Connected Commercial Vehicles—Integrated Truck Project

Model Deployment Operational Analysis Report

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16. Abstract

Connected vehicle wireless data communications can enable safety applications that may reduce injuries and fatalities suffered on our roads and highways, as well as enabling reductions in traffic congestion and impacts on the environment. As a critical part of achieving these goals, the USDOT contracted with a Team led by Battelle to integrate and validate connected vehicle on-board equipment (OBE) and safety applications on selected Class 8 commercial vehicles and to support those vehicles in research and testing activities that provide information and data needed to assess their safety benefits and support regulatory decision processes.

This document describes the operational experience of the integrated commercial vehicles in the Safety Pilot Model Deployment. It includes the travel distances, safety application alert counts and rates, communication interactions, and the ability of DSRC units onboard these vehicles to receive other vehicles' messages.

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Executive Summary

Connected vehicle telecommunications for vehicle data can transform vehicle travel in North America, enabling major reductions in injuries and fatalities suffered on our roads and highways, as well as enabling reductions in traffic congestion and effects on the environment. Under this Connected Commercial Vehicle Safety Applications Development Program, the USDOT has contracted with a Team led by Battelle to integrate connected vehicle onboard equipment (OBE) and safety applications on selected Class 8 commercial vehicles and to support those vehicles in research and testing that provide information and data needed to assess their safety benefits and support regulatory decision processes.

This report summarizes the results of Task 8 of the project in which the integrated trucks participated in the Safety Pilot Model Deployment. For more than one year, approximately 2800 vehicles with V2V collision avoidance technology drove in the Ann Arbor, Michigan, geographic area. Among these vehicles were the three truck tractors in which V2V technology had been integrated as part of this project, each in combination with a trailer. The tractors exchanged Basic Safety Messages (BSMs) with the other vehicles, and alerts were generated.

Nearly 14,000 miles of data were collected as the tractors drove within a 10-km radius, and more than 55,000 encounters between vehicles. More than 2800 driver alerts were generated by the V2V applications, an average of approximately one alert every five miles.

The Safety Pilot Model Deployment produced a database with tens of billions of records, including every BSM broadcast by every light, commercial, and transit vehicle during the study. These records provide a rich opportunity to examine the reliability of message capture in various circumstances. More than 90 percent of the BSMs broadcast by vehicles 20 m behind to 80 m ahead of the instrumented tractor were recorded by the tractor. While BSMs were occasionally dropped, 97 percent of the encounters had gaps of no more than 0.3 s.

Chapter 1 Introduction

As part of the Connected Commercial Vehicles—Integrated Truck (CCV-IT) Project, three truck tractors were equipped with safety equipment enabled by Dedicated Short-Range Communication (DSRC). Vehicles with this technology broadcast radio signals indicating their position and other information to surrounding vehicles. This information is intended to help drivers avoid crashes. The project has evaluated the technology in a number of ways, culminating in the Safety Pilot Model Deployment, where the three equipped tractors drove in and around Ann Arbor, Michigan along with approximately 2800 other similarly equipped light vehicles, tractors, and transit buses.

In this project conducted for the United States Department of Transportation (USDOT), equipment to provide vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) safety was integrated with new commercial vehicles. The integrated trucks were equipped with four V2V safety applications:

- Forward Collision Warning (FCW),
- Emergency Electronic Brake Lights (EEBL),
- Lane Change Warning and Blind Spot Warning (LCW),
- Intersection Movement Assist (IMA),

and two V2I safety applications:

- Curve Speed Warning (CSW) and
- Bridge Height Inform (BHI).

This report presents a summary of the CCV integrated truck experience in the Model Deployment, including:

- A description of the integrated trucks, the safety applications, and the travel of the integrated trucks within the Model Deployment area,
- The scope of the integrated trucks' interactions with other vehicles in the study, including episodes of wireless communication between vehicles and the driver alerts that occurred within the integrated trucks,
- A study of the communication performance associated with the integrated trucks, particularly seeking any issues that appear to be truck-specific, and
- A summary of the overall experiences of the integrated trucks in the Model Deployment.

