Sharing Data between Mobile Devices, Connected Vehicles and Infrastructure

Task 8: D2X Hub Proof-of-Concept Test Evaluation Report

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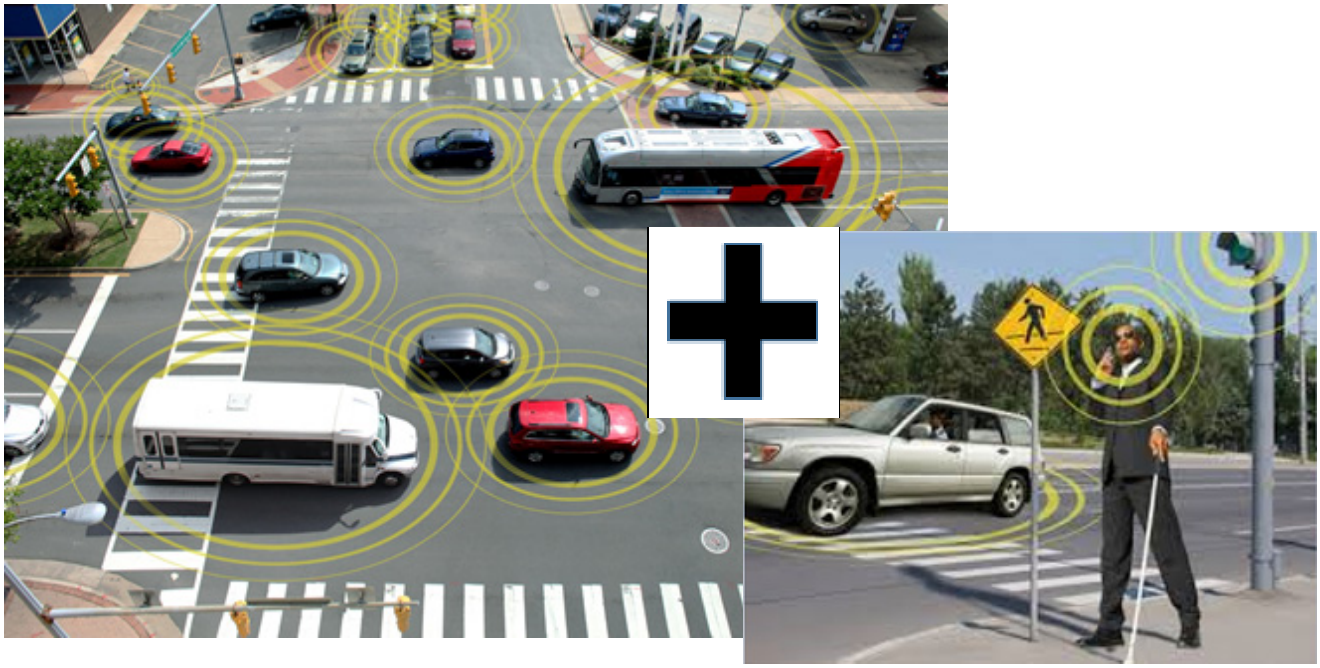

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16. Abstract

The Task 8 D2X Hub Proof-of-Concept Test Evaluation Report provides results of the experimental data analysis performed in accordance with the experimental plan for the proof-of-concept version of the prototype system. The data set analyzed includes the tests formally conducted at Battelle facilities as well as those conducted at Turner-Fairbank Highway Research Center (TFHRC) during January 2017 and concluding February 1, 2017. The findings from these tests provide the basis for recommended prototype system changes and enhancements to be implemented for the larger-scale Prototype Field Test to be conducted in June 2017 at Battelle and the Ohio State University (OSU).

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Revision History

Revision	Date	Change Description	Affected Sections/Pages
1	6/28/2017	Draft Release	
2	10/25/2017	Final Release addressing comments	All Chapters

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Chapter 1 Scope

This D2X Hub Proof-of-Concept Test Evaluation Report presents results of the experimental data analysis performed in accordance with the Experimental Plan for the proof-of-concept version of the D2X Hub prototype system. The data set analyzed includes the tests formally conducted at Battelle facilities (i.e., prototype acceptance test) as well as those conducted at Turner-Fairbank Highway Research Center (TFHRC) during January 2017 and concluding February 1, 2017. Since, the same experimental plan was used for tests conducted at Battelle facilities, as well as TFHRC, data from both the tests were fused to perform the data analysis. This report provides the results of the data analysis. Detailed test logs and digital data logs are not included in their entirety.

The Proof-of-Concept testing and subsequent data analysis was conducted in accordance with the Proof-of-Concept Experimental Plan. The Experimental Plan was designed to answer the research questions posed by the subject contract. The same Acceptance Test Plan (ATP) procedures used for Acceptance Testing were used to supply the data for Proof-of-Concept testing and analysis.

The purpose of the Proof-of-Concept testing was to evaluate the technical functionality of the system, but not to test the system's ability to address user needs. Further, the Proof-of-Concept testing will provide basis for recommended prototype system changes and enhancements to be implemented for the larger-scale Prototype Field Test to be conducted in June 2017 at Battelle and the Ohio State University (OSU). Additionally, this testing provided the first step towards answering the research questions in the contract.

Finally, it should be noted that the subject system is an experimental system for the purpose of answering research questions. System performance is limited by the quality of input data and the limits of the underlying technology and equipment employed. As such, there is not a specific threshold for an "acceptable" level of overall system performance. All results, whether "pass" or "fail", are instructive outcomes of this testing to answer the subject research questions.

Chapter 2 Referenced Documents

Battelle Memorial Institute

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-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)

Chapter 3 Test Conduct

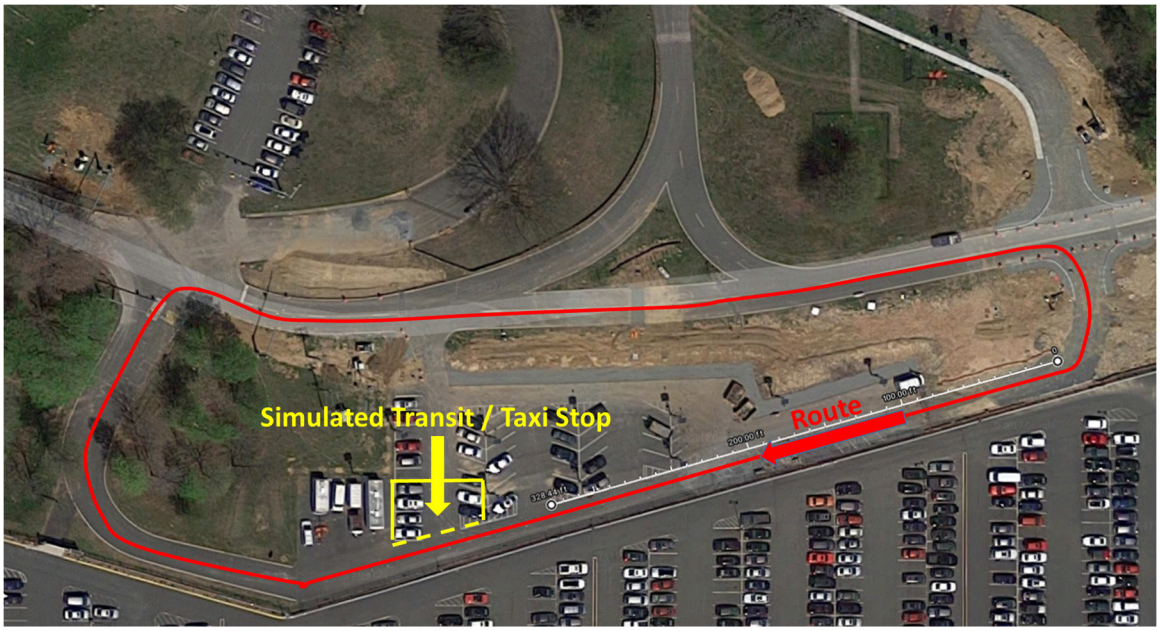
Prototype Proof-of-Concept tests for safety and mobility were conducted at TFHRC on January 30 through February 1, 2017 in a controlled environment. A two-lane undivided road at TFHRC with light traffic was selected as the test route. The parking lot adjacent to the selected route was used to establish a temporary Road Side Unit (RSU) and a traveler taxi stop. Three vehicles were used in this test; one each for a simulated taxi, a light-duty vehicle, and to power the RSU. The RSU Experimental Application (REA) and Vehicle Experimental Application (VEA) were installed in the RSU and taxi vehicles respectively. The light-duty vehicle had an OBU installed that generated BSMs only. Up to three mobile devices installed with the Mobile Device Experimental Application (MDEA) were used in this testing depending on the test case requirements. After installation of test equipment at the test location, checks were conducted to ensure message generation, transmission, and reception.

