workflow
d. Vehicle Data Surrogates for Metrics
    i. Acceleration (all three axis)
    ii. Wiper status & rain sensors
    iii. Traction & stability control status
    iv. Ambient temperature
    v. Headlamp status
    vi. Etc.
e. Vehicle Algorithms (triggers)
    i. Swerve
    ii. Compromised traction
    iii. Road surface defect
    iv. High cross-wind detection
    v. Etc.

3. Incident Detection and Decision Support – *Event*
    a. Purpose: Permit rapid response to traffic incidents by providing operational decision support for identification, response planning, and execution
    b. Infrastructure Metrics
        i. Crash detection
        ii. Crash classification and severity assessment
        iii. Operational impact monitoring
    c. Operational Responses
        i. Display incident on interface with notification
        ii. Initiate investigation using traffic behavior tool
        iii. Coordinate with emergency vehicle dispatch
        iv. Provide crash type and severity information
        v. Provide routing recommendations
        vi. Recommend temporary traffic control methods
        vii. Initiate SSP dispatch workflow
        viii. Initiate update to traveler information systems (e.g. TIM)

   d. Vehicle Data Surrogates for Metrics
      i. Acceleration
      ii. Airbag deployment
      iii. ACN status
      iv. Etc.
   e. Vehicle Algorithms (triggers)
      i. Crash detection
4. Infrastructure Design Assessment – *Event*
   a. Purpose: Monitor performance across the roadway network by capturing notable vehicle dynamic events to proactively improve infrastructure design
   b. Infrastructure Metrics
      i. Excessive speed hot spot
      ii. High lateral acceleration hot spot
      iii. Hard braking hot spot
   c. Operational Responses
      i. Initiate investigation using traffic behavior tool
      ii. Initiate workflow to traffic engineering for eyes-on assessment
      iii. Plan risk mitigation strategies using existing SOPs
   d. Vehicle Data Surrogates for Metrics
      i. Speed
      ii. Acceleration
      iii. Location
   e. Vehicle Algorithms (triggers)
      i. Simple threshold triggers based on vehicle data