Chapter 2 Description of the Experiment

Computers, specialized radios, GPS receivers, and specialized antennas were installed on three new truck tractors. The computers had software that implemented six collision-avoidance safety applications. Four of the applications communicated with other vehicles to avoid vehicle-to-vehicle crashes, and two of the applications communicated with the fixed infrastructure for avoiding single-vehicle crashes. In addition to the equipment to implement the safety applications, the tractors were equipped with equipment for recording the vehicles' positions, messages sent and received, and the alerts that were generated. This recorded data was analyzed to assess the performance of the collision avoidance technology.

CCV Integrated Trucks

The integrated trucks specified by the USDOT team and were 2012 Freightliner Cascadia tractors with tandem drive axles. They were outfitted in the course of this project with prototype CCV hardware and software to provide connected vehicle safety application functions. The functions consist of driver warnings to help prevent specific types of vehicle crashes. No vehicle or powertrain control functions are affected by the CCV system. The three CCV-IT tractors are shown in Figure 2-1:

- a blue day cab on the left
- a red mid-roof sleeper cab in the middle
- a white raised-roof sleeper cab on the right.

The CCV functionality and equipment is the same on all vehicles, except for minor details of installation. The type of cab played no role in the Model Deployment except that the size and maneuverability of the day cab was more suited to the urban routes than the sleepers.

UMTRI

Figure 2-1. CCV-IT tractors used in the Safety Pilot Model Deployment.

The integrated CCV package can be considered as two subsystems: the safety application system and the data acquisition system (DAS). The safety applications are explained in the final report for this project [2], and the DAS is fully described in a separate report [1].

The safety applications used the DSRC were developed by MBRDNA using the DENSO wireless safety unit (WSU) which provides the DSRC communications with other vehicles, in addition to other support functions. The safety applications include

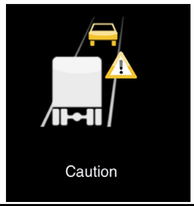
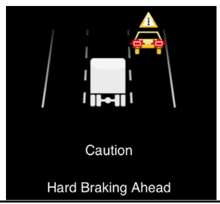
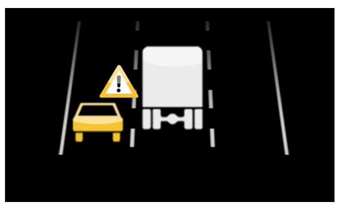
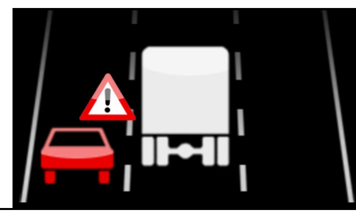
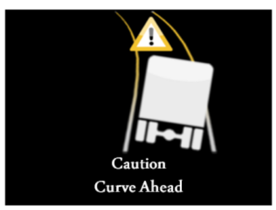
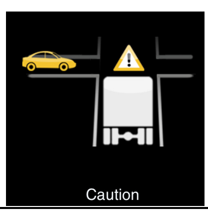
- **Forward Collision Warning (FCW):** provides audible and visual cues intended to help the driver avoid or mitigate crashing into the rear end of other vehicles.
- **Emergency Electronic Brake Lights (EEBL):** provides audible and visual cues to the driver when there is hard braking by a same-direction vehicle that is ahead in the vehicle stream (not necessarily the vehicle directly ahead).
- **Curve Speed Warning (CSW):** provides the driver with audible and visual cues when the driver appears to be heading toward a curve at a speed that may be higher than desired.
- **Lane Change Warning (LCW):** provides the driver with audible and visual cues when the driver initiates a turn signal or a lane change while same-direction adjacent vehicle traffic is present.
- **Intersection Movement Assist (IMA):** provides the driver with audible and visual cues if the driver begins to accelerate from rest on a side road or driveway onto a roadway, and there is cross-traffic nearby.
- **Bridge Height Inform (BHI):** provides the driver with information about bridge heights in the general area.

Note, of course, that the vehicle-to-vehicle applications presume that other vehicles are broadcasting the DSRC standard basic safety message (BSM). The CCV function will not respond to a crash threat posed by another vehicle unless it is equipped with the connected vehicle equipment and is broadcasting BSMs with appropriate security credentials.

