Sharing Data between Mobile Devices, Connected Vehicles and Infrastructure

Task 12: D2X Hub Prototype Field Test, Evaluation Plan and Results

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Final Report — October 25, 2017

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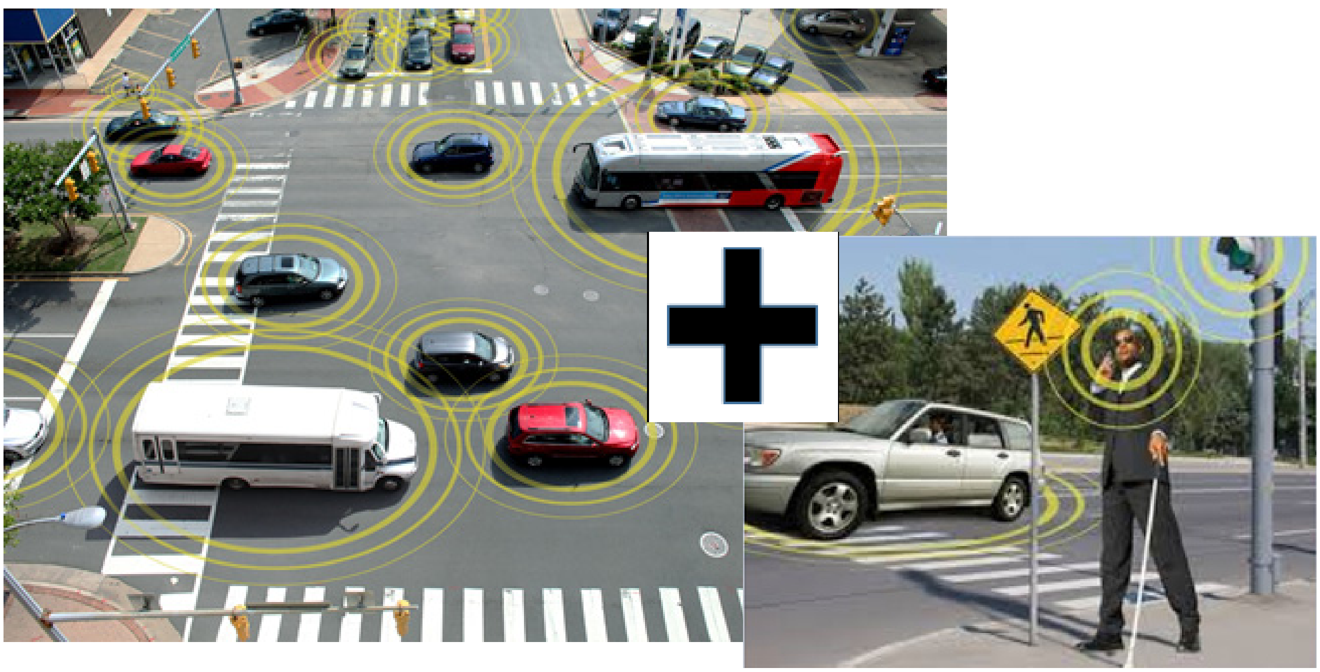

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16. Abstract

"Sharing Data between Mobile Devices, Connected Vehicles and Infrastructure" was a U.S. DOT-sponsored research project to study the integration of mobile devices (such as smartphones) into the Connected Vehicle (CV) environment. Objectives included examining the feasibility and benefits of utilizing non-DSRC communication mechanisms for the transmission of mobility and safety messages, developing and testing modifications to the existing mobility and safety messages to make them applicable for mobile devices, and creating and demonstrating potential methods for coordinating messages and communications related to safety and mobility between mobile devices, vehicles, and infrastructure. The Field Test Plan / Field Test Evaluation Report documents the field test plan, experimental design, system, and results, including answers to the research questions posed by the contract, lessons learned, and recommendations for future research. Overall, results showed the ability to reliably generate, transmit, and receive messages between mobile devices and connected vehicles. The messages to incorporate mobile devices into the CV environment functioned as designed and provided the necessary data for the prototype mobility and safety applications to perform their functions. Furthermore, coordination of messages between mobile devices functioned as designed, reducing mobile device DSRC message volume and thereby improving CV message and application processing time.

17. Key Words Connected Vehicle, Mobile Device, Personal Mobility Message, Personal Safety Message, Basic Safety Message, Test Case, Coordinated Message, Experimental Prototype System, Experimental Plan, Test Evaluation Report	**18. Distribution Statement**		
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Revision History

Revision	Date	Change Description	Affected Sections/Pages
Initial	9/1/2017	Draft Release	
1	10/23/2017	Final Release addressing comments	All Chapters
2	10/25/2017	Revised Final Release addressing comments on Revision 1	Title Page, Technical Report Documentation Page, Table of Contents, Executive Summary

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Executive Summary

The United States Department of Transportation (U.S. DOT) has conducted significant research on the use, benefits, and operational issues associated with using dedicated short-range communications (DSRC) and cellular devices in both vehicular and infrastructure-based communications. Specifically, the benefits are intended to improve the safety, mobility and environmental impact on our surface transportation system. And while originally conceived as an enabler for the mobility-impaired and other travelers with unique needs when the concept of the connected vehicle environment first emerged, the unprecedented adoption of smartphones and similar devices in the general population has necessitated a renewed analysis of it role in the broader connected vehicle environment. To date, less research has been conducted on implementation pathways, policy and institutional impediments, as well as the feasibility of deployment of low-latency wireless communications on mobile devices in concert with the current cellular and WiFi communications protocols. In particular, key questions and issues exist related to the expected impact that personal mobile devices (e.g., tablets, smartphones, etc.), that are also equipped with DSRC technology, will have on channel congestion and error-rates in the connected vehicle environment. If saturation is reached, it will likely degrade the anticipated benefits of connected vehicle safety applications by requiring more processing of radio messages than can be performed in low-latency required situations. It is with these considerations that this research was conducted, the objectives of which were:

1. Examine the feasibility and benefits of utilizing non-DSRC communication mechanisms for the transmission of mobility and safety messages.
2. Develop and test modifications to the existing mobility and safety messages to make them applicable for mobile devices.
3. Create and demonstrate potential methods for coordinating messages and communications related to safety and mobility between mobile devices, vehicles, and infrastructure.

Importantly, the scope of this project was limited to an experimental system that was used to test and demonstrate new communication messages and message types as well as explore the effectiveness and potential mechanisms for coordinating these messages across multiple mobile device, vehicles, and infrastructure. This was intended as a research project and therefore did not seek to identify, define, summarize, or propose a system suitable for immediate wide-scale deployment.

This report documents the field test plan, experimental design, system, and results, including answers to the research questions posed by the contract, lessons learned, and recommendations for future research. Overall, results showed the ability to reliably generate, transmit, and receive messages between mobile devices and connected vehicles. The messages to incorporate mobile devices into the CV environment functioned as designed and provided the necessary data for the prototype mobility and safety applications to perform their functions. Furthermore, coordination of messages between mobile devices functioned as designed, reducing mobile device DSRC message volume and thereby improving CV message and application processing time.

Following is a more comprehensive summary of experimental results, answers to research questions, lessons learned, and recommendations also found in Chapter 4 of this report. The Mobile Device Experimental Application (MDEA) and In-Vehicle Experimental Application (VEA) referenced below are key software components of the experimental system used to conduct the field test.

Table ES-1. Experimental Analysis Results Executive Summary

Hypothesis Description	Data Analysis Results Summary
Hypothesis 1 – The MDEA only broadcasts PSMs when in the range of a vehicle broadcasting a BSM	Confirmed at 100% Level of Confidence (LOC)
Hypothesis 2 – The PSM and PMM message transmission rates by MDEAs are lower when travel groups have been formed (coordinated travel) than when travel groups have not been formed (uncoordinated travel)	Confirmed at 100% LOC
Hypothesis 3 – The MDEA can cease the broadcast of PSMs when in a vehicle	Confirmed at 100% LOC
Hypothesis 4 – The Mobile Device can broadcast a PSM a radius of 250 meters at 10 Hz under clear, unobstructed conditions, regardless of where the mobile device is located on the pedestrian's person or clothing	Confirmed at 86% LOC (variations in antenna orientation and line of sight believed to impede transmission)
Hypothesis 5 – Vehicles OBUs can capture and process Mobile Device PSMs and issue warnings at sufficient distance for drivers to avoid imminent pedestrian collision	Confirmed at 100% LOC
Hypothesis 6 – Mobile Devices can capture and process Vehicle BSMs and issue warnings in time for pedestrians to avoid imminent vehicle collision	Confirmed at 100% LOC
Hypothesis 7 – Mobile Device applications can detect if a pedestrian is in a safe or unsafe zone	Confirmed at 100% LOC
Hypothesis 8 – The VEA can coordinate transit trip requests received from an MDEA	Confirmed at 100% LOC
Hypothesis 9 – The MDEA can receive arrival updates from a transit vehicle	Confirmed at 94% LOC (DSRC HW connection failure during one test scenario iteration)
Hypothesis 10 – The MDEA can detect when a traveler transitions from being a pedestrian to a rider on a transit vehicle or from a transit vehicle rider to a pedestrian	Confirmed at 100% LOC
Hypothesis 11 – The MDEA can send and receive messages to coordinate, maintain, and cancel trip requests with other travelers using an MDEA	Confirmed at 91% LOC (MDEA operator error caused coordination failures including a "hung" travel group)
Hypothesis 12 – The RSU can broadcast a SPaT and MAP message via DSRC that can be received by mobile devices	Confirmed at 100% LOC

Hypothesis Description	Data Analysis Results Summary
Hypothesis 13 – The RSU can receive and save all messages transmitted by MDEAs and VEAs	Confirmed at 100% LOC
Hypothesis 14 – Travelers using MDEAs that have formed Travel Groups (coordinated travel) will have an effect on message performance (DSRC message transmission and reception) as compared to Travelers using MDEAs that have not formed Travel Groups (uncoordinated travel)	Not Confirmed (based on size of experiment, no impact observed on DSRC message *transmission and reception*; however, reduced message *processing latency* was observed when Travelers formed Travel Groups)
Hypothesis 15 – Travelers using MDEAs that have not formed Travel Groups (uncoordinated travel) will have an effect on message performance (DSRC message transmission and reception) as compared to not using MDEAs	Not Confirmed (based on size of experiment, no impact observed on DSRC message *transmission and reception*; message *processing latency* was not considered since the baseline scenario does not use MDEAs)

Research Questions

Research Question # 1: Are current messaging standards applicable to enable the practical incorporation of mobile devices supporting connected vehicle applications?

The current messaging standards are applicable to enable the practical incorporation of mobile devices supporting connected vehicle applications, but they required improvements to enable the full range of capabilities tested in this project. From the field testing, it could be observed that the messages communicated between mobile devices and connected vehicle applications effectively performed the safety and mobility tasks.

Research Question # 2: What improvements to existing mobile device messaging standards (or new approaches) can be identified to help achieve the highest potential impact from mobile devices for broader connected vehicle application deployment?

The existing J2735 messages do not include a personal mobility aspect. Battelle defined and added the PMM message to the J2735 message set for this project. This addition is not an update or improvement to the existing message standards, but rather is an approach used on this project to test mobility capabilities for the mobile device user. No additions or improvements were required to the existing J2735 safety messages for this project. With the addition of PMM messages on this project, the potential for broader CV application deployment was realized with the integration of mobile device safety and mobility applications with connected vehicles.

Research Question # 3: What are the implications of a broadly unconstrained and uncoordinated deployment of mobile devices and connected vehicles operating in close proximity for connected vehicle applications?

The frequency and number of messages transmitted by unconstrained and uncoordinated deployment of mobile devices pose challenges to the operational capability of other connected vehicle applications. During execution of the uncoordinated scenarios, an additional message processing latency of 170 ms during safety and 477 ms during mobility tests were observed. As shown in our field test results, a higher number of messages received by other CV applications implies increased application processing time.

Research Question # 4: Can protocols or other methods be developed that coordinate the generation of safety and mobility-related messages among multiple mobile devices transported within connected vehicles as well as with the connected vehicle itself?

One key objective of this project was to develop methods to introduce coordination between multiple mobile devices communicating with each other and with connected vehicles. The field test results clearly show the effectiveness gained by coordination between mobile devices and connected vehicles. The field test showed that same amount of safety and mobility related information could be communicated with a significant reduction in the number of messages resulting in reduction of message processing latency in the CV applications.

Research Question # 5: Do these coordination protocols have a practical benefit in enhancing mobility and safety of connected vehicle applications in potential large-scale connected vehicle deployments where many devices and vehicles may be located in close proximity?

Coordination ensures a reduced number of messages between mobile devices and connected vehicles, which improves the processing time of the messages. In a large-scale environment, minimum latency ensures timely communication of safety and mobility messages. During the field test, the coordinated mobile devices communicated mobility and safety messages with a faster processing speed and lesser latency when compared to uncoordinated mobile devices.

Translating a 170ms reduction in safety message processing time to a practical safety benefit, a vehicle travelling at 25 mph will cover 1.9 meters (6.23 feet) in 170ms. Given an average human reaction time of 250ms, a vehicle would travel 2.79 meters before a driver can react to an alert. In a scenario where a pedestrian unexpectedly steps into the path of an approaching vehicle, the driver's effective reaction time increases by over 50% with the 170ms reduction in safety message processing time. 1.9 meters of additional braking distance to the driver can be critical in coming to a safe stop.

Similarly, for a mobility scenario, assume an express transit vehicle is traveling towards a bus stop and will only stop if a rider has scheduled a pickup. If the bus is close when a rider schedules a trip, a small delay can mean the difference between the driver reacting to the scheduled ride and stopping or determining he can't stop and passing the bus stop.

Research Question # 6: What policy and technical issues can be anticipated for dense connected vehicle/connected mobile device deployments?

1) Considering the increase in latency that we observed for uncoordinated travel, we can expect that high volume uncoordinated scenarios would have a negative effect on the existing DSRC infrastructure. 2) The security feature of the messages was not tested during the field test. When many devices are used in a dense environment, security of the messages must be ensured to have safe and reliable communications. Current technical solutions are not scalable.

Lessons Learned

The Lessons Learned from this experiment are summarized as follows:

1. The ability to reliably generate, transmit, and receive messages between mobile devices and connected vehicles was demonstrated.
2. The messages to incorporate mobile devices into the CV environment functioned as designed and provided the necessary data for the prototype mobility and safety scenarios.
3. The D2X Hub prototype software functioned well (as designed) for sending and receiving safety and mobility messages.
4. Mixed results were achieved for the various communication methods tested:
    a. Cellular functioned well with the D2X Hub. During the field test, cellular messages were communicated timely and accurate.
    b. Handheld DSRC hardware caused communication connection problems with our system. There were occasional Bluetooth connection failures between the handheld DSRC radios and the smartphones, as well as occasional DSRC transmission/reception failures by the DSRC handheld radios. Longer term, it is assumed that DSRC radios will be integrated into smartphones thus obviating the issues experienced on this project.
5. GPS accuracy limitations were observed, as expected. The GPS accuracy stated by the U.S. Government is +/- 4 m. With this level of accuracy, quick changes in state from “safe” to “unsafe” and “unsafe” to “safe” were observed when the user did not move.
6. A mismatch in time synchronization between MDEA, VEA, and RSU data logs was observed. This mismatch acted as a limiting factor in determination of latency in communication messages between mobile devices and the CV environment.
7. In few instances, the transit VEA did not initiate ride-arrive due to the transit vehicle stopping at a distance beyond the configured arrival zone at the bus stop.
8. Traveler user state changes between “in-vehicle” and “on-foot” were observed while the traveler remained in the transit vehicle. This was caused by the transit vehicle traveling at very low speeds in some instances before coming to a complete stop.
9. Throttling the frequency for the messages communicated from the handheld DSRC radio to the smartphone should be determined on a per message source basis (mobile devices, connected vehicles, and roadside units). With a higher number of units from each source, the mobile DSRC radio was limited in the number of messages it could process.

Recommendations

Recommendations for future research or development are summarized as follows:

<u>General</u>

1. Time synchronization issues between the devices used in the field test limited the usefulness of some of the log data gathered during the field tests. All communication devices must be time synchronized to the accuracy of milliseconds.
2. The cellular and DSRC trip scheduling mechanisms operated independently, which limited the system’s ability to coordinate trip scheduling using multiple communication protocols. Additional

coordination between DSRC and cellular for trip management would facilitate handling transit vehicle capacity calculations.

3. The field test used cellular and DSRC as the communication protocols. Further investigation of other available and emerging communication protocols including but not limited to 5G and Android Neighbor Aware Networking (NAN) is recommended.
4. The existing trip scheduling only consists of the rider's pick-up information but not the drop-off or destination option. Integration of rider drop-off information into the trip scheduling is recommended.
5. DSRC and cellular communication medias were used to test the ability to schedule trips. The DSRC was considered as the primary communication media and was always tried first for ride scheduling. If a request over DSRC failed over a configurable time (20 seconds), then the communication media was switched to cellular and the mobility request was repeated. A more intelligent communication media switching strategy should be implemented in future systems.

<u>MDEA</u>

1. "In-vehicle" and "on-foot" detection was unreliable in some cases. A refinement of the user-state transition algorithm can mitigate the issue. (Note: The transition algorithm was accurate enough to trigger "in-vehicle" and "on-foot" transitions during the Hypothesis 10 testing. However, reliability issues were observed, as additional false transitions were triggered when the pedestrian was still in the vehicle. This was due to stoppage of transit at multiple locations. These false transitions did not affect the Hypothesis 10 test results, since they were outside the time window that the associated performance measures were evaluated.)
2. The PMM developed for taxi trip requests was insufficient for supporting transit trip requests. Therefore, modification of the PMM or a new message is needed to handle transit data such as route and transit ID information, as opposed to simple GPS coordination for pick-up and drop-off.
3. Maximum group size was limited to 12 mobile devices for field testing. Further study on maximum coordinated group size with respect to capacity and performance is recommended.
4. Ride arrived messages were not received for trips scheduled via cellular due to lack of coordination between messages sent via cellular and DSRC for trip scheduling. Adding coordination between cellular and DSRC messages for trip scheduling will enable implementation of ride-arrival messages for scheduled trips.
5. DSRC or application failure of the travel leader's MDEA can cause the ride request for the entire group to fail. A recovery method should be designed into future systems such as switching to another traveler's MDEA as the group leader.
6. The group leader heartbeat is used to determine if the group should be cancelled. During field testing, a few "hung" groups took too long to clear and created problems with subsequent trip requests. A decrease in the timeout period for the group leader heartbeat should be used to determine if the group is no longer valid and thereby clear the trip.
7. The field test was performed using devices that run the android operating system. Further investigation of devices that run on other operating systems including, but not limited to IOS (Apple) is recommended.

VEA

1. In the field test, there were several cases where the transit bus stopping distance and stopping speed adversely affected the transmission of ride arrive messages and in-vehicle and on-foot detections. A study of transit bus behavior including stopping distance and stopping speed could be factored into future application algorithms.
2. Trip request functionality is currently geared towards the experiment. Add feature to provide the driver the ability to manage trip requests, instead of auto-accepting trips as was done for the purposes of this experiment.

REA

1. RSUs could have the same functionality as VEAs with respect to scheduling trips. This way, mobile devices could communicate with RSUs via DSRC instead of needing a transit vehicle to be within DSRC range for DSRC-based communication.

Security Credential Management System

1. To maintain a safe, secure and privacy-protective manner of information sharing between V2V and V2I, U.S. Department of Transportation is working on a Proof of Concept (POC) security solution called Security Credential Management System (SCMS). The security feature of messages was not implemented or tested during this project's field test. Incorporation of the SCMS standards, protocol, and other requirements to sign and secure messages is recommended as a part of the future research
2. The project team envisions a tenfold increase in certificate volume and communication message traffic when mobile devices are incorporated into SCMS. A recommendation for future research is to investigate the impact of increased certificate volume and total communication message traffic on SCMS system performance when mobile devices are incorporated into SCMS.

Chapter 1. Scope / Introduction

This D2X Hub Prototype Field Test, Evaluation Plan and Results report presents the plan and results for an experiment designed to demonstrate the coordination of mobile devices and connected vehicles in a more realistic physical environment than the earlier proof-of-concept test. The prototype system, named D2X Hub, coordinated multiple message-generating mobile entities in a field test combining mobile devices together with connected light vehicles and transit vehicles. Travelers with mobile devices transition from pedestrians to vehicle passengers and back throughout the demonstration as the target vehicle stopped to collect and discharge passengers along its route. Safety functionality was tested in a separate closed-loop environment for personnel safety considerations, during the same timeframe.

D2X Hub Version 2.0 was developed and used for this experiment, with the changes based on the lessons learned from the earlier proof-of-concept test, as well as functional differences for a transit vehicle versus a taxi mode of operation. A summary of these changes is provided in Section 3.3.

The Experimental Plan was designed to answer the research questions posed by the contract. As part of the plan, the test scenarios were designed to supply the data set required for the analysis. The data set analyzed includes the tests formally conducted at the Ohio State University as well as those conducted at Battelle facilities starting June 12, 2017 and concluding June 20, 2017. This report provides the results of the data analysis as well as answers to the research questions, lessons learned, and recommendations. Detailed test logs and digital data logs are not included in this report.

Finally, it should be noted that the subject system is an experimental system, designed for answering research questions. System performance was limited by the quality of input data and the limits of the underlying technology and equipment employed.

This report is organized as follows:

- **Chapter 1 Scope / Introduction:** Summarizes the scope of this report and its organization.
- **Chapter 2 Referenced Documents:** Lists the Battelle documents prepared under this contract providing the foundation for this report, as well as other documents referenced from within this report.
- **Chapter 3 Field Test Plan:** Documents the plan for conducting the field test and its evaluation. This section covers the experimental plan, testing site, experimental system, test personnel, and the execution timeline.
- **Chapter 4 Field Test Evaluation:** Documents the evaluation of the field test. This section includes an experimental analysis results summary, as well as details of the experimental analysis. This section answers the research questions posed by the contract, as well as providing lessons learned, and recommendations for future research or systems.
- **APPENDIX A:** Provides the comprehensive data analysis tables.
- **APPENDIX B:** Provides the field test scenario scripts.

- **APPENDIX C:** Defines acronyms and abbreviations used in this report.
- **APPENDIX D:** Defines terms used in this report.

Chapter 2. Referenced Documents

Following are the Battelle documents prepared under this contract providing the foundation for this report, as well as other documents referenced from within this report.

Battelle Memorial Institute

FHWA-JPO-16-422	Task 3: Concept of Operations Document *(ConOps)* for Coordination of Mobile devices for Connected Vehicle Applications (3rd Revised Report from July 13, 2016)
FHWA-JPO-16-423	Task 3: System Requirements Specifications (SyRS) for Sharing Data between Mobile Devices, Connected Vehicles, and Infrastructure (July 14, 2016)
FHWA-JPO-17-476	Task 4: System Architecture and Design Document for Sharing Data between Mobile Devices, Connected Vehicles, and Infrastructure (October 26, 2016)
FHWA-JPO-17-475	Task 5: Prototype Proof-of-Concept Field Demonstration Experimental / Field Demonstration Site Plan for Sharing Data between Mobile Devices, Connected Vehicles, and Infrastructure (October 6, 2016)
FHWA-JPO-16-17-477	Task 6: Prototype Acceptance Test Plan for Sharing Data between Mobile Devices, Connected Vehicles, and Infrastructure (December 21, 2016)
FHWA-JPO-17-507	Task 6: Prototype Acceptance Test Summary Report for Sharing Data between Mobile Devices, Connected Vehicles, and Infrastructure (February 10, 2017)
FHWA-JPO-17-TBD	Task 8: Prototype Proof-of-Concept Test Evaluation Report for Sharing Data between Mobile Devices, Connected Vehicles, and Infrastructure (June 28, 2017)
FHWA-JPO-17-TBD	Task 10: System Architecture and Design Document for Sharing Data between Mobile Devices, Connected Vehicles, and Infrastructure (TBD)
FHWA-JPO-17-TBD	Task 10: Prototype Acceptance Test Plan for Sharing Data between Mobile Devices, Connected Vehicles, and Infrastructure (May 12, 2017)
FHWA-JPO-17-TBD	Task 10: Prototype Acceptance Test Summary Report for Sharing Data between Mobile Devices, Connected Vehicles, and Infrastructure (TBD)

Society of Automotive Engineers (SAE)

J2735:2016	Object Dedicated Short Range Communications (DSRC) Message Set Dictionary

Chapter 3. Field Test Plan

3.1 Experimental Plan

The Experimental Plan was designed to answer the research questions posed by the contract:

- Are current messaging standards applicable to enable the practical incorporation of mobile devices supporting connected vehicle applications?
- What improvements to existing mobile device messaging standards (or new approaches) can be identified to help achieve the highest potential impact from mobile devices for broader connected vehicle application deployment?
- What are the implications or a broadly unconstrained and uncoordinated deployment of mobile devices and connected vehicles operating in close proximity for connected vehicle applications?
- Can protocols or other methods be developed that coordinate the generation of safety and mobility-related messages among multiple mobile devices transported within connected vehicles as well as with the connected vehicle itself?

  Do these coordination protocols have a practical benefit in enhancing mobility and safety of connected vehicle applications in potential large-scale connected vehicle deployments where many devices and vehicles may be located in close proximity?
- What policy and technical issues can be anticipated for dense connected vehicle/connected mobile device deployments?

The Experimental Plan, summarized in Table 3-1, starts with the hypotheses to be tested. For each hypothesis, the performance measures, target values, data logs/elements, and analyses to be used to test the hypothesis were specified and approved prior to the field test. After the field test, each performance measure was evaluated in accordance with the approved plan. Step-by-step test scripts (i.e. scenarios) were designed to generate the data required for the analyses. The step-by-step field test scenarios are presented in Appendix B, and are summarized as follows:

- **Scenario 0, Baseline (no mobile devices):** This is the baseline scenario to be run at each bus stop (Buckeye Lot Loop, 12th Avenue/Cannon Drive, and the Battelle parking lot simulated bus stop). Its purpose is to record baseline DSRC message traffic from the RSU and OBUs without mobile devices in the CV environment.
- **Scenario 1, Mobility-Uncoordinated:** This is a park-and-ride mobility scenario to travel to/from work, with travelers using MDEA for uncoordinated trip requests. This scenario is conducted at the Buckeye Lot Loop bus stop and the 12th Avenue/Cannon Drive bus stop.
- **Scenario 2, Safety-Uncoordinated:** This is a safety scenario, with travelers using MDEA for safety without travel group coordination. This scenario is conducted in the Battelle parking lot to allow maximum control of the experiment to ensure safety of test personnel.