Seven Battelle staff participated in the testing by carrying out the roles of travelers, pedestrians, vehicle operator, and test engineers. A total of sixteen (16) test cases were employed at both TFHRC and Battelle facilities to generate the data necessary for experimental analysis. Five (5) iterations were performed for each test case at TFHRC, while 15 iterations performed at Battelle facilities were also included in the data set.

The tests associated with coordination of mobile devices were performed in a highly-controlled environment. This meant selection of specific devices and designating them with specific roles. This approach was chosen due to poor Wi-Fi Direct performance that would have otherwise hindered the ability to conduct the testing and collect the necessary data.

Detection of a pedestrian within a 2 meter cluster radius was a challenge based on earlier testing. This error in GPS accuracy was balanced by increasing the cluster radius to 7 meters for all the tests at TFHRC. This modification in cluster radius increased the efficiency of pedestrian detection by closing out the difference in 'Cross Track Distance'. Cross track distance is the perpendicular distance between pedestrian and light duty vehicle path.

The TFHRC test site location and route are shown in Figure 3-1.



Source: Battelle, Google Maps, January 2017

Figure 3-1. Turner-Fairbank Highway Research Center – Testing Location

Chapter 4 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. While the prototype safety and mobility software applications functioned well (as designed), the performance shortfalls that were observed are largely attributed to current technology limitations and hardware issues.

Mixed results were achieved for the various communication methods tested; Cellular functioned well, while Wi-Fi Direct connectivity was unreliable, and DSRC hardware problems caused communication problems with our system. GPS accuracy limitations were observed, as expected.

Table 4-1 provides a summary of the experimental analysis results by hypothesis, while Chapter 5 provides more in depth coverage of the analysis.

Table 4-1. Experimental Analysis Results Summary

Test Case No.	Hypothesis Description	Data Analysis Results
5.4.1.1 – PSM	Hypothesis 1 – The MDEA only broadcasts PSMs when in the range of a vehicle broadcasting a BSM	No False Negatives. Satisfied at 100% Level of Confidence (LOC)
5.4.1.3 – PSM	Hypothesis 2 – The overall MDEA DSRC message broadcast rate is lower during travel group coordination	Wi-Fi Direct Grouping Issue. 8 False Negatives. Satisfied at 87.5% LOC
5.4.1.2 – PSM	Hypothesis 3 – The MDEA can cease the broadcast of PSMs when in a vehicle	No False negatives. Satisfied at 100% LOC
5.4.1.1 – PSM	Hypothesis 4 – The Mobile Device can broadcast a PSM a radius of 250 meters 10 Hz under clear, unobstructed conditions, regardless of where the mobile device is located on the pedestrian's person or clothing	Radius limited to 100 m. Satisfied at a 43% level of confidence
5.4.7.1 – SFY	Hypothesis 5 – Vehicles OBUs can capture and process Mobile Device PSMs and issue warnings at sufficient distance for drivers to avoid imminent pedestrian collision	No False negatives. TFHRC satisfied at 100% LOC
5.4.7.1 – SFY	Hypothesis 6 – Mobile Devices can capture and process Vehicle BSMs and issue warnings in time for pedestrians to avoid imminent vehicle collision	No False negatives. TFHRC satisfied at 100% LOC
5.4.1.4 – PSM	Hypothesis 7 – Mobile Device applications can detect if a pedestrian is in a safe or unsafe zone	No False negatives. TFHRC satisfied at 100% LOC

Test Case No.	Hypothesis Description	Data Analysis Results
5.4.2.1; 5.4.2.2; 5.4.2.3 – PMM	Hypothesis 8 & 9 – The VEA can coordinate taxi travel requests from an MDEA	No False negatives. TFHRC satisfied at 100% LOC
5.4.2.4 – PMM	Hypothesis 10 – The traveler can receive arrival updates from a taxi or transit vehicle	2 False Negatives out of 14. TFHRC Satisfied at 85.71% LOC
5.4.5.1; 5.4.5.2 – LDV	Hypothesis 11 & 12 – The MDEA can detect when a traveler transitions from a pedestrian to a light duty vehicle or from a light duty vehicle to a pedestrian	No False negatives. Accelerator tests Satisfied at 100% LOC. Bluetooth tests failed.
5.4.4.1; 5.4.4.3; 5.4.4.4 – ATG	Hypothesis 13 – The MDEA can coordinate, maintain, and cancel travel with another MDEA via Wi-Fi Direct	Wi-Fi Direct Grouping Failure. 30 False Negatives out of 198. Satisfied at 84.84% LOC.
5.4.8.1 – SMP	Hypothesis 14 – The RSU can broadcast a SPaT and MAP message via DSRC that can be received by mobile devices	No False negatives. Satisfied at 100% LOC
5.4.1.1; 5.4.4.4; 5.4.7.1 – MSG	Hypothesis 15 - The RSU can store all messages received via DSRC	RSU - CCP logging issues. Not satisfied at 100% LOC

Note: The LOC was calculated as a ratio of the total number of successful steps in the test script divided by the total number of steps in the test script. (Each hypothesis has a specific test script)

Chapter 5 Experimental Analysis

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

Data logs verified: MDEA Log – 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 5-1. Hypothesis 1 Analysis Data Sample

Date	Time	Vehicle Range and Advisory Distance w.r.t. Speed	Speed (mph)	In Range	Out of Range	Distance (m)
1/31/17	10:13:16	IsBsmClose: Dist: 97.5500061708885<? AdvDist: 102.4200201024	25.5	X		98
1/31/17	10:13:32	IsBsmClose: Dist: 57.0797651794001<? AdvDist: 66.6000057888	17.3	X		57
1/31/17	10:13:40	IsBsmClose: Dist: 57.448436831453<? AdvDist: 60.1199821728	14.9	X		57
1/31/17	10:15:29	IsBsmClose: Dist: 97.5729907380225<? AdvDist: 102.240014976	25.4	X		98

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

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

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

Where:

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

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 overall MDEA DSRC message broadcast rate is lower during travel group coordination

Data logs verified: MDEA Log – 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 64 log checks performed, 56 true positives were observed. Two tests had a grouping failure due to Wi-Fi Direct issues.

Table 5-2. Hypothesis 2 Analysis Data Sample

Date	**1/31/17**	**1/31/17**	**1/31/17**	**1/31/17**	**1/31/17**
Description \ Test Number	TFHRC 1	TFHRC 3	TFHRC 4	TFHRC 5	TFHRC 6
PSMs Generated by Traveler X and Traveler Y	11:11:16	11:23:46	11:42:08	11:46:09	11:52:22
Transition to 'In Group'	11:12:40	11:24:48	11:43:01	11:46:58	11:53:13
Traveler Y PSM ceased	Check	Check	Check	Check	Check
only Traveler X PSM received	11:13:05	11:25:08	11:43:45	11:47:21	11:53:42

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

Results: There were 8 False Negatives in the data analyzed. Hence, Hypothesis 2 is satisfied at 87.5% level of confidence

Hypothesis 3: MDEA Log – Travel Mode Status, PSM send occurrences

Data logs verified: MDEA Log – BSM received and 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 5-3. Hypothesis 3 Analysis Data Sample

Description \ Test Number	TFHRC 1	TFHRC 2	TFHRC 3	TFHRC 4	TFHRC 5	TFHRC 6
MDEA not in vehicle	Check	Check	Check	Check	Check	Check
MDEA Transmits PSMs	Check	Check	Check	Check	Check	Check
Time of MDEA Mode Transition	10:38:04	10:41:09	10:44:30	10:46:24	10:48:05	10:50:24
MDEA Ceases Transmitting PSMs	Check	Check	Check	Check	Check	Check

For the complete analysis, please refer to Table A-3 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 10 Hz under clear, unobstructed conditions, regardless of where the mobile device is located on the pedestrian's person or clothing

Data logs verified: VEA Log – PSM receive occurrences at a distance of 10 m, 50 m, 100 m

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, in-pocket, and in a backpack.

Observations:
Due to DSRC limitations in the CCPs, tests could not be performed beyond 100 m range. Considering the RSU logging issues, VEA Logs were used to analyze PSM broadcasting capacity of MDEA. All the tests logged PSMs at a rate of 10/sec. Therefore 150, 200, 250, 300 m radius could not be analyzed. Only three (10, 50, and 100m) out of seven (10, 50, 100, 150, 200, 250, and 300 m) cases were tested, which resulted in a 43% Level of Confidence.