Table 2-1 shows the cues that are given to the driver as part of the safety applications. The cues are given to the driver using a prototype display and speakers installed in the cab as part of this project. The display is an iPad mounted on the instrument panel, which has 1024 x 768 pixels on a 9.7-in. diagonal screen. Some applications include both an “inform” message to inform the driver about a lesser potential crash risk as well as a “warning” for conflicts that are perceived to have higher and more imminent crash risk. The term “alert” is used to refer to both inform-level and warning-level cues provided to drivers.

The DAS is used to capture data for the analysis of system performance, driver interactions, and ultimately the safety benefit of the safety applications. The DAS captures signals from the vehicle, the driver’s throttle and steering inputs, the safety applications, and more. The DAS also includes a number of sensors installed for the purpose of analyzing the experiment.

Table 2-1. The images in this table were displayed on the iPad when an alert occurred.

Safety Application	Inform	Warning (with audible tones)
Forward Collision Warning (FCW)		
Emergency Electronic Brake Light (EEBL)		
Blind Spot Warning (BSW)		
Curve Speed Warning (CSW)		
Intersection Movement Assist (IMA)		
Bridge Height Inform (BHI)		(BHI did not have a warning-level alert.)

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Operation in the Model Deployment

The Safety Pilot Model Deployment was intended to explore how well connected vehicle safety technologies and systems work in a real-life environment with real drivers and vehicles. Over 2800 vehicles and 29 infrastructure sites (mainly signalized intersections) were instrumented with V2V and V2I technology. The geographical center of the Model Deployment is the northeast region of Ann Arbor, Michigan, which is a medium size community of 116,000 people and home of the University of the Michigan. The Model Deployment geographical area (MDGA) is considered to be an urban environment with a mixture of major and minor surface streets which service large institutions including the University of Michigan, technology centers for several automobile manufacturers, many City of Ann Arbor public schools, and a vibrant business environment.

The Safety Pilot Test Conductor sought fleets in the area that could use the CCV integrated tractors in their normal operations. This became a challenge in part because two of the tractors (Red and White) were built as over-the-road sleeper units and therefore were not ideal for regular use in an urban environment where tight turning radius and good visibility are critical. The third tractor (Blue) was built as a day cab; however, it has an unusually long wheel-base (and large turning radius) and tandem drive-axle suspension making it unfavorable for fleets that regularly operate in a city environment. The configurations had been specified by USDOT well before selection of the Model Deployment region , and they had other considerations beside use in the Model Deployment. Two commercial fleets did operate the tractors in the early months of the Model Deployment, but UMTRI drivers later took over and operated them on fixed routes to provide better interaction with other vehicles in the Model Deployment.

The fleets were 4H Transportation Inc. and Rightaway Delivery, LLC. Table 2-2 shows the timeline of the Safety Pilot including the fleet affiliations over time for each of the trucks. The table shows that a total of nine drivers used the vehicles, including four commercial fleet drivers and five UMTRI drivers.

The blue day-cab tractor was assigned to the Rightaway Delivery fleet. Rightaway parked the blue tractor at UMTRI and made nightly runs (generally starting around 7 pm) to Marshall, Grand Rapids, Lansing, and St. Joseph, Michigan. These cities are between 75 and 170 miles from the starting point in Ann Arbor. All runs ended back at UMTRI in the early hours of the following day and all runs stayed within the state of Michigan. In general, exposure to the MDGA occurred at the start and end of a driver’s shift when passing near or through Ann Arbor. Rightaway employed two drivers to cover this route and both drivers participated in the study. In mid February 2013, Rightaway lost the freight contract that covered these cities and decided to end its involvement with the study.

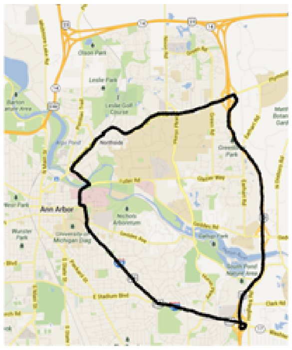
Table 2-2. Fleet and drivers assigned to integrated trucks.