APPENDIX E. VCC Monitor: Screen Captures from Full Scale Testing

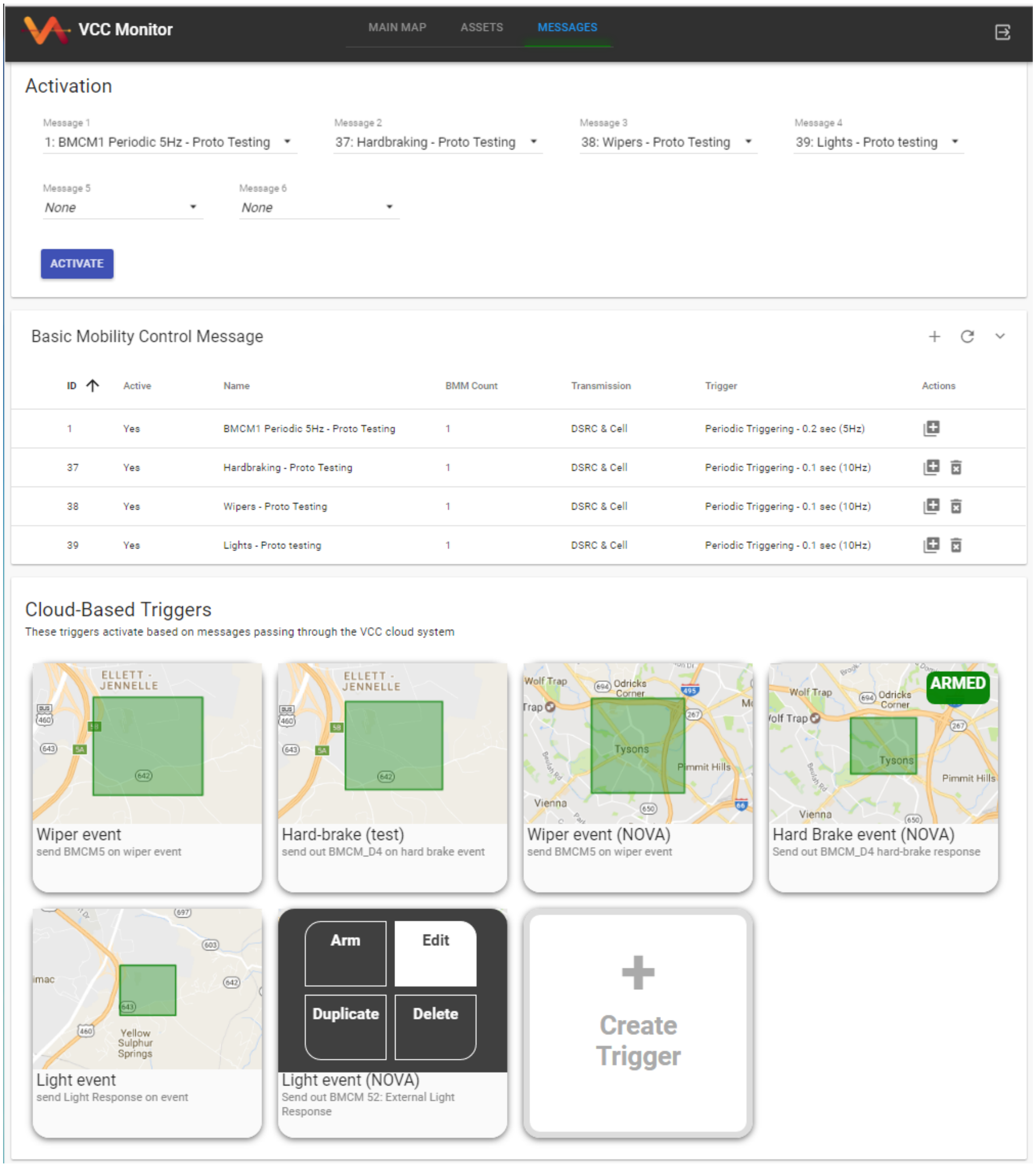
E.1 Overview

The following provides an overview of how the messages are configured and monitored using the VCC Monitor application. To demonstrate the tools and information available, a real-world example is provided that steps through the process of setting up the CMs and cloud-based triggers and subsequently monitoring the activity of the vehicles. The screen captures are from the recordings taken during full scale testing. The focus is on the BMM, but similar functionality is present, where applicable, to other message types.

It is important to remember that these tools are configured primarily for research purposes. The vehicles that are displayed in these images are part of the AMCD study and therefore displayed all the available information to the experimenter to facilitate conducting the study. Start and stop triggers were intentionally not activated so that continuous monitoring of the vehicles was possible. By collecting data in this way, future analysis of the data can include different methods of setting up start/stop conditions to maximize privacy.