Table 5-4. Hypothesis 4 Analysis Data Sample

Date	Time	Vehicle Range and Advisory Distance w.r.t. Speed	Speed (mph)	In Range	Out of Range	True Distance (m)	VEA Log PSM Message Rate
1/31/17	10:13:16	IsBsmClose: Dist: 97.5500061708885<? AdvDist: 102.4200201024	25.5	✓		98	10
1/31/17	10:13:32	IsBsmClose: Dist: 57.0797651794001<? AdvDist: 66.6000057888	17.3	✓		57	10
1/31/17	10:13:40	IsBsmClose: Dist: 57.448436831453<? AdvDist: 60.1199821728	14.9	✓		57	10
1/31/17	10:15:29	IsBsmClose: Dist: 97.5729907380225<? AdvDist: 102.240014976	25.4	✓		98	10
1/31/17	10:15:38	IsBsmClose: Dist: 3.99317028326919<? AdvDist: 102.240014976	25.0	✓		4	10

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

Results: Due to the DSRC limitations, the radius was limited to 100 m. Hence, Hypothesis 4 is satisfied at a 43% 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: VEA Log – PSM Location, GPS Location, Advisory Display, Alert Display and Warning Display

Analysis:

1. Assessing the distance at which an Advisory, Alert and Warning were issued based on the speed of the vehicle (in the VEA Log).

Observations:

a. Considering TFHRC tests, the average difference in distance for VEA Logging of Advisories, Alerts and Warnings were on average 20.28 m, 2.75 m, and 1.94 m respectively.
b. The higher difference in advisory was due to the delay in the time between VEA deciding to send PSM and Arada sending a PSM.
c. Latency of less than a second was observed between PSM received and the message display time on MDEA and VEA Logs.

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

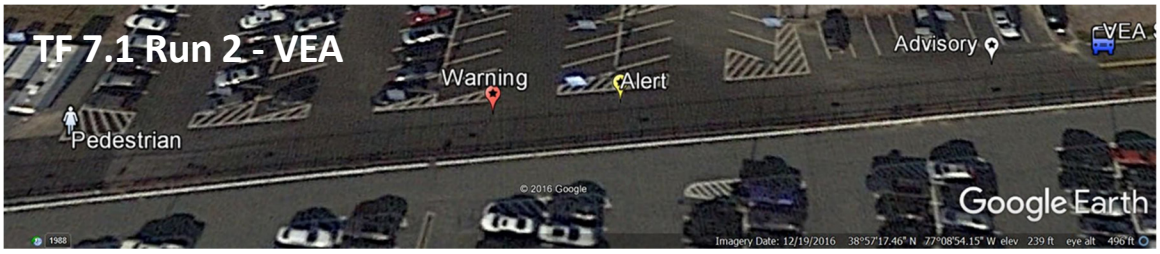
$$d_{Advisory} = v * 9$$

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

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

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, February 2017

Figure 5-1 Advisory, Alert and Warning Distances with Respect to VEA

Table 5-5. Hypothesis 5 Analysis Data Sample

	TFHRC1			TFHRC2			TFHRC3		
	Advisory	Alert	Warning	Advisory	Alert	Warning	Advisory	Alert	Warning
True Distance (m)	75.84	55.45	48.74	85.52	51.67	45.15	78.76	58.27	51.24
Speed (MPH)	24.71	25.23	24.98	25.95	24.61	24.33	23.81	25.90	26.24
Expected Distance (m)	99.42	57.80	49.10	104.41	55.88	47.51	95.80	59.89	52.22
Difference (m)	23.58	2.35	0.36	18.89	4.21	2.36	17.04	1.62	0.98

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

Table 5-6. Total and Average Differences between Actual and Calculated Advisories, Alerts and Warnings (VEA)

TFHRC	Advisory	Alert	Warning
Total Difference (m)	101.39	13.76	9.71
Average Difference (m)	20.28	2.75	1.94

Results: There were no outliers (False Negatives) in the data analyzed. 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 – BSM Location, GPS Location, Advisory Display, Alert Display and Warning Display

Analysis:

1. Assessing the distance at which an Advisory, Alert and Warning were issued based on the speed of the vehicle (in the BSM received by the mobile device).

Observations:

a. Considering the TFHRC results, the average difference in distance for MDEA logging of Advisories, Alerts, and Warnings were on average 2.78 m, 3.23 m, and 3.34 m respectively.
b. Latency of less than a second was observed on MDEA and VEA Logs.

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, February 2017

Figure 5-2. Advisory, Alert and Warning Distances with Respect to MDEA

Table 5-7. Hypothesis 6 Analysis Data Sample

	TFHRC1			TFHRC2			TFHRC3		
	Advisory	Alert	Warning	Advisory	Alert	Warning	Advisory	Alert	Warning
True Distance (m)	87.56	53.20	46.51	99.28	52.76	46.24	89.52	55.95	48.90
Speed (mph)	22.90	25.09	24.87	25.14	24.47	24.15	23.04	26.03	26.17
Expected distance (m)	92.13	57.36	48.83	101.15	55.46	47.07	92.70	60.30	52.05
Difference (m)	4.58	4.16	2.32	1.87	2.70	0.84	3.18	4.36	3.15

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

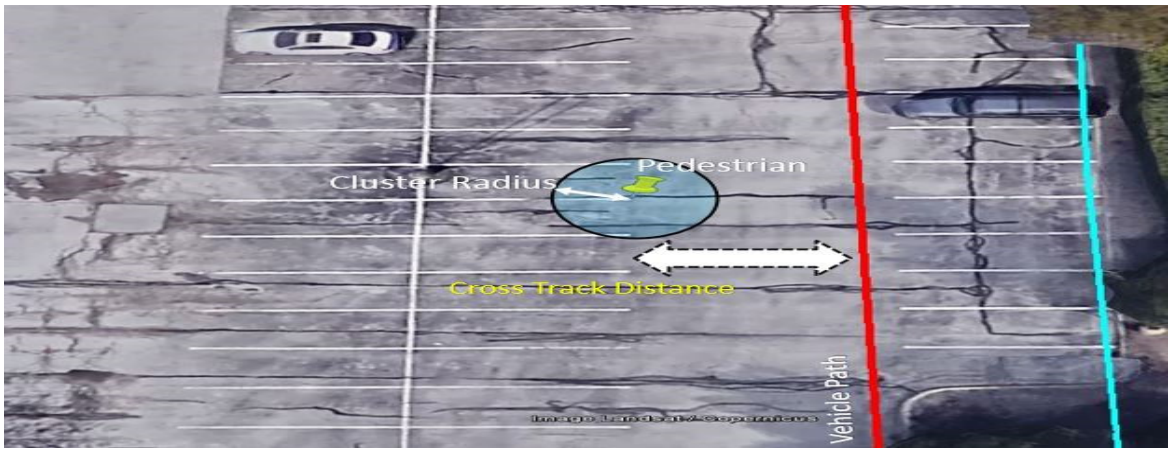
Table 5-8. Total and Average Differences between Actual and Calculated Advisories, Alerts and Warnings (MDEA)

TFHRC	Advisory	Alert	Warning
Total Difference (m)	13.92	16.17	16.71
Average Difference (m)	2.78	3.23	3.34

Results: There were no false alarms detected at neither of the TFHRC/ATP tests performed. Hence, Hypothesis 6 is satisfied at a 100% level of confidence.

Issues Identified: GPS Inaccuracy – Cross Track Distance Issue

- The accuracy of GPS as per the US government claims is +/- 4 m. This error in GPS accuracy was balanced by increasing the cluster radius to 7 m for all the tests at TFHRC. This modification in cluster radius increased the efficiency of pedestrian detection by closing out the difference in 'Cross Track Distance'.
- There were no false alarms detected at neither of the TFHRC/ATP tests performed.