Fleet (Number of Drivers)	Tractor		
	Red	**White**	**Blue**
4H Transport (2)	Jan 14—Jun 6, 2013	Jan 14—May 31, 2013	N/A
Rightaway (2)	N/A	N/A	Nov 11, 2012—Feb 15, 2013
UMTRI (5)	Jun 27—Oct 28, 2013	Jun 19—Oct 28, 2013	May 31—Oct 28, 2013

UMTRI

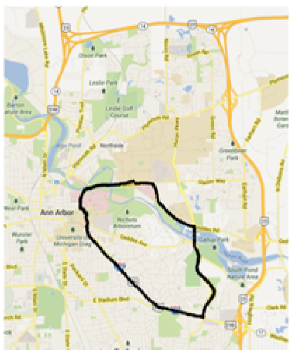
4H Transportation Inc. used the red and white sleeper tractors in its operations from mid January to early June, 2013. 4H is a small over-the-road bulk freight company that bids on the open market for the delivery of general cargo and had three tractors besides the Safety Pilot tractors. Since this mode of operation involves pick-up and delivery of freight outside of the MDGA, the fleet operators assured the Safety Pilot Test Conductor that special arrangements would be made to maximize the exposure to MDGA when the opportunity arose and the vehicles where in the area. However, market forces kept these vehicles in the southeastern United States for most of the time they were with the fleet. This low exposure to other V2V vehicles in the MDGA was not justifying the use of the vehicles, and the tractors where recalled to UMTRI in early May 2013.

To increase the exposure of these vehicles to other similarly equipped vehicles in the MDGA, the Safety Pilot Test Conductor began driving these vehicles with empty trailers in the MDGA in late May and June 2013. Four UMTRI drivers were assigned to the three tractors with the goal of having two tractors driven every weekday for a total of four hours each on two shifts during the peak traffic times in the morning and late afternoon. A fifth driver drove only occasionally. The routes used by the UMTRI drivers are shown in Figure 2-2. Drivers were instructed to drive the routes in both directions. The drivers were instructed to drive as they normally would–safely–and not attempt to either provoke or avoid the driver alerts.



Route 1: Plymouth/Washtenaw/US23

- Plymouth Rd between US23 and Maiden Lane (City Truck Route)
- Maiden Lane between Plymouth Rd and Fuller Rd (City Truck Route)
- Glen Ave between Maiden Lane and E Huron St (City Truck Route)
- E Huron St between Glen Ave and Washtenaw Ave (MDOT Trunkline)
- Washtenaw Ave between E Huron St and US23 (MDOT Trunkline)
- US23 between Washtenaw Ave and Plymouth Rd (Freeway)

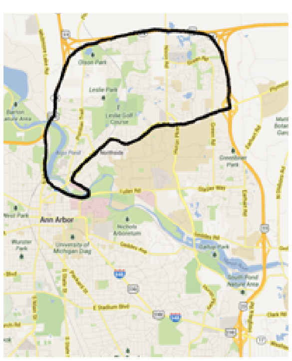


Route 2: Huron Pkwy/Fuller/Glen/Washtenaw

- Huron Pkwy between Washtenaw Ave and Fuller/Geddes Rd
- Fuller Rd between Huron Pkwy and Glen Ave
- Glen Ave between Maiden Lane and E Huron St (City Truck Route)
- E Huron St between Glen Ave and Washtenaw Ave (MDOT Trunkline)
- Washtenaw Ave between E Huron St and Huron Pkwy (MDOT Trunkline)

Route 3: Huron Pkwy/Plymouth/Maiden Lane/Fuller Rd

- Huron Pkwy between Fuller Rd and Plymouth Rd
- Plymouth Rd between Huron Pkwy and Maiden Lane (City Truck Route)
- Maiden Lane between Plymouth Rd and Fuller Rd (City Truck Route)
- Fuller Rd between Glen Ave and Huron Pkwy



Route 4: US23/M14/Main/Depot/Fuller/Maiden Lane/Plymouth

- US23 between Plymouth Rd and M14 (Freeway)
- M-14 between US23 and Main St (Freeway)
- Main St between M14 and Depot (City Truck Route)
- Depot between Main St and Fuller Rd
- Fuller Rd between Depot and Maiden Lane (City Truck Route)
- Maiden Lane between Fuller Rd and Plymouth Rd (City Truck Route)
- Plymouth Rd between Maiden Lane and US23 (City Truck Route)

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Figure 2-2. UMTRI routes for CCV-IT driving.