E.2 VCC Message Configuration

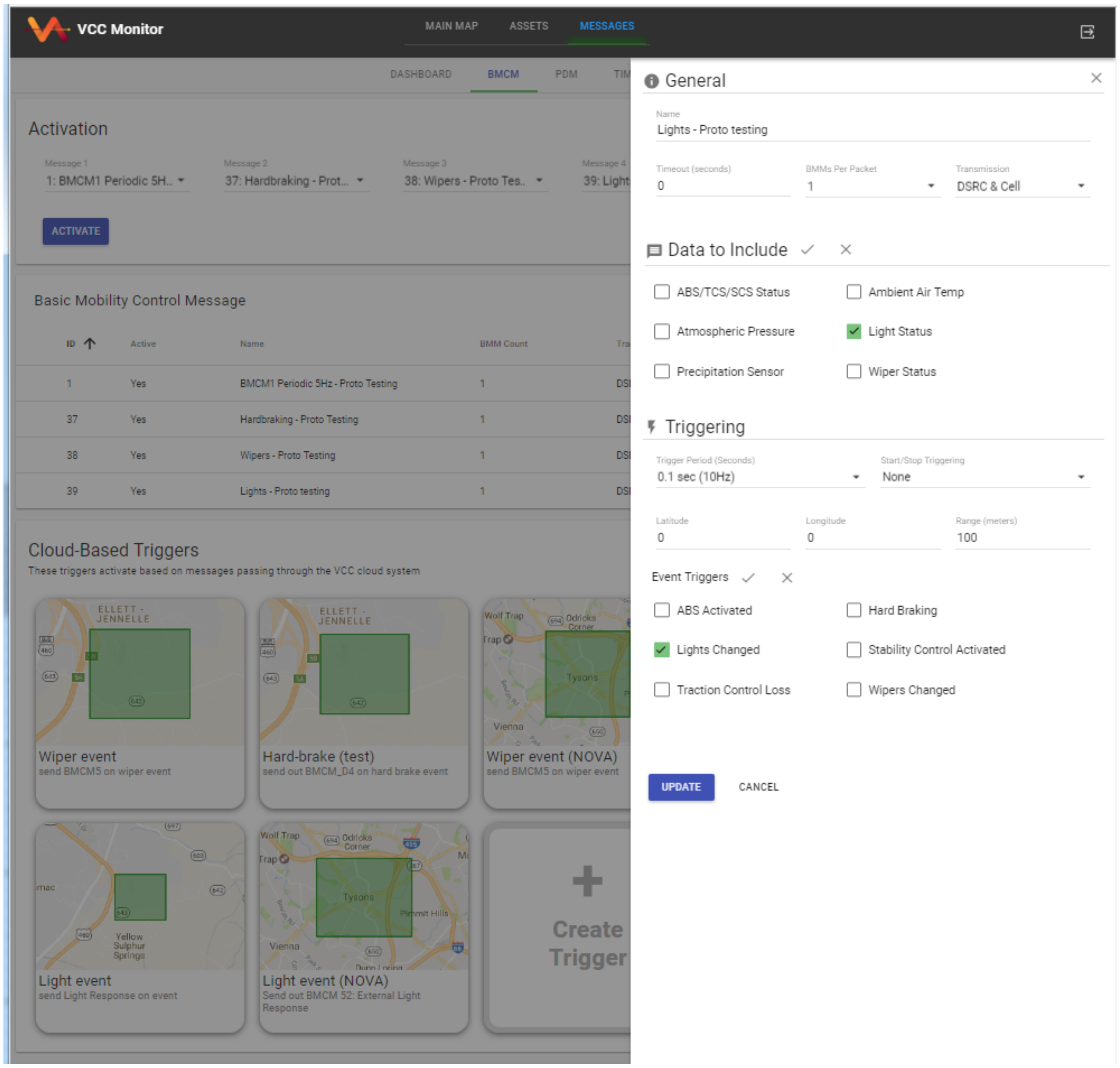
Figure 56 shows the VCC configuration tool for setting up the control messages. Figure 57 shows the main page associated with configuring BMMs. The top section labeled “Activation” allows selection of existing CMs and subsequent activation. The next section, “Basic Mobility Control Message,” shows the list of the currently active CMs. It can expand to show all CMs stored in the database and allows for editing of these messages or creation of new ones. The last section, “Cloud-Based Triggers,” displays the current triggers that exist on the server for the purpose of automatically activating new CMs. The “Hard Brake event (NOVA)” trigger is armed, while the “Light event (NOVA)” is shown with the access buttons revealed by holding the cursor over the icon. The icon itself shows the active geographic area for the trigger.