- **Scenario 3, Mobility-Coordinated:** This is a park-and-ride mobility scenario to travel to/from work, with travelers using MDEA for coordinated trip requests. This scenario is conducted at the Buckeye Lot Loop bus stop and the 12th Avenue/Cannon Drive bus stop.
- **Scenario 4, Safety-Coordinated:** This is a safety scenario, with travelers using MDEA for safety with travel group coordination. This scenario is conducted in the Battelle parking lot to allow maximum control of the experiment to ensure safety of test personnel.
- **Scenario 5, Broadcast Range:** This is a scenario for testing DSRC message broadcast range of the mobile device. This scenario is conducted from the Buckeye Lot Loop bus stop.

The traceability from each hypothesis to the scenario(s) used to generate the data is provided in the last column of Table 3-1.

Table 3-1. Experimental Plan

Hypothesis	Performance Measure	Target	Data Log – Data Type	Analysis	Scenario
1. The MDEA only broadcasts PSMs when in the range of a vehicle broadcasting a BSM	PSM Message Rate prior to vehicle being in range	0 Hz	MDEA log (1-12) – GPS Location	Determine if vehicle is out of range of mobile device, based on vehicle speed.	2, 4
			MDEA log (1-12) – BSM received Occurrence		
			MDEA log (1-12) – PSM send occurrences	Analysis of PSMs sent while vehicle is out of range.	
	PSM Message Rate while vehicle is in range	10 Hz	MDEA log (1-12) – GPS Location	Determine if vehicle is in range of mobile device, based on vehicle speed	
			MDEA log (1-12) – BSM received Occurrence		
			MDEA log (1-12) – PSM send occurrences	Analysis of PSMs sent while vehicle is in range.	
2. The PSM and PMM message transmission rates by MDEAs are lower when travel groups have been formed (coordinated travel) than when travel groups have not been formed (uncoordinated travel)	PSM Message Rate prior to coordination	N x 10 Hz	MDEA Log (1) (2-12) – Coordination Status	Determine Coordination Status	1, 3
			MDEA Log (1) (2-12) – PSM send occurrences	Analysis of PSMs sent while not part of travel group	
	PSM Message Rate after coordination (travel group leader)	10 Hz	MDEA Log (1) (2-12) – Coordination Status	Determine Coordination Status	
			MDEA Log (1) (2-12) – PSM send occurrences	Analysis of PSMs sent while part of travel group (travel group leader)	
	PSM Message Rate after coordination (travel group member)	0 Hz	MDEA Log (1) (2-12) – PSM send occurrences	Analysis of PSMs sent while part of travel group (travel group member)	
	PMM Message Rate without coordination	N x 1 Hz	MDEA Log (1) (2-12) – Coordination Status	Determine Coordination Status	1, 3
			MDEA Log (1) (2-12) –PMM send occurrences	Analysis of PMMs sent while not part of travel group	
	PMM Message Rate with coordination (travel group leader)	1 Hz	MDEA Log (1) (2-12) – Coordination Status	Determine Coordination Status	
			MDEA Log (1) (2-12) – PMM send occurrences	Analysis of PMMs sent while part of travel group (travel group leader)	
	PMM Message Rate with coordination (travel group member)	0 Hz	MDEA Log (1) (2-12) – PMM send occurrences	Analysis of PMMs sent while part of travel group (travel group member)	
3. The MDEA can cease the broadcast of PSMs when in a vehicle	PSM Message Rate prior to detection of entering vehicle	N x 10 Hz	MDEA Log (1-12) – Travel Mode Status	Determine that mobile device is not in a vehicle	1, 3
			MDEA Log (1-12) – PSM send occurrences	Analysis of PSMs sent while not in a vehicle	
	PSM Message Rate after detection of entering vehicle	0 Hz	MDEA Log (1-12) – Travel Mode Status	Determine that mobile device is in a vehicle	
			MDEA Log (1-12) – PSM send occurrences	Analysis of PSMs sent while in a vehicle	

Hypothesis	Performance Measure	Target	Data Log – Data Type	Analysis	Scenario
4. The Mobile Device can broadcast a PSM a radius of 250 meters at 10 Hz under clear, unobstructed conditions, regardless of where the mobile device is located on the pedestrian's person or clothing	PSM Message Rate at a distance of less than 10 m	10 Hz	RSU Log – PSM receive occurrences	The rate at which PSMs are received by the RSU will be assessed. The mobile device will be placed in multiple locations on the pedestrian including, in-hand, in-pocket, and in a purse or backpack.	5
	PSM Message Rate at a distance of 50 m	10 Hz	RSU Log – PSM receive occurrences	The rate at which PSMs are received by the RSU will be assessed. The mobile device will be placed in multiple locations on the pedestrian including, in-hand, in-pocket, and in a purse or backpack.	
	PSM Message Rate at a distance of 100 m	10 Hz	RSU Log – PSM receive occurrences	The rate at which PSMs are received by the RSU will be assessed. The mobile device will be placed in multiple locations on the pedestrian including, in-hand, in-pocket, and in a purse or backpack.	
	PSM Message Rate at a distance of 150 m	10 Hz	RSU Log – PSM receive occurrences	The rate at which PSMs are received by the RSU will be assessed. The mobile device will be placed in multiple locations on the pedestrian including, in-hand, in-pocket, and in a purse or backpack.	
	PSM Message Rate at a distance of 200 m	10 Hz	RSU Log – PSM receive occurrences	The rate at which PSMs are received by the RSU will be assessed. The mobile device will be placed in multiple locations on the pedestrian including, in-hand, in-pocket, and in a purse or backpack.	
	PSM Message Rate at a distance of 250 m	10 Hz	RSU Log – PSM receive occurrences	The rate at which PSMs are received by the RSU will be assessed. The mobile device will be placed in multiple locations on the pedestrian including, in-hand, in-pocket, and in a purse or backpack.	
	PSM Message Rate at a distance of 300 m	10 Hz	RSU Log – PSM receive occurrences	The rate at which PSMs are received by the RSU will be assessed. The mobile device will be placed in multiple locations on the pedestrian including, in-hand, in-pocket, and in a purse or backpack.	
5. Vehicles OBUs can capture and process Mobile Device PSMs and issue warnings at sufficient distance for drivers to avoid imminent pedestrian collision	Distance at which Advisory is displayed	100 m	Light-duty VEA Log (1) – Advisory Display Light-duty VEA Log (1) – GPS Location Light-duty VEA Log (1) – PSM Location	Based on the speed of the vehicle (in the VEA Log), assess the distance at which an Advisory is issued.	2, 4
	Distance at which Alert is displayed	58 m	Light-duty VEA Log (1) – Alert Display Light-duty VEA Log (1) – GPS Location Light-duty VEA Log (1) – PSM Location	Based on the speed of the vehicle (in the VEA Log), assess the distance at which an Alert is issued.	
	Distance at which Warning is displayed	50 m	Light-duty VEA Log (1) – Warning Display Light-duty VEA Log (1) – GPS Location Light-duty VEA Log (1) – PSM Location	Based on the speed of the vehicle (in the VEA Log), assess the distance at which a warning is issued.	
	Advisory False Alarm Rate	1%	Light-duty VEA Log (1) – Advisory Display Light-duty VEA Log (1) – GPS Location Light-duty VEA Log (1) – PSM Location	Based on the speed of the vehicle (in the VEA Log), assess the Advisory false alarm rate.	
	Alert False Alarm Rate	1%	Light-duty VEA Log (1) – Alert Display Light-duty VEA Log (1) – GPS Location Light-duty VEA Log (1) – PSM Location	Based on the speed of the vehicle (in the VEA Log), assess the Alert false alarm rate.	
	Warning False Alarm Rate	1%	Light-duty VEA Log (1) – Warning Display Light-duty VEA Log (1) – GPS Location Light-duty VEA Log (1) – PSM Location	Based on the speed of the vehicle (in the VEA Log), assess the Warning false alarm rate.	
	Latency (message sent from Mobile Device to display in Vehicle)	500 ms	MDEA Log (1) – PSM Send Occurrence Light-duty VEA (1) Log – Warning Display	Analyze time difference between PSM sent and the message display time.	

Hypothesis	Performance Measure	Target	Data Log – Data Type	Analysis	Scenario
6. Mobile Devices can capture and process Vehicle BSMs and issue warnings in time for pedestrians to avoid imminent vehicle collision	Distance at which Advisory is displayed	100 m	MDEA Log (1) – Advisory Display MDEA Log (1) – GPS Location MDEA Log (1) – BSM Location	Based on the speed of the vehicle (in the BSM received by the mobile device), assess the distance at which an Advisory is issued.	2, 4
	Distance at which Alert is displayed	58 m	MDEA Log (1) – Alert Display MDEA Log (1) – GPS Location MDEA Log (1) – BSM Location	Based on the speed of the vehicle (in the BSM received by the mobile device), assess the distance at which an Alert is issued.	
	Distance at which Warning is displayed	50 m	MDEA Log (1) – Warning Display MDEA Log (1) – GPS Location MDEA Log (1) – BSM Location	Based on the speed of the vehicle (in the BSM received by the mobile device), assess the distance at which a warning is issued.	
	Advisory False Alarm Rate	1%	MDEA Log (1) – Advisory Display MDEA Log (1) – GPS Location MDEA Log (1) – BSM Location	Based on the speed of the vehicle (in the BSM received by the mobile device), assess the Advisory false alarm rate.	
	Alert False Alarm Rate	1%	MDEA Log (1) – Alert Display MDEA Log (1) – GPS Location MDEA Log (1) – BSM Location	Based on the speed of the vehicle (in the BSM received by the mobile device), assess the Alert false alarm rate.	
	Warning False Alarm Rate	1%	MDEA Log (1) – Warning Display MDEA Log (1) – GPS Location MDEA Log (1) – BSM Location	Based on the speed of the vehicle (in the BSM received by the mobile device), assess the Warning false alarm rate.	
	Latency (message sent from Vehicle to display on Mobile Device)	500 ms	Light-duty VEA Log (1) – BSM Send Occurrence MDEA Log (1) – Warning Display	Analyze time difference between BSM sent and the message display time.	
7. Mobile Device applications can detect if a pedestrian is in a safe or unsafe zone	Mobile Device In-Road Positioning Rate	>91%	MDEA Log – GPS Location MDEA Log – Safe/Unsafe Zone Status MDEA Log – MAP Message Contents	Analyze percentage of properly classified safe/unsafe zone detections. The device is placed in the roadway – mobile device location is properly classified if it positions itself in an unsafe zone.	2
	Mobile Device away from Road Positioning Rate	>99%	MDEA Log – GPS Location MDEA Log – Safe/Unsafe Zone Status MDEA Log – MAP Message Contents	Analyze percentage of properly classified safe/unsafe zone detections. The device is placed outside of the roadway – mobile device location is properly classified if it positions itself in a safe zone.	

Hypothesis	Performance Measure	Target	Data Log – Data Type	Analysis	Scenario
8. The VEA can coordinate transit trip requests received from an MDEA	PMM Successful Processing Rate (Transit) – DSRC	100%	MDEA Log (1-12) – PMM Send occurrence MDEA Log (1-12) – PMM contents Transit VEA Log – PMM Receive occurrence	Analyze the percentage of PMM messages properly processed by in-vehicle devices.	1
	PMM-RSP Successful Processing Rate (Transit) – DSRC	100%	Transit VEA Log – Driver acceptance Transit VEA Log – PMM-RSP Send occurrence MDEA Log (1-12) – PMM-RSP Receive occurrence MDEA Log (1-12) – Coordination Status	Analyze the percentage of PMM-RSP messages properly processed by mobile devices.	
	PMM-Cancel Successful Processing Rate (Transit) – DSRC	100%	MDEA Log (1-12) – PMM-Cancel Sent Occurrence Transit VEA Log – PMM-Cancel Received Occurrence	Analyze the percentage of PMM-Cancel messages properly processed by in-vehicle devices.	
	PMM Successful Processing Rate (Transit) – Cellular	100%	MDEA Log (1-12) – PMM Send occurrence MDEA Log (1-12) – PMM contents Transit VEA Log – PMM Receive occurrence	Analyze the percentage of PMM messages properly processed by in-vehicle devices.	
	PMM-RSP Successful Processing Rate (Transit) – Cellular	100%	Transit VEA Log – Driver acceptance Transit VEA Log – PMM-RSP Send occurrence MDEA Log (1-12) – PMM-RSP Receive occurrence MDEA Log (1-12) – Coordination Status	Analyze the percentage of PMM-RSP messages properly processed by mobile devices.	
	PMM-Cancel Successful Processing Rate (Transit) – Cellular	100%	MDEA Log (1-12) – PMM-Cancel Sent Occurrence Transit VEA Log – PMM-Cancel Received Occurrence	Analyze the percentage of PMM-Cancel messages properly processed by in-vehicle devices.	
9. The MDEA can receive arrival updates from a transit vehicle	PMM-Arrive Successful Processing Rate for uncoordinated travelers (Transit) – DSRC	100%	Transit VEA Log – PMM-ARRIVE Send occurrence MDEA Log (1-12) – PMM-ARRIVE Receive occurrence	Analyze the success rate of receiving a PMM-Arrive message.	1
10. The MDEA can detect when a traveler transitions from being a pedestrian to a rider on a transit vehicle or from a transit vehicle rider to a pedestrian	Mode Transition Detection Time (on-foot to passenger)	10 seconds	MDEA Log (1) – Travel Mode Status Experimental Log – Time from vehicle motion to traveler transition	Assess change in “Travel Mode Status” after the pedestrian enters the vehicle.	1, 3
	Mode Transition Detection (on-foot to passenger) False Positive Rate	10%	MDEA Log (1) –Travel Mode Status Experimental Log – Time from vehicle motion to traveler transition	Assess false positive rate of transition detection.	
	Mode Transition Detection Time (passenger to on-foot)	10 seconds	MDEA Log (1) – Travel Mode Status Experimental Log – Time from traveler motion off the bus to traveler transition	Assess change in “Travel Mode Status” after the pedestrian exits the vehicle.	
	Mode Transition Detection (passenger to on-foot) False Positive Rate	10%	MDEA Log (1) –Travel Mode Status Experimental Log – Time from traveler motion off the bus to traveler transition	Assess false positive rate of transition detection.	

Hypothesis	Performance Measure	Target	Data Log – Data Type	Analysis	Scenario
11. The MDEA can send and receive messages to coordinate, maintain, and cancel trip requests with other travelers using an MDEA	Coordination Request Message Successful Processing Rate (trip details match)	100%	MDEA (1) Log – Coordination Request Received Occurrence	Determine percentage of Coordination Request messages properly processed by mobile devices.	3
			MDEA (2-12) Log – Coordination Request Sent Occurrence		
			MDEA (2-12) Log – Coordination Confirmation Received Occurrence		
			MDEA (2-12) Log – Coordination Heartbeat Sent Occurrence		
			MDEA (1) Log – PMM Received Contents		
	Coordination Request Message Successful Processing Rate (trip details do not match)	100%	MDEA (1) Log – Coordination Request Sent Occurrence	Determine percentage of Coordination Request messages properly processed by mobile devices.	
	Coordination Acceptance Message Successful Processing Rate	100%	MDEA (2-12) Log – Coordination Acceptance Received Occurrence	Determine percentage of Coordination Acceptance messages properly processed by mobile devices.	
			MDEA (1) Log – Coordination Acceptance Sent Occurrence		
			MDEA (1) Log – Coordination Acceptance Notification		
	Coordination Heartbeat Response Message Successful Processing Rate (coordination heartbeat response received)	100%	MDEA (1) Log – Coordination Heartbeat Response Received Occurrence	Determine percentage of Coordination Heartbeat Response messages properly processed by mobile devices.	
			MDEA (2-12) Log – Coordination Heartbeat Response Sent Occurrence		
	Coordination Cancel Message Successful Processing Rate	100%	MDEA (2-12) Log – Coordination Cancel Response Received Occurrence	Determine percentage of Coordination Cancel messages properly processed by mobile devices.	
			MDEA (1) Log – Coordination Cancel Response Sent Occurrence		
	Coordination Disband Message Successful Processing Rate	100%	MDEA (2-12) Log – Coordination Disband Received Occurrence	Determine percentage of Coordination Disband messages properly processed by mobile devices.	
			MDEA (1) Log – Coordination Disband Sent Occurrence		
12. The RSU can broadcast a SPaT and MAP message via DSRC that can be received by mobile devices	SPaT Message Performance – DSRC communication media at a distance of 100 meters or less.	100%	RSU Log – SPaT sent Occurrence	Determine percentage of SPaT messages received by mobile devices when within 100 meters of RSU. Assess message contents for consistency.	1, 2, 3, 4
			RSU Log – SPaT message Content		
			Experimental Log – RSU Position		
			MDEA (1-12) Log – Mobile Device Position		
			MDEA Log (1-12) – SPaT message receipt		
			MDEA Log (1-12) – SPaT message content		
	MAP Message Performance – DSRC communication media at a distance of 100 meters or less	100%	RSU Log – MAP message send Occurrence	Determine percentage of MAP messages received by mobile devices when within 100 meters of RSU. Assess message contents for consistency.	
			RSU Log – MAP message Content		
			Experimental Log – RSU Position		
			MDEA (1-12) Log – Mobile Device Position		
			MDEA Log (1-12) – MAP message receive occurrence		
			MDEA Log (1-12) – MAP message content		

Hypothesis	Performance Measure	Target	Data Log – Data Type	Analysis	Scenario
13. The RSU can receive and save all messages transmitted by MDEAs and VEAs	RSUs receive messages transmitted by MDEAs and VEAs via DSRC	99%	Transit VEA Log, Light-duty VEA Log, MDEA Log (1-12) – all occurrences of messages sent via DSRC	Assess percentage of messages received from mobile devices within 100 meters of RSU. Assess message contents to make sure they are consistent.	1, 2, 3, 4
			Transit VEA Log, Light-duty VEA Log, MDEA Log (1-12) – message contents		
			Transit VEA Log, Light-duty VEA Log, MDEA (1-12) Log – device position		
			Experimental Log – RSU Position		
			RSU Log – Message Received Occurrence		
			RSU Log – Message Contents		
	RSUs save all messages transmitted by MDEAs and VEAs via DSRC	RSU Log Storage Capacity	RSU Log – Stored Message Data	Assess size of messages and rate at which on-board storage is used.	

Hypothesis	Performance Measure	Target	Data Log – Data Type	Analysis	Scenario
14. Travelers using MDEAs that have formed Travel Groups (coordinated travel) will have an effect on message performance (DSRC message transmission and reception) as compared to Travelers using MDEAs that have not formed Travel Groups (uncoordinated travel)	DSRC message transmission and reception (during uncoordinated travel, safety scenario)	<100%	Light-duty VEA Log, RSU Log and MDEA (1-12) Log	Analyze transmission and reception rate of PSM, BSM, MAP, and SPaT messages and contents of the messages	2
	Warning Latency (message sent from Vehicle to display on Mobile Device, during uncoordinated travel, safety scenario)	> 500 ms	Light-duty VEA Log (pcap files) – BSM send occurrence and MDEA (1) Log – warning display	Analyze time difference between BSM sent and the message display time	
	Warning Latency (message sent from Mobile Device to display on Vehicle, during uncoordinated travel, safety scenario)	> 500 ms	MDEA (1) Log – PSM send occurrence and Light-duty VEA Log – warning display	Analyze time difference between PSM sent and the message display time	
	RSUs save all messages transmitted (during uncoordinated travel, safety scenario)	RSU Log Storage Capacity	RSU Log – Stored Message Data	Assess size of messages and rate at which on-board storage is used.	
	DSRC message transmission and reception (during coordinated travel, safety scenario)	100%	Light-duty VEA Log, RSU Log and MDEA (1-12) Log	Analyze transmission and reception rate of PSM, BSM, MAP, and SPaT messages and contents of the messages	4
	Warning Latency (message sent from Vehicle to display on Mobile Device, during coordinated travel, safety scenario)	500 ms	Light-duty VEA Log – BSM send occurrence and MDEA (1) Log – warning display	Analyze time difference between BSM sent and the message display time	
	Warning Latency (message sent from Mobile Device to display on Vehicle, during coordinated travel, safety scenario)	500 ms	MDEA (1) Log – PSM send occurrence and Light-duty VEA Log – warning display	Analyze time difference between PSM sent and the message display time	
	RSUs save all messages transmitted (during coordinated travel, safety scenario)	RSU Log Storage Capacity	RSU Log – Stored Message Data	Assess size of messages and rate at which on-board storage is used.	
	DSRC message transmission and reception (during uncoordinated travel, mobility scenario)	< 100%	Transit VEA Log, Light-duty VEA Log, RSU Log and MDEA (1-12) Log	Analyze transmission and reception rate of PMM, BSM, MAP, and SPaT and contents of the messages	1
	PMM Latency (message sent from Vehicle to display on Mobile Device, during uncoordinated travel, mobility scenario)	> 500 ms	Transit VEA Log (pcap files) and MDEA (1-12) Log	Analyze time difference between PMM sent and the message display time.	
	PMM Latency (message sent from Mobile Device to display on Vehicle, during uncoordinated travel, mobility scenario)	> 500 ms	Transit VEA Log (pcap files) and MDEA (1-12) Log	Analyze time difference between PMM sent and the message display time	
	RSUs save all messages transmitted (during uncoordinated travel, mobility scenario)	RSU Log Storage Capacity	RSU Log – Stored Message Data	Assess size of messages and rate at which on-board storage is used.	
	DSRC message transmission and reception (during coordinated travel, mobility scenario)	100%	Transit VEA Log, Light-duty VEA Log, RSU Log and MDEA (1-12) Log	Analyze transmission and reception rate of PMM, BSM, MAP, and SPaT and contents of the messages	3
	PMM Latency (message sent from Vehicle to display on Mobile Device, during coordinated travel, mobility scenario)	500 ms	Transit VEA Log (pcap files) and MDEA (1) Log	Analyze time difference between PMM sent and the message display time	
	PMM Latency (message sent from Mobile Device to display on Vehicle, during coordinated travel, mobility scenario)	500 ms	Transit VEA Log (pcap files) and MDEA (1) Log	Analyze time difference between PMM sent and the message display time	
	RSUs save all messages transmitted (during coordinated travel, mobility scenario)	RSU Log Storage Capacity	RSU Log – Stored Message Data	Assess size of messages and rate at which on-board storage is used.	

Hypothesis	Performance Measure	Target	Data Log – Data Type	Analysis	Scenario
15. Travelers using MDEAs that have not formed Travel Groups (uncoordinated travel) will have an effect on message performance (DSRC message transmission and reception) as compared to not using MDEAs.	DSRC message transmission and reception (during uncoordinated travel)	<100%	Transit VEA Log, Light-duty VEA Log, RSU Log and MDEA (1-12) Log	Analyze DSRC transmission and reception of PSM, PMM, BSM, MAP and SPaT messages	1, 2
	RSUs save all messages transmitted (during uncoordinated travel)	RSU Log Storage Capacity	RSU Log – Stored Message Data	Assess size of messages and rate at which on-board storage is used.	
	DSRC message transmission and reception (while not using MDEAs)	100%	Transit VEA Log, Light-duty VEA Log and RSU log	Analyze DSRC transmission and reception of BSM, MAP and SPaT messages	0
	RSUs save all messages transmitted (while not using MDEAs)	RSU Log Storage Capacity	RSU Log – Stored Message Data	Assess size of messages and rate at which on-board storage is used.	

3.2 Testing Site

Mobility scenarios (Scenario 1 and Scenario 3) were performed on the Ohio State University campus using transit buses on the Medical Center Express route. Two bus stops were used: The 12th Avenue/Cannon Drive bus stop and the Buckeye Lot Loop stop. This provided a real-world physical environment for testing the communication methods, messages, message coordination, and mobility applications. Figure 3-1 shows the location of the mobility route and bus stops.

Safety scenarios (Scenario 2 and Scenario 4) were performed in the Battelle 5th Avenue Parking Lot using a Battelle-rented light vehicle. This was done to provide full control of the test vehicle and to ensure the safety of test participants while performing safety scenarios. Figure 3-2 shows the safety route.