Description of Data

Numerous data sources were used. Below is a brief overview of these data archives to provide context and scope to the type, quantity, and thoroughness of the entire Model Deployment data archive. Since the findings here give a general overview of the CCV-IT operations during Model Deployment, not all data sources listed below were used in these findings.

Over-the-Air Sent Basic Safety Messages

A database of all the wireless messages sent by all vehicles participating in the Model Deployment was constructed by the Safety Pilot Test Conductor, using data provided by the teams that provided vehicles for the test. This database was available for use by the CCV team. (Note that UMTRI is part of the CCV team and was also the Safety Pilot Test Conductor).

This database was constructed as follows: All vehicles participating in Safety Pilot were equipped with technology to broadcast the Basic Safety Message (BSM), as defined by the draft standard SAE J2735. The content of a BSM can vary in complexity, but at a minimum must include information about the vehicle position (location and elevation), motion (speed, heading, and acceleration), brake system status, and size (width and length). The message also includes a message count, a limited time stamp (milliseconds within the current minute), and a temporary ID. The temporary ID is a 4-byte random number that changes every five minutes to ensure the overall anonymity of the vehicle; however, for Model Deployment the bytes 3 and 4 are fixed to represent a unique ID assigned by the Safety Pilot Conductor. This allows all BSM to be associated with a vehicle in the Model Deployment. Bytes 1 and 2 of the Temporary ID remain are unchanged and randomly change periodically

In addition to this minimum content, optional parts can be appended to a BSM. These include the Vehicle Safety Extension and Vehicle Status data frames. BSMs in the Model Deployment required that the Vehicle Safety Extension part of the BSM include the Event Flag (to indicate events such as a hard braking, stability control, anti-lock brake, or air-bag deployment), the Path History, and the Path Prediction data frames. Populating other parts of the Vehicle Safety Extension and Vehicle Status components of the BSM was allowed but not required. Two additional requirements for DSRC devices in Model Deployment were that they broadcast the BSM at a rate of 10 messages per second (10 Hz) and that the device log all broadcasted, over-the-air (OTA) BSMs within the device.

The archive of sent BSM messages downloaded from all vehicles during Model Deployment constitutes a major data source for some of the analyses in this report. With over 2800 vehicles deployed for a year or more, the number of sent OTA BSMs is in the tens of billions. A key responsibility of the Safety Pilot Test Conductor was the collection of all OTA BSMs and the creation of a relational database that accurately contains the rich content of all these messages.

Data Collected from Data Acquisition System (DAS)

There were 116 DAS-equipped vehicles in Model Deployment. That includes all three of the CCV integrated tractors, eight CCV Retrofit Safety Device (RSD) heavy vehicles, three Transit Safety Retrofit Package (TRP) transit buses, and 100 aftermarket safety device (ASD) passenger vehicles. (Data from the integrated passenger vehicles from CAMP and the RSD vehicles from Southwest Research Institute was not available to the CCV team.) The DAS units recorded the following data, generally at 10 Hz:

- **Vehicle CAN.** Examples of these signals include accelerator pedal, brake pedal, cruise control status, engine speed, fuel use, head lamp state, odometer, speed, turn-signal, wiper, etc. Overall, there were several different vehicle types up-fit with DAS for Model Deployment and each of these vehicle types had a unique set of signals available from the CAN. Common signals among the fleet were standardized by the DAS and recorded in a consistent format for archiving in a database, while unique signals were saved in distinct records specific for each vehicle type.
- **UMTRI GPS.** The DAS includes its own GPS receiver to record the standard list of GPS signals like latitude, longitude, altitude, heading, speed, number of satellites, etc. Also important is the logging of very accurate GPS time signals (using a 10 s sync pulse). These time signals allow the association of DAS collected data to other data saved in Model Deployment like the OTA sent BSM archive.
- **UMTRI Sensor Cluster.** An independent vehicle motion sensor set was installed on each vehicle. This allowed the DAS to record high-resolution values of vehicle acceleration and yaw rate. The sample rate was 50 Hz.
- **Ranging Sensor.** All DAS equipped vehicles were up-fit with a vision-based ranging sensor to measure the relative position vehicles and objects in the forward scene. This sensor also provided estimates of vehicle lane position and road curvature by tracking the lane boundary marks on the roadway.
- **DSRC Devices.** Signals from the V2V equipment were also logged by the DAS. Similar to the requirement that all V2V devices log their sent OTA BSMs, devices in UMTRI DAS equipped vehicles delivered signals to the DAS that detailed information about all received BSMs and signals related to any warning or alert given to the driver via the driver-vehicle interface (DVI).
- **Video.** The UMTRI DAS logged video from four cameras. The images captured the forward scene, the right and left rearward scene, and the driver's face and head motions. The face camera included infrared illumination to enhance images in low-light conditions typical of during night driving.
- **Audio.** The UMTRI DAS logged audio from a short period surrounding warnings issued by the DSRC devices. A four second pre-trigger time and eight second post-trigger time was used to capture any audio before, during and after the warning. In general, the audio microphone was mounted near the camera that captured the driver's face.

All UMTRI DAS recorded signals are time-stamped and saved by the DAS on a trip-by-trip basis where a trip is defined by an ignition cycle. Periodically, these files are downloaded to a server and then uploaded to a database. This database is typically referred to as the Model Deployment Driving Database to distinguish it from the OTA Sent BSM Database.

The full set of data from the DAS's was provided in a previous CCV report. [1]

Road Side Equipment (RSE) Data Archive

In addition to the data archive associated with vehicles, the Model Deployment area also has infrastructure DSRC units to support security and V2I applications, and also monitors the health of the Model Deployment fleet by recording received BSM from these vehicles. These messages were saved in files by the Safety Pilot Test Conductor and were parsed to build a database of RSE received BSM messages. Structured identically to the OTA Sent BSM database, but barely a tenth the size, the RSE BSM database is used during Model Deployment to identify ‘missing’ vehicles so they can be brought into UMTRI for investigation.

In some locations, the RSE also broadcast infrastructure based messages like SPaT (Signal Phase and Timing), MAP (or GID) which spatially describes an intersection, and TIM (Traveler Information Message) for various types of advisory and road sign messages. These messages are used by the Curve Speed and Pedestrian warning V2I safety application in Model Deployment. The RSE database was not used for this report.

Other Data Archives

In addition to the RSE, OTA Sent BSM, and Driving databases, the Safety Pilot Test Conductor also created archives of facts related to all the vehicles involved in the Model Deployment, along with their drivers including subjective questionnaires about their experience with the technology. Much of these data have the potential to support analyses to explore the different dimensions of Model Deployment, such as, vehicle model or size or driver age and gender. Also, in this general category are data related to weather, traffic (counts from the City of Ann Arbor), and special applications like a V2V bicycle and V2I ice warning.

Chapter 3 Analysis of Data

This chapter first presents the amount of time and distance that the CCV-IT tractors traveled during the model deployment. Then it analyzes the exchange of BSMs with other vehicles.