Source: Battelle, Google Maps, February 2017

Figure 5-3. Cross Track Distance between Pedestrian and Vehicle Path

Hypothesis 7: MDEA Log – GPS Location, Safe/Unsafe Zone Status, and MAP Message Contents

Data logs verified: MDEA Log – GPS Location, Safe/Unsafe Zone Status, and MAP Message Contents

Analysis:

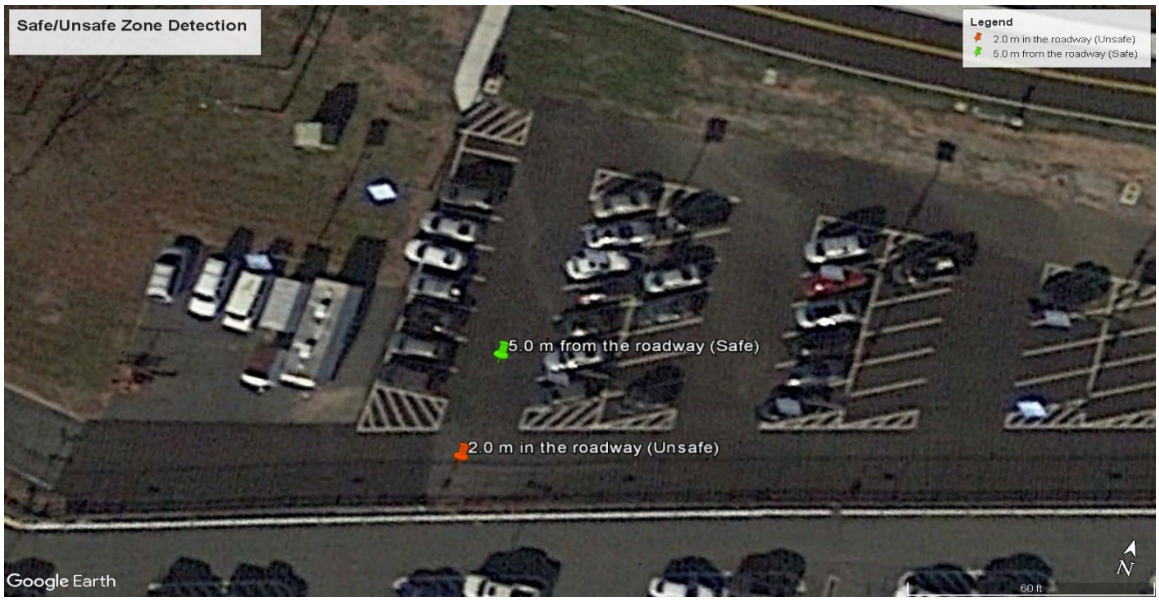
1. Analyzed the percentage of properly classified safe/unsafe zone detections. The device was placed in the roadway – mobile device location was properly classified if it positions itself in an unsafe zone.

Observations:
User State Change from 'Safe to Unsafe' (when placed 2.0 m in the roadway) and 'Unsafe to Safe' (when placed 5.0 m from the roadway) were captured accurate and timely.

Table 5-9. Hypothesis 7 Analysis Data Sample

	TFHRC 1	TFHRC 2	TFHRC 3	TFHRC 4	TFHRC 5
User State Change: Is Safe Icon False (2 m in the roadway)	11:14:38	11:25:33	11:44:00	11:48:01	11:54:08
Properly Processed	✓	✓	✓	✓	✓
User State Change: Is Safe Icon True (5 m from the roadway)	11:15:04	11:26:19	11:44:38	11:48:29	11:54:44
Properly Processed	✓	✓	✓	✓	✓

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



Source: Battelle, Google Maps, February 2017

Figure 5-4. Safe and Unsafe Zones at TFHRC 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 & 9: The VEA can coordinate taxi travel requests from an MDEA

Data logs verified: MDEA Log – PMM Send Occurrence, PMM contents, PMM-RSP Receive Occurrence, Coordination Status, and PMM-Cancel Sent 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:
16 out of 204 checks had a failure during tests performed under ATP.

Table 5-10. Hypothesis 8 & 9 Analysis Data Sample

		TFHRC 1	TFHRC 2	TFHRC 3	TFHRC 4	TFHRC 5
Analyze the percentage of PMM messages properly processed by in-vehicle devices.	MDEA Log – PMM Send occurrence	Check	Check	Check	Check	Check
	MDEA Log – PMM contents	All Present	All Present	All Present	All Present	All Present
	Experimental Log – Information entered into Mobile Device by Traveler					
	VEA Log – PMM Receive occurrence	Check	Check	Check	Check	Check
Analyze the percentage of PMM-RSP messages properly processed by mobile devices.	Experimental Log – Driver Acceptance					
	VEA Log – Driver acceptance	Check	Check	Check	Check	Check
	VEA Log – PMM-RSP Send occurrence	Check	Check	Check	Check	Check
	MDEA Log – PMM-RSP Receive occurrence	Check	Check	Check	Check	Check
	MDEA Log – Coordination Status	Check	Check	Check	Check	Check
	Experimental Log – Coordination Success Display					

		TFHRC 1	TFHRC 2	TFHRC 3	TFHRC 4	TFHRC 5
Analyze the percentage of PMM-Cancel messages properly processed by in-vehicle devices.	MDEA Log – PMM-Cancel Sent Occurrence	Check	Check	Check	Check	Check
	VEA Log – PMM-Cancel Received Occurrence	Check	Check	Check	Check	Check

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

Results: Considering the tests performed at TFHRC, Hypothesis 8 is satisfied at a 100% level of confidence. However, ATP tests satisfied the hypothesis at a confidence level of 92.15%

Issues Identified:

- Some issues observed for cloud communication during ATP testing at Columbus, OH
  - Delay in Cloud PMM-cancel for VEA – 8 instances
  - Adding a trip twice – 5 instances
  - Some PMMs not being cancelled – 3 instances
- All these issues were addressed prior to TFHRC tests
- TFHRC tests did not have any of the above issues

Hypothesis 10: The traveler can receive arrival updates from a taxi or transit vehicle

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

MDEA Log – PMM-ARRIVE receive occurrence.

Analysis:

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

Observations:
One test case at TFHRC failed due to equipment failure (CCP lost its location). All other tests satisfied the hypothesis.

Table 5-11. Hypothesis 10 Analysis Data Sample

			TFHRC 1	TFHRC 2	TFHRC 3	TFHRC 4	TFHRC 5	TFHRC 6	TFHRC 7
DSRC (Taxi)	Analyze the success rate of receiving a PMM-Arrive message.	VEA Log – PMM-ARRIVE Send occurrence	Fail	Check	Check	Check	Check	Check	Check
		MDEA Log – PMM-ARRIVE Receive occurrence	Fail	Check	Check	Check	Check	Check	Check

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

Results: Considering the tests at TFHRC, the hypothesis is satisfied at a confidence level of 85.71 %. 12 out of 14 tests were successful.

Hypothesis 11 & 12: The MDEA can detect when a traveler transitions from a pedestrian to a light duty vehicle or from a light duty vehicle to a pedestrian

Data logs verified: MDEA Log – Travel Mode Status Change; Experimental Log – Mode Transition Detection Log

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. Assessed the false positive rate of transition detection.

Observations:

Accelerometer tests on average took 7.5 secs and 4.4 secs to detect in-vehicle and on-foot respectively. However, Bluetooth beacon tests on average took 17 secs and 11 secs to detect in-vehicle and on-foot respectively. This quantifies the unreliable nature of Bluetooth Beacons as used in this system.

Table 5-12. Hypothesis 11 & 12 Analysis Data Sample

Mode Detection Method	On-foot to In-Vehicle Transition time (Sec)	In-Vehicle to On-foot Transition Time (Sec)
Accelerometer	7.5	4.4
Bluetooth Beacon	17	11

Results: Hypothesis is proved as 100% confident during the accelerometer tests. However, none of the tests with Bluetooth Beacon satisfied the hypothesis (all false negatives).

Hypothesis 13: The MDEA can coordinate, maintain, and cancel travel with another MDEA via Wi-Fi Direct

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

MDEA (2) Log – Coordination Request Sent Occurrence, Coordination Confirmation received Occurrence, Coordination Heartbeat Response Sent Occurrence, Coordination Acceptance received 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:
This test is performed in a highly-controlled environment. This means selection of specific devices and designating them with specific roles. This approach was chosen due to poor Wi-Fi direct performance with our system that would have otherwise hindered the ability to conduct the testing and collect the necessary data.

Table 5-13. Hypothesis 13 Analysis Data Sample

	1/31/17					2/1/17				
	TFHRC 1	TFHRC 2	TFHRC 3	TFHRC 4	TFHRC 5	TFHRC 6	TFHRC 7	TFHRC 8	TFHRC 9	TFHRC 10
Coordination Request Sent by Y	Fail. Traveler Y could not join the ad-hoc travel group.	4:09:51	Check	Fail. Traveler Y could not join the ad-hoc travel group.	Check	Check	Check	Check	Check	Check
Coordination Request Received by X		check	Check		Check	Check	Check	Check	Check	Check
Request Confirmed by X		check	Check		Check	Check	Check	Check	Check	Check
Confirmation Received by Y		check	Check		Check	Check	Check	Check	Check	Check
Coordination Request Sent by Z		4:10:47	Check		Check	Check	Check	Check	Check	Check
Coordination Request Received by X		check	Check		Check	Check	Check	Check	Check	Check
Request Confirmed by X		check	Check		Check	Check	Check	Check	Check	Check
Confirmation Received by Z		check	Check		Check	Check	Check	Check	Check	Check
Coordination Heart Beat Transmitted by Y & Z		check	Check		Check	Check	Check	Check	Check	Check
Heart Beat Response received by X		check	Check		Check	Check	Check	Check	Check	Check
Ride Arrived Messages		4:13:03	Check		Check	Check	Check	Check	Check	Check
Coordination Cancel by walking away	Check	Check	Check	Check	Check	This step not tested on this day.				
Coordination Cancel by Manual request	This step not tested on this day.					Check	Check	Check	Check	Check
Disband Group after entering into vehicle						Check	Check	Check	Check	Check

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

Results: There were 30 outliers out of 198 checks (False Negatives) in the data analyzed. Hence, Hypothesis 13 is satisfied at an 84.84% level of confidence.