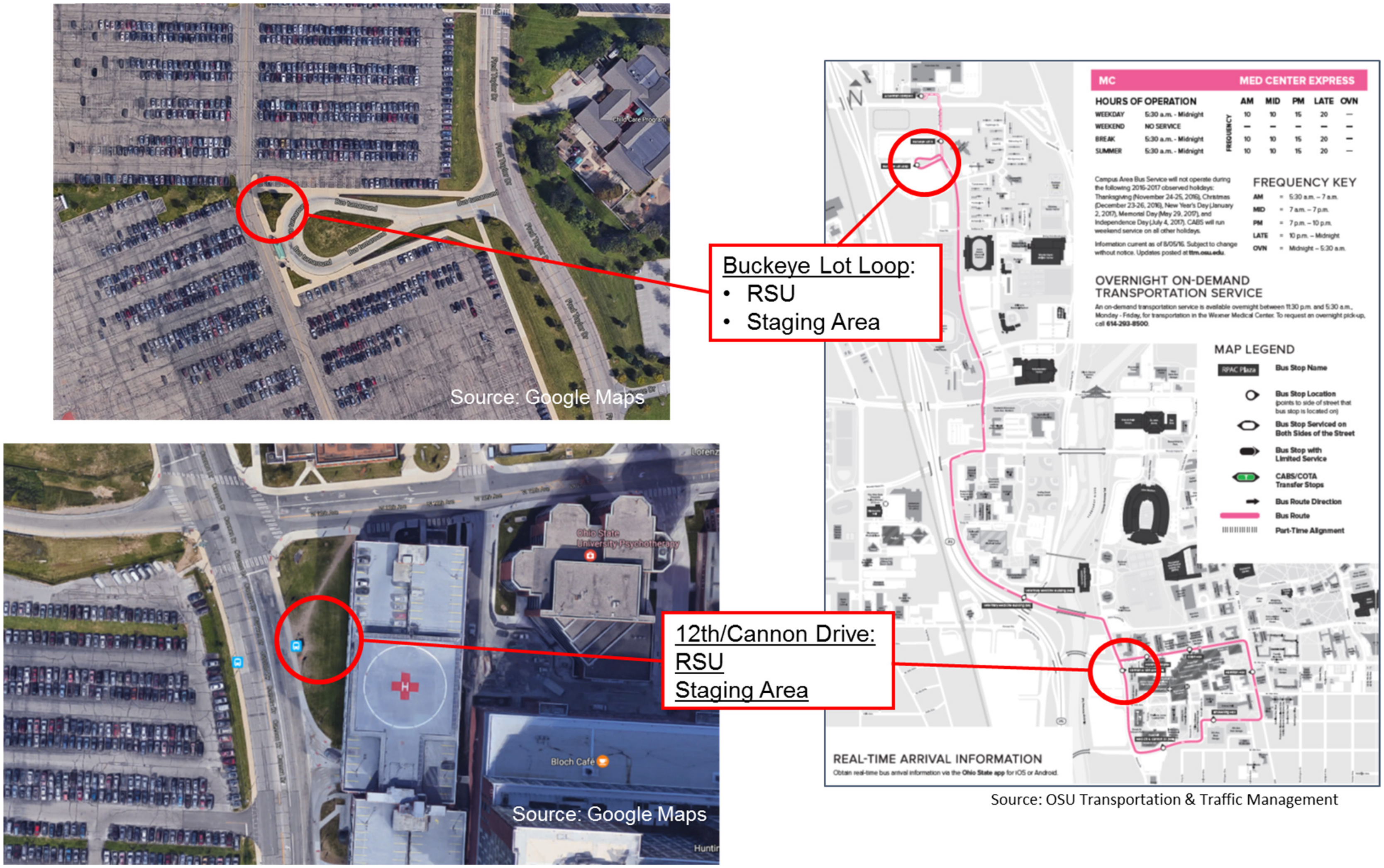
The PSM Broadcast Range scenario (Scenario 5) was performed at the Ohio State Buckeye Lot and involved only mobile devices and an RSU, where a pedestrian walked to distances of 10, 50, 100, 150, 200, 250, and 300 meters from the RSU. Figure 3-3 shows the walking route for the broadcast range test.

Collection of baseline data without mobile devices (Scenario 0) was performed at each location on a daily basis.

Table 3-2 summarizes the scenarios performed on each location or route.

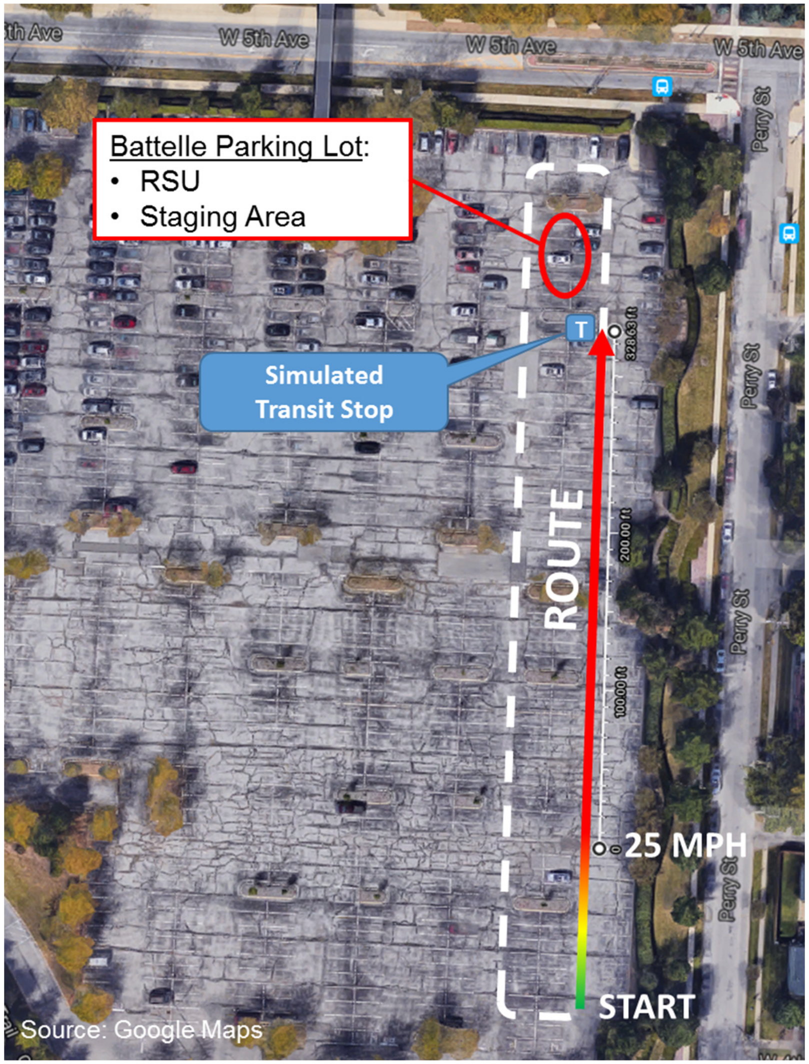
Table 3-2. Scenarios Performed each Location

Test Scenarios	Location	Iterations Planned	Notes
0-Baseline	OSU 12th Ave/Cannon Dr., OSU Buckeye Lot, Battelle Parking Lot	8	1 iteration each day for each location (no travelers)
1-Mobility-Uncoordinated	OSU Buckeye Lot Loop to 12th Ave/Cannon Dr.	10	Southbound transit bus trips
2-Safety-Uncoordinated	Battelle Parking Lot	10	Scenario within lot
3-Mobility-Coordinated	OSU 12th Ave/Cannon Dr. to Buckeye Lot Loop	10	Northbound transit bus trips
4-Safety-Coordinated	Battelle Parking Lot	10	Scenario within lot
5-Broadcast Range	OSU-Buckeye Lot	10	Traveler walking



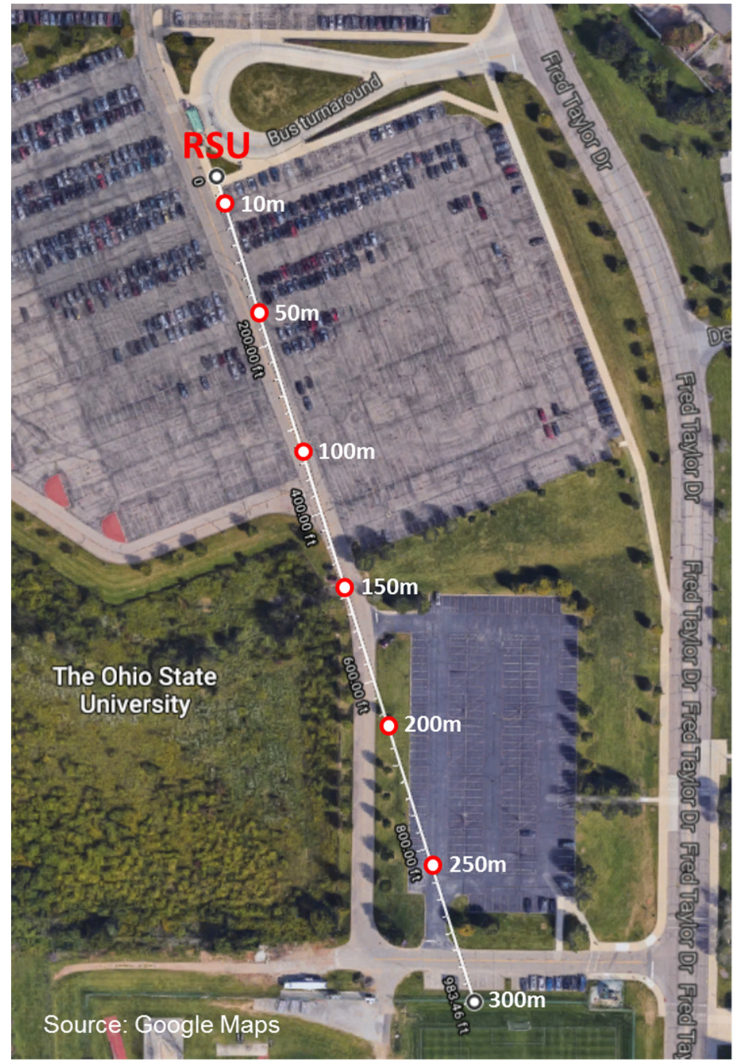
Source: Battelle, Google Maps, OSU Transportation & Traffic Management, June 2017

Figure 3-1. Ohio State University – Medical Center Transit Route (Scenarios 0, 1, 3)



Source: Battelle, Google Maps, June 2017

Figure 3-2. Battelle Parking Lot (Scenarios 0, 2, 4)

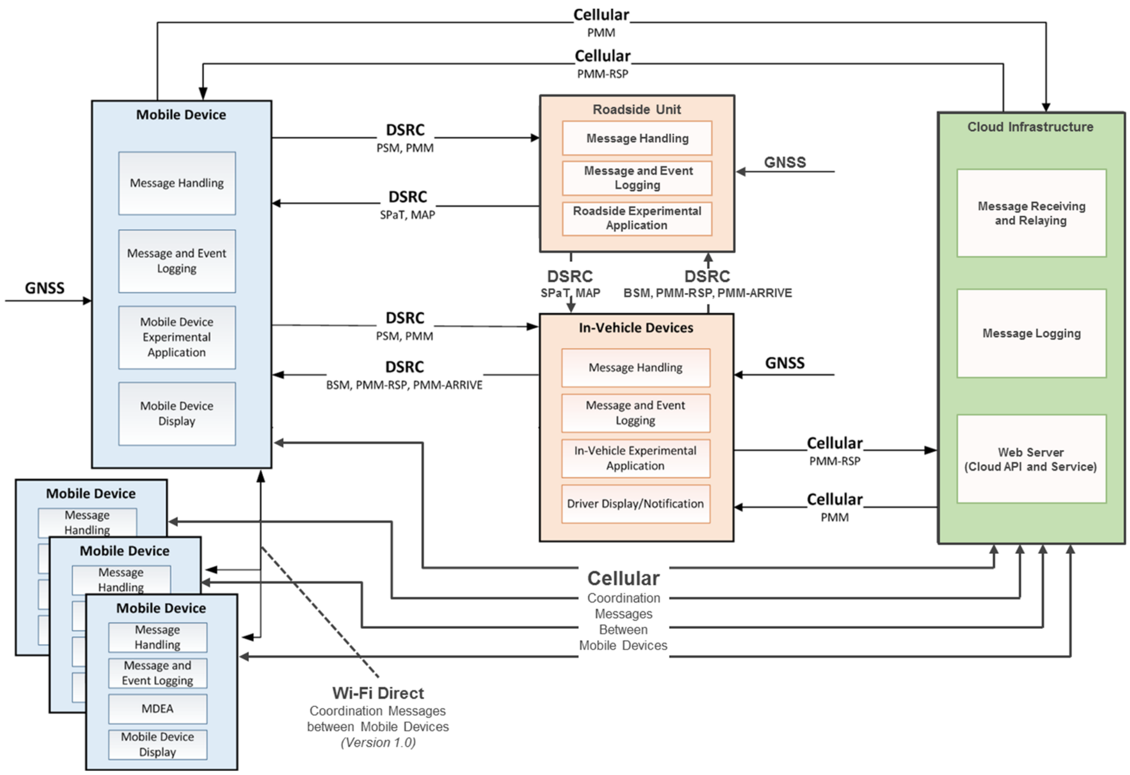


Source: Battelle, Google Maps, June 2017

Figure 3-3. OSU Buckeye Lot (Scenarios 5)

3.3 Experimental System

The prototype system, named D2X Hub, is the system of interest for the field test. It executes the messages, communication methods, coordination algorithms, and mobility and safety applications being tested. Figure 3-4 provides an architectural view of the system.



Source: Battelle, May 2017

Figure 3-4. D2X Hub Architecture

The D2X Hub includes the following components:

Hardware Components:

- Mobile Devices
- In-Vehicle Devices
- Roadside Equipment
- Cloud Infrastructure

Software Components:

- Mobile Device Experimental Application (MDEA)
- In-Vehicle Device Experimental Application (VEA)
- Roadside Unit (RSU) Experimental Application (REA)
- DSRC Message Handler
- Cloud API

Source: Battelle, Google, Motorola, Cohda, May 2017

Figure 3-5. D2X Hub Components

The D2X hub system components were deployed as shown in Table 3-3 to conduct the field test.

Table 3-3. Deployment of D2X Hub for Field Test

Subsystem	D2X Hub Components Deployed

Mobile Devices with MDEA (13)	• Smartphones
	  ○ Google Nexus 5X (6)
	  ○ Motorola MOTO G4 Play (7)
	• Arada Locomate ME (13)
	• MDEA software on smartphone
	• DSRC Message Handler software on Arada Locomate ME

Transit Buses with OBU/VEA (2)	• Battelle Common Computer Platform (CCP) as OBU • Mobile Mark Antenna • Wi-Fi Antenna for communication with CCP • VEA software on CCP
Light-Duty Vehicle with OBU/VEA (1)	• Battelle Common Computer Platform (CCP) as OBU • Mobile Mark Antenna • Wi-Fi Antenna for communication with CCP • VEA software on CCP
Light-Duty Vehicle with OBU/BSM-only (3 subsystems in 1 vehicle)	• Cohda MK5 OBU • Mobile Mark Antenna

Subsystem	D2X Hub Components Deployed
RSUs with REA (2)	• Cohda MK5 RSU • Boundary Devices Nit 6QP_MAX single board computer • Portable power generator • REA software on Nit 6QP_MAX
Cloud Infrastructure	• Webserver (Cloud API and Service)

D2X Hub Version 2.0 was developed and used for this experiment, with the changes based on the lessons learned from the earlier proof-of-concept test, as well as functional differences for a transit vehicle versus a taxi mode of operation. Following is summary of software changes.

<u>MDEA/Cloud</u>

- Cellular / Cloud-based travel group coordination replaced the Wi-Fi Direct method, implemented for the transit bus environment: The Cloud database tracks all travel groups and coordination messages. The Web API was expanded. The Cloud Service handles grouping travelers and determines the leader. The Leader continues to handle DSRC messaging with VEA as in Version 1.0.
- Taxi Trip Requests via Cloud were retained, though they are limited to a travel group size of one (Taxi functionality not part of field test).

<u>MDEA</u>

- Basic changes for the transit bus environment to enable execution of transit-based test scenarios: Transit-mode Trip Request processing was added.
- Enhanced application realism for the transit bus environment: The UI was customized for Transit – Trip Request with dropdown menus for Bus Route and Bus Stop.
- In-vehicle detection now defaults to Accelerometer method.
- Existing safety notifications are now issued verbally on the MDEA.
- PSM fix (cluster size population) for the DSRC Message Handler.

<u>VEA</u>

- Basic changes for the transit bus environment to enable execution of transit-based test scenarios: Taxi/Transit mode parameter and associated code was added. Transit-mode Trip Request processing was added. Pedestrian alert processing was enhanced to display most urgent alert when detecting multiple pedestrians.
- Enhanced application realism for the transit bus environment: Added bus stop markers on UI.
- Existing safety notifications are now issued verbally on the VEA.
- CCP diversity mode is now initiated automatically on system startup

Table 3-4 summarizes the messages and communication methods being tested. For each message type, the communications media, sending device type, receiving device type, and message frequency is listed. These correspond to the D2X Hub communications shown in Figure 3-4.

Table 3-4. Field Test Message Types

Message Type	Communication Media	Sent by	Received by/ Supports Apps on	Frequency
BSM	DSRC	In-vehicle device	Mobile device, RSU	10 Hz
PSM	DSRC	Mobile device	Vehicles, RSU	10 Hz
PMM	DSRC	Mobile device	In-vehicle device, RSU	one time
	Cellular	Mobile device	In-vehicle device	one time
PMM-RSP	DSRC	In-vehicle device	Mobile device, RSU	one time
	Cellular	In-vehicle device	Mobile device	one time
PMM-ARRIVE	DSRC	In-vehicle device	Mobile device, RSU	one time
	Cellular	In-vehicle device	Mobile device	one time
PMM-CANCEL	DSRC	Mobile device	In-vehicle device, RSU	one time
	Cellular	Mobile device	In-vehicle device	one time
Coordination Request	Cellular	Mobile device	Mobile device	one time
Coordination Confirmation	Cellular	Mobile device	Mobile device	one time
Coordination Heartbeat	Cellular	Mobile device	Mobile device	0.2 Hz
Coordination Cancel	Cellular	Mobile device	Mobile device	one time
SPaT	DSRC	RSU	Mobile device, In-vehicle device	10 Hz
MAP	DSRC	RSU	Mobile device, In-vehicle device	1 Hz

3.4 Test Personnel

Field test roles for Mobility scenarios are shown in Table 3-5. For Safety scenarios (Battelle parking lot), the core project team handled all roles since it was a controlled environment without transit buses and a table could be used to "hold" the mobile devices other than the Travel Group Leader.

Table 3-5. Test Personnel / Roles

Role	Description	Name
OSU Transit Driver (2)	Med Center Express Route, in service bus driver	Assigned by OSU
Traveler (12)	Battelle Staff (recruits beyond core project team)	Co-Ops/Interns
Light Vehicle VEA Operator	Drives light-duty vehicle and monitors equipment	Rama Boyapati
Light Vehicle BSM-only Operator	Drives light-duty vehicle and monitors equipment	Tony Polinori

Role	Description	Name
12th Ave/Cannon Dr. Staging Area Manager	Manages staging area and supports testing as needed for duration of time equipment is set up	Greg Baumgardner
Buckeye Loop Staging Area Manager and Traveler 13	Manages staging area and supports testing as needed for duration of time equipment is set up	Alejandro Sanchez-Badillo, Will Conlon
Test Leader	Guides participants through scenarios using MDEAs	Ben Paselsky
Test Engineer	Monitors VEAs, RSUs, CV Inspector as needed to ensure equipment is operating properly and data is being collected and stored	Greg Baumgardner
Test Director	Directs overall conduct of testing	Dave Valentine

3.5 Execution Timeline

The field test was conducted the week of June 12 and June 19, 2017, as planned. Prior to the field test, equipment was installed on two OSU transit buses and the system was checked out as operational and ready for test. Classroom training was provided for twelve Battelle staff recruits that served in the role of Travelers. After all testing was completed, equipment was removed from the buses on June 23 as planned. Table 3-6 provides the complete timeline of events.

Table 3-6. Execution Timeline

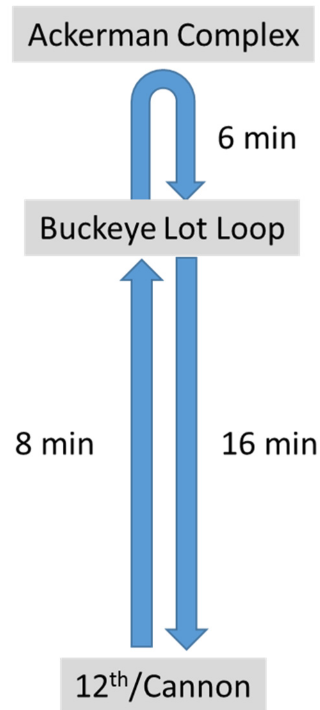
Date	Test Event	Notes
June 5	Install First OSU Transit Bus	At OSU TTM garage
June 6	Install Second OSU Transit Bus	At OSU TTM garage
June 8	Battelle Participant Briefing	Classroom style at Battelle
June 7-9	Checkout / Dry Run	All equipment, including light vehicles
June 12	OSU Field Test – Day 1	Mobility
June 13	OSU Field Test – Day 2	Mobility
June 14	OSU Field Test – Day 3	Mobility
June 15	Client Demo	Mobility, Safety
June 19	Battelle Field Test	Safety
June 20	PSM Broadcast Range – OSU	PSM Broadcast Range at Buckeye Lot Loop
June 23	Uninstall OSU Transit Buses	At OSU TTM garage

Safety Scenarios were executed exclusively by Battelle staff in a controlled environment. Other than accounting for the time required to execute the specified number of test iterations, there were no other timing parameters that needed to be considered in planning.

Mobility Scenarios had numerous timing parameters to consider in planning:

- 3 buses, 2 equipped on Med Center Express Route
- 30-minute loop, buses nominally 10 minutes apart
- All Mobility scenario sessions to start and end at the 12th Ave/Cannon Dr. Bus Stop
- Equipped buses were #1106 and #1108
- Equipped buses were planned to run on Med Center Express 1 and 3 schedules
- Plan to ride one bus AM, the other bus PM
- On-bus testing done before 3:00 OSU shift change

Figure 3-6 depicts the 30-minute loop and route segment times for the bus stops being used for a single round trip.

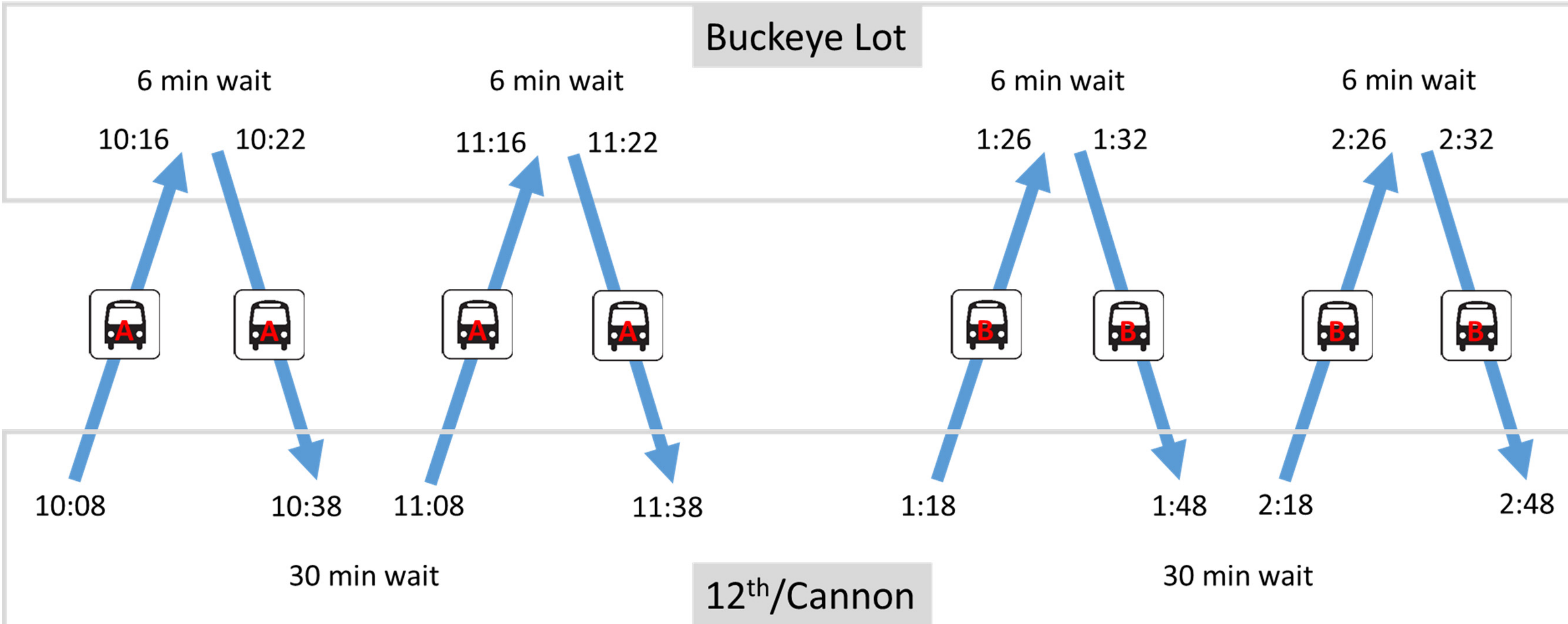


Source: Battelle, May 2017

Figure 3-6. Trip Timing Parameters

Based on the service schedules for the equipped buses, four round trips per day were planned as shown in *Source: Battelle, May 2017*

Figure 3-7, for executing the Mobility scenarios. Over the course of three Mobility test days, a maximum of 24 Mobility iterations could have been performed (12 Coordinated and 12 Uncoordinated scenarios). This allowed the first round trip (2 iterations) to be a dry-run and provided time for one extra round trip in the event of bad weather or equipment problems.



Source: Battelle, May 2017

Figure 3-7. Medical Center Express Trips, Daily Timeline

3.6 Data Collection

This section summarizes how field test data was collected and processed.

MDEA log files – These log files contain a database table with the following columns:

- ID – This is the Unique Primary Key column
- DateSecEpoch – This column contains timestamp (seconds since January 1st, 1970)
- LogLevel – Contain different log levels (integers)
- DateString – String representation of date and time with millisecond accuracy
- Message – Is the log message

An example MDEA database record is shown in Table 3-7.

Table 3-7. Example MDEA Database Record

ID	DateSecEpoch	LogLevel	DateString	Message
"35481"	*"1497377218"*	*"1"*	*"2017-06-13 18:06:58.199"*	*"Dsrc: Rx: Bsm Lat:39.9922615 Long: -83.0207158 Head: 275.8125 Sp: 0"*

All data was extracted from the SQLite database on each mobile device containing log messages generated by log statements embedded in the MDEA application. This included all DSRC messages received from the Arada radio. For the field test, the MDEA software was modified to log the time with millisecond accuracy. This revealed a time synchronization issue during data analysis. Absolute times recorded by the MDEA software were not reliable due to a synchronization error that varied randomly after each MDEA device reboot and could not be used when compared to RSU and VEA timestamps. Since devices were not rebooted between each coordinated/uncoordinated mobility test iteration, comparisons were nonetheless possible. For the safety scenarios in the controlled environment, most of the tests were run without rebooting the mobile devices thus maintaining a constant synchronization error and allowing for data analysis based on relative rather than absolute time.

VEA log files – These are text files containing a timestamp, module name, and a message. An example VEA tmxcore.log file record is as follows:

[2017-05-16 16:11:23.893] VeaPedestrianMonPlugin.cpp (635) – DEBUG: Vehicle speed: 32.1696 km/hr, 19.989263 miles/hr, 8.936 meters/sec

Raw DSRC traffic was extracted from DSRC traffic packet capture files generated by Cohda software on the CCP. DSRC pcap files contain raw packet capture format data that is readable by Wireshark Application. All other data was extracted from log files generated by log statements embedded in the VEA software.