Source: CAMP V2I Consortium, VTTI and Map data – Google

Figure 56: VCC Monitor BMM Control Message Page

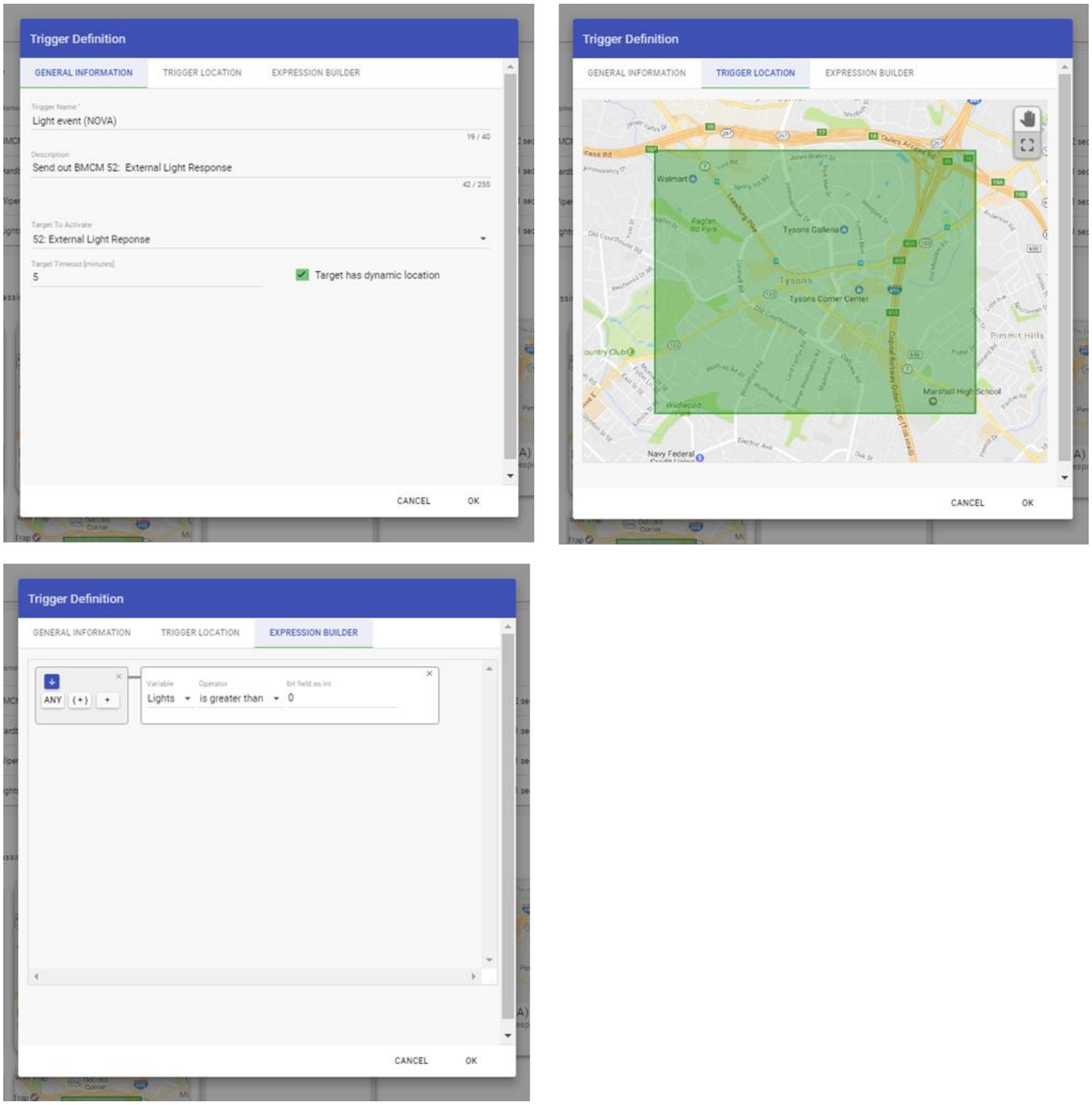
The following image (Figure 57) shows the Configuration Panel, which allows the user to configure different parameters of the CM, including the number of BMMs per packet (1–4), the mode of transmission (DSRC, cellular or both), the data to include (in addition to the default Part 1 elements), sampling interval, geofence parameters, and the trigger variable. The CM shown was used for the light-triggered event. It includes light status information in the BMM and triggers off a change in the light status as shown by the check boxes.



Source: CAMP V2I Consortium, VTTI and Map data – Google

Figure 57: Control Message Configuration Panel

Figure 58 shows the configuration parameters for the cloud-based triggers.



Source: CAMP V2I Consortium, VTTI and Map data – Google

Figure 58: Cloud-Based Trigger Configuration

In addition to a name and description, the first tab allows the selection of whether the CM will be activated when the event occurs, the duration the CM is active, and whether the geofence parameters in the CM are set dynamically based on the location of the event that fired the trigger. The next tab allows a geofenced area to be selected for the cloud-based trigger. Only DMs coming in from this region will be considered for this particular cloud-based trigger. The last tab is where the expression that defines the conditions for the trigger is built any combination of variables can be added and/or nested here to create more complex trigger conditions. This is similar to the functionality being recommended for the OBU triggers.

E.3 Event Trigger Sequence

The following sequence of screen captures provides an example of the information provided on the VCC Monitor. The beginning of one of the test runs is shown in the first screen capture to demonstrate how the tool can be used to monitor what is happening on the VCC, and the second screen capture shows the system response to a change in light status on one of the vehicles.