Model Deployment Geographic Area

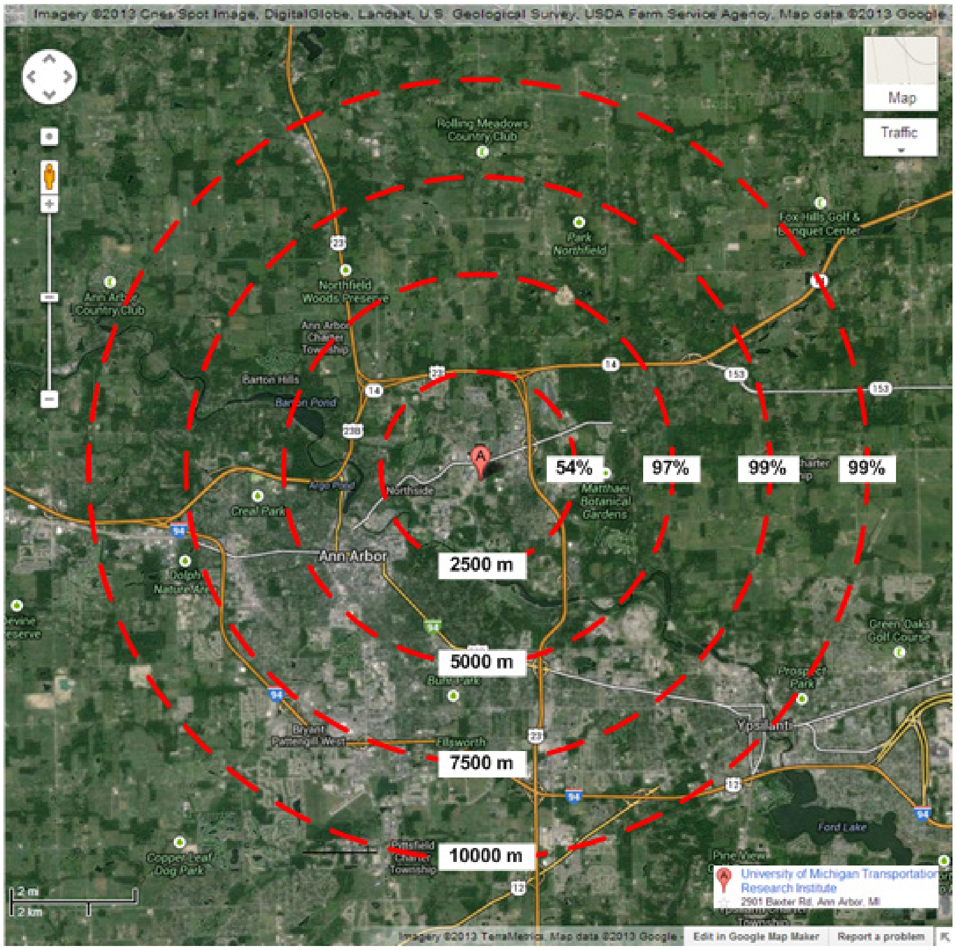
The Model Deployment Geographical Area (MDGA) is defined as a circle with a radius of 10 km centered at UMTRI, as shown in Figure 3-1. UMTRI is within 800 m of the geometric center of the roadside installations of Model Deployment and has latitude of 42.298351 degrees and a longitude of -83.703129 degrees.

The 10-km radius was chosen to include almost all message exchanges between vehicles, and yet to exclude the substantial travel by CCV vehicles away from Ann Arbor that did not include any interactions with other Model Deployment vehicles. Figure 3-1 shows the cumulative fraction of V2V interactions as function of distance from the MDGA center. The MDGA contains over 98.9 percent of all interactions between a CCV-IT tractor and other V2V-equipped vehicles.

Analysis of message exchanges excludes interactions that occur within 150 m of UMTRI because there is a substantial amount of non-naturalistic message broadcasting that occurs as vehicles and systems are tested before and after installation on vehicles, and as researchers continue development of broadcasting devices.