RSU log files –All data was extracted from DSRC traffic packet capture files generated by Cohda software on the RSU.

At the end of each testing day, all data was archived and checks were conducted to ensure logging of all message data. The data used for the experimental analysis was extracted from the data logs and filtered for the time windows that the subject tests occurred. No further data cleaning was required.

Chapter 4. Field Test Evaluation

4.1 Experimental Analysis Results Summary

Overall, the testing and subsequent analysis showed the ability to reliably generate, transmit, and receive messages between mobile devices and connected vehicles. The messages to incorporate mobile devices into the CV environment functioned as designed and provided the necessary data for the prototype mobility and safety applications to perform their functions. Furthermore, coordination of messages between mobile devices functioned as designed, reducing mobile device DSRC message volume and thereby improving CV message and application processing time.

Some performance shortfalls were observed, which are attributed mostly to limitations of the underlying technology and hardware available to this project. Discussion of these shortfalls is deferred to the detailed results presented in the remainder of this report.

Table 4-1 provides a summary of the experimental analysis results by hypothesis, while Section 4.2 provides in-depth coverage of the experimental analysis. Section 4.3 directly answers the research questions and provides lessons learned and recommendations.

Results are stated as the Level of Confidence (LOC) that the hypothesis has been confirmed to be true. Each hypothesis has multiple performance measures that were each evaluated against their respective target value. In general, to determine an overall LOC for each hypothesis, the sum of the results for all performance measures over all test iterations (the count falling within the performance threshold) was expressed as a percentage of the total number of performance measure iterations.

$$\mathrm{LOC} = \frac{No.\,of\ performance\ measure\ iterations\ within\ performance\ thresholds}{Total\ No.\,of\ performance\ measure\ iterations}$$

Table 4-1. Experimental Analysis Results Summary

Hypothesis Description	Data Analysis Results Summary	Success Count (Successful / Total)
Hypothesis 1 – The MDEA only broadcasts PSMs when in the range of a vehicle broadcasting a BSM	Confirmed at 100% Level of Confidence (LOC)	20 / 20
Hypothesis 2 – The PSM and PMM message transmission rates by MDEAs are lower when travel groups have been formed (coordinated travel) than when travel groups have not been formed (uncoordinated travel)	Confirmed at 100% LOC	460 / 460
Hypothesis 3 – The MDEA can cease the broadcast of PSMs when in a vehicle	Confirmed at 100% LOC	264 / 264

Hypothesis Description	Data Analysis Results Summary	Success Count (Successful / Total)
Hypothesis 4 – The Mobile Device can broadcast a PSM a radius of 250 meters at 10 Hz under clear, unobstructed conditions, regardless of where the mobile device is located on the pedestrian's person or clothing	Confirmed at 86% LOC (variations in antenna orientation and line of sight believed to impede transmission)	121 / 140
Hypothesis 5 – Vehicles OBUs can capture and process Mobile Device PSMs and issue warnings at sufficient distance for drivers to avoid imminent pedestrian collision	Confirmed at 100% LOC	66 / 66
Hypothesis 6 – Mobile Devices can capture and process Vehicle BSMs and issue warnings in time for pedestrians to avoid imminent vehicle collision	Confirmed at 100% LOC	66 / 66
Hypothesis 7 – Mobile Device applications can detect if a pedestrian is in a safe or unsafe zone	Confirmed at 100% LOC	22 / 22
Hypothesis 8 – The VEA can coordinate transit trip requests received from an MDEA	Confirmed at 100% LOC	1238 / 1238
Hypothesis 9 – The MDEA can receive arrival updates from a transit vehicle	Confirmed at 94% LOC (DSRC HW connection failure during one test scenario iteration)	194 / 207
Hypothesis 10 – The MDEA can detect when a traveler transitions from being a pedestrian to a rider on a transit vehicle or from a transit vehicle rider to a pedestrian	Confirmed at 100% LOC	528 / 528
Hypothesis 11 – The MDEA can send and receive messages to coordinate, maintain, and cancel trip requests with other travelers using an MDEA	Confirmed at 91% LOC (MDEA operator error caused coordination failures including a "hung" travel group)	517 /571
Hypothesis 12 – The RSU can broadcast a SPaT and MAP message via DSRC that can be received by mobile devices	Confirmed at 100% LOC	140 / 140
Hypothesis 13 – The RSU can receive and save all messages transmitted by MDEAs and VEAs	Confirmed at 100% LOC	See Section 4.2 Hypothesis #13
Hypothesis 14 – Travelers using MDEAs that have formed Travel Groups (coordinated travel) will have an effect on message performance (DSRC message transmission and reception) as compared to Travelers using MDEAs that have not formed Travel Groups (uncoordinated travel)	Not Confirmed (based on size of experiment, no impact observed on DSRC message *transmission and reception*; however, reduced message *processing latency* was observed when Travelers formed Travel Groups)	See Section 4.2 Hypothesis #14

Hypothesis Description	Data Analysis Results Summary	Success Count (Successful / Total)
Hypothesis 15 – Travelers using MDEAs that have not formed Travel Groups (uncoordinated travel) will have an effect on message performance (DSRC message transmission and reception) as compared to not using MDEAs	Not Confirmed (based on size of experiment, no impact observed on DSRC message *transmission and reception*; message *processing latency* was not considered since the baseline scenario does not use MDEAs)	See Section 4.2 Hypothesis #15

4.2 Experimental Analysis

Hypothesis 1: The MDEA only broadcasts PSMs when in the range of a vehicle broadcasting a BSM

Data logs verified: MDEA Log (1-12) – GPS location, BSM received and PSM send occurrences

Analysis:

1. Determination of vehicle range from mobile device, based on vehicle speed
2. Analysis of PSMs sent with respect to vehicle range. (In range and out of range scenarios)

Observations:

In all the test cases, PSMs were broadcasted by MDEA when the vehicle was in its range with respect to vehicle speed. (“fast enough, close enough”)

Table 4-2. Hypothesis 1 Analysis Data Sample

Date	Time	Vehicle range and advisory distance w.r.t. speed (meters)	Speed (mph)	In Range	Out of Range
6/19/2017	14:26:26	IsBsmClose: Dist: 125.306402493779<? AdvDist: 126.539999999494	31.18	Yes	
6/19/2017	14:26:45	IsBsmClose: Dist: 14.2212394331821<? AdvDist: 16.5599999999338	4.33	Yes	
6/19/2017	14:27:49	IsBsmClose: Dist: 121.866993844552<? AdvDist: 126.719999999493	31.8	Yes	
6/19/2017	14:28:06	IsBsmClose: Dist: 13.2365484265217<? AdvDist: 13.499999999946	3.35	Yes	

For the complete analysis, please refer to Table A-1 in Appendix A.

$Equation\ for\ calculating\ advisory\ distance\ w.r.t.\ speed$:

$$d_{Advisory} = v * 9 \text{ sec}$$

Where:

- $d_{Advisory}$ is the advisory display distance (meters)
- v is the velocity of the vehicle (meters per second)
- 9 seconds of perception, reaction, and braking time are provided for the driver

Results: There were no outliers (False Negatives) in the data analyzed. Hence, Hypothesis 1 is satisfied at a 100% level of confidence

Hypothesis 2: The PSM and PMM message transmission rates by MDEAs are lower when travel groups have been formed (coordinated travel) than when travel groups have not been formed (uncoordinated travel)

Data logs verified: MDEA Log (1-12) – Coordination Status, PSM send occurrences before and after coordination

Analysis:

1. Determination of coordination status
2. Analysis of PSMs sent while not part of the travel group and while part of the travel group (Travel group leader)
3. Analysis of PSMs sent while not part of the travel group and while part of the travel group (Travel group Member)

Observations:

Out of 11 uncoordinated iterations, iteration number 8 was not considered for the analysis as the travelers formed a travel group. Similarly, out of 11 coordinated iterations, 2 iterations were eliminated due to grouping failure. Comparing the 10 uncoordinated iteration results with 9 coordination iteration results, coordinated travel groups transmitted lower number of PSMs and PMMs than the uncoordinated travelers.

Table 4-3. Hypothesis 2 Analysis Data Sample (PSM and PMM transmission by MDEAs before coordination)

			Bashful		Cinderella		Donald	
Iteration	**Date**	**Bus**	**PSM**	**PMM**	**PSM**	**PMM**	**PSM**	**PMM**
1	12-Jun	1106	Yes	Yes	Yes	Yes	Yes	Yes
2	12-Jun	1106	Yes	Yes	Yes	Yes	Yes	Yes

Table 4-4. Hypothesis 2 Analysis Data Sample (PSM and PMM transmission by MDEAs after coordination)

			Bashful (follower)		Doc (leader)		Donald (follower)	
Iteration	**Date**	**Bus**	**PSM**	**PMM**	**PSM**	**PMM**	**PSM**	**PMM**
1	12-Jun	1106	NO	NO	Yes	Yes	NO	NO
2	12-Jun	1106	NO	NO	Yes	Yes	NO	NO

For the complete analysis, please refer to Table A-2 and Table A-3 in Appendix A.

Results: There were no False Negatives in the data analyzed. Hence, Hypothesis 2 is satisfied at 100% level of confidence

Hypothesis 3: The MDEA can cease the broadcast of PSMs when in a vehicle

Data logs verified: MDEA Log (1-12) – Travel mode Status, PSM send occurrences

Analysis:

1. Determination of mobile device travel mode status
2. Analysis of PSMs sent before and after transition of travel mode (on-foot and In-vehicle)

Observations:

All the test logs indicate that the PSMs were ceased after the MDEA transitioned its travel mode to In-vehicle.

Table 4-5. Hypothesis 3 Analysis Data Sample (MDEAs ceasing PSMs after in-vehicle)

			Bashful		Doc		Donald	
Iteration	**Date**	**Bus**	**In Vehicle**	**Ceased PSM broadcast after being In-Vehicle**	**In Vehicle**	**Ceased PSM broadcast after being In-Vehicle**	**In Vehicle**	**Ceased PSM broadcast after being In-Vehicle**
1	12-Jun	1106	Yes	Ceased	Yes	Ceased	Yes	Ceased
2	12-Jun	1106	Yes	Ceased	Yes	Ceased	Yes	Ceased

For the complete analysis, please refer to Table A-4 and Table A-5 in Appendix A.

Results: There were no outliers (False Negatives) in the data analyzed. Hence, Hypothesis 3 is satisfied at a 100% level of confidence

Hypothesis 4: The Mobile Device can broadcast a PSM a radius of 250 meters at 10 Hz under clear, unobstructed conditions, regardless of where the mobile device is located on the pedestrian's person or clothing

Data logs verified: RSU Log – PSM receive occurrences at a distance of 10 m, 50 m, 100 m, 150 m, 200 m, 250 m, and 300 m from the RSU.

Analysis:

1. The rate at which PSMs were received by the RSU had been assessed. The mobile device was placed in multiple locations on the pedestrian including, in-hand and in a backpack.

Observations:

Due to DSRC connection and hardware issues, a PSM reception rate of 10 Hz was not observed in all tests at all distances.

Table 4-6. Hypothesis 4 Analysis Data Sample (PSM broadcast at difference distances)

Iteration	Date	10 m	PSM rate at 10 m	50 m	PSM rate at 50 m	100 m	PSM rate at 100 m	150 m	PSM rate at 150 m
1	20-Jun	10:28:57	10/sec	10:29:40	10/sec	10:30:27	10/sec	10:31:15	10/sec
2	20-Jun	10:40:31	10/sec	10:41:17	10/sec	10:42:12	10/sec	10:43:04	10/sec

For the complete analysis, please refer to Table A-6 in Appendix A.

Results: 19 False Negatives out of 140 checks were identified. Hence, Hypothesis 4 is satisfied at an 86.4% level of confidence.

Hypothesis 5: Vehicles OBUs can capture and process Mobile Device PSMs and issue warnings at sufficient distance for drivers to avoid imminent pedestrian collision

Data logs verified: Light-Duty VEA Log – PSM Location, GPS Location, Advisory Display, Alert Display and Warning Display

Analysis:

1. Assess the calculated target distance versus actual distance when an Advisory, Alert and Warning were issued by the VEA. Calculated distance is based on the actual speed of the vehicle in the VEA Log. A tolerance of 10% from the calculated distance is allowed since it is impossible to generate a notification at the exact time the system determines a notification condition exists, due to inherent computational and messaging latency.

Observations:

a. Uncoordinated Safety: The average difference in calculated versus actual distance when an Advisory, Alert and Warning were issued on the VEA are 11.21 m, 4.3 m, and 1.52 m respectively. The average notification distances are within the 10% tolerance of target.

b. Coordinated Safety: The average difference in calculated versus actual distance when an Advisory, Alert and Warning were issued on the VEA are 6.95 m, 1.48 m, and 1.06 m respectively. The average notification distances are within the 10% tolerance of target.

c. The greater difference in Advisory notifications was due to the fact that the MDEA does not send PSMs until the VEA reaches the Advisory distance, thus there is an additional delay for Advisories before the VEA can start the notification determination process. This latency is in addition to the inherent computational and messaging latency once PSMs are received.

d. All types of notifications were received significantly faster for coordinated scenarios (actual notification distance was closer to calculated distance).

e. Absolute latency (message sent from Mobile Device to display in Vehicle) could not be determined since the MDEA and VEA logs were not time-synchronized.

Equations for calculating advisory, alert and warning *distance w.r.t. speed*:

$$d_{Advisory} = v * 9 \text{ sec}$$

$$d_{alert} = 1.1 * \left\{[(0.5 + 2.5) * v] + \frac{v^2}{2(3.4)}\right\}$$

$$d_{warning} = 1.1 * \left\{[(0.5 + 2.5) * v] + \frac{v^2}{2(5.6)}\right\}$$

Where:

- $d_{Advisory}$ is the advisory display distance (meters)
- d_{Alert} is the alert display distance (meters)
- $d_{Warning}$ is the warning display distance (meters)
- v is the velocity of the vehicle (meters per second)

Source: Battelle, Google Maps, Sept 2017

Figure 4-1. Advisory, Alert and Warning Distances with Respect to VEA

Table 4-7. Hypothesis 5 Analysis Data Sample

Advisory Speed (mph)	Advisory (actual) (meters)	Advisory Difference (meters)	Advisory (calculated) (meters)	Alert Speed (mph)	Alert (actual) (meters)	Alert Difference (meters)	Alert (calculated) (meters)	Warning Speed (mph)	Warning (actual) (meters)	Warning Difference (meters)	Warning (calculated) (meters)
32.00	109.54	19.21	128.75	33.58	85.34	0.65	85.99	33.22	70.40	0.27	70.67
31.78	108.93	18.93	127.86	30.74	72.85	3.05	75.90	30.17	61.97	0.40	62.37
29.27	92.45	25.31	117.76	31.34	75.97	2.02	77.99	32.67	64.50	4.64	69.14
30.90	107.56	16.76	124.32	33.35	84.20	0.95	85.15	33.14	69.58	0.87	70.45
27.53	108.58	2.18	110.76	27.66	64.22	1.32	65.54	26.75	52.18	1.33	53.51
29.02	112.39	4.37	116.76	26.80	62.64	0.12	62.76	25.77	48.69	2.36	51.05
29.34	116.16	1.89	118.05	28.52	67.53	0.84	68.37	27.70	52.72	3.20	55.92
29.71	108.22	11.31	119.53	28.89	66.59	3.01	69.60	27.98	56.52	0.12	56.64
30.17	107.05	14.33	121.38	28.97	67.42	2.45	69.87	27.53	54.66	0.83	55.49
28.07	110.38	2.56	112.94	25.87	29.19	30.61	59.80	24.86	47.86	0.94	48.80
28.63	108.75	6.44	115.19	27.06	61.25	2.34	63.59	26.75	51.75	1.76	53.51
	Average	11.21	119			4.30	71			1.52	59

Note: Here the 'actual' values indicate the distance between MDEA and VEA, when the notification (Advisory, alert, or warning) was issued. Similarly, 'calculated' values indicate the expected distance between MDEA and VEA, which is calculated based on the speed of the VEA.

For the complete analysis, please refer to Table A-7 and Table A-8 in Appendix A.

Results: There were no missed notifications (False Negatives) or false notifications (False Positives). The average notification distances are all within tolerance of the calculated target distances. Hence, Hypothesis 5 is satisfied at a 100% level of confidence.

Hypothesis 6: Mobile Devices can capture and process Vehicle BSMs and issue warnings in time for pedestrians to avoid imminent vehicle collision

Data logs verified: MDEA Log (1-12) – BSM Location, GPS Location, Advisory Display, Alert Display and Warning Display

Analysis:

1. Assess the calculated target distance versus actual distance when an Advisory, Alert and Warning were issued by the MDEA. Calculated distance is based on the actual speed of the vehicle in the BSM received. A tolerance of 10% from the calculated distance is allowed since it is impossible to generate a notification at the exact time the system determines a notification condition exists, due to inherent computational and messaging latency.

Observations:

a. Uncoordinated Safety: The average difference in calculated versus actual distance when an Advisory, Alert and Warning were issued on the MDEA are 4.21 m, 3.04 m, and 2.01 m respectively. The average notification distances are within the 10% tolerance of target.

b. Coordinated Safety: The average difference in calculated versus actual distance when an Advisory, Alert and Warning were issued on the MDEA are 3.9 m, 3.24 m, and 2.57 m respectively. The average notification distances are within the 10% tolerance of target.

c. MDEA responded similarly during both coordinated and uncoordinated safety scenarios.

d. Absolute latency (message sent from Mobile Device to display in Vehicle) could not be determined since the MDEA and VEA logs were not time-synchronized.

Equations for calculating advisory, alert and warning *distance w.r.t. speed*:

$$d_{Advisory} = v * 9$$

$$d_{alert} = 1.1 * \left\{[(0.5 + 2.5) * v] + \frac{v^2}{2(3.4)}\right\}$$

$$d_{warning} = 1.1 * \left\{[(0.5 + 2.5) * v] + \frac{v^2}{2(5.6)}\right\}$$

Where:

- $d_{Advisory}$ is the advisory display distance (meters)
- d_{Alert} is the alert display distance (meters)

- $d_{Warning}$ is the warning display distance (meters)
- v is the velocity of the vehicle (meters per second)

Source: Battelle, Google Maps, Sept 2017

Figure 4-2. Advisory, Alert and Warning Distances with Respect to MDEA

Table 4-8. Hypothesis 6 Analysis Data Sample

Advisory Speed (mph)	Advisory (actual) (meters)	Advisory Difference (meters)	Advisory (calculated) (meters)	Alert Speed (mph)	Alert (actual) (meters)	Alert Difference (meters)	Alert (calculated) (meters)	Warning Speed (mph)	Warning (actual) (meters)	Warning Difference (meters)	Warning (calculated) (meters)
31.45	125.30	1.23	126.53	34.98	85.21	5.95	91.16	32.88	67.46	2.26	69.72
31.49	121.86	4.84	126.70	31.13	75.57	1.68	77.25	30.01	59.29	2.66	61.95
28.54	98.94	15.89	114.83	31.45	74.58	3.79	78.37	32.03	66.01	1.38	67.39
30.19	119.22	2.25	121.47	33.50	85.70	0.00	85.70	32.61	68.16	0.82	68.98
27.69	111.04	0.37	111.41	26.93	59.44	3.73	63.17	27.06	52.17	2.12	54.29
29.93	117.28	3.14	120.42	26.84	61.44	1.44	62.88	25.85	47.54	3.71	51.25
31.76	118.58	9.20	127.78	28.94	64.97	4.80	69.77	27.06	53.98	0.31	54.29
30.33	118.89	3.14	122.03	29.70	63.98	8.35	72.33	27.20	52.84	1.81	54.65
29.03	116.18	0.62	116.80	28.09	64.98	1.97	66.95	27.38	53.44	1.67	55.11
28.85	112.84	3.23	116.07	26.66	61.43	0.88	62.31	26.39	47.68	4.92	52.60
28.58	112.58	2.41	114.99	27.33	63.66	0.80	64.46	25.32	49.52	0.42	49.94
	Average	4.21	120			3.04	72			2.01	58

Note: Here the 'actual' values indicate the distance between MDEA and VEA, when the notification (Advisory, alert, or warning) was issued. Similarly, 'calculated' values indicate the expected distance between MDEA and VEA, which is calculated based on the speed of the VEA.

For the complete analysis, please refer to Table A-9 and Table A-10 in Appendix A.

Results: There were no missed notifications (False Negatives) or false notifications (False Positives). The average notification distances are all within tolerance of the calculated target distances. Hence, Hypothesis 6 is satisfied at a 100% level of confidence.

Hypothesis 7: Mobile Device applications can detect if a pedestrian is in a safe or unsafe zone

Data logs verified: MDEA Log (1-12) – GPS Location, Safe/Unsafe Zone Status, and MAP Message Contents

Analysis:

1. Analyzed the percentage of properly classified safe/unsafe zone detections. The device was placed in the roadway – mobile device location was properly classified if it positions itself in an unsafe zone.

Observations:

User State Change from 'Safe' to 'Unsafe' (when placed in the middle of the roadway) and 'Unsafe' to 'Safe' (when placed away from the roadway) were captured accurate and timely.

Table 4-9. Hypothesis 7 Analysis Data Sample

Iteration	Date	Leader MDEA	Is Safe Icon True	Is Safe Icon False
1	19-Jun	Doc	Satisfied	Satisfied
2	19-Jun	Doc	Satisfied	Satisfied
3	19-Jun	Doc	Satisfied	Satisfied
4	19-Jun	Doc	Satisfied	Satisfied

For the complete analysis, please refer to Table A-11 and Table A-12 in Appendix A.

Source: Battelle, Google Maps, Sept 2017

Figure 4-3. Safe and Unsafe Zones at Battelle Test Site

Results: There were no outliers (False Negatives) in the data analyzed. Hence, Hypothesis 7 is satisfied at a 100% level of confidence

Hypothesis 8: The VEA can coordinate transit trip requests received from an MDEA

Data logs verified: MDEA Log (1-12) – PMM Send Occurrence, PMM contents, PMM-RSP Receive Occurrence, Coordination Status, and PMM-Cancel Sent Occurrence

Transit VEA Log – PMM Receive Occurrence, Driver Acceptance, PM-RSP Send Occurrence, and PMM-Cancel Received Occurrence

Analysis:

1. Analyzed the percentage of PMM and PMM – Cancel messages properly processed by in-vehicle devices
2. Analyzed the percentage of PMM-RSP messages properly processed by mobile devices
3. This analysis was performed for PMM Messages communicated through both DSRC and Cellular

Observations:

a. Out of 11 uncoordinated iterations, iteration number 8 was not considered for the analysis as the travelers formed a travel group. Similarly, out of 11 coordinated iterations, 2 iterations were eliminated due to grouping failure.

b. During all the considered iterations, VEA successfully coordinated transit trip requests received from an MDEA.

Table 4-10. Hypothesis 8 Analysis Data Sample

	PMM Successful Processing Rate (Transit) – DSRC			PMM-RSP Successful Processing Rate (Transit) – DSRC				PMM-Cancel Successful Processing Rate (Transit) – DSRC	
Iteration	**PMM Send-MDEA log**	**PMM Contents**	**PMM Receive - Transit Log**	**Transit VEA Log – Driver Acceptance**	**PMM-RSP Send-Transit log**	**PMM-RSP Received-MDEA Log**	**MDEA Log – Coordination Status**	**PMM-Cancel Sent-MDEA Log**	**PMM-Cancel Received-Transit Log**
1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

For the complete analysis, please refer to Table A-13, Table A-14, Table A-15, and Table A-16 in Appendix A.

Results: During all the considered iterations, Hypothesis 8 is satisfied at a 100% level of confidence.

Issues Identified:

- During one of the coordinated mobility tests, MDEA (group leader) cancelled the trip request and killed the MDEA application before the trip cleared. This left a leaderless group in the database to timeout. Other MDEAs (Followers) joined this hung group and were not able to schedule a trip.

Hypothesis 9: The MDEA can receive arrival updates from a transit vehicle

Data logs verified: Transit VEA Log – PMM-ARRIVE Send Occurrence.

MDEA Log (1-12) – PMM-ARRIVE receive occurrence.

Analysis:

1. Analyzed the success rate of receiving a PMM-Arrive message via DSRC

Observations:

a. During one instance MDEA lost DSRC connection. Ride-arrival messages were not triggered in this iteration.

b. In three instances, transit VEA did not initiate ride-arrive due to the transit vehicle stopping at a distance greater than the configured arrival distance from the bus stop location.

c. In all other instances where the prerequisite conditions were met and the VEA was able to trigger Ride-Arrive transmissions and MDEA was able to receive, the ride arrive messages were successfully communicated.

Table 4-11. Hypothesis 9 Analysis Data Sample

Iteration	Date	MDEA1	MDEA2	MDEA3	MDEA4	MDEA5
		Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive
1	12-Jun	Yes	Yes	Yes	Yes	Yes
2	12-Jun	Yes	Yes	Yes	Yes	Yes
3	12-Jun	NO	NO	NO	NO	NO
4	12-Jun	Yes	Yes	Yes	Yes	Yes
5	13-Jun	Yes	Yes	Yes	Yes	Yes

For the complete analysis, please refer to Table A-17 and Table A-18 in Appendix A.

Results: 1 out of 17 tests failed due to DSRC hardware connection failure. During all other instances where the conditions were right when the VEA was able to trigger Ride-Arrive transmissions, MDEA received Ride-Arrival Messages. This Hypothesis is satisfied at 94% level of Confidence.

Hypothesis 10: The MDEA can detect when a traveler transitions from being a pedestrian to a rider on a transit vehicle or from a transit vehicle rider to a pedestrian

Data logs verified: MDEA Log – Travel Mode Status Change; Experimental Log – Time from vehicle motion to traveler transition, and Time from traveler motion off the bus to traveler transition

Analysis:

1. Assessed the change in "Travel Mode Status" after the pedestrian enters the vehicle. (The threshold value for Travel Mode Status Change is 10 secs).
2. The average values were considered for in-vehicle and on-foot transitions, as the basis for hypothesis evaluation.

Observations:

- Accelerometer tests on average took 8.51 secs and 5.83 secs to detect in-vehicle and on-foot respectively.