Hypothesis 14: The RSU can broadcast a SPaT and MAP message via DSRC that can be received by mobile devices

Data logs verified: MDEA Log – BSM received and PSM send occurrences

Analysis:

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

Observations:
Considering test 5.4.4.4. all the SPaT messages were transmitted and received at a rate of 1/sec. Similarly, all the MAP messages were transmitted and received at a rate better than 5/sec.

Table 5-14. Hypothesis 14 Analysis Data Sample

ID	Date	Message
5	1/31/17 16:38:42	Dsrc: Rx: Spat id:19
6	1/31/17 16:38:42	Dsrc: Rx: Map id:18
9	1/31/17 16:38:43	Dsrc: Rx: Spat id:19
10	1/31/17 16:38:43	Dsrc: Rx: Bsm Lat:38.9546323 Long: -77.1488295 Head: 271.3375 Sp: 0
12	1/31/17 16:38:43	Dsrc: Rx: Bsm Lat:38.9546138 Long: -77.1483988 Head: 255.9125 Sp: 0
13	1/31/17 16:38:44	Dsrc: Rx: Spat id:19
14	1/31/17 16:38:44	Dsrc: Rx: Bsm Lat:38.9546323 Long: -77.1488297 Head: 271.3375 Sp: 0
16	1/31/17 16:38:44	Dsrc: Rx: Bsm Lat:38.9546138 Long: -77.1483987 Head: 255.9125 Sp: 0
17	1/31/17 16:38:44	Dsrc: Rx: Map id:18
18	1/31/17 16:38:44	Dsrc: Rx: Bsm Lat:38.9546322 Long: -77.14883 Head: 271.3375 Sp: 0
20	1/31/17 16:38:45	Dsrc: Rx: Bsm Lat:38.9546137 Long: -77.1483987 Head: 255.9125 Sp: 0
21	1/31/17 16:38:45	Dsrc: Rx: Bsm Lat:38.9546322 Long: -77.1488302 Head: 271.3375 Sp: 0
22	1/31/17 16:38:45	Dsrc: Rx: Spat id:19
23	1/31/17 16:38:45	Dsrc: Rx: Bsm Lat:38.9546137 Long: -77.1483987 Head: 255.9125 Sp: 0
25	1/31/17 16:38:45	Dsrc: Rx: Bsm Lat:38.954632 Long: -77.1488302 Head: 271.3375 Sp: 0
26	1/31/17 16:38:46	Dsrc: Rx: Bsm Lat:38.9546135 Long: -77.1483987 Head: 255.9125 Sp: 0
27	1/31/17 16:38:46	Dsrc: Rx: Spat id:19
29	1/31/17 16:38:46	Dsrc: Rx: Bsm Lat:38.9546318 Long: -77.1488303 Head: 271.3375 Sp: 0
31	1/31/17 16:38:46	Dsrc: Rx: Map id:18

Results: There were no outliers (False Negatives) in the data analyzed. Hence, Hypothesis 14 is satisfied at a 100% level of confidence.

Hypothesis 15: The RSU can store all messages received via DSRC

Data logs verified: MDEA Log – All Occurrences of messages sent via DSRC, and Message Contents; RSU Log – Message Received Occurrence, and Message Contents.

Analysis:

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

Observations:

a. Considering the message logs from test cases 5.4.1.1; 5.4.4.4; 5.4.7.1, there were instances where PSMs were logged at a rate of less than 10/sec. Also, there were test cases that had no reception of PSMs. This clearly indicates the reception issues with RSU CCP unit. One prime focus for the Large-Scale Field Test is to improve the reliability of the hardware associated with RSU.
b. The message contents in all the DSRC messages were consistent throughout the test logs.

Table 5-15. Hypothesis 15 Analysis Data Sample

Date	Time	Vehicle Range and Advisory Distance w.r.t. Speed	Speed (mph)	In Range	Out of Range	Distance (m)	RSU Log PSM Message Rate/Sec
1/31/17	10:13:16	IsBsmClose: Dist: 97.5500061708885<? AdvDist: 102.4200201024	25.5	✓		98	8
1/31/17	10:13:32	IsBsmClose: Dist: 57.0797651794001<? AdvDist: 66.6000057888	17.3	✓		57	6
1/31/17	10:13:40	IsBsmClose: Dist: 57.448436831453<? AdvDist: 60.1199821728	14.9	✓		57	1
1/31/17	10:15:29	IsBsmClose: Dist: 97.5729907380225<? AdvDist: 102.240014976	25.4	✓		98	0
1/31/17	10:15:38	IsBsmClose: Dist: 3.99317028326919<? AdvDist: 102.240014976	25.0	✓		4	1

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

Table 5-16. Data Usage Statistics

	17-Jan	18-Jan	19-Jan	20-Jan	31-Jan	1-Feb	Average	Maximum
Total Usage (MB)	380.5	626	714	2713	487.3	135.5	984	2713
TMX core usage (MB)	271	450	468	1991	345	90	705	1991
% of TMX usage	71	72	66	73	71	66	71	73

Results: The hypothesis statement of RSU being able to store all messages received via DSRC is not satisfied at 100% level of confidence due to hardware issues.

Chapter 6 Lessons Learned and Recommendations

Lessons Learned

The Lessons Learned from the Proof-of-Concept testing 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 applications
3. The prototype safety and mobility software applications functioned well (as designed)
4. Limitations of technology and hardware issues caused the majority of performance shortfalls
5. Mixed results were achieved for the various communication methods tested:
    a. Cellular functioned well with our system
    b. Wi-Fi Direct connectivity was unreliable with our system
    c. DSRC hardware problems caused communication problems with our system
6. GPS accuracy limitations were observed, as expected

Wi-Fi Direct Connectivity

- The connection process was prone to failure at multiple points with no indication to the application why connection failed
- TFHRC success rate was achieved by selecting specific devices that worked best for specific roles; otherwise, a failure rate >50% would have been expected based on earlier testing
- Canvasing of developer community found similar observations, no solutions for our system
- Wi-Fi Direct connection process requires authorization from the user of the target device; in a real world environment such a request would most likely be denied if noticed at all

DSRC Hardware

- Common Computer Platform (CCP): Pre-production engineering units were used, which were determined to have an impedance mismatch between the DSRC chip and RF connector that caused reduction of signal strength
- Arada LocoMate ME: There were occasional Bluetooth connection failures to mobile devices, as well as occasional DSRC transmission/reception failures. Longer term, it is assumed that DSRC radios will be integrated into smartphones thus obviating the current issues.

Recommendations

Based on outcomes of Proof-of-Concept Testing, the following prototype system design changes are recommended to be implemented prior to the larger-scale prototype field test:

- Add Cellular-based communication for Travel Group coordination between mobile devices
- New and improved CCP units will be used for the larger-scale field test
- For in-vehicle detection, use Accelerometer method as the most reliable option

APPENDIX A. Comprehensive Data Analysis Tables

Note: For all the analysis results depicted below, the term "check" refers to the "success" of desired action.

Table A-1. Complete Data Analysis – Hypothesis 1, 4, & 15

Date	Time	Vehicle Range and Advisory Distance w.r.t. Speed	Speed	In Range	Out of Range	Distance	RSU Log PSM Message Rate/Sec	VEA Log PSM Message Rate
1/31/2017	10:13:16	IsBsmClose: Dist: 97.5500061708885<? AdvDist: 102.4200201024	25.5	X		98	8	10
1/31/2017	10:13:32	IsBsmClose: Dist: 57.0797651794001<? AdvDist: 66.6000057888	17.3	X		57	6	10
1/31/2017	10:13:40	IsBsmClose: Dist: 57.448436831453<? AdvDist: 60.1199821728	14.9	X		57	1	10
1/31/2017	10:15:29	IsBsmClose: Dist: 97.5729907380225<? AdvDist: 102.240014976	25.4	X		98	0	10
1/31/2017	10:15:38	IsBsmClose: Dist: 3.99317028326919<? AdvDist: 102.240014976	25.0	X		4	1	10
1/31/2017	10:15:53	IsBsmClose: Dist: 60.0719107941917<? AdvDist: 70.199987616	17.4	X		60	0	10
1/31/2017	10:20:29	IsBsmClose: Dist: 94.4643508928866<? AdvDist: 100.8000141984	25.1	X		95	0	9
1/31/2017	10:20:48	IsBsmClose: Dist: 59.2561932680623<? AdvDist: 62.8200188352	15.6	X		59	0	9