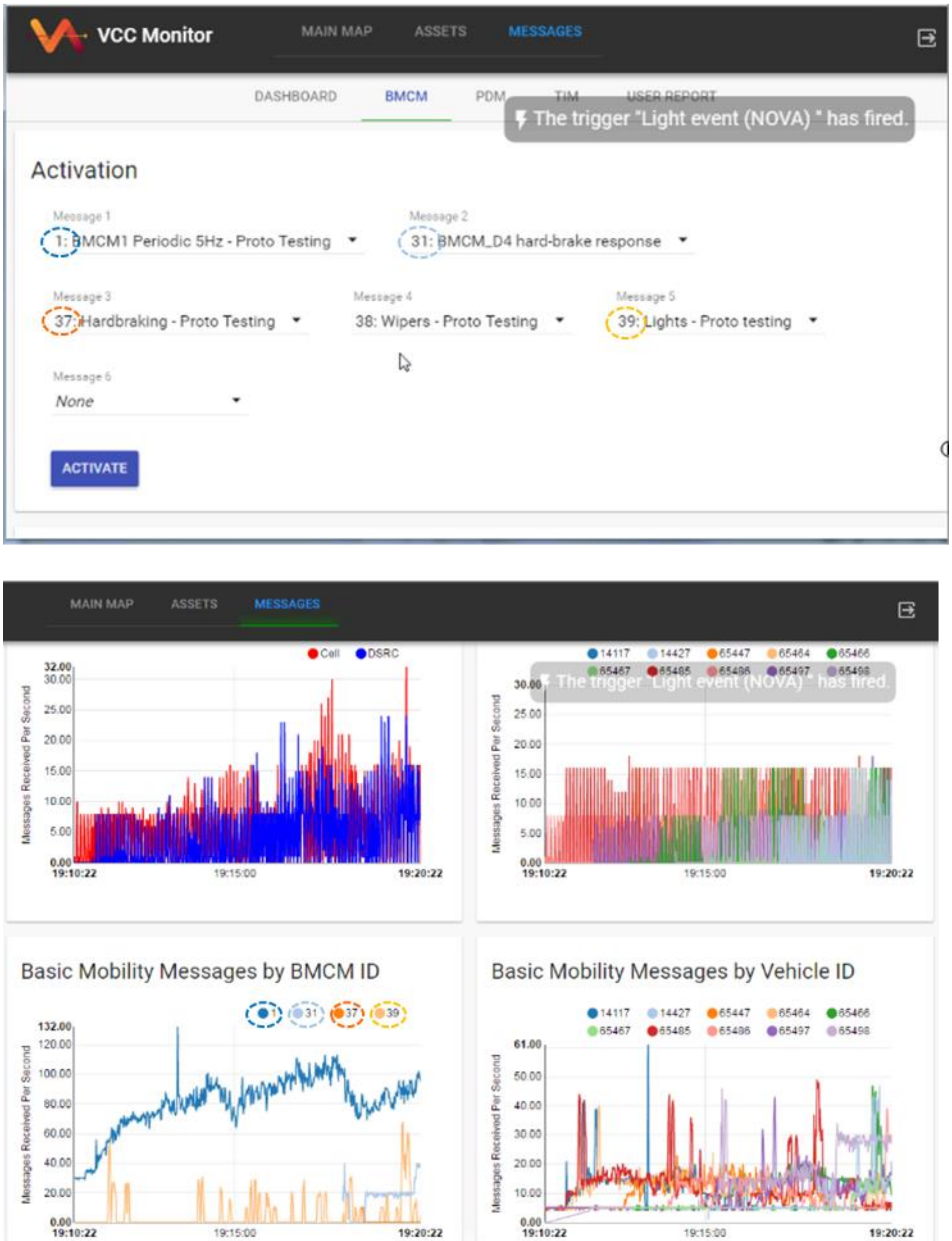
Figure 59 shows two of the six charts displayed on the Dashboard window of the VCC Monitor (see
Source: VTTI