Table 4-12. Hypothesis 10 Analysis Data Sample

Performance Measure	In-Vehicle	On-Foot
Time (sec)	8.51	5.83

Results: Hypothesis is satisfied at 100% LOC.

Hypothesis 11: The MDEA can send and receive messages to coordinate, maintain, and cancel trip requests with other travelers using an MDEA

Data logs verified:

MDEA (1) Log – Coordination Request Received Occurrence, PMM Received Contents, Coordination Acceptance Sent Occurrence, Coordination Acceptance Notification, Coordination Heartbeat Received Occurrence, Coordination Cancel Response Sent occurrence, and Coordination Disband Sent occurrence

MDEA (2-12) Log – Coordination Request Sent Occurrence, Coordination Confirmation received Occurrence, Coordination Heartbeat Response Sent Occurrence, Coordination Acceptance received Occurrence

MDEA (13) Log – Coordination Request Sent occurrence

Analysis:

1. Determined the percentage of Coordination Request, Acceptance, Heartbeat, Cancel and Disband messages properly processed by mobile devices.
2. Assessed the message contents for consistency.

Observations:

- Except for iteration #5 where trip requests are not processed due to “hung” group, in all other iterations, MDEA successfully transmitted and received messages to coordinate, maintain and cancel trip requests.

Table 4-13. Hypothesis 11 Analysis Data Sample

Performance Measure	Doc	Bashful	Donald	Dopey	Goofy	Grumpy	Happy	Mickey	Pluto	Sneezy	Vader	Cinderella	Tigger
Coordination Request Sent		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Coordination Request Received	Yes												
Coordination Request Acceptance sent	Yes												
Coordination Acceptance received		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Coordination Heartbeat Sent		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Coordination Heartbeat Received	Yes												
Coordination Cancel Sent												Yes	
Coordination Cancel Received	Yes												
Coordination Disband Sent	Yes												

Performance Measure	Doc	Bashful	Donald	Dopey	Goofy	Grumpy	Happy	Mickey	Pluto	Sneezy	Vader	Cinderella	Tigger
Coordination Disband Received		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Coordination Request Sent (trip details do not match													Yes
MDEA forms its own group													Yes

For the complete analysis, please refer to Table A-21 in Appendix A.

Results: This hypothesis is satisfied at 91% level of confidence.

Hypothesis 12: The RSU can broadcast a SPaT and MAP message via DSRC that can be received by mobile devices

Data logs verified: MDEA Log – Mobile Device Position, SPaT message receive occurrence, SPaT message content, MAP message receive occurrence, and MAP message contents

RSU Log – SPaT sent occurrences, SPaT message contents, MAP send occurrences, MAP message contents

Experimental Log – RSU position

Analysis:

1. Determined the percentage of SPaT messages received by mobile devices when within 100 meters of RSU. Assessed message contents for consistency.
2. Determined the percentage of MAP messages received by mobile devices when within 100 meters of RSU. Assessed message contents for consistency.

Observations:

a. During all iterations, RSU transmitted Map messages at 1/sec and SPaT messages at 10/sec. But, MDEA received Map messages at 1/sec and SPaT messages at less than or equal to 5/sec.
b. The reason for this behavior is the throttle frequency set on MDEA. Throttle frequency of SPaT messages was set at 200ms, which means, a maximum of 5 SPaT messages will be transferred to MDEA.
c. Further, Arada Bluetooth connection was slicing down the throughput messages.

Table 4-14. Hypothesis 12 Analysis Data Sample

Iteration	Date	10 m	Spat and Map Broadcast rate at 10 m	50 m	Spat and Map Broadcast rate at 50 m	100 m	Spat and Map Broadcast rate at 100 m	150 m	Spat and Map Broadcast rate at 150 m
1	20-Jun	10:28:57	1/sec	10:29:40	1/sec	10:30:27	1/sec	10:31:15	1/sec
2	20-Jun	10:40:31	1/sec	10:41:17	1/sec	10:42:12	1/sec	10:43:04	1/sec
3	20-Jun	10:55:33	1/sec	10:56:18	1/sec	10:57:10	1/sec	10:58:18	1/sec
4	20-Jun	11:08:45	1/sec	11:09:30	1/sec	11:10:25	1/sec	11:11:18	1/sec
5	20-Jun	11:22:21	1/sec	11:23:01	1/sec	11:24:00	1/sec	11:24:56	1/sec
6	20-Jun	11:35:01	1/sec	11:35:54	1/sec	11:36:56	1/sec	11:38:17	1/sec
7	20-Jun	11:54:15	1/sec	11:55:06	1/sec	11:55:55	1/sec	11:56:44	1/sec
8	20-Jun	12:06:15	1/sec	12:07:01	1/sec	12:08:06	1/sec	12:09:36	1/sec

For the complete analysis, please refer to Table A-22 in Appendix A.

Results: During all instances, RSU broadcasted SPaT and MAP messages at designated frequency. MDEA received all the MAP and SPaT messages to its maximum limit. So, the hypothesis is satisfied at a 100% level of confidence.

Hypothesis 13: The RSU can receive and save all messages transmitted by MDEAs and VEAs

Data logs verified: MDEA Log (1-12) – All Occurrences of messages sent via DSRC, and Message Contents; Device position

Transit VEA and Light-Duty VEA Log – All Occurrences of messages sent via DSRC, and Message Contents; Device position

RSU Log – Message Received Occurrence, and Message Contents.

Experimental Log – RSU position, Stored message data

Analysis:

1. Assessed the percentage of messages received from mobile devices within 100 meters of RSU. Assess message contents to make sure they are consistent.

Observations:

a. During all the instances, RSU received and saved all the DSRC messages communicated by MDEA and VEA.

Table 4-15. Hypothesis 13 Analysis Data Sample

Date	Time	Vehicle range and advisory distance w.r.t. speed (meters)	RSU Log PSM and BSM Rate
6/19/2017	14:26:26	IsBsmClose: Dist: 125.306402493779<? AdvDist: 126.539999999494	10/Sec
6/19/2017	14:26:45	IsBsmClose: Dist: 14.2212394331821<? AdvDist: 16.5599999999338	10/Sec
6/19/2017	14:27:49	IsBsmClose: Dist: 121.866993844552<? AdvDist: 126.719999999493	10/Sec
6/19/2017	14:28:06	IsBsmClose: Dist: 13.2365484265217<? AdvDist: 13.499999999946	10/Sec
6/19/2017	14:32:00	IsBsmClose: Dist: 102.750789580626<? AdvDist: 114.839999999541	10/Sec
6/19/2017	14:32:16	IsBsmClose: Dist: 10.7089899814409<? AdvDist: 13.1399999999474	10/Sec

Analysis data for Hypothesis 13 is found in the following tables in Appendix A: A-1 through A-10, A-17, A-18, A-22 through A-25, and A-28.

Results: The hypothesis statement of RSU being able to store all messages received via DSRC is satisfied at 100% level of confidence.

Hypothesis 14: Travelers using MDEAs that have formed Travel Groups (coordinated travel) will have an effect on message performance (DSRC message transmission and reception) as compared to Travelers using MDEAs that have not formed Travel Groups (uncoordinated travel)

Data logs verified: MDEA Log (1-12) – PSM Send Occurrence, BSM Received Occurrence, PMM Send Occurrence, PMM Receive Occurrence, Warning Display, MAP Receive Occurrence, SPaT Receive Occurrence and Message Contents;

Transit VEA Log: BSM Send Occurrence, PSM Received Occurrence, PMM Received Occurrence, PMM Send Occurrence, and Message Contents;

Light-Duty VEA Log: BSM Send Occurrence, PSM Received Occurrence, Warning Display and Message Contents;

RSU Log – All DSRC Message Received Occurrence, MAP Send Occurrence, SPaT Send Occurrence and Message Contents.

Analysis:

1. Analyzed transmission and reception rate of BSM, PSM, PMM, MAP and SPaT messages and contents of the messages. (Uncoordinated Safety vs. Coordinated Safety; Uncoordinated Mobility vs. Coordinated Mobility)
2. Analyzed the time difference between BSM sent and message display (from VEA to MDEA).
3. Analyzed the time difference between PMM sent and message display time (from VEA to MDEA).
4. Analyzed the storage rate of DSRC messages in RSU log.

Observations:

a. During Coordinated and uncoordinated scenarios, no significant difference of transmission or reception frequency or message content was observed in the communication between MDEA, VEA, and RSU.

b. MDEA had issues with DSRC connection failure in few coordinated and uncoordinated scenarios.

c. During experimental analysis, a time synchronization mismatch was observed between MDEA, VEA, and RSU logs. The time difference was within the range of 1-3 seconds. This issue was not anticipated by the test team during the design of test procedure. This limited the test team from calculating the absolute latency in message communication between Mobile Devices and other CV applications.

d. During mobility scenarios, the data log time difference for each MDEA with respect to VEA was the same between coordinated and uncoordinated iteration for each round trip.

e. During safety scenarios, the data log time difference for each MDEA with respect to VEA was the same throughout coordinated and uncoordinated iterations.

f. This allowed the comparison of observed delays. The difference between these delays was used to calculate the difference in latency.

g. From these numbers, it could be concluded that uncoordinated safety scenarios have an additional message processing latency of 170ms for message communication, when compared to coordinated safety scenarios.

h. Similarly, uncoordinated mobility scenarios have an additional message processing latency of 477 ms for message communication, when compared to coordinated mobility scenarios

i. RSU Storage capacity required for each of Uncoordinated safety, Coordinated Safety, Uncoordinated Mobility and Coordinated Mobility scenarios is provided in Table 4-17.

Table 4-16. Hypothesis 14 Sample Analysis Data (Uncoordinated Safety Scenario)

Iteration	1	2	3	4	5	6	7	8	9	10	11
Date	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun
Leader MDEA	Doc	Doc	Doc	Doc	Doc	Doc	Cinderella	Cinderella	Cinderella	Cinderella	Cinderella
Start Time	10:25:30	10:27:15	10:31:30	10:32:50	10:34:05	10:35:10	10:38:35	10:41:00	10:43:50	10:45:25	10:47:27
End Time	10:26:45	10:28:10	10:32:15	10:33:45	10:35:00	10:37:23	10:39:30	10:43:10	10:44:40	10:46:25	10:48:20
BSM sent by VEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM Received on MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM reception by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSMs received by VEA and OBU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM Contents	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PSM sent by MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PSM received by VEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PSM reception by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PSM Contents	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SPaT and Map Transmission by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SPaT and Map Reception by MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 4-17. Data Usage Statistics

Performance Measure	Uncoordinated Safety	Coordinated Safety	Uncoordinated Mobility	Coordinated Mobility
Average Message Size (Bytes)	213	227	300	321
Total Number of Messages	45009	70932	198640	192283
Total RSU Storage Space used (Mega Bytes)	9.57	16.1	59.59	61.99
No of Messages / sec/device	10	10	10	10
No of Messages / minute/device	600	600	600	600
No of Messages / hour/device	36000	36000	36000	36000
No of Messages / day/device	864000	864000	864000	864000
Data Required / day/device (Bytes)	183707259	1961008949	259200000	277344000
Data Required / day/device (Mega Bytes)	184	196	259	277

For the complete analysis, please refer to Table A-23, Table A-24, Table A-25, Table A-26, and Table A-27 in Appendix A.

Results: Coordinated mobility and safety scenarios had lesser message processing latency compared to uncoordinated mobility and safety scenarios respectively. However, no considerable difference was observed in the transmission and reception of DSRC messages between coordinated and uncoordinated scenarios. Coordinated scenarios showed a higher storage rate in RSU, when compared to uncoordinated scenarios.

Note: Absolute processing latency could not be determined due to the time synchronization problem; however, relative processing latency could be determined. The main issue with time synchronization between MDEA, VEA and RSU logs occurred due to the mobile devices failing to properly sync time and having a different error offset with every reboot. The time synchronization error was the same during coordinated and uncoordinated tests, as the mobile devices were not rebooted. Even though the exact amount of time synchronization error was not known, the difference in time from BSM transmission logged in VEA and the BSM processing logged by MDEA during the coordinated and uncoordinated scenarios accurately reflected the additional latency during uncoordinated tests.

Hypothesis 15: Travelers using MDEAs that have not formed Travel Groups (uncoordinated travel) will have an effect on message performance (DSRC message transmission and reception) as compared to not using MDEAs

Data logs verified: MDEA Log (1-12) – PSM Send Occurrence, BSM Received Occurrence, PMM Send Occurrence, PMM Receive Occurrence, Warning Display, MAP Receive Occurrence, SPaT Receive Occurrence and Message Contents;

Transit VEA Log: BSM Send Occurrence, PSM Received Occurrence, PMM Received Occurrence, PMM Send Occurrence, and Message Contents;

Light-Duty VEA Log: BSM Send Occurrence, PSM Received Occurrence, Warning Display and Message Contents;

RSU Log – All DSRC Message Received Occurrence, MAP Send Occurrence, SPaT Send Occurrence and Message Contents.

Analysis:

1. Analyzed transmission and reception rate of BSM, MAP, and SPaT messages and contents of the messages. (Uncoordinated Safety vs. Baseline; Uncoordinated Mobility vs. Baseline)
2. Analyzed the storage rate of DSRC messages in RSU log.

Observations:

a. During Coordinated and uncoordinated scenarios, no significant difference of transmission or reception frequency or message content was observed in the communication between VEA and RSU.

b. RSU Storage capacity required for each of Uncoordinated Safety, Coordinated Safety, and Baseline Scenarios is provided in Table 4-19.

Table 4-18. Hypothesis 15 Sample Analysis Data (Baseline Scenario)

Iteration	1	2	3	4	5	6	7
Date	12-Jun	12-Jun	13-Jun	13-Jun	14-Jun	14-Jun	19-Jun
BSM sent by VEA and OBUs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM reception by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM Contents	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SPaT and Map Transmission by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSMs received by VEA and OBU	Yes	Yes	Yes	Yes	Yes	Yes	Yes

For the complete analysis, please refer to Table A-28 in Appendix A.

Table 4-19. Data Usage Statistics

Performance Measure	Uncoordinated Safety	Uncoordinated Mobility	Baseline Scenario
Average Message Size (Bytes)	213	300	311
Total Number of Messages	45009	198640	84024
Total RSU Storage Space used (Mega Bytes)	9.57	59.59	26.22
No of Messages / sec/device	10	10	10
No of Messages / minute/device	600	600	600
No of Messages / hour/device	36000	36000	36000
No of Messages / day/device	864000	864000	864000
Data Required / day/device (Bytes)	183707259	259200000	268640012
Data Required / day/device (Mega Bytes)	184	259	269

Results: No considerable difference was observed in the transmission and reception of DSRC messages between uncoordinated and baseline scenarios. Baseline scenario required higher storage rate than uncoordinated scenarios, as only safety messages were communicated. So, with the limited number (12) of mobile devices involved, Travelers using MDEAs that have not formed Travel Groups (uncoordinated travel) did not have a considerable effect on message performance (DSRC message transmission and reception) as compared to not using MDEAs. Note that message processing latency is not considered since the baseline scenario does not use MDEA to process messages.

4.3 Research Questions, Lessons Learned, and Recommendations

Research Questions

Research Question # 1: Are current messaging standards applicable to enable the practical incorporation of mobile devices supporting connected vehicle applications?

The current messaging standards are applicable to enable the practical incorporation of mobile devices supporting connected vehicle applications, but they required improvements to enable the full range of capabilities tested in this project. From the field testing, it could be observed that the messages communicated between mobile devices and connected vehicle applications effectively performed the safety and mobility tasks.

Research Question # 2: What improvements to existing mobile device messaging standards (or new approaches) can be identified to help achieve the highest potential impact from mobile devices for broader connected vehicle application deployment?

The existing J2735 messages do not include a personal mobility aspect. Battelle defined and added the PMM message to the J2735 message set for this project. This addition is not an update or improvement to the existing message standards, but rather is an approach used on this project to test mobility capabilities for the mobile device user. No additions or improvements were required to the existing J2735 safety messages for this project. With the addition of PMM messages on this project, the potential for broader CV application deployment was realized with the integration of mobile device safety and mobility applications with connected vehicles.

Research Question # 3: What are the implications of a broadly unconstrained and uncoordinated deployment of mobile devices and connected vehicles operating in close proximity for connected vehicle applications?

The frequency and number of messages transmitted by unconstrained and uncoordinated deployment of mobile devices pose challenges to the operational capability of other connected vehicle applications. During execution of the uncoordinated scenarios, an additional message processing latency of 170 ms during safety and 477 ms during mobility tests were observed. As shown in our field test results, a higher number of messages received by other CV applications implies increased application processing time.

Research Question # 4: Can protocols or other methods be developed that coordinate the generation of safety and mobility-related messages among multiple mobile devices transported within connected vehicles as well as with the connected vehicle itself?

One key objective of this project was to develop methods to introduce coordination between multiple mobile devices communicating with each other and with connected vehicles. The field test results clearly show the effectiveness gained by coordination between mobile devices and connected vehicles. The field test showed that same amount of safety and mobility related information could be communicated with a significant reduction in the number of messages resulting in reduction of message processing latency in the CV applications.

Research Question # 5: Do these coordination protocols have a practical benefit in enhancing mobility and safety of connected vehicle applications in potential large-scale connected vehicle deployments where many devices and vehicles may be located in close proximity?

Coordination ensures a reduced number of messages between mobile devices and connected vehicles, which improves the processing time of the messages. In a large-scale environment, minimum latency ensures timely communication of safety and mobility messages. During the field test, the coordinated mobile devices communicated mobility and safety messages with a faster processing speed and lesser latency when compared to uncoordinated mobile devices.

Translating a 170ms reduction in safety message processing time to a practical safety benefit, a vehicle travelling at 25 mph will cover 1.9 meters (6.23 feet) in 170ms. Given an average human reaction time of 250ms, a vehicle would travel 2.79 meters before a driver can react to an alert. In a scenario where a pedestrian unexpectedly steps into the path of an approaching vehicle, the driver's effective reaction time increases by over 50% with the 170ms reduction in safety message processing time. 1.9 meters of additional braking distance to the driver can be critical in coming to a safe stop.

Similarly, for a mobility scenario, assume an express transit vehicle is traveling towards a bus stop and will only stop if a rider has scheduled a pickup. If the bus is close when a rider schedules a trip, a small delay can mean the difference between the driver reacting to the scheduled ride and stopping or determining he can't stop and passing the bus stop.

Research Question # 6: What policy and technical issues can be anticipated for dense connected vehicle/connected mobile device deployments?

1) Considering the increase in latency that we observed for uncoordinated travel, we can expect that high volume uncoordinated scenarios would have a negative effect on the existing DSRC infrastructure. 2) The security feature of the messages was not tested during the field test. When many devices are used in a dense environment, security of the messages must be ensured to have safe and reliable communications. Current technical solutions are not scalable.

Lessons Learned

The Lessons Learned from this experiment are summarized as follows:

1. The ability to reliably generate, transmit, and receive messages between mobile devices and connected vehicles was demonstrated.
2. The messages to incorporate mobile devices into the CV environment functioned as designed and provided the necessary data for the prototype mobility and safety scenarios.
3. The D2X Hub prototype software functioned well (as designed) for sending and receiving safety and mobility messages.
4. Mixed results were achieved for the various communication methods tested:
    a. Cellular functioned well with the D2X Hub. During the field test, cellular messages were communicated timely and accurate.

   b. Handheld DSRC hardware caused communication connection problems with our system. There were occasional Bluetooth connection failures between the handheld DSRC radios and the smartphones, as well as occasional DSRC transmission/reception failures by the DSRC handheld radios. Longer term, it is assumed that DSRC radios will be integrated into smartphones thus obviating the issues experienced on this project.

5. GPS accuracy limitations were observed, as expected. The GPS accuracy stated by the U.S. Government is +/- 4 m. With this level of accuracy, quick changes in state from “safe” to “unsafe” and “unsafe” to “safe” were observed when the user did not move.
6. A mismatch in time synchronization between MDEA, VEA, and RSU data logs was observed. This mismatch acted as a limiting factor in determination of latency in communication messages between mobile devices and the CV environment.
7. In few instances, the transit VEA did not initiate ride-arrive due to the transit vehicle stopping at a distance beyond the configured arrival zone at the bus stop.
8. Traveler user state changes between “in-vehicle” and “on-foot” were observed while the traveler remained in the transit vehicle. This was caused by the transit vehicle traveling at very low speeds in some instances before coming to a complete stop.
9. Throttling the frequency for the messages communicated from the handheld DSRC radio to the smartphone should be determined on a per message source basis (mobile devices, connected vehicles, and roadside units). With a higher number of units from each source, the mobile DSRC radio was limited in the number of messages it could process.

Recommendations

Recommendations for future research or development are summarized as follows:

<u>General</u>

1. Time synchronization issues between the devices used in the field test limited the usefulness of some of the log data gathered during the field tests. All communication devices must be time synchronized to the accuracy of milliseconds.
2. The cellular and DSRC trip scheduling mechanisms operated independently, which limited the system’s ability to coordinate trip scheduling using multiple communication protocols. Additional coordination between DSRC and cellular for trip management would facilitate handling transit vehicle capacity calculations.
3. The field test used cellular and DSRC as the communication protocols. Further investigation of other available and emerging communication protocols including but not limited to 5G and Android Neighbor Aware Networking (NAN) is recommended.
4. The existing trip scheduling only consists of the rider’s pick-up information but not the drop-off or destination option. Integration of rider drop-off information into the trip scheduling is recommended.
5. DSRC and cellular communication medias were used to test the ability to schedule trips. The DSRC was considered as the primary communication media and was always tried first for ride scheduling. If a request over DSRC failed over a configurable time (20 seconds), then the communication media was switched to cellular and the mobility request was repeated. A more intelligent communication media switching strategy should be implemented in future systems.

MDEA

1. “In-vehicle” and “on-foot” detection was unreliable in some cases. A refinement of the user-state transition algorithm can mitigate the issue. (Note: The transition algorithm was accurate enough to trigger “in-vehicle” and “on-foot” transitions during the Hypothesis 10 testing. However, reliability issues were observed, as additional false transitions were triggered when the pedestrian was still in the vehicle. This was due to stoppage of transit at multiple locations. These false transitions did not affect the Hypothesis 10 test results, since they were outside the time window that the associated performance measures were evaluated.)
2. The PMM developed for taxi trip requests was insufficient for supporting transit trip requests. Therefore, modification of the PMM or a new message is needed to handle transit data such as route and transit ID information, as opposed to simple GPS coordination for pick-up and drop-off.
3. Maximum group size was limited to 12 mobile devices for field testing. Further study on maximum coordinated group size with respect to capacity and performance is recommended.
4. Ride arrived messages were not received for trips scheduled via cellular due to lack of coordination between messages sent via cellular and DSRC for trip scheduling. Adding coordination between cellular and DSRC messages for trip scheduling will enable implementation of ride-arrival messages for scheduled trips.
5. DSRC or application failure of the travel leader’s MDEA can cause the ride request for the entire group to fail. A recovery method should be designed into future systems such as switching to another traveler’s MDEA as the group leader.
6. The group leader heartbeat is used to determine if the group should be cancelled. During field testing, a few “hung” groups took too long to clear and created problems with subsequent trip requests. A decrease in the timeout period for the group leader heartbeat should be used to determine if the group is no longer valid and thereby clear the trip.
7. The field test was performed using devices that run the android operating system. Further investigation of devices that run on other operating systems including, but not limited to IOS (Apple) is recommended.

VEA

1. In the field test, there were several cases where the transit bus stopping distance and stopping speed adversely affected the transmission of ride arrive messages and in-vehicle and on-foot detections. A study of transit bus behavior including stopping distance and stopping speed could be factored into future application algorithms.
2. Trip request functionality is currently geared towards the experiment. Add feature to provide the driver the ability to manage trip requests, instead of auto-accepting trips as was done for the purposes of this experiment.

REA

1. RSUs could have the same functionality as VEAs with respect to scheduling trips. This way, mobile devices could communicate with RSUs via DSRC instead of needing a transit vehicle to be within DSRC range for DSRC-based communication.

<u>Security Credential Management System</u>

1. To maintain a safe, secure and privacy-protective manner of information sharing between V2V and V2I, U.S. Department of Transportation is working on a Proof of Concept (POC) security solution called Security Credential Management System (SCMS). The security feature of messages was not implemented or tested during this project's field test. Incorporation of the SCMS standards, protocol, and other requirements to sign and secure messages is recommended as a part of the future research
2. The project team envisions a tenfold increase in certificate volume and communication message traffic when mobile devices are incorporated into SCMS. A recommendation for future research is to investigate the impact of increased certificate volume and total communication message traffic on SCMS system performance when mobile devices are incorporated into SCMS.