Date	Time	Vehicle Range and Advisory Distance w.r.t. Speed	Speed	In Range	Out of Range	Distance	RSU Log PSM Message Rate/Sec	VEA Log PSM Message Rate
1/31/2017	10:20:54	IsBsmClose: Dist: 61.6348297460404<? AdvDist: 64.4399845056	16.0	X		62	3	11
1/31/2017	10:21:05	IsBsmClose: Dist: 87.1180496389495<? AdvDist: 109.2600137376	24.7	X		87	4	9
1/31/2017	10:22:06	IsBsmClose: Dist: 97.7301610734722<? AdvDist: 113.0400006912	29.5	X		98	0	10
1/31/2017	10:22:28	IsBsmClose: Dist: 57.7576034007057<? AdvDist: 60.659997552	15.1	X		58	2	10
1/31/2017	10:23:32	IsBsmClose: Dist: 101.193300977461<? AdvDist: 103.86002088	25.8	X		101	10	10
1/31/2017	10:23:56	IsBsmClose: Dist: 59.5641466972855<? AdvDist: 66.0599904096	16.4	X		60	6	10
1/31/2017	10:26:23	IsBsmClose: Dist: 100.217014111125<? AdvDist: 102.4200201024	25.3	X		100	7	10
1/31/2017	10:26:50	IsBsmClose: Dist: 54.0919707235241<? AdvDist: 88.7399925984	22.1	X		54	0	10
1/17/2017	11:15:04	IsBsmClose: Dist: 100.564061581794<? AdvDist: 116.9999927712	29.1	X		101	10	10
1/17/2017	11:24:37	IsBsmClose: Dist: 99.2912014791515<? AdvDist: 103.86002088	25.8	X		99	10	10
1/17/2017	11:28:37	IsBsmClose: Dist: 106.684353810469<? AdvDist: 107.6400078336	26.1	X		107	10	10

Date	Time	Vehicle Range and Advisory Distance w.r.t. Speed	Speed	In Range	Out of Range	Distance	RSU Log PSM Message Rate/Sec	VEA Log PSM Message Rate
1/17/2017	11:31:48	IsBsmClose: Dist: 112.4753473133<? AdvDist: 118.6199986752	26.8	X		112	10	10
1/17/2017	11:33:32	IsBsmClose: Dist: 106.022149777593<? AdvDist: 112.6799904384	26.0	X		106	10	10
1/17/2017	11:33:36	IsBsmClose: Dist: 59.429630331283<? AdvDist: 119.6999892	29.8	X		59	10	10
1/17/2017	11:33:57	IsBsmClose: Dist: 65.7937887214709<? AdvDist: 119.3400191808	29.7	X		66	10	10
1/17/2017	11:36:27	IsBsmClose: Dist: 96.5542357439439<? AdvDist: 108.0000180864	26.0	X		97	10	10
1/17/2017	11:36:29	IsBsmClose: Dist: 82.1301583410616<? AdvDist: 107.4600027072	27.0	X		82	10	10
1/17/2017	11:38:03	IsBsmClose: Dist: 99.4884887192582<? AdvDist: 104.580001152	25.1	X		99	10	10
1/17/2017	11:38:11	IsBsmClose: Dist: 16.809952777894<? AdvDist: 106.200007056	25.7	X		17	10	10
1/17/2017	11:41:14	IsBsmClose: Dist: 94.8985801452811<? AdvDist: 98.6399929152	24.5	X		95	10	10
1/17/2017	11:41:33	IsBsmClose: Dist: 14.1255704529106<? AdvDist: 96.3000067392	24.2	X		14	10	10
1/17/2017	11:41:36	IsBsmClose: Dist: 37.7627357471613<? AdvDist: 97.7400075168	24.3	X		38	10	10

Date	Time	Vehicle Range and Advisory Distance w.r.t. Speed	Speed	In Range	Out of Range	Distance	RSU Log PSM Message Rate/Sec	VEA Log PSM Message Rate
1/17/2017	11:44:03	IsBsmClose: Dist: 114.490146784404<? AdvDist: 122.5799907552	26.6	X		114	10	10
1/17/2017	11:44:15	IsBsmClose: Dist: 28.0463490772458<? AdvDist: 71.100013248	16.1	X		28	10	10
1/17/2017	11:47:35	IsBsmClose: Dist: 102.043927314914<? AdvDist: 104.0399857728	25.9	X		102	10	10
1/17/2017	11:47:55	IsBsmClose: Dist: 18.5020887331204<? AdvDist: 112.499985312	27.5	X		19	10	10
1/19/2017	3:56:05	IsBsmClose: Dist: 107.928079653642<? AdvDist: 110.7000145152	27.2	X		108	9	9
1/19/2017	3:56:30	IsBsmClose: Dist: 99.759104887202<? AdvDist: 118.4399935488	29.4	X		100	10	10
1/19/2017	3:58:37	IsBsmClose: Dist: 110.291146846666<? AdvDist: 115.020016848	28.6	X		110	10	10
1/19/2017	4:00:57	IsBsmClose: Dist: 99.8997459961241<? AdvDist: 126.0000076896	31.3	X		100	10	10
1/19/2017	4:03:00	IsBsmClose: Dist: 100.209094247195<? AdvDist: 106.919987328	26.0	X		100	10	10
1/19/2017	4:04:10	IsBsmClose: Dist: 100.723184500334<? AdvDist: 109.7999888832	27.3	X		101	6	10
1/19/2017	4:11:03	IsBsmClose: Dist: 97.7354295877856<? AdvDist: 100.8000141984	25.1	X		98	10	10

Date	Time	Vehicle Range and Advisory Distance w.r.t. Speed	Speed	In Range	Out of Range	Distance	RSU Log PSM Message Rate/Sec	VEA Log PSM Message Rate
1/19/2017	4:13:11	IsBsmClose: Dist: 101.90842581135<? AdvDist: 104.0399857728	25.9	X		102	10	10
1/19/2017	4:14:23	IsBsmClose: Dist: 99.5536361906761<? AdvDist: 100.9799790912	25.1	X		100	10	10
1/19/2017	4:15:34	IsBsmClose: Dist: 100.75608603652<? AdvDist: 106.919987328	26.4	X		101	10	10

Table A-2. Complete Data Analysis – Hypothesis 2

Date	Test Number	PSMs Generated by Trav X and Trav Y	Transition to 'In Group'	Trav Y PSM Ceased	Only Trav X PSM Received
1/31/2017	TFHRC 1	11:11:16	11:12:40	Check	11:13:05
1/31/2017	TFHRC 2	Grouping Failed	Grouping Failed	Grouping Failed	Grouping Failed
1/31/2017	TFHRC 3	11:23:46	11:24:48	Check	11:25:08
1/31/2017	TFHRC 4	11:42:08	11:43:01	Check	11:43:45
1/31/2017	TFHRC 5	11:46:09	11:46:58	Check	11:47:21
1/31/2017	TFHRC 6	11:52:22	11:53:13	Check	11:53:42
1/18/2017	ATP 1	10:44:00	10:45:27	Check	10:46:01
1/18/2017	ATP 2	10:53:56	10:54:55	Check	10:55:46
1/18/2017	ATP 3	11:00:59	11:01:50	Check	11:03:22
1/18/2017	ATP 4	11:12:22	11:13:10	Check	11:13:29
1/18/2017	ATP 5	11:15:15	11:16:16	Check	11:16:30
1/18/2017	ATP 6	11:18:23	11:19:06	Check	11:19:17
1/18/2017	ATP 7	11:21:16	11:21:57	Check	11:22:09
1/18/2017	ATP 8	11:28:14	11:28:55	Check	11:29:17
1/18/2017	ATP 9	11:31:42	11:32:30	Check	11:32:48
1/18/2017	ATP 10	11:35:01	11:35:45	Check	11:36:08
1/19/2017	ATP 11	4:47:28	4:48:42	Check	4:50:07
1/19/2017	ATP 12	Radio Failure. Test Terminated	Radio Failure. Test Terminated	Radio Failure. Test Terminated	Radio Failure. Test Terminated
1/19/2017	ATP 13	4:55:48	4:56:37	Check	4:57:28
1/19/2017	ATP 14	4:59:46	5:00:47	Check	5:01:07
1/19/2017	ATP 15	5:03:53	5:04:44	Check	5:05:13
1/19/2017	ATP 16	5:07:30	5:08:23	Check	5:08:39