Figure 24 for a view and description of the other charts available on the Dashboard). This captures the vehicles being turned on at the start of a test run. As the OBUs boot up, each vehicle's OBU retrieves the list of active CMs from the server and starts to broadcast the associated DM. To start with, only the 5 Hz periodic message associated with CM 1 is active, as seen in the second chart. In the first chart, as each vehicle comes on line, the total number of messages received by the server increases in 5 Hz increments, with the last vehicle starting to broadcast at approximately 13:55:30 UTC, at which point the server is receiving the expected 50 messages per second (10 vehicles at 5 Hz). These are all transmitted via cellular because they are out of range of any of the RSUs. However, as the vehicles head towards Leesburg Pike, they start transmitting via DSRC, with the first vehicle coming in range at ~13:57 UTC. Very shortly after the first RSU starts broadcasting, the second RSU picks up the first vehicle heading out. This can be observed in the jump from 5 Hz to 10 Hz in the first chart at ~13:57:30. The second chart shows total messages received by CM ID via both cellular and DSRC. Since the only messages are from the baseline periodic, the messages in the second chart is the sum of those in the first chart.

Source: CAMP V2I Consortium, VTTI and Map data – Google

Figure 59: BMM Dashboard During Test Fleet Startup

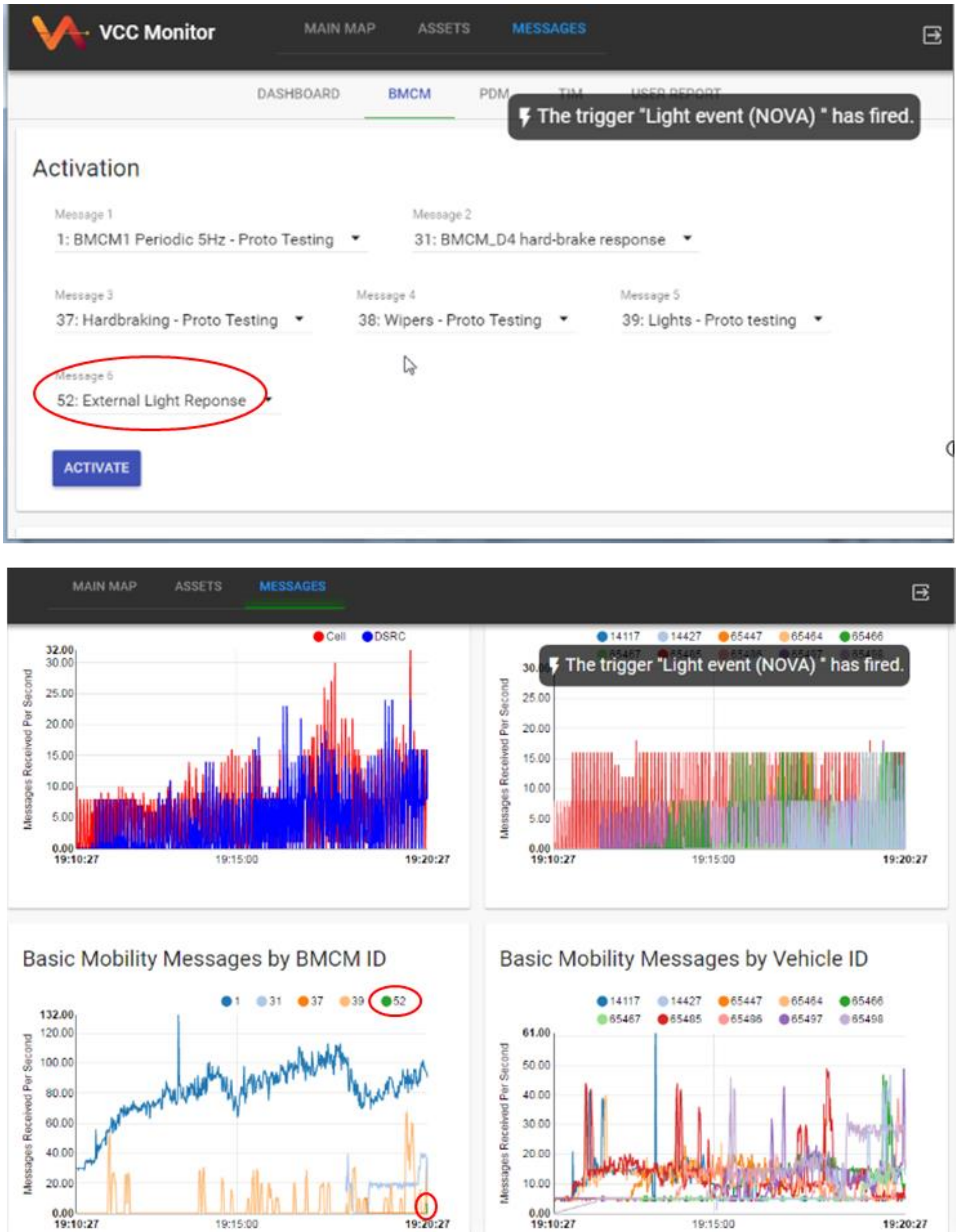
The next series of images shows a triggered light event at two time steps – 19:20:22 and 19:20:27. In Figure 60, the active CMs are shown along with a portion of the Dashboard. While the BMM charts are the ones of interest, the upper portion of the Dashboard was included to show the trigger notification that is displayed in the upper right portion of any open VCC monitor screens. This is at the onset of the trigger — the notification is just starting to display and the associated CM has not yet been activated. The associated CM numbers have been circled in the Activation pane and the Dashboard to show the connection between the two displays.