APPENDIX A. Comprehensive Data Analysis Tables

Table A-1. Complete Data Analysis – Hypothesis 1

MDEA	Date	Time	Vehicle range and advisory distance w.r.t. speed (meters)	Speed (mph)	In Range	Out of Range	RSU Log PSM and BSM Rate
Doc	6/19/2017	14:26:26	IsBsmClose: Dist: 125.306402493779<? AdvDist: 126.539999999494	31.18	Yes		10/Sec
Doc	6/19/2017	14:26:45	IsBsmClose: Dist: 14.2212394331821<? AdvDist: 16.5599999999338	4.33	Yes		10/Sec
Doc	6/19/2017	14:27:49	IsBsmClose: Dist: 121.866993844552<? AdvDist: 126.719999999493	31.8	Yes		10/Sec
Doc	6/19/2017	14:28:06	IsBsmClose: Dist: 13.2365484265217<? AdvDist: 13.499999999946	3.35	Yes		10/Sec
Doc	6/19/2017	14:32:00	IsBsmClose: Dist: 102.750789580626<? AdvDist: 114.839999999541	28.94	Yes		10/Sec
Doc	6/19/2017	14:32:16	IsBsmClose: Dist: 10.7089899814409<? AdvDist: 13.1399999999474	3.26	Yes		10/Sec
Doc	6/19/2017	15:09:09	IsBsmClose: Dist: 111.047923144879<? AdvDist: 111.419999999554	27.69	Yes		10/Sec
Doc	6/19/2017	15:09:25	IsBsmClose: Dist: 16.2612899341913<? AdvDist: 17.999999999928	4.47	Yes		10/Sec
Doc	6/19/2017	15:14:55	IsBsmClose: Dist: 117.285999260844<? AdvDist: 120.419999999518	28.99	Yes		10/Sec
Doc	6/19/2017	15:15:07	IsBsmClose: Dist: 15.2569918797678<? AdvDist: 19.259999999923	5.36	Yes		10/Sec
Cinderella	6/19/2017	14:39:12	IsBsmClose: Dist: 118.588106766523<? AdvDist: 127.799999999489	31.76	Yes		10/Sec

MDEA	Date	Time	Vehicle range and advisory distance w.r.t. speed (meters)	Speed (mph)	In Range	Out of Range	RSU Log PSM and BSM Rate
Cinderella	6/19/2017	14:39:31	IsBsmClose: Dist: 12.1775355545961<? AdvDist: 13.6799999999453	3.4	Yes		10/Sec
Cinderella	6/19/2017	14:42:10	IsBsmClose: Dist: 118.895305420963<? AdvDist: 122.039999999512	30.24	Yes		10/Sec
Cinderella	6/19/2017	14:43:11	IsBsmClose: Dist: 12.4628773002208<? AdvDist: 13.3199999999467	3.31	Yes		10/Sec
Cinderella	6/19/2017	14:44:22	IsBsmClose: Dist: 116.184412617541<? AdvDist: 116.819999999533	30.19	Yes		10/Sec
Cinderella	6/19/2017	14:44:40	IsBsmClose: Dist: 6.47786596754427<? AdvDist: 10.4399999999582	2.59	Yes		10/Sec
Cinderella	6/19/2017	15:39:57	IsBsmClose: Dist: 112.841625583902<? AdvDist: 116.099999999536	28.09	Yes		10/Sec
Cinderella	6/19/2017	15:36:09	IsBsmClose: Dist: 10.7061648666181<? AdvDist: 11.8799999999525	2.92	Yes		10/Sec
Cinderella	6/19/2017	16:25:40	IsBsmClose: Dist: 112.586796468099<? AdvDist: 115.01999999954	28.58	Yes		10/Sec
Cinderella	6/19/2017	16:25:55	IsBsmClose: Dist: 10.6884865904201<? AdvDist: 10.9799999999561	2.72	Yes		10/Sec

Table A-2. Complete Data Analysis – Hypothesis 2 (Uncoordinated Mobility Scenario)

MDEA	Iteration	1	2	3	4	5	7	8	9	10	11	12
	Date	12-Jun	12-Jun	12-Jun	12-Jun	13-Jun	13-Jun	13-Jun	14-Jun	14-Jun	14-Jun	14-Jun
1	PSM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
2	PSM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
3	PSM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
4	PSM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
5	PSM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
6	PSM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
7	PSM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
8	PSM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
9	PSM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
10	PSM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
11	PSM	Yes	NO	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
12	PSM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes

Note: Golden color highlighted boxes indicates the leader MDEAs for respective iterations. In one of the uncoordinated scenarios, grouping size was not reduced to 1. As a result, a travel group was formed with MDEA 7 as their leader.

Table A-3. Complete Data Analysis – Hypothesis 2 (Coordinated Mobility Scenario)

MDEA	Iteration	1	2	3	4	5	7	8	9	10	11	12
	Date	12-Jun	12-Jun	12-Jun	12-Jun	13-Jun	13-Jun	13-Jun	14-Jun	14-Jun	14-Jun	14-Jun
1	PSM	NO	NO	Yes	NO	Yes	NO	NO	NO	NO	NO	NO
	PMM	NO	NO	NO	NO	Yes	NO	NO	NO	NO	NO	NO
2	PSM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	PMM	NO	NO	NO	NO	NO	Yes	NO	NO	NO	NO	NO
3	PSM	Yes	Yes	Yes	Yes	NO	NO	Yes	Yes	Yes	Yes	Yes
	PMM	Yes	Yes	Yes	Yes	Yes	NO	Yes	Yes	Yes	Yes	Yes
4	PSM	NO	NO	NO	NO	NO	NO	NO	Yes	Yes	NO	NO
	PMM	NO	NO	NO	NO	NO	NO	NO	Yes	Yes	NO	NO
5	PSM	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
	PMM	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
6	PSM	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
	PMM	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
7	PSM	NO	Yes	NO	NO	NO	NO	NO	NO	NO	NO	NO
	PMM	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
8	PSM	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
	PMM	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
9	PSM	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
	PMM	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
10	PSM	NO	NO	Yes	NO	NO	NO	NO	NO	NO	NO	NO
	PMM	Yes	Yes	NO	Yes	NO	NO	NO	NO	NO	NO	NO
11	PSM	NO	Yes	NO	NO	NO	NO	NO	NO	NO	NO	NO
	PMM	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
12	PSM	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
	PMM	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

Note: Golden color highlighted boxes indicates the leader MDEAs for respective iterations.

Table A-4. Complete Data Analysis – Hypothesis 3 (Uncoordinated Mobility Scenario)

MDEA	Iteration	1	2	3	4	5	7	8	9	10	11	12
	Date	12-Jun	12-Jun	12-Jun	12-Jun	13-Jun	13-Jun	13-Jun	14-Jun	14-Jun	14-Jun	14-Jun
MDEA 1	Ceased PSM broadcast after being In-Vehicle	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.
MDEA 2	Ceased PSM broadcast after being In-Vehicle	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.
MDEA 3	Ceased PSM broadcast after being In-Vehicle	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.
MDEA 4	Ceased PSM broadcast after being In-Vehicle	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.
MDEA 5	Ceased PSM broadcast after being In-Vehicle	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.
MDEA 6	Ceased PSM broadcast after being In-Vehicle	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.
MDEA 7	Ceased PSM broadcast after being In-Vehicle	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.

MDEA	Iteration	1	2	3	4	5	7	8	9	10	11	12
MDEA 8	Ceased PSM broadcast after being In-Vehicle	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.
MDEA 9	Ceased PSM broadcast after being In-Vehicle	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.
MDEA 10	Ceased PSM broadcast after being In-Vehicle	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.
MDEA 11	Ceased PSM broadcast after being In-Vehicle	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.	Ceased.

Table A-5. Complete Data Analysis – Hypothesis 3 (Coordinated Mobility Scenario)

MDEA	Iteration	1	2	3	4	5	7	8	9	10	11	12
	Date	12-Jun	12-Jun	12-Jun	12-Jun	13-Jun	13-Jun	13-Jun	14-Jun	14-Jun	14-Jun	14-Jun
MDEA 1	Ceased PSM broadcast after being In-Vehicle	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased
MDEA 2	Ceased PSM broadcast after being In-Vehicle	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased
MDEA 3	Ceased PSM broadcast after being In-Vehicle	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased
MDEA 4	Ceased PSM broadcast after being In-Vehicle	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased
MDEA 5	Ceased PSM broadcast after being In-Vehicle	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased
MDEA 6	Ceased PSM broadcast after being In-Vehicle	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased

MDEA	Iteration	1	2	3	4	5	7	8	9	10	11	12
MDEA 7	Ceased PSM broadcast after being In-Vehicle	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased
MDEA 8	Ceased PSM broadcast after being In-Vehicle	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased
MDEA 9	Ceased PSM broadcast after being In-Vehicle	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased
MDEA 10	Ceased PSM broadcast after being In-Vehicle	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased
MDEA 11	Ceased PSM broadcast after being In-Vehicle	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased	Ceased

Table A-6. Complete Data Analysis – Hypothesis 4

Iteration	1	2	3	4	5	6	7	8	9	10
Date	20-Jun	20-Jun	20-Jun	20-Jun	20-Jun	20-Jun	20-Jun	20-Jun	20-Jun	20-Jun
10 m	10:28:57	10:40:31	10:55:33	11:08:45	11:22:21	11:35:01	11:54:15	12:06:15	12:20:47	12:32:50
PSM rate at 10 m	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	6/sec
50 m	10:29:40	10:41:17	10:56:18	11:09:30	11:23:01	11:35:54	11:55:06	12:07:01	12:21:31	12:33:32
PSM rate at 50 m	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec
100 m	10:30:27	10:42:12	10:57:10	11:10:25	11:24:00	11:36:56	11:55:55	12:08:06	12:22:21	12:34:33
PSM rate at 100 m	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec
150 m	10:31:15	10:43:04	10:58:18	11:11:18	11:24:56	11:38:17	11:56:44	12:09:36	12:23:32	12:35:35
PSM rate at 150 m	10/sec	10/sec	10/sec	8/sec	10/sec	9/sec	10/sec	10/sec	10/sec	10/sec
200 m	10:32:07	10:44:00	10:59:08	11:12:14	11:25:45	11:39:22	11:57:34	12:10:30	12:24:22	12:36:35
PSM rate at 200 m	10/sec	10/sec	10/sec	9/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec
250 m	10:32:55	10:44:54	11:00:00	11:13:25	11:26:36	11:40:49	11:58:36	12:11:21	12:25:15	12:37:31
PSM rate at 250 m	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec
300 m	10:33:44	10:45:51	11:00:48	11:15:07	11:27:20	11:41:50	11:59:24	12:12:14	12:26:02	12:38:38
PSM rate at 300 m	10/sec	10/sec	0/sec	0/sec	10/sec	0/sec	10/sec	10/sec	10/sec	10/sec
300 m	10:34:50	10:47:45	11:02:30	11:15:55	11:28:10	11:46:09	12:00:19	12:13:00	12:27:00	12:39:31
PSM rate at 300 m	10/sec	10/sec	2/sec	0/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec
250 m	10:35:38	10:48:42	11:03:23	11:16:55	11:28:55	11:47:17	12:01:09	12:13:53	12:27:50	12:40:30
PSM rate at 250 m	10/sec	10/sec	10/sec	9/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec
200 m	10:36:27	10:49:44	11:04:22	11:17:50	11:29:50	11:48:19	12:02:00	12:14:49	12:28:39	12:41:24
PSM rate at 200 m	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	5/sec
150 m	10:37:18	10:50:39	11:05:12	11:18:44	11:30:46	11:49:50	12:02:54	12:16:00	12:29:37	12:42:24

Iteration	1	2	3	4	5	6	7	8	9	10
PSM rate at 150 m	10/sec	8/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	5/sec
100 m	10:38:08	10:51:35	11:06:03	11:19:42	11:31:40	11:50:55	12:03:45	12:16:56	12:30:22	12:43:20
PSM rate at 100 m	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	9/sec	10/sec	10/sec
50 m	10:38:58	10:52:27	11:06:54	11:20:36	11:32:30	11:51:54	12:04:45	12:17:49	12:31:10	12:44:15
PSM rate at 50 m	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	8/sec	10/sec	7/sec
10 m	10:39:40	10:53:12	11:07:36	11:21:21	11:33:14	11:52:40	12:05:26	12:18:35	12:31:51	12:45:00
PSM rate at 10 m	10/sec	10/sec	9/sec	10/sec	10/sec	10/sec	10/sec	8/sec	10/sec	8/sec
End Time	10:40:00	10:53:30	11:07:55	11:22:00	11:34:00	11:53:00	12:06:00	12:19:00	12:32:00	12:45:30

Table A-7. Complete Data Analysis – Hypothesis 5 (Uncoordinated Safety Scenario – VEA)

Iteration Number	1	2	3	4	5	6	7	8	9	10	11
Advisory Speed (mph)	32	31.78	29.27	30.9	27.53	29.02	29.34	29.71	30.17	28.07	28.63
Advisory (actual) (meters)	109.54	108.93	92.45	107.56	108.58	112.39	116.16	108.22	107.05	110.38	108.75
Advisory Difference (meters)	14.78	15.39	31.87	16.76	15.74	11.93	8.16	16.1	17.27	13.94	15.57
Advisory (calculated) (meters)	128.75	127.86	117.76	124.32	110.76	116.76	118.05	119.53	121.38	112.94	115.19
Alert Speed (mph)	33.58	30.74	31.34	33.35	27.66	26.8	28.52	28.89	28.97	25.87	27.06
Alert (actual) (meters)	85.34	72.85	75.97	84.2	64.22	62.64	67.53	66.59	67.42	29.19	61.25
Alert Difference (meters)	0.65	3.05	2.02	0.95	1.32	0.12	0.84	3.01	2.45	30.61	2.34
Alert (calculated) (meters)	85.99	75.9	77.99	85.15	65.54	62.76	68.37	69.6	69.87	59.8	63.59
Warning Speed (mph)	33.22	30.17	32.67	33.14	26.75	25.77	27.7	27.98	27.53	24.86	26.75
Warning (actual) (meters)	70.4	61.97	64.5	69.58	52.18	48.69	52.72	56.52	54.66	47.86	51.75
Warning Difference (meters)	0.27	0.4	4.64	0.87	1.33	2.36	3.2	0.12	0.83	0.94	1.76
Warning (calculated) (meters)	70.67	62.37	69.14	70.45	53.51	51.05	55.92	56.64	55.49	48.8	53.51
RSU Log PSM Rate	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec
RSU Log BSM Rate	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec

Note: Here the 'actual' values indicate the distance between MDEA and VEA, when the notification (Advisory, alert, or warning) was issued. Similarly, 'calculated' values indicate the expected distance between MDEA and VEA, which is calculated based on the speed of the VEA.

Table A-8. Complete Data Analysis – Hypothesis 5 (Coordinated Safety Scenario – VEA)

Iteration Number	1	2	3	4	5	6	7	8	9	10	11
Advisory Speed (mph)	29.35	31	26.82	30.11	29.1	29.33	30.01	29.87	29.05	27.74	28.58
Advisory (actual) (meters)	115.4	114.82	101.69	113.82	111.45	110.4	110.68	116.42	104.54	104.66	111
Advisory Difference (meters)	9.32	9.9	23.03	10.9	13.27	14.32	14.04	8.3	20.18	20.06	13.72
Advisory (calculated) (meters)	118.09	124.72	107.91	121.14	117.08	118.01	120.74	120.18	116.88	111.61	114.99
Alert Speed (mph)	27.74	34.3	24.02	28.48	27.19	28.38	28.53	28.84	28.67	26.31	28.94
Alert (actual) (meters)	64.49	87.56	51.84	66.9	63.45	66.73	68.4	66.85	65.62	60.91	67.3
Alert Difference (meters)	1.31	1.07	2.25	1.34	0.56	1.17	0	2.58	3.25	0.28	2.47
Alert (calculated) (meters)	65.8	88.63	54.09	68.24	64.01	67.9	68.4	69.43	68.87	61.19	69.77
Warning Speed (mph)	27.03	26.63	23.05	27.59	26.91	28.48	28.8	28.33	27.88	25.39	28.3
Warning (actual) (meters)	52.4	52.84	43.54	54.39	51.45	56.53	58.1	56.7	55.54	49.34	57.08
Warning Difference (meters)	1.82	0.36	0.89	1.25	2.46	1.4	0.67	0.85	0.85	0.77	0.39
Warning (calculated) (meters)	54.22	53.2	44.43	55.64	53.91	57.93	58.77	57.55	56.39	50.11	57.47
RSU Log PSM Rate	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec
RSU Log BSM Rate	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec

Note: Here the 'actual' values indicate the distance between MDEA and VEA, when the notification (Advisory, alert, or warning) was issued. Similarly, 'calculated' values indicate the expected distance between MDEA and VEA, which is calculated based on the speed of the VEA.

Table A-9. Complete Data Analysis – Hypothesis 6 (Uncoordinated Safety Scenario – MDEA)

Iteration Number	1	2	3	4	5	6	7	8	9	10	11
Advisory Speed (mph)	31.45	31.49	28.54	30.19	27.69	29.93	31.76	30.33	29.03	28.85	28.58
Advisory (actual) (meters)	125.30	121.86	98.94	119.22	111.04	117.28	118.58	118.89	116.18	112.84	112.58
Advisory Difference (meters)	1.23	4.84	15.89	2.25	0.37	3.14	9.20	3.14	0.62	3.23	2.41
Advisory (calculated) (meters)	126.53	126.70	114.83	121.47	111.41	120.42	127.78	122.03	116.80	116.07	114.99
Alert Speed (mph)	34.98	31.13	31.45	33.50	26.93	26.84	28.94	29.70	28.09	26.66	27.33
Alert (actual) (meters)	85.21	75.57	74.58	85.70	59.44	61.44	64.97	63.98	64.98	61.43	63.66
Alert Difference (meters)	5.95	1.68	3.79	0.00	3.73	1.44	4.80	8.35	1.97	0.88	0.80
Alert (calculated) (meters)	91.16	77.25	78.37	85.70	63.17	62.88	69.77	72.33	66.95	62.31	64.46
Warning Speed (mph)	32.88	30.01	32.03	32.61	27.06	25.85	27.06	27.20	27.38	26.39	25.32
Warning (actual) (meters)	67.46	59.29	66.01	68.16	52.17	47.54	53.98	52.84	53.44	47.68	49.52
Warning Difference (meters)	2.26	2.66	1.38	0.82	2.12	3.71	0.31	1.81	1.67	4.92	0.42
Warning (calculated) (meters)	69.72	61.95	67.39	68.98	54.29	51.25	54.29	54.65	55.11	52.60	49.94
RSU Log PSM Rate	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec
RSU Log BSM Rate	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec

Note: Here the 'actual' values indicate the distance between MDEA and VEA, when the notification (Advisory, alert, or warning) was issued. Similarly, 'calculated' values indicate the expected distance between MDEA and VEA, which is calculated based on the speed of the VEA.

Table A-10. Complete Data Analysis – Hypothesis 6 (Coordinated Safety Scenario – MDEA)

Iteration Number	1	2	3	4	5	6	7	8	9	10	11
Advisory Speed (mph)	29.75	30.37	27.02	30.06	29.75	29.39	30.95	32.61	28.18	27.91	30.46
Advisory (actual) (meters)	116.72	120.31	105.12	116.54	116.69	115.70	118.78	120.33	112.28	112.10	115.99
Advisory Difference (meters)	2.97	1.88	3.59	4.40	3.00	2.55	5.74	10.87	1.10	0.19	6.56
Advisory (calculated) (meters)	119.69	122.19	108.71	120.94	119.69	118.25	124.52	131.20	113.38	112.29	122.55
Alert Speed (mph)	27.69	37.08	23.03	28.81	27.73	28.85	29.66	29.16	28.76	28.18	29.16
Alert (actual) (meters)	63.26	93.44	50.84	65.63	63.43	69.22	70.88	65.55	61.78	64.38	65.99
Alert Difference (meters)	2.38	5.71	0.28	3.70	2.34	0.25	1.31	4.96	7.39	2.86	4.52
Alert (calculated) (meters)	65.64	99.15	51.12	69.33	65.77	69.47	72.19	70.51	69.17	67.24	70.51
Warning Speed (mph)	26.44	26.79	22.90	27.82	27.38	29.43	28.94	28.23	28.72	25.76	28.05
Warning (actual) (meters)	52.41	52.82	41.50	54.36	49.04	57.69	55.53	54.18	54.17	50.48	54.57
Warning Difference (meters)	0.32	0.79	2.58	1.87	6.07	2.73	3.60	3.11	4.39	0.55	2.25
Warning (calculated) (meters)	52.73	53.61	44.08	56.23	55.11	60.42	59.13	57.29	58.56	51.03	56.82
RSU Log PSM Rate	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec
		10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec	10/sec

Note: Here the 'actual' values indicate the distance between MDEA and VEA, when the notification (Advisory, alert, or warning) was issued. Similarly, 'calculated' values indicate the expected distance between MDEA and VEA, which is calculated based on the speed of the VEA.

Table A-11. Complete Data Analysis – Hypothesis 7 (Uncoordinated Safety Scenario)

Iteration	Date	Leader MDEA	Is Safe Icon True	Is Safe Icon False
1	19-Jun	Doc	Satisfied	Satisfied
2	19-Jun	Doc	Satisfied	Satisfied
3	19-Jun	Doc	Satisfied	Satisfied
4	19-Jun	Doc	Satisfied	Satisfied
5	19-Jun	Doc	Satisfied	Satisfied
6	19-Jun	Doc	Satisfied	Satisfied
7	19-Jun	Cinderella	Satisfied	Satisfied
8	19-Jun	Cinderella	Satisfied	Satisfied
9	19-Jun	Cinderella	Satisfied	Satisfied
10	19-Jun	Cinderella	Satisfied	Satisfied
11	19-Jun	Cinderella	Satisfied	Satisfied

Table A-12. Complete Data Analysis – Hypothesis 7 (Coordinated Safety Scenario)

Iteration	Date	Leader MDEA	Is Safe Icon True	Is Safe Icon False
1	19-Jun	Doc	Satisfied	Satisfied
2	19-Jun	Doc	Satisfied	Satisfied
3	19-Jun	Doc	Satisfied	Satisfied
4	19-Jun	Doc	Satisfied	Satisfied
5	19-Jun	Doc	Satisfied	Satisfied
6	19-Jun	Doc	Satisfied	Satisfied
7	19-Jun	Cinderella	Satisfied	Satisfied
8	19-Jun	Cinderella	Satisfied	Satisfied
9	19-Jun	Cinderella	Satisfied	Satisfied
10	19-Jun	Cinderella	Satisfied	Satisfied
11	19-Jun	Cinderella	Satisfied	Satisfied

Table A-13. Complete Data Analysis – Hypothesis 8 (Uncoordinated Mobility Scenario – Part A)

MDEA	Iteration	PMM Successful Processing Rate (Transit) – DSRC			PMM-RSP Successful Processing Rate (Transit) – DSRC				PMM-Cancel Successful Processing Rate (Transit) – DSRC	
		PMM Send – MDEA log	PMM Contents	PMM Receive – Transit Log	Transit VEA Log – Driver acceptance	PMM-RSP Send – Transit log	PMM-RSP Received – MDEA Log	MDEA Log – Coordination Status	PMM-Cancel Sent – MDEA Log	PMM-Cancel Received – Transit Log
MDEA1	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	8	No	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MDEA2	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	8	No	Fail	Fail	Fail	Fail	Fail	Fail	NA	NA
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA

MDEA	Iteration	PMM Successful Processing Rate (Transit) – DSRC			PMM-RSP Successful Processing Rate (Transit) – DSRC				PMM-Cancel Successful Processing Rate (Transit) – DSRC	
		PMM Send – MDEA log	PMM Contents	PMM Receive – Transit Log	Transit VEA Log – Driver acceptance	PMM-RSP Send – Transit log	PMM-RSP Received – MDEA Log	MDEA Log – Coordination Status	PMM-Cancel Sent – MDEA Log	PMM-Cancel Received – Transit Log
MDEA3	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	8	NO	Fail	Fail	Fail	Fail	Fail	Fail	NA	NA
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
MDEA4	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	8	NO	Fail	Fail	Fail	Fail	Fail	Fail	NA	NA
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA

MDEA	Iteration	PMM Successful Processing Rate (Transit) – DSRC			PMM-RSP Successful Processing Rate (Transit) – DSRC				PMM-Cancel Successful Processing Rate (Transit) – DSRC	
		PMM Send – MDEA log	PMM Contents	PMM Receive – Transit Log	Transit VEA Log – Driver acceptance	PMM-RSP Send – Transit log	PMM-RSP Received – MDEA Log	MDEA Log – Coordination Status	PMM-Cancel Sent – MDEA Log	PMM-Cancel Received – Transit Log
MDEA5	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	8	NO	Fail	Fail	Fail	Fail	Fail	Fail	NA	NA
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
MDEA6	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	2	NO	Fail	Fail	Fail	Fail	Fail	Fail	NA	NA
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	8	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA

MDEA	Iteration	PMM Successful Processing Rate (Transit) – DSRC			PMM-RSP Successful Processing Rate (Transit) – DSRC				PMM-Cancel Successful Processing Rate (Transit) – DSRC	
		PMM Send – MDEA log	PMM Contents	PMM Receive – Transit Log	Transit VEA Log – Driver acceptance	PMM-RSP Send – Transit log	PMM-RSP Received – MDEA Log	MDEA Log – Coordination Status	PMM-Cancel Sent – MDEA Log	PMM-Cancel Received – Transit Log
MDEA7	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	8	NO	Fail	Fail	Fail	Fail	Fail	Fail	NA	NA
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
MDEA8	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	8	NO	Fail	Fail	Fail	Fail	Fail	Fail	NA	NA
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA

MDEA	Iteration	PMM Successful Processing Rate (Transit) – DSRC			PMM-RSP Successful Processing Rate (Transit) – DSRC				PMM-Cancel Successful Processing Rate (Transit) – DSRC	
		PMM Send – MDEA log	PMM Contents	PMM Receive – Transit Log	Transit VEA Log – Driver acceptance	PMM-RSP Send – Transit log	PMM-RSP Received – MDEA Log	MDEA Log – Coordination Status	PMM-Cancel Sent – MDEA Log	PMM-Cancel Received – Transit Log
MDEA9	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	8	NO	Fail	Fail	Fail	Fail	Fail	Fail	NA	NA
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
MDEA10	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	8	NO	Fail	Fail	Fail	Fail	Fail	Fail	NA	NA
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA

MDEA	**Iteration**	**PMM Successful Processing Rate (Transit) – DSRC**			**PMM-RSP Successful Processing Rate (Transit) – DSRC**				**PMM-Cancel Successful Processing Rate (Transit) – DSRC**	
		PMM Send – MDEA log	**PMM Contents**	**PMM Receive – Transit Log**	**Transit VEA Log – Driver acceptance**	**PMM-RSP Send – Transit log**	**PMM-RSP Received – MDEA Log**	**MDEA Log – Coordination Status**	**PMM-Cancel Sent – MDEA Log**	**PMM-Cancel Received – Transit Log**
MDEA11	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	8	NO	Fail	Fail	Fail	Fail	Fail	Fail	NA	NA
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NA	NA

Note: Golden color highlighted boxes indicates the leader MDEAs for respective iterations.