Table A-3. Complete Data Analysis – Hypothesis 3

Date	Description	MDEA not in Vehicle	MDEA Transmits PSMs	Time of MDEA Mode Transition	MDEA Ceases Transmitting PSMs
1/31/2017	TFHRC 1	Check	Check	0.443101852	Check
1/31/2017	TFHRC 2	Check	Check	0.445243056	Check
1/31/2017	TFHRC 3	Check	Check	0.447569444	Check
1/31/2017	TFHRC 4	Check	Check	0.448888889	Check
1/31/2017	TFHRC 5	Check	Check	0.45005787	Check
1/31/2017	TFHRC 6	Check	Check	0.451666667	Check
1/17/2017	ATP 1	Check	Check	0.501898148	Check
1/17/2017	ATP 2	Check	Check	0.504201389	Check
1/17/2017	ATP 3	Check	Check	0.506215278	Check
1/17/2017	ATP 4	Check	Check	0.507858796	Check
1/17/2017	ATP 5	Check	Check	0.508981481	Check
1/17/2017	ATP 6	Check	Check	0.510219907	Check
1/17/2017	ATP 7	Check	Check	0.511736111	Check
1/17/2017	ATP 8	Check	Check	0.5128125	Check
1/17/2017	ATP 9	Check	Check	0.513831019	Check
1/17/2017	ATP 10	Check	Check	0.514884259	Check
1/17/2017	ATP 11	Check	Check	0.185590278	Check
1/17/2017	ATP 12	Check	Check	0.187210648	Check
1/17/2017	ATP 13	Check	Check	0.188425926	Check
1/17/2017	ATP 14	Check	Check	0.190289352	Check
1/17/2017	ATP 15	Check	Check	0.191863426	Check

Table A-4. Complete Data Analysis – Hypothesis 5 (VEA)

Test Number	Type of Message	True Distance (m)	Speed (MPH)	Expected Distance (m)	Difference (m)
TFHRC1	Advisory	75.84	24.71	99.42	23.58
	Alert	55.45	25.23	57.80	2.35
	Warning	48.74	24.98	49.10	0.36
TFHRC2	Advisory	85.52	25.95	104.41	18.89
	Alert	51.67	24.61	55.88	4.21
	Warning	45.15	24.33	47.51	2.36
TFHRC3	Advisory	78.76	23.81	95.80	17.04
	Alert	58.27	25.90	59.89	1.62
	Warning	51.24	26.24	52.22	0.98
TFHRC4	Advisory	75.29	28.18	113.38	38.09
	Alert	60.47	27.44	64.82	4.35
	Warning	53.23	27.14	54.50	1.27
TFHRC5	Advisory	92.92	24.04	96.72	3.80
	Alert	53.50	24.23	54.72	1.22
	Warning	40.81	23.52	45.56	4.75
ATP1	Advisory			0.00	0.00
	Alert			0.00	0.00
	Warning			0.00	0.00
ATP2	Advisory	57.87	16.44	66.14	8.27
	Alert	30.74	16.40	32.89	2.15
	Warning	26.27	16.40	29.47	3.20
ATP3	Advisory	42.04	16.85	67.79	25.75
	Alert	33.00	16.72	33.70	0.70
	Warning	28.54	16.58	29.85	1.31
ATP4	Advisory	42.96	17.53	70.53	27.57
	Alert	33.46	17.91	36.79	3.33
	Warning	28.71	17.55	31.94	3.23
ATP5	Advisory			0.00	0.00
	Alert			0.00	0.00
	Warning	10.69	17.06	30.88	20.19
ATP6	Advisory	36.32	16.40	65.98	29.66
	Alert			0.00	0.00
	Warning	27.70	15.94	28.50	0.80

Test Number	Type of Message	True Distance (m)	Speed (MPH)	Expected Distance (m)	Difference (m)
ATP7	Advisory			0.00	0.00
	Alert			0.00	0.00
	Warning	19.19	18.87	34.83	15.64
ATP8	Advisory	44.92	17.41	70.05	25.13
	Alert	31.13	16.87	34.09	2.96
	Warning	26.61	16.80	30.32	3.71
ATP9	Advisory	46.94	16.28	65.50	18.56
	Alert	29.91	15.70	31.13	1.22
	Warning	25.72	15.49	27.56	1.84
ATP10	Advisory			0.00	0.00
	Alert			0.00	0.00
	Warning	6.50	25.05	49.27	42.77
ATP11	Advisory			0.00	0.00
	Alert			0.00	0.00
	Warning	19.14	23.98	46.66	27.52
ATP12	Advisory			0.00	0.00
	Alert			0.00	0.00
	Warning	4.60	22.93	44.15	39.55
ATP13	Advisory			0.00	0.00
	Alert			0.00	0.00
	Warning	27.32	25.35	50.01	22.69
ATP14	Advisory			0.00	0.00
	Alert			0.00	0.00
	Warning	23.58	23.61	45.77	22.19
ATP15	Advisory			0.00	0.00
	Alert			0.00	0.00
	Warning	11.07	24.59	48.14	37.07
ATP16	Advisory	56.68	19.82	79.74	23.06
	Alert			0.00	0.00
	Warning	15.02	19.06	35.25	20.23
ATP17	Advisory			0.00	0.00
	Alert			0.00	0.00
	Warning	31.83	24.20	47.20	15.37

Table A-5. Complete Data Analysis – Hypothesis 6 (MDEA)

Test Number	Type of Message	True Distance (m)	Speed (MPH)	Expected Distance (m)	Difference (m)
TFHRC1	Advisory	87.56	22.90	92.13	4.57
	Alert	53.20	25.09	57.36	4.16
	Warning	46.51	24.87	48.83	2.32
TFHRC2	Advisory	99.28	25.14	101.15	1.87
	Alert	52.76	24.47	55.46	2.70
	Warning	46.24	24.15	47.07	0.84
TFHRC3	Advisory	89.52	23.04	92.70	3.18
	Alert	55.95	26.03	60.30	4.36
	Warning	48.90	26.17	52.05	3.15
TFHRC4	Advisory	97.52	25.14	101.15	3.63
	Alert	62.90	27.69	65.64	2.74
	Warning	48.44	26.93	53.96	5.52
TFHRC5	Advisory	96.13	24.06	96.80	0.67
	Alert	52.42	24.20	54.63	2.21
	Warning	40.80	23.57	45.68	4.88
ATP1	Advisory	59.38	21.83	87.83	28.45
	Alert	43.14	21.20	45.80	2.66
	Warning	36.44	21.11	39.89	3.45
ATP2	Advisory	64.52	16.41	66.02	1.50
	Alert	32.96	16.91	34.19	1.23
	Warning	26.00	16.01	28.65	2.65
ATP3	Advisory	62.12	16.28	65.50	3.38
	Alert	32.00	16.55	33.27	1.27
	Warning	27.07	16.41	29.49	2.42
ATP4	Advisory	64.20	16.46	66.22	2.02
	Alert	33.00	17.80	36.50	3.50
	Warning	28.78	17.04	30.84	2.06
ATP5	Advisory	66.73	16.77	67.47	0.74
	Alert	34.00	18.47	38.28	4.28
	Warning	29.72	18.07	33.07	3.35
ATP6	Advisory	61.00	16.28	65.50	4.50
	Alert	31.00	16.37	32.81	1.81
	Warning	25.00	15.97	28.57	3.57

Test Number	Type of Message	True Distance (m)	Speed (MPH)	Expected Distance (m)	Difference (m)
ATP7	Advisory	75.00	19.72	79.34	4.34
	Alert	38.82	19.14	40.08	1.26
	Warning	34.00	19.46	36.14	2.14
ATP8	Advisory	66.59	17.44	70.17	3.58
	Alert	32.63	16.82	33.96	1.33
	Warning	29.00	16.82	30.37	1.37
ATP9	Advisory	66.05	16.59	66.75	0.70
	Alert	29.00	15.56	30.78	1.78
	Warning	23.65	15.61	27.81	4.16
ATP10	Advisory	92.14	24.91	100.22	8.08
	Alert	58.59	26.88	63.01	4.42
	Warning	52.00	26.44	52.73	0.73
ATP11	Advisory	84.85	24.87	100.06	15.21
	Alert	53.76	24.87	56.68	2.92
	Warning	47.16	24.83	48.73	1.57
ATP12	Advisory	90.01	24.33	97.89	7.88
	Alert	53.95	24.20	54.63	0.68
	Warning	41.03	23.30	45.03	4.00
ATP13	Advisory	86.15	25.59	102.96	16.81
	Alert	0.00	0.00	0.00	0.00
	Warning	49.30	25.81	51.15	1.85
ATP14	Advisory	61.19	24.91	100.22	39.03
	Alert	55.00	24.91	56.81	1.81
	Warning	38.00	24.02	46.76	8.76
ATP15	Advisory	75.46	26.03	104.73	29.27
	Alert	60.00	26.61	62.15	2.15
	Warning	31.00	26.03	51.70	20.70
ATP16	Advisory	79.31	20.89	84.05	4.74
	Alert	39.95	19.50	41.06	1.11
	Warning	35.00	19.23	35.63	0.63
ATP17	Advisory	82.43	20.49	82.44	0.01
	Alert	52.60	24.65	56.01	3.41
	Warning	47.18	24.38	47.63	0.45