Source: CAMP V2I Consortium and VTTI

Figure 60: Onset of Triggered Event

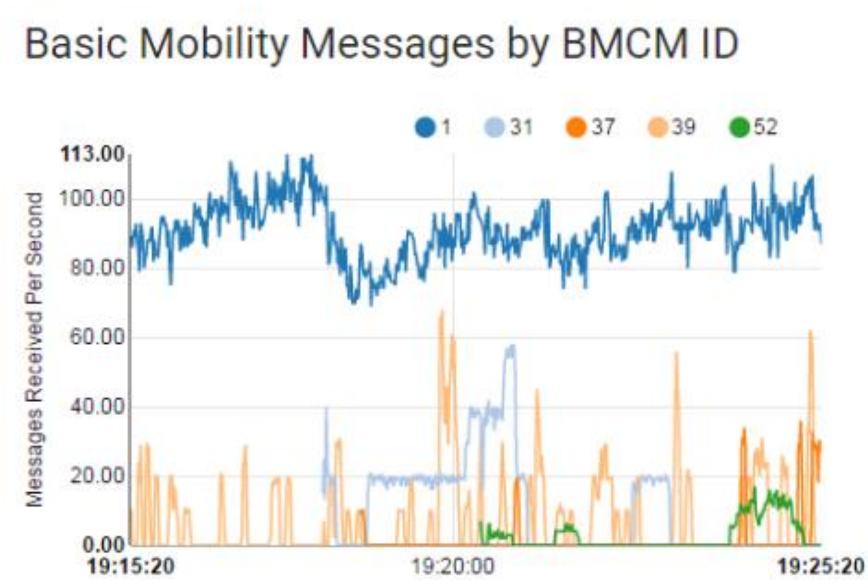
The next sequence shows the same panes five seconds later at 19:20:27. The CM is activated and the display is updated just two seconds later, though the response from the vehicles on the road to the new CM is not easily seen in the display until five seconds later. The server automatically activated CM 52 according to the trigger configuration (Figure 58). This is seen in both the Activation screen and in the Dashboard display, where we see ID 52 now displayed and data being returned in response to CM 52 (all circled in red).



Source: CAMP V2I Consortium and VTTI

Figure 61: Vehicle Response to Cloud-Based Trigger

Figure 62 shows the response to the trigger five minutes later at the end of the timeout period. CM 52 was configured with a sample frequency of 2 Hz and a geofence range of 50 m. From the green trace, it is observed that initially there was some traffic through the region, but during the middle of the active time, no vehicles passed through the geofenced area. At 19:24, several vehicles entered the geofence, as indicated by the increase in message flow.



Source: CAMP V2I Consortium and VTTI

Figure 62: Long-term Response to Cloud-Based Trigger

Other information available in this last chart includes the hard-braking event that triggered CM 31. This is a 10 Hz message and likely occurred within view of two RSUs, since the increments that the light blue trace jumps are 20 Hz. If this is true, three vehicles were in the geofenced area for a brief period. This type of information is readily available utilizing a multi-threaded message structure.

U.S. Department of Transportation
ITS Joint Program Office-HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free “Help Line” 866-367-7487
www.its.dot.gov

FHWA-JPO-18-620

U.S. Department of Transportation