Table A-14. Complete Data Analysis – Hypothesis 8 (Uncoordinated Mobility Scenario – Part B)

MDEA	Iteration	PMM Successful Processing Rate (Transit) – Cellular			PMM-RSP Successful Processing Rate (Transit) – Cellular				PMM-Cancel Successful Processing Rate (Transit) – Cellular	
		MDEA Log (1-12) – PMM Send Occurrence	MDEA Log (1-12) – PMM Contents	Transit VEA Log – PMM Receive Occurrence	Transit VEA Log – Driver Acceptance	Transit VEA Log – PMM-RSP Send Occurrence	MDEA Log (1-12) – PMM-RSP Receive Occurrence	MDEA Log (1-12) – Coordination Status	MDEA Log (1-12) – PMM-Cancel Sent Occurrence	Transit VEA Log – PMM-Cancel Received Occurrence
MDEA1	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	8	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table A-15. Complete Data Analysis – Hypothesis 8 (Coordinated Mobility Scenario – Part A)

MDEA	Iteration	PMM Successful Processing Rate (Transit) – DSRC			PMM-RSP Successful Processing Rate (Transit) – DSRC				PMM-Cancel Successful Processing Rate (Transit) – DSRC	
		PMM Send-MDEA log	PMM Contents	PMM receive - Transit Log	Transit VEA Log – Driver acceptance	PMM-RSP send-Transit log	PMM-RSP received-MDEA Log	MDEA Log – Coordination Status	PMM-Cancel Sent-MDEA Log	PMM-Cancel Received-Transit Log
MDEA1	1								Yes	Yes
	2								Yes	Yes
	3								Yes	Yes
	4								Yes	Yes
	5								Fail	Fail
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes		
	8								Yes	Yes
	9								Yes	Yes
	10								Yes	Yes
	11								Yes	Yes
	12								Yes	Yes
MDEA2	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes		
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes		
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes		
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes		
	5									
	7									
	8	Yes	Yes	Yes	Yes	Yes	Yes	Yes		
	9									
	10									
	11	**NO**	Fail	Fail	Fail	Fail	Fail	Fail		
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes		

MDEA	Iteration	PMM Successful Processing Rate (Transit) – DSRC			PMM-RSP Successful Processing Rate (Transit) – DSRC				PMM-Cancel Successful Processing Rate (Transit) – DSRC	
		PMM Send-MDEA log	PMM Contents	PMM receive - Transit Log	Transit VEA Log – Driver acceptance	PMM-RSP send-Transit log	PMM-RSP received-MDEA Log	MDEA Log – Coordination Status	PMM-Cancel Sent-MDEA Log	PMM-Cancel Received-Transit Log
MDEA3	1									
	2									
	3									
	4									
	5									
	7									
	8									
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes		
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes		
	11									
	12									
MDEA4	1									
	2									
	3									
	4									
	5	**NO**	Fail	Fail	Fail	Fail	Fail	Fail		
	7									
	8									
	9									
	10									
	11									
	12									

Note: Golden color highlighted boxes indicates the leader MDEAs for respective iterations.

Table A-16. Complete Data Analysis – Hypothesis 8 (Coordinated Mobility Scenario – Part B)

MDEA	Iteration	PMM Successful Processing Rate (Transit) – Cellular			PMM-RSP Successful Processing Rate (Transit) – Cellular				PMM-Cancel Successful Processing Rate (Transit) – Cellular	
		MDEA Log (1-12) – PMM Send Occurrence	MDEA Log (1-12) – PMM Contents	Transit VEA Log – PMM Receive Occurrence	Transit VEA Log – Driver Acceptance	Transit VEA Log – PMM-RSP Send Occurrence	MDEA Log (1-12) – PMM-RSP Receive occurrence	MDEA Log (1-12) – Coordination Status	MDEA Log (1-12) – PMM-Cancel Sent Occurrence	Transit VEA Log – PMM-Cancel Received Occurrence
MDEA1	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	8	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

MDEA	Iteration	PMM Successful Processing Rate (Transit) – Cellular			PMM-RSP Successful Processing Rate (Transit) – Cellular				PMM-Cancel Successful Processing Rate (Transit) – Cellular	
		MDEA Log (1-12) – PMM Send Occurrence	MDEA Log (1-12) – PMM Contents	Transit VEA Log – PMM Receive Occurrence	Transit VEA Log – Driver Acceptance	Transit VEA Log – PMM-RSP Send Occurrence	MDEA Log (1-12) – PMM-RSP Receive occurrence	MDEA Log (1-12) – Coordination Status	MDEA Log (1-12) – PMM-Cancel Sent Occurrence	Transit VEA Log – PMM-Cancel Received Occurrence
MDEA2	1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	8	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table A-17. Complete Data Analysis – Hypothesis 9 (Uncoordinated Mobility Scenario)

Iteration	Date	MDEA 1	MDEA 2	MDEA 3	MDEA 4	MDEA 5	MDEA 6	MDEA 7	MDEA 8	MDEA 9	MDEA 10	MDEA 11
		Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive
1	12-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2	12-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3	12-Jun	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
4	12-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5	13-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	**NO**	Yes
7	13-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
8	13-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
9	14-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes
10	14-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	**NO**
11	14-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
12	14-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table A-18. Complete Data Analysis – Hypothesis 9 (Coordinated Mobility Scenario)

Iteration	Date	MDEA 1	MDEA 2	MDEA 3	MDEA 4	MDEA 5	MDEA 6	MDEA 7	MDEA 8	MDEA 9	MDEA 10	MDEA 11
		Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive	Ride Arrive
1	12-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2	12-Jun	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes
3	12-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes
4	12-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5	13-Jun	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
7	13-Jun	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
8	13-Jun	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
9	14-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
10	14-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
11	14-Jun	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
12	14-Jun	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: Golden color highlighted boxes indicates the leader MDEAs for respective iterations.

Table A-19. Complete Data Analysis – Hypothesis 10 (Uncoordinated Mobility Scenario)

Iteration	Date	Bus	Start Time	In-Vehicle Transition		Out-of-vehicle Transition		End Time
				MDEA	Elapsed Time (sec)	MDEA	Elapsed Time (sec)	
1	12-Jun	1106	10:28:00	Donald	8.40	Pluto	6.07	10:46:00
2	12-Jun	1106	11:27:00	Dopey	7.50	Dopey	3.80	11:47:00
3	12-Jun	1106	13:31:00	Goofy	8.60	Mickey	7.80	13:50:45
4	12-Jun	1106	14:27:45	Donald	7.50	Donald	6.80	14:49:30
5	13-Jun	1108	10:18:30	Dopey	8.26	Cinderella	8.90	10:39:00
7	13-Jun	1108	13:49:00	Grumpy	8.90	Goofy	9.45	14:09:45
8	13-Jun	1108	14:47:00	Dopey	7.69	Vader	5.65	15:10:30
9	14-Jun	1108	10:17:30	Happy	10.07	Cinderella	2.34	10:37:00
10	14-Jun	1108	11:18:00	Cinderella	8.47	Goofy	*	11:39:45
11	14-Jun	1106	13:24:00	Sneezy	8.20	Vader	4.30	13:46:00
12	14-Jun	1106	14:30:00	Cinderella	7.00	Cinderella	3.30	14:47:30

*Note: *Asterisk indicates that the data could not be logged due to MDEA hardware issues or human errors.*

Table A-20. Complete Data Analysis – Hypothesis 10 (Coordinated Mobility Scenario)

Iteration	Date	Bus	Start Time	In-Vehicle Transition		Out-of-vehicle Transition		End Time
				MDEA	Elapsed Time (sec)	MDEA	Elapsed Time (sec)	
1	12-Jun	1106	10:05:00	Grumpy	9.20	Grumpy	6.50	10:23:00
2	12-Jun	1106	11:06:00	Doc	14.40	Happy	4.80	11:24:30
3	12-Jun	1106	13:06:00	Pluto	7.20	Goofy	6.60	13:27:00
4	12-Jun	1106	14:07:00	Pluto	8.01	Vader	6.30	14:26:00
5	13-Jun	1108	9:55:30	Pluto	9.87	Doc	*	10:15:00
7	13-Jun	1108	13:25:00	Cinderella	7.70	Happy	2.13	13:46:00
8	13-Jun	1108	14:25:30	Sneezy	7.59	Bashful	*	14:45:00
9	14-Jun	1108	9:56:00	Pluto	8.40	Doc	*	10:13:30
10	14-Jun	1108	10:55:00	see note	*	Donald	6.03	11:14:45
11	14-Jun	1106	13:04:00	Cinderella	7.90	Donald	6.50	13:22:30
12	14-Jun	1106	14:05:00	Grumpy	7.95	Grumpy	7.60	14:22:22

*Note: *Asterisk indicates that the data could not be logged due to MDEA hardware issues or human errors.*

Table A-21. Complete Data Analysis – Hypothesis 11 (Coordinated Mobility Scenario)

	MDEA	Coordination Request Sent	Coordination Request Received	Coordination Request Acceptance sent	Coordination Acceptance received	Coordination Heartbeat Sent	Coordination Heartbeat Received	Coordination Cancel Sent	Coordination Cancel Received	Coordination Disband Sent	Coordination Disband Received	Coordination Request Sent (trip details do not match	MDEA forms its own group
Iteration #1 (06/12/17) 10:16:00	MDEA1		Yes	Yes			Yes		Yes	Yes			
	MDEA2	Yes			Yes	Yes					Yes		
	MDEA3	Yes			Yes	Yes					Yes		
	MDEA4	Yes			Yes	Yes					Yes		
	MDEA5	Yes			Yes	Yes					Yes		
	MDEA6	Yes			Yes	Yes					Yes		
	MDEA7	Yes			Yes	Yes					Yes		
	MDEA8	Yes			Yes	Yes					Yes		
	MDEA9	Yes			Yes	Yes					Yes		
	MDEA10	Yes			Yes	Yes					Yes		
	MDEA11	Yes			Yes	Yes					Yes		
	MDEA12	Yes			Yes	Yes		Yes			Yes		
	MDEA13											Yes	Yes
Iteration #2 (06/12/17) 11:16:00	MDEA1		Yes	Yes			Yes		Yes	Yes			
	MDEA2	Yes			Yes	Yes					Yes		
	MDEA3	Yes			Yes	Yes					Yes		
	MDEA4	Yes			Yes	Yes					Yes		
	MDEA5	Yes			Yes	Yes					Yes		
	MDEA6	Fail			Fail	Fail					Fail		
	MDEA7	Yes			Yes	Yes					Yes		
	MDEA8	Yes			Yes	Yes					Yes		
	MDEA9	Yes			Yes	Yes					Yes		
	MDEA10	Yes			Yes	Yes					Yes		
	MDEA11	Yes			Yes	Yes					Yes		
	MDEA12	Yes			Yes	Yes		Yes			Yes		
	MDEA13											Yes	Yes

	MDEA	Coordination Request Sent	Coordination Request Received	Coordination Request Acceptance sent	Coordination Acceptance received	Coordination Heartbeat Sent	Coordination Heartbeat Received	Coordination Cancel Sent	Coordination Cancel Received	Coordination Disband Sent	Coordination Disband Received	Coordination Request Sent (trip details do not match	MDEA forms its own group
Iteration #3 (06/12/17) 13:16:00	MDEA1		Yes	Yes			Yes		Yes	Yes			
	MDEA2	Yes			Yes	Yes					Yes		
	MDEA3	Yes			Yes	Yes					Yes		
	MDEA4	Yes			Yes	Yes					Yes		
	MDEA5	Yes			Yes	Yes					Yes		
	MDEA6	Yes			Yes	Yes					Yes		
	MDEA7	Yes			Yes	Yes					Yes		
	MDEA8	Yes			Yes	Yes					Yes		
	MDEA9	Yes			Yes	Yes					Yes		
	MDEA10	Yes			Yes	Yes					Yes		
	MDEA11	Yes			Yes	Yes					Yes		
	MDEA12	Yes			Yes	Yes		Yes			Yes		
	MDEA13											Yes	Yes
Iteration #4 (06/12/17) 14:16:00	MDEA1		Yes	Yes			Yes		Yes	Yes			
	MDEA2	Yes			Yes	Yes					Yes		
	MDEA3	Yes			Yes	Yes					Yes		
	MDEA4	Yes			Yes	Yes					Yes		
	MDEA5	Yes			Yes	Yes					Yes		
	MDEA6	Yes			Yes	Yes					Yes		
	MDEA7	Yes			Yes	Yes					Yes		
	MDEA8	Yes			Yes	Yes					Yes		
	MDEA9	Yes			Yes	Yes					Yes		
	MDEA10	Yes			Yes	Yes					Yes		
	MDEA11	Yes			Yes	Yes					Yes		
	MDEA12	Yes			Yes	Yes		Yes			Yes		
	MDEA13											Yes	Yes

	MDEA	Coordination Request Sent	Coordination Request Received	Coordination Request Acceptance sent	Coordination Acceptance received	Coordination Heartbeat Sent	Coordination Heartbeat Received	Coordination Cancel Sent	Coordination Cancel Received	Coordination Disband Sent	Coordination Disband Received	Coordination Request Sent (trip details do not match	MDEA forms its own group
Iteration #5 (06/13/17) 10:16:00	MDEA1		Fail	Fail			Fail		Fail	Fail			
	MDEA2	Fail			Fail	Fail					Fail		
	MDEA3	Fail			Fail	Fail					Fail		
	MDEA4	Fail			Fail	Fail					Fail		
	MDEA5	Fail			Fail	Fail					Fail		
	MDEA6	Fail			Fail	Fail					Fail		
	MDEA7	Fail			Fail	Fail					Fail		
	MDEA8	Fail			Fail	Fail					Fail		
	MDEA9	Fail			Fail	Fail					Fail		
	MDEA10	Fail			Fail	Fail					Fail		
	MDEA11	Fail			Fail	Fail					Fail		
	MDEA12	Fail			Fail	Fail		Fail			Fail		
	MDEA13											Fail	Fail
Iteration #6 (06/13/17) 13:37:00	MDEA1		Yes	Yes			Yes		Yes	Yes			
	MDEA2	Yes			Yes	Yes					Yes		
	MDEA3	Yes			Yes	Yes					Yes		
	MDEA4	Yes			Yes	Yes					Yes		
	MDEA5	Yes			Yes	Yes					Yes		
	MDEA6	Yes			Yes	Yes					Yes		
	MDEA7	Yes			Yes	Yes					Yes		
	MDEA8	Yes			Yes	Yes					Yes		
	MDEA9	Yes			Yes	Yes					Yes		
	MDEA10	Yes			Yes	Yes					Yes		
	MDEA11	Yes			Yes	Yes					Yes		
	MDEA12	Yes			Yes	Yes					Yes		
	MDEA13											Yes	Yes

	MDEA	Coordination Request Sent	Coordination Request Received	Coordination Request Acceptance sent	Coordination Acceptance received	Coordination Heartbeat Sent	Coordination Heartbeat Received	Coordination Cancel Sent	Coordination Cancel Received	Coordination Disband Sent	Coordination Disband Received	Coordination Request Sent (trip details do not match	MDEA forms its own group
Iteration #7 (06/13/17) 14:25:00	MDEA1		Yes	Yes			Yes		Yes	Yes			
	MDEA2	Yes			Yes	Yes					Yes		
	MDEA3	Yes			Yes	Yes					Yes		
	MDEA4	Yes			Yes	Yes					Yes		
	MDEA5	Yes			Yes	Yes					Yes		
	MDEA6	Yes			Yes	Yes					Yes		
	MDEA7	Yes			Yes	Yes					Yes		
	MDEA8	Yes			Yes	Yes					Yes		
	MDEA9	Yes			Yes	Yes					Yes		
	MDEA10	Yes			Yes	Yes					Yes		
	MDEA11	Yes			Yes	Yes					Yes		
	MDEA12	Yes			Yes	Yes		Yes			Yes		
	MDEA13											Yes	Yes
Iteration #8 (06/14/17) 10:05:00	MDEA1		Yes	Yes			Yes		Yes	Yes			
	MDEA2	Yes			Yes	Yes					Yes		
	MDEA3	Yes			Yes	Yes					Yes		
	MDEA4	Yes			Yes	Yes					Yes		
	MDEA5	Yes			Yes	Yes					Yes		
	MDEA6	Yes			Yes	Yes					Yes		
	MDEA7	Yes			Yes	Yes					Yes		
	MDEA8	Yes			Yes	Yes					Yes		
	MDEA9	Yes			Yes	Yes					Yes		
	MDEA10	Yes			Yes	Yes					Yes		
	MDEA11	Yes			Yes	Yes					Yes		
	MDEA12	Yes			Yes	Yes		Yes			Yes		
	MDEA13											Yes	Yes

	MDEA	Coordination Request Sent	Coordination Request Received	Coordination Request Acceptance sent	Coordination Acceptance received	Coordination Heartbeat Sent	Coordination Heartbeat Received	Coordination Cancel Sent	Coordination Cancel Received	Coordination Disband Sent	Coordination Disband Received	Coordination Request Sent (trip details do not match	MDEA forms its own group
Iteration #9 (06/14/17) 11:06:00	MDEA1		Yes	Yes			Yes		Yes	Yes			
	MDEA2	Yes			Yes	Yes					Yes		
	MDEA3	Yes			Yes	Yes					Yes		
	MDEA4	Yes			Yes	Yes					Yes		
	MDEA5	Yes			Yes	Yes					Yes		
	MDEA6	Yes			Yes	Yes					Yes		
	MDEA7	Yes			Yes	Yes					Yes		
	MDEA8	Yes			Yes	Yes					Yes		
	MDEA9	Yes			Yes	Yes					Yes		
	MDEA10	Yes			Yes	Yes					Yes		
	MDEA11	Yes			Yes	Yes					Yes		
	MDEA12	Yes			Yes	Yes		Yes			Yes		
	MDEA13											Yes	Yes
Iteration #11 (06/14/17) 13:04:00)	MDEA1		Fail	Fail			Fail		Fail	Fail			
	MDEA2	Fail			Fail	Fail					Fail		
	MDEA3	Fail			Fail	Fail					Fail		
	MDEA4	Fail			Fail	Fail					Fail		
	MDEA5	Fail			Fail	Fail					Fail		
	MDEA6	Fail			Fail	Fail					Fail		
	MDEA7	Fail			Fail	Fail					Fail		
	MDEA8	Fail			Fail	Fail					Fail		
	MDEA9	Fail			Fail	Fail					Fail		
	MDEA10	Fail			Fail	Fail					Fail		
	MDEA11	Fail			Fail	Fail					Fail		
	MDEA12	Fail			Fail	Fail		Fail			Fail		
	MDEA13											Fail	Fail

	MDEA	Coordination Request Sent	Coordination Request Received	Coordination Request Acceptance sent	Coordination Acceptance received	Coordination Heartbeat Sent	Coordination Heartbeat Received	Coordination Cancel Sent	Coordination Cancel Received	Coordination Disband Sent	Coordination Disband Received	Coordination Request Sent (trip details do not match	MDEA forms its own group
Iteration #11 (06/14/17) 14:05:00	MDEA1		Yes	Yes			Yes		Yes	Yes			
	MDEA2	Yes			Yes	Yes					Yes		
	MDEA3	Yes			Yes	Yes					Yes		
	MDEA4	Yes			Yes	Yes					Yes		
	MDEA5	Yes			Yes	Yes					Yes		
	MDEA6	Yes			Yes	Yes					Yes		
	MDEA7	Yes			Yes	Yes					Yes		
	MDEA8	Yes			Yes	Yes					Yes		
	MDEA9	Yes			Yes	Yes					Yes		
	MDEA10	Yes			Yes	Yes					Yes		
	MDEA11	Yes			Yes	Yes					Yes		
	MDEA12	Yes			Yes	Yes		Yes			Yes		
	MDEA13											Yes	Yes

Table A-22. Complete Data Analysis – Hypothesis 12

Iteration	1	2	3	4	5	6	7	8	9	10
Date	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**
Leader MDEA	**MDEA 1**	**MDEA 2**	**MDEA 1**	**MDEA 2**	**MDEA 1**	**MDEA 2**	**MDEA 1**	**MDEA 2**	**MDEA 1**	**MDEA 2**
Start Time	10:28:45	10:40:29	10:55:20	11:08:30	11:22:01	11:34:01	11:53:01	12:06:01	12:20:00	12:32:31
10 m	10:28:57	10:40:31	10:55:33	11:08:45	11:22:21	11:35:01	11:54:15	12:06:15	12:20:47	12:32:50
Spat and Map Broadcast rate at 10 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
50 m	10:29:40	10:41:17	10:56:18	11:09:30	11:23:01	11:35:54	11:55:06	12:07:01	12:21:31	12:33:32
Spat and Map Broadcast rate at 50 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
100 m	10:30:27	10:42:12	10:57:10	11:10:25	11:24:00	11:36:56	11:55:55	12:08:06	12:22:21	12:34:33
Spat and Map Broadcast rate at 100 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
150 m	10:31:15	10:43:04	10:58:18	11:11:18	11:24:56	11:38:17	11:56:44	12:09:36	12:23:32	12:35:35
Spat and Map Broadcast rate at 150 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
200 m	10:32:07	10:44:00	10:59:08	11:12:14	11:25:45	11:39:22	11:57:34	12:10:30	12:24:22	12:36:35
Spat and Map Broadcast rate at 200 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
250 m	10:32:55	10:44:54	11:00:00	11:13:25	11:26:36	11:40:49	11:58:36	12:11:21	12:25:15	12:37:31
Spat and Map Broadcast rate at 250 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
300 m	10:33:44	10:45:51	11:00:48	11:15:07	11:27:20	11:41:50	11:59:24	12:12:14	12:26:02	12:38:38
Spat and Map Broadcast rate at 300 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec

Iteration	1	2	3	4	5	6	7	8	9	10
Date	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**	**20-Jun**
Leader MDEA	**MDEA 1**	**MDEA 2**	**MDEA 1**	**MDEA 2**	**MDEA 1**	**MDEA 2**	**MDEA 1**	**MDEA 2**	**MDEA 1**	**MDEA 2**
300 m	10:34:50	10:47:45	11:02:30	11:15:55	11:28:10	11:46:09	12:00:19	12:13:00	12:27:00	12:39:31
Spat and Map Broadcast rate at 300 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
250 m	10:35:38	10:48:42	11:03:23	11:16:55	11:28:55	11:47:17	12:01:09	12:13:53	12:27:50	12:40:30
Spat and Map Broadcast rate at 250 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
200 m	10:36:27	10:49:44	11:04:22	11:17:50	11:29:50	11:48:19	12:02:00	12:14:49	12:28:39	12:41:24
Spat and Map Broadcast rate at 200 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
150 m	10:37:18	10:50:39	11:05:12	11:18:44	11:30:46	11:49:50	12:02:54	12:16:00	12:29:37	12:42:24
Spat and Map Broadcast rate at 150 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
100 m	10:38:08	10:51:35	11:06:03	11:19:42	11:31:40	11:50:55	12:03:45	12:16:56	12:30:22	12:43:20
Spat and Map Broadcast rate at 100 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
50 m	10:38:58	10:52:27	11:06:54	11:20:36	11:32:30	11:51:54	12:04:45	12:17:49	12:31:10	12:44:15
Spat and Map Broadcast rate at 50 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
10 m	10:39:40	10:53:12	11:07:36	11:21:21	11:33:14	11:52:40	12:05:26	12:18:35	12:31:51	12:45:00
Spat and Map Broadcast rate at 10 m	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec	1/sec
End Time	10:40:00	10:53:30	11:07:55	11:22:00	11:34:00	11:53:00	12:06:00	12:19:00	12:32:00	12:45:30

Table A-23. Complete Data Analysis – Hypothesis 14 (Coordinated Safety Scenario)

Iteration	1	2	3	4	5	6	7	8	9	10	11
Date	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun	19-Jun
Leader MDEA	MDEA 1	MDEA 1	MDEA 1	MDEA 1	MDEA 1	MDEA 1	MDEA 2	MDEA 2	MDEA 2	MDEA 2	MDEA 2
Start Time	11:06:40	11:12:28	11:16:45	11:20:30	11:24:50	11:28:30	11:33:50	11:37:40	12:19:40	12:23:30	12:27:20
End Time	11:09:30	11:15:10	11:19:10	11:23:05	11:27:15	11:31:00	11:36:25	11:40:15	12:22:10	12:26:00	12:30:10
BSM sent by VEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM Received on MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM reception by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSMs received by VEA and OBU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM Contents	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PSM sent by MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PSM received by VEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PSM reception by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PSM Contents	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SPaT and Map Transmission by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SPaT and Map Reception by MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table A-24. Complete Data Analysis – Hypothesis 14 (Uncoordinated Mobility Scenario)

Iteration	1	2	3	4	5	7	8	9	10	11	12
Date	12-Jun	12-Jun	12-Jun	12-Jun	13-Jun	13-Jun	13-Jun	14-Jun	14-Jun	14-Jun	14-Jun
Bus	1106	1106	1106	1106	1108	1108	1108	1108	1108	1106	1106
Start Time	10:28:00	11:27:00	13:31:00	14:27:45	10:18:30	13:49:00	14:47:00	10:17:30	11:18:00	13:24:00	14:30:00
End Time	10:46:00	11:47:00	13:50:45	14:49:30	10:39:00	14:09:45	15:10:30	10:37:00	11:39:45	13:46:00	14:47:30
BSM sent by VEA and OBUs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM Received on MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM reception by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSMs received by VEA and OBU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM Contents	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PMM sent by MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PMM received by VEA and OBUs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PMM-RSP sent by VEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PMM-RSP received by MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PMM reception by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PMM Contents	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SPaT and Map Transmission by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SPaT and Map Reception by MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table A-25. Complete Data Analysis – Hypothesis 14 (Coordinated Mobility Scenario)

Iteration	1	2	3	4	5	7	8	9	10	11	12
Date	12-Jun	12-Jun	12-Jun	12-Jun	13-Jun	13-Jun	13-Jun	14-Jun	14-Jun	14-Jun	14-Jun
Bus	1106	1106	1106	1106	1108	1108	1108	1108	1108	1106	1106
Start Time	10:05:00	11:06:00	13:06:00	14:07:00	9:55:30	13:25:00	14:25:30	9:56:00	10:55:00	13:04:00	14:05:00
End Time	10:23:00	11:24:30	13:27:00	14:26:00	10:15:00	13:46:00	14:45:00	10:13:30	11:14:45	13:22:30	14:22:22
BSM sent by VEA and OBUs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM Received on MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM reception by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSMs received by VEA and OBU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM Contents	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PMM sent by MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PMM received by VEA and OBUs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PMM-RSP sent by VEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PMM-RSP received by MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PMM reception by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PMM Contents	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SPaT and Map Transmission by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SPaT and Map Reception by MDEA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table A-26. Complete Data Analysis – Hypothesis 14 (Mobility Scenarios)

Iteration	***Uncoordinated Mobility*** Time Difference between PMM -Arrive Sent on VEA and Received by MDEA (sec)	***Coordinated Mobility*** Time Difference between PMM -Arrive Sent on VEA and Received by MDEA (sec)
1	3.573	3.456
2	4.696	2.278
3	1.104	1.026
4	1.064	1.414
5	-0.333	-0.455
Average	2.0208	1.5438

Table A-27. Complete Data Analysis – Hypothesis 14 (Safety Scenarios)

Iteration	***Uncoordinated Safety*** Time Difference between PSM Logged on RSU and VEA (sec)	***Coordinated Safety*** Time Difference between PSM Logged on RSU and VEA (sec)
1	-0.485	-0.774
2	-0.488	-0.574
3	-0.470	-0.534
4	-0.485	-0.564
5	-0.487	-0.728
6	-0.389	-0.588
7	-0.45	-0.748
8	-0.468	-0.576
Average	-0.465	-0.636

Table A-28. Complete Data Analysis – Hypothesis 15 (Baseline Scenario)

Iteration	1	2	3	4	5	6	7
Date	12-Jun	12-Jun	13-Jun	13-Jun	14-Jun	14-Jun	19-Jun
Location	Buckeye Lot	12th/Cannon	Buckeye Lot	12th/Cannon	Buckeye Lot	12th/Cannon	Battelle
Bus	1106	1106	1106	1106	1106	1106	Minivan
Start Time	14:55:00	15:16:50	15:31:30	15:17:00	14:59:55	15:15:45	12:05:30
Bus Arrive	14:57:00	15:18:50	15:33:30	15:19:00	15:01:55	15:17:45	12:07:50
Bus Depart	14:57:40	15:19:00	15:34:20	15:19:35	15:02:44	15:18:15	12:07:50
End Time	14:59:40	15:21:00	15:36:20	15:21:35	15:04:44	15:20:15	12:09:50
BSM sent by VEA and OBUs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM reception by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSM Contents	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SPaT and Map Transmission by RSU	Yes	Yes	Yes	Yes	Yes	Yes	Yes
BSMs received by VEA and OBU	Yes	Yes	Yes	Yes	Yes	Yes	Yes

APPENDIX B. Field Test Scenarios

The following six scenarios were designed to extract the data required for hypotheses described in the experimental plan.