Table A-6. Complete Data Analysis – Hypothesis 7

Date	Test Number	User State Change: Is Safe Icon False	Properly Processed	User State Change: Is Safe Icon True	Properly Processed
1/31/2017	TFHRC 1	11:14:38	X	11:15:04	X
1/31/2017	TFHRC 3	11:25:33	X	11:26:19	X
1/31/2017	TFHRC 4	11:44:00	X	11:44:38	X
1/31/2017	TFHRC 5	11:48:01	X	11:48:29	X
1/31/2017	TFHRC 6	11:54:08	X	11:54:44	X
1/18/2017	ATP 1	10:50:56	X	10:51:16	X
1/18/2017	ATP 2	10:56:22	X	10:56:56	X
1/18/2017	ATP 3	11:03:48	X	11:04:36	X
1/18/2017	ATP 4	11:13:55	X	11:14:17	X
1/18/2017	ATP 5	11:16:55	X	11:17:17	X
1/18/2017	ATP 6	11:19:47	X	11:20:07	X
1/18/2017	ATP 7	11:22:35	X	11:23:05	X
1/18/2017	ATP 8	11:29:37	X	11:30:13	X
1/18/2017	ATP 9	11:33:13	X	11:33:53	X
1/18/2017	ATP 10	11:36:36	X	11:37:08	X
1/19/2017	ATP 11	4:50:35	X	4:50:57	X
1/19/2017	ATP 13	4:58:06	X	4:58:28	X
1/19/2017	ATP 14	5:01:44	X	5:02:02	X
1/19/2017	ATP 15	5:05:42	X	5:06:00	X
1/19/2017	ATP 16	5:09:03	X	5:09:29	X

Table A-7. Complete Data Analysis – Hypothesis 8 & 9

Test Number	Analyze the percentage of PMM messages properly processed by in-vehicle devices.			Analyze the percentage of PMM-RSP messages properly processed by mobile devices.				Analyze the percentage of PMM-Cancel messages properly processed by in-vehicle devices.	
	MDEA Log – PMM Send occurrence	MDEA Log – PMM contents	VEA Log – PMM Receive occurrence	VEA Log – Driver acceptance	VEA Log – PMM-RSP Send occurrence	MDEA Log – PMM-RSP Receive occurrence	MDEA Log – Coordination Status	MDEA Log – PMM-Cancel Sent Occurrence	VEA Log – PMM-Cancel Received Occurrence
TFHRC 1	Check	All Present	Check	Check	Check	Check	Check	Check	Check
TFHRC 2	Check	All Present	Check	Check	Check	Check	Check	Check	Check
TFHRC 3	Check	All Present	Check	Check	Check	Check	Check	Check	Check
TFHRC 4	Check	All Present	Check	Check	Check	Check	Check	Check	Check
TFHRC 5	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 1	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 2	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 3	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 4	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 5	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 6	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 7	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 8	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 9	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 10	Check	All Present	Check	Check	Check	Check	Check	Check	Check

Test Number	Analyze the percentage of PMM messages properly processed by in-vehicle devices.			Analyze the percentage of PMM-RSP messages properly processed by mobile devices.				Analyze the percentage of PMM-Cancel messages properly processed by in-vehicle devices.	
	MDEA Log – PMM Send occurrence	MDEA Log – PMM contents	VEA Log – PMM Receive occurrence	VEA Log – Driver acceptance	VEA Log – PMM-RSP Send occurrence	MDEA Log – PMM-RSP Receive occurrence	MDEA Log – Coordination Status	MDEA Log – PMM-Cancel Sent Occurrence	VEA Log – PMM-Cancel Received Occurrence
ATP 11	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 12	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 13	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 14	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 15	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 16	Check	All Present	Check	Check	Check	Check	Check	Check	Check
ATP 17	Check	All Present	Check	Check	Check	Check	Check	Check	Check

Table A-8. Complete Data Analysis – Hypothesis 10

Date	Test Number	Analyze the Success Rate of Receiving a PMM-Arrive Message	
		VEA Log – PMM-ARRIVE Send Occurrence	MDEA Log – PMM-ARRIVE Receive Occurrence
1/31/2017	TFHRC 1	Fail	Fail
1/31/2017	TFHRC 2	Check	Check
1/31/2017	TFHRC 3	Check	Check
1/31/2017	TFHRC 4	Check	Check
1/31/2017	TFHRC 5	Check	Check
1/31/2017	TFHRC 6	Check	Check
1/31/2017	TFHRC 7	Check	Check
1/18/2017	ATP 1	Not Available	Check
1/18/2017	ATP 2	Not Available	Check
1/18/2017	ATP 3	Not Available	Check
1/18/2017	ATP 4	Not Available	Check
1/18/2017	ATP 5	Not Available	Check
1/18/2017	ATP 6	Not Available	Check
1/18/2017	ATP 7	Not Available	Check
1/18/2017	ATP 8	Not Available	Check
1/18/2017	ATP 9	Not Available	Check
1/18/2017	ATP 10	Not Available	Check
1/20/2017	ATP 11	Check	Check
1/20/2017	ATP 12	Check	Check
1/20/2017	ATP 13	Check	Check
1/20/2017	ATP 14	Check	Check
1/20/2017	ATP 15	Check	Check

Table A-9. Complete Data Analysis – Hypothesis 13 (Part A)

Test Number	Coordination Request Sent by Y	Coordination Request Received by X	Request Confirmed by X	Confirmation Received by Y	Coordination Request Sent by Z	Coordination Request Received by X	Request Confirmed by X	Confirmation Received by Z	Coordination Heart Beat Transmitted by Y & Z	Heart Beat Response received by X	Ride Arrived Messages
TFHRC 1	Fail. Traveler Y could not join the ad-hoc travel group.										
TFHRC 2	Check	check	check	check	4:10:47	check	check	check	check	check	4:13:03
TFHRC 3	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
TFHRC 4	Fail. Traveler Y could not join the ad-hoc travel group.										
TFHRC 5	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
TFHRC 6	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
TFHRC 7	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
TFHRC 8	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
TFHRC 9	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
TFHRC 10	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
ATP 1	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
ATP 2	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check

Test Number	Coordination Request Sent by Y	Coordination Request Received by X	Request Confirmed by X	Confirmation Received by Y	Coordination Request Sent by Z	Coordination Request Received by X	Request Confirmed by X	Confirmation Received by Z	Coordination Heart Beat Transmitted by Y & Z	Heart Beat Response received by X	Ride Arrived Messages
ATP 3	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
ATP 4	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
ATP 5	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
ATP 6	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
ATP 7	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	No ride arrives received
ATP 8	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
ATP 9	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	No ride arrives received
ATP 10	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
ATP 11	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
ATP 12	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	No ride arrives received
ATP 13	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
ATP 14	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check
ATP 15	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check	Check

Table A-10. Complete Data Analysis – Hypothesis 13 (Part B)

Test Number	Coordination Cancel by Walking Away	Coordination Cancel by Manual Request	Disband Group after Entering into Vehicle
TFHRC 1	Check	This step not tested on this day.	
TFHRC 2	Check	This step not tested on this day.	
TFHRC 3	Check	This step not tested on this day.	
TFHRC 4	Check	This step not tested on this day.	
TFHRC 5	Check	This step not tested on this day.	
TFHRC 6	This step not tested on this day.	Check	Check
TFHRC 7	This step not tested on this day.	Check	Check
TFHRC 8	This step not tested on this day.	Check	Check
TFHRC 9	This step not tested on this day.	Check	Check
TFHRC 10	This step not tested on this day.	Check	Check
ATP 1	Check	Check	Check
ATP 2	Check	Check	Check
ATP 3	Check	Check	Check
ATP 4	Check	Check	Check
ATP 5	Check	Check	Check
ATP 6	Check	Check	Check
ATP 7	Check	Check	Check
ATP 8	Check	Check	Check
ATP 9	Check	Check	Check

Test Number	Coordination Cancel by Walking Away	Coordination Cancel by Manual Request	Disband Group after Entering into Vehicle
ATP 10	Check	Check	Check
ATP 11	Fail. Could not cancel by distance.	Check	Check
ATP 12	Check	Check	Check
ATP 13	Fail. Could not cancel by distance.	Check	Check
ATP 14	Check	Check	Check
ATP 15	Check	Check	Check

APPENDIX B. 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
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
PR	Performance Requirement
PSM	Personal Safety Message
REA	Roadside Experimental Application
RSU	Roadside Unit
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 C. 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 establish 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)
Wi-Fi	Local area wireless technology that allows enabled devices to connect to the Internet

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