Scenario 0: Baseline (no mobile devices)

This is the baseline scenario to be run at each bus stop (Buckeye Lot Loop, 12th Avenue/Cannon Drive, and the Battelle parking lot simulated bus stop). Its purpose is to record baseline DSRC message traffic from the RSU and OBUs without mobile devices in the CV environment.

Setup / checkout:

1. Check that the RSU near the subject bus stop is operating properly, including broadcasting of simulated SPaT and MAP
2. Park vehicles with BSM-generating OBUs within the vicinity of the subject bus stop and check that the OBUs are operating properly
   a. Four (4) OBUs in two (2) vehicles for OSU bus stops
   b. Three (3) OBUs in one (1) vehicle for Battelle parking lot
3. Check that subject transit vehicle with OBU (VEA) is operating properly
   a. Transit vehicle with OBU (VEA) for OSU bus stops
   b. Simulated transit vehicle (minivan) with OBU (VEA) for Battelle parking lot
4. Test starts approximately two (2) minutes prior to transit vehicle arrival

Execution:

1. Test engineer logs start time ____________________
2. Transit vehicle arrives at the bus stop
3. Transit vehicle departs the bus stop
4. Test continues for approximately two (2) minutes after transit vehicle departs
5. Test engineer logs end time ____________________

Test Engineering Notes:

1. CV Inspector can be used to observe that BSMs, SPaT, and MAP are being broadcast by the appropriate devices
2. BSMs are received by the RSU and recorded in data log files
3. BSMs, SPaT, and MAP are received by the VEA and recorded in data log files
4. Archive log files at the end of each test day

Scenario 1: PMM Ride Request, Uncoordinated

This is a park and ride mobility scenario to travel to/from work, with travelers using MDEA for uncoordinated trip requests. This scenario is conducted at the Buckeye Lot Loop bus stop and the 12th Avenue/Cannon Drive bus stop.

Setup / checkout:

1. Configure cloud for maximum travel group size of one (1)
2. Check that the RSU near the subject bus stop is operating properly, including broadcasting of simulated SPaT and MAP
3. Park vehicles with BSM-generating OBUs within the vicinity of the subject bus stop and check that the OBUs are operating properly
    a. Four (4) OBUs in two (2) vehicles for OSU bus stops
4. Check that subject transit vehicle with OBU (VEA) is operating properly
    a. Transit vehicle with OBU (VEA) for OSU bus stops
    b. Ride Request plugin only enabled on bus being used
5. Check that all smartphones (MDEA) and Arada radios are operating properly, including broadcasting of PSMs and reception of BSMs
6. Travelers (1-12) stand at subject bus stop (safe zone) holding smartphones and wearing holsters with Arada ME radios
7. Test starts with transit vehicle far enough outside of DSRC range (as determined by test engineer) to allow for one traveler to request a trip over cellular and cancel the trip prior to transit vehicle entering DSRC range of the bus stop

Execution:

1. Test engineer logs start time ______________________
2. Traveler 1 uses MDEA to request trip (while transit vehicle outside DSRC range)
    a. Traveler 1 becomes travel group leader as indicated on MDEA display by solid green travel group (head) icon at bottom
    b. Trip request acceptance is indicated on MDEA and VEA displays
3. Traveler 1 uses MDEA to cancel trip (while transit vehicle outside DSRC range)
    a. Trip cancellation is indicated on MDEA display
    b. VEA displays no travelers to pickup
4. Test engineer determines that transit vehicle is within DSRC range
5. Travelers (1-12) immediately use MDEAs to request trips at the same time
    a. All travelers becomes travel group leaders as indicated on MDEA displays by solid green travel group (head) icon at bottom
    b. Trip request acceptance is indicated on MDEA and VEA displays
    c. VEA displays 12 travelers to pickup

6. One (1) of the 12 travelers uses MDEA to cancel trip
   a. Trip cancellation is indicated on MDEA display
   b. VEA displays eleven (11) travelers to pickup
7. Transit vehicle arrives at origin bus stop and VEA sends PMM-Arrive message
   a. Ride Arrived is indicated on MDEA displays of eleven (11) travelers
8. Test engineer with a stopwatch enters the transit vehicle before travelers
9. All twelve (12) travelers enter the transit vehicle
   a. One (1) traveler doesn't have a trip request, since it was cancelled
10. Transit vehicle departs the bus stop
11. Test engineer starts stopwatch as soon as transit vehicle starts to move
12. Test engineer observes one (1) MDEA display for transition to in-vehicle status
    a. When in-vehicle icon at top right of MDEA display turns green, test engineer stops stopwatch
13. Test engineer records elapsed time as well as subject MDEA name
    a. Elapsed time ____________________
    b. MDEA name ____________________
14. Trips will clear on eleven (11) MDEAs as they transition to in-vehicle
    a. In-vehicle icon at top right of MDEA display turns green
    b. Trip details clear from MDEA display
    c. Travel group (head) icon at bottom turns grey
15. Transit vehicle arrives at destination bus stop
16. Test engineer with stopwatch exits transit vehicle before travelers
17. All twelve (12) travelers exit the transit vehicle
18. Test engineer starts stopwatch as soon as one (1) selected traveler exits the transit vehicle and observes MDEA display for transition to not-in-vehicle
    a. Selected traveler immediately walks away from bus stop
    b. When in-vehicle icon at top right of MDEA display turns red, test engineer stops stopwatch
19. Test engineer records elapsed time as well as subject MDEA name
    a. Elapsed time ____________________
    b. MDEA name ____________________
20. Test engineer logs end time ______________________

Test Engineering Notes:

1. CV Inspector can be used to observe that PSMs, PMMs, BSMs, SPaT, and MAP are being broadcast by the appropriate devices
   a. MDEA broadcasts PSMs only when transit vehicle is close enough and fast enough (e.g. 25 mph at 100 meters)
2. PSMs, PMMs, and BSMs are received by the RSU and recorded in data log files
3. PSMs, PMMs, BSMs, SPaT, and MAP are received by the VEA and recorded in data log files
4. PMMs, BSMs, SPaT, and MAP are received by the MDEA and recorded in data log files
5. Archive log files at the end of each test day

Scenario 2: PSM Safety, Uncoordinated

This is a safety scenario, with travelers using MDEA for safety without travel group coordination. This scenario is conducted in the Battelle parking lot to allow maximum control of the experiment to ensure safety of test personnel.

Setup / checkout:

1. Check that the RSU near the subject bus stop is operating properly, including broadcasting of simulated SPaT and MAP
2. Park vehicle with BSM-generating OBUs within the vicinity of the subject bus stop and check that the OBUs are operating properly
   a. Three (3) OBUs in one (1) vehicle for Battelle parking lot
3. Check that subject transit vehicle with OBU (VEA) is operating properly
   a. Simulated transit vehicle (minivan) with OBU (VEA) for Battelle parking lot
4. Check that all smartphones (MDEA) and Arada radios are operating properly, including broadcasting of PSMs and reception of BSMs
5. A test engineer plays the role of traveler 1 standing at the simulated bus stop holding a smartphone and wearing a holster with an Arada radio
6. Eleven (11) smartphones and Arada radios operated by test engineers are placed on tables 15 meters perpendicular from edge of the simulated roadway
7. Place safety cones at 0, 50, 58, and 100 meters from the bus stop in the simulated roadway
8. Test starts when test team is ready

Execution:

1. Test engineer logs start time ____________________
2. Traveler 1 stands five (5) meters perpendicular from the edge of the simulated roadway (safe zone) near the simulated bus stop
   a. MDEA display indicates traveler in safe zone with grey safe zone icon
3. Traveler 1 walks into the middle of the simulated roadway (2 meters inside edge)
   a. MDEA display indicates traveler in unsafe zone with red safe zone icon
4. Traveler 1 returns to bus stop until MDEA indicates safe, then goes to the edge of the simulated roadway for subsequent safety notification steps
   a. MDEA display may show safe or unsafe status due to being near boundary of safe zone and due to GPS variability
5. Travelers (2-12) are 15 meters perpendicular from the edge of the simulated roadway (smartphones and Arada radios on tables)
   a. MDEAs (2-12) will generates PSMs when the simulated transit vehicle moves fast enough, but should not cause alerts on either the MDEAs or VEA since they are not in the path of the vehicle

6. Simulated transit vehicle starts moving in simulated lane towards traveler 1 and accelerates reaching a constant speed of 25 mph at a distance of 100 meters
   a. Traveler 1 MDEA and vehicle VEA each display an advisory notification when the vehicle is within 100 meters of traveler
   b. Traveler 1 MDEA and vehicle VEA each display an alert notification when the vehicle is within 58 meters of traveler
   c. Traveler 1 MDEA and vehicle VEA each display a warning notification when the vehicle is within 50 meters of traveler
7. Simulated transit vehicle decelerates to zero mph after passing traveler 1
   a. MDEA and VEA notifications cease
8. Test engineer logs end time ___________________

Test Engineering Notes:

1. CV Inspector can be used to observe that PSMs, BSMs, SPaT, and MAP are being broadcast by the appropriate devices
   a. MDEA broadcasts PSMs only when transit vehicle is close enough and fast enough (e.g. 25 mph at 100 meters)
2. PSMs and BSMs are received by the RSU and recorded in data log files
3. PSMs, BSMs, SPaT, and MAP are received by the VEA and recorded in data log files
4. BSMs, SPaT, and MAP are received by the MDEA and recorded in data log files

Archive log files at the end of each test day

Scenario 3: PMM Ride Request, Coordinated

This is a park and ride mobility scenario to travel to/from work, with travelers using MDEA for coordinated trip requests. This scenario is conducted at the Buckeye Lot Loop bus stop and the 12th Avenue/Cannon Drive bus stop.

Setup / checkout:

1. Configure cloud for maximum travel group size of twenty (20)
2. Check that the RSU near the subject bus stop is operating properly, including broadcasting of simulated SPaT and MAP
3. Park vehicles with BSM-generating OBUs within the vicinity of the subject bus stop and check that the OBUs are operating properly
    a. Four (4) OBUs in two (2) vehicles for OSU bus stops
4. Check that subject transit vehicle with OBU (VEA) is operating properly
    a. Transit vehicle with OBU (VEA) for OSU bus stops
    b. Ride Request plugin only enabled on bus being used
5. Check that all smartphones (MDEA) and Arada radios are operating properly, including broadcasting of PSMs and reception of BSMs
6. Travelers (1-12) stand at subject bus stop (safe zone) holding smartphones and wearing holsters with Arada ME radios
7. Traveler thirteen (13) stands at the other bus stop holding smartphone and wearing holsters with Arada ME radio
8. Test starts with transit vehicle far enough outside of DSRC range (as determined by test engineer) to allow for two travelers to sequentially request trips over cellular and cancel trips prior to transit vehicle entering DSRC range

Execution:

1. Test engineer logs start time ______________________
2. Traveler 13 uses MDEA to request trip when instructed by test engineer (while transit vehicle outside DSRC range)
    a. Traveler 13 becomes travel group leader as indicated on MDEA display by solid green travel group (head) icon at bottom
    b. Trip request acceptance is indicated on MDEA and VEA displays
3. Traveler 1 uses MDEA to request trip when instructed by test engineer (while transit vehicle outside DSRC range)
    a. Traveler 1 becomes travel group leader as indicated on MDEA display by solid green travel group (head) icon at bottom
    b. Trip request acceptance is indicated on MDEA
4. Traveler 1 uses MDEA to cancel trip when instructed by test engineer

   a. Trip cancellation is indicated on MDEA display
   b. VEA display shows next traveler pickup
5. Traveler 13 uses MDEA to cancel trip when instructed by test engineer
   a. Trip cancellation is indicated on MDEA display
   b. VEA displays no travelers to pickup
6. Test engineer determines that transit vehicle is within DSRC range
7. Travelers (1-12) immediately use MDEAs to request trips at the same time
   a. One traveler becomes travel group leader as indicated on MDEA display by solid green travel group (head) icon at bottom
   b. Other travelers become travel group followers as indicated on MDEA display by green outline travel group (head) icon at bottom
   c. Trip request acceptance is indicated on MDEA and VEA displays
   d. VEA displays 12 travelers to pickup
8. One (1) of the 12 travelers (other than leader) uses MDEA to cancel trip
   a. Trip cancellation is indicated on MDEA display
   b. VEA displays eleven (11) travelers to pickup
9. Transit vehicle arrives at origin bus stop and VEA sends PMM-Arrive message
   a. Ride Arrived is indicated on MDEA displays of eleven (11) travelers
10. Test engineer with a stopwatch enters the transit vehicle before travelers
11. All twelve (12) travelers enter the transit vehicle
    a. One (1) traveler doesn't have a trip request, since it was cancelled
12. Transit vehicle departs the bus stop
13. Test engineer starts stopwatch as soon as transit vehicle starts to move
14. Test engineer observes one (1) MDEA display for transition to in-vehicle status
    a. When in-vehicle icon at top right of MDEA display turns green, test engineer stops stopwatch
15. Test engineer records elapsed time as well as subject MDEA name
    a. Elapsed time ____________________
    b. MDEA name ____________________
16. Trips will clear on eleven (11) MDEAs as they transition to in-vehicle
    a. In-vehicle icon at top right of MDEA display turns green
    b. Trip details clear from MDEA display
    c. Travel group (head) icon at bottom turns grey
17. Transit vehicle arrives at destination bus stop
18. Test engineer with stopwatch exits transit vehicle before travelers

19. All twelve (12) travelers exit the transit vehicle
20. Test engineer starts stopwatch as soon as one (1) selected traveler exits the transit vehicle and observes MDEA display for transition to not-in-vehicle
    a. Selected traveler immediately walks away from bus stop
    b. When in-vehicle icon at top right of MDEA display turns red, test engineer stops stopwatch
21. Test engineer records elapsed time as well as subject MDEA name
    a. Elapsed time ____________________
    b. MDEA name ____________________
22. Test engineer logs end time ____________________

Test Engineering Notes:

1. CV Inspector can be used to observe that PSMs, PMMs, BSMs, SPaT, and MAP are being broadcast by the appropriate devices
    a. MDEA broadcasts PSMs when transit vehicle is close enough and fast enough (e.g. 25 mph at 100 meters)
    b. MDEA travel group followers in safe zone do not broadcast PSMs
    c. MDEA travel group followers do not broadcast or receive PMMs (followers coordinate trip requests with travel group leader via cellular/cloud)
2. PSMs, PMMs, and BSMs are received by the RSU and recorded in data log files
3. PSMs, PMMs, BSMs, SPaT, and MAP are received by the VEA and recorded in data log files
4. PMMs, BSMs, SPaT, and MAP are received by the MDEA and recorded in data log files
5. Archive log files at the end of each test day

Scenario 4: PSM Safety, Coordinated

This is a safety scenario, with travelers using MDEA for safety with travel group coordination. This scenario is conducted in the Battelle parking lot to allow maximum control of the experiment to ensure safety of test personnel.

Setup / checkout:

1. Configure cloud for maximum travel group size of twenty (20)
2. Check that the RSU near the subject bus stop is operating properly, including broadcasting of simulated SPaT and MAP
3. Park vehicle with BSM-generating OBUs within the vicinity of the subject bus stop and check that the OBUs are operating properly
    a. Three (3) OBUs in one (1) vehicle for Battelle parking lot
4. Check that subject transit vehicle with OBU (VEA) is operating properly
    a. Simulated transit vehicle (minivan) with OBU (VEA) for Battelle parking lot
5. Check that all smartphones (MDEA) and Arada radios are operating properly, including broadcasting of PSMs and reception of BSMs
6. A test engineer plays the role of traveler 1 standing at the simulated bus stop holding a smartphone and wearing a holster with an Arada radio
7. Eleven (11) smartphones and Arada radios operated by test engineers are placed on tables 15 meters perpendicular from edge of the simulated roadway
8. Place safety cones at 0, 50, 58, and 100 meters from the bus stop in the simulated roadway
9. Test starts when test team is ready

Execution:

1. Test engineer logs start time ___________________
2. Traveler 1 uses MDEA to request trip (while transit vehicle is within DSRC range)
    a. Traveler 1 becomes travel group leader as indicated on MDEA display by solid green travel group (head) icon at bottom
    b. Trip request acceptance is indicated on MDEA and VEA displays
3. Other travelers (2-12) use MDEAs to request trips at the same time
    a. Travelers (2-12) become travel group followers as indicated on MDEA display by green outline travel group (head) icon at bottom
    b. Trip request acceptance is indicated on MDEA and VEA displays
    c. VEA displays 12 travelers to pickup
4. Traveler 1 goes to the edge of the simulated roadway
    a. MDEA display may show safe or unsafe status due to being near boundary of safe zone and due to GPS variability

5. Travelers (2-12) are 15 meters perpendicular from the edge of the simulated roadway (smartphones and Arada radios on tables)
    a. MDEAs (2-12) will not generate PSMs when the simulated transit vehicle moves fast enough since they are travel group followers in a safe zone
    b. MDEAs (2-12) will not cause alerts on the VEA since they are not in the path of the vehicle AND since they are not generating PSMs
    c. MDEAs (2-12) will not cause alerts on the MDEAs since they are not in the path of the vehicle (independent of PSM status)
6. Simulated transit vehicle starts moving in simulated lane towards traveler 1 and accelerates reaching a constant speed of 25 mph at a distance of 100 meters
    a. Traveler 1 MDEA and vehicle VEA each display an advisory notification when the vehicle is within 100 meters of traveler
    b. Traveler 1 MDEA and vehicle VEA each display an alert notification when the vehicle is within 58 meters of traveler
    c. Traveler 1 MDEA and vehicle VEA each display a warning notification when the vehicle is within 50 meters of traveler
7. Simulated transit vehicle decelerates to zero mph after passing traveler 1
    a. MDEA and VEA notifications cease
8. Traveler 1 uses MDEA to cancel trip
    a. Other travelers (2-12) MDEAs will display trip cancelled
    b. Trip will clear from VEA display (no trip displayed)
9. Test engineer logs end time ______________________

Test Engineering Notes:

1. CV Inspector can be used to observe that PSMs, PMMs, BSMs, SPaT, and MAP are being broadcast by the appropriate devices
    a. MDEA broadcasts PSMs when transit vehicle is close enough and fast enough (e.g. 25 mph at 100 meters)
    b. MDEA travel group followers in safe zone do not broadcast PSMs
    c. MDEA travel group followers do not broadcast or receive PMMs (followers coordinate trip requests with travel group leader via cellular/cloud)
2. PSMs, PMMs, and BSMs are received by the RSU and recorded in data log files
3. PSMs, PMMs, BSMs, SPaT, and MAP are received by the VEA and recorded in data log files
4. PMMs, BSMs, SPaT, and MAP are received by the MDEA and recorded in data log files
5. Archive log files at the end of each test day

Scenario 5: PSM Broadcast Range

This is a scenario for testing DSRC message broadcast range of the mobile device. This scenario is conducted from the Buckeye Lot Loop bus stop.

Setup / checkout:

1. Check that the RSU near the subject bus stop is operating properly
2. Check that a smartphone (MDEA) and Arada radio are operating properly, including broadcasting of PSMs (MDEA set to always send PSMs)
3. A test engineer plays the role of a traveler holding a smartphone and wearing a holster with an Arada radio (during the scenario, the holster will be worn over the shoulder and placed in a backpack as indicated)
4. Mark 10, 50, 100, 150, 200, 250, and 300 meter birds-eye distances from the RSU on the travelers walking route using chalk (see figure of route/distances)
5. Test starts when test team is ready

Execution:

1. Test engineer logs start time ______________________
2. Wearing a backpack containing the holster/radio, traveler walks to successive distances of 10, 50, 100, 150, 200, 250, and 300 meters away from the RSU as marked, pausing at each distance for around 15 seconds
    a. Traveler notifies test engineer when each distance is reached and test engineer logs the time
        i. 10 meter arrival time ________________
        ii. 50 meter arrival time ________________
        iii. 100 meter arrival time ________________
        iv. 150 meter arrival time ________________
        v. 200 meter arrival time ________________
        vi. 250 meter arrival time ________________
        vii. 300 meter arrival time ________________
3. While stopped at 300 meters distance, Traveler removes holster/radio from the backpack and places it over the shoulder.
4. Wearing the holster/radio over the shoulder, traveler walks to successive distances of 300, 250, 200, 150, 100, 50, and 10 meters away from the RSU as marked, pausing at each distance for around 15 seconds
    a. Traveler notifies test engineer when each distance is reached and test engineer logs the time
        i. 300 meter arrival time ________________
        ii. 250 meter arrival time ________________
        iii. 200 meter arrival time ________________
        iv. 150 meter arrival time ________________

v. 100 meter arrival time _______________
vi. 50 meter arrival time _______________
vii. 10 meter arrival time _______________

5. Traveler returns to the bus stop
6. Test engineer logs end time ________________________

Test Engineering Notes:

1. CV Inspector can be used to observe that PSMs are being broadcast by the mobile device (MDEA set to always send PSMs)
2. PSMs are received by the RSU and recorded in data log files
3. Archive log files at the end of each test day

APPENDIX C. Acronyms and Abbreviations

ATG	Ad-Hoc Travel Group
ATP	Acceptance Test Plan
BSM	Basic Safety Message
CCP	Common Computing Platform
CV	Connected Vehicle
DSRC	Dedicated Short Range Communications
EPS	Experimental Prototype System
FHWA	Federal Highway Administration
FR	Functional Requirement
ITS	Intelligent Transportation Systems
LDV	Light-Duty Vehicle
LOC	Level of Confidence
MAP	Map Data
MDEA	Mobile Device Experimental Application
MGL	Message Logging
OBU	On-board Unit
PMM	Personal Mobility Message
PMM-ARRIVE	Personal Mobility Message Arrival Message
PMM-CANCEL	Personal Mobility Message Cancel Message
PMM-RSP	Personal Mobility Message Response Message
POC	Proof of Concept
PR	Performance Requirement
PSM	Personal Safety Message
REA	Roadside Experimental Application
RSU	Roadside Unit
SCMS	Security Credential Management System
SFY	Safety
SIR	System Interface Requirement
SMP	SPaT and MAP

SPaT	Signal Phasing and Timing
SyRS	System Requirements Specifications
TFHRC	Turner-Fairbank Highway Research Center
U.S. DOT	U.S. Department of Transportation
VEA	Vehicle Experimental Application
Wi-Fi	Wireless Fidelity

APPENDIX D. Terms and Definitions

Basic Safety Message (BSM)	Connected vehicle message type which contains vehicle safety-related information that is broadcast to surrounding vehicles
Bluetooth	Short range wireless technology used to exchange data between enabled devices
Cellular	Uses short-range radio stations to cover areas of communication
Connected Vehicle	A vehicle that can communicate with other vehicles and infrastructure via communication media such as DSRC, Wi-Fi, cellular or Bluetooth
Coordinated	Messages are coordinated when two or more mobile devices have established a travel group based on the same origin, destination, and time, and function as a single, cohesive sender/recipient
CV Inspector	An application that verifies if the Mobile Device is broadcasting messages to Connected Vehicles
Destination	The end point of a traveler's trip
DSRC	Dedicated Short-Range Communications; a low-latency, high-reliability, two-way communications tool used for sending transportation safety messages
Light-Duty Vehicle	Of or relating to vehicles that way less than 4,000 lbs
Message Type	Type of personal safety or personal mobility message that is transmitted based on the technology used and level of coordination available
Personal Mobility Message (PMM)	Similar to PDM, message intended for the exchange of mobility messages between individual travelers and vehicles/infrastructure, via mobile device
Personal Safety Message (PSM)	Similar to BSM, message intended to transmit low-latency, urgent safety messages between individual travelers and vehicles/infrastructure, via mobile device
Test Case	A set of conditions or variables that a Tester can determine if system meets requirements
Transit Vehicle	Large vehicles mainly used for public transportation as well as support services.
Transmitting	The state in which a traveler has opted in and is sending/receiving messages via mobile device
Uncoordinated	Messages are uncoordinated when travel groups are not established (see coordinated definition)

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