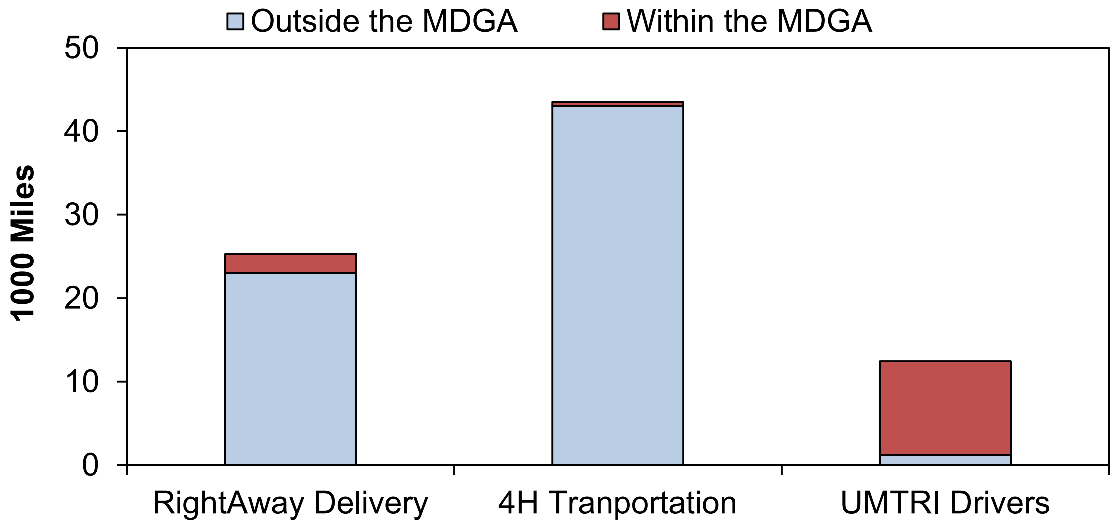
Travel During the Model Deployment

A total of 81,209 miles traveled by the three CCV-IT tractors is available for analysis. These miles exclude trips identified as having potential data quality issues, such as problematic CCV system behavior or suspect data collection. Trips with known hardware or software failures and those dedicated to application testing were also excluded. For reference the actual total distance traveled by the CCV-IT tractors was 118,226 miles in 2369 trips. Figure 3-2 shows the number of miles driven by the two commercial fleets and by the UMTRI drivers. It distinguishes between miles in the MDGA and those outside the area.



UMTRI

Figure 3-1. CCV-IT message interactions (cumulative fraction) as a function of distance from UMTRI.



UMTRI

Figure 3-2. Distances traveled by the three fleets during Model Deployment.

Travel by drivers in the 4H and Rightaway fleets was mostly outside the MDGA, as Table 3-1 shows: only nine percent of Rightaway and one percent of 4H Transportation travel distance was within the 10 km radius that defines the MDGA. This, of course, was one of the reasons for UMTRI CDL-equipped staff to drive the tractors with trailers around the MDGA. The travel by UMTRI drivers summed up to 11,237 miles out of the total of 13,957 miles in the MDGA, i.e., UMTRI professionals accounted for 81 percent of MDGA travel despite the fact that they account for only 12,432 of the 81,209 miles (or 15 percent) of the total distance by CCV-IT tractors during the Model Deployment.

The values of travel distance and some other measures are not broken down by UMTRI driver because there is no reason to study individual members' experiences. This statement assumes that these UMTRI drivers may not qualify as useful subjects in any human factors or behavioral analysis because they are accustomed to advanced safety technologies and were well aware of the purpose of the Model Deployment. Thus they may not be representative of drivers who would eventually use the V2V and V2I technologies on heavy vehicles.

Table 3-1. Travel in Safety Pilot by tractor, driver, and fleet.

Tractor	Driver	Fleet	All Travel			Travel in MDGA		Percent Travel within MDGA	
			Trips	Hours	Miles	Hours	Miles	Hours	Miles
Blue	1	Rightaway	321	447	19564	68	1757	15%	9%
Blue	2	Rightaway	115	143	5718	21	535	15%	9%
Red	1	4H	300	588	21747	10	172	2%	1%
White	2	4H	254	947	21749	22	256	2%	1%
Blue	1	UMTRI	233	236	4580	222	4166	94%	91%
Red	2	UMTRI	196	222	4344	219	4273	99%	98%
White	3	UMTRI	123	167	3508	143	2798	86%	80%
Totals			1,542	2,750	81,210	705	13,957	26%	17%

UMTRI

Trailer configurations during travel were different with the three fleets as well. 4H Transportation and Rightaway Delivery ran primarily with 53-ft van trailers, but their relatively low operation near Ann Arbor means that the exact configurations are not important in analysis. The UMTRI drivers were almost always in the MDGA and ran with a variety of van trailers, as shown in Table 3-2 below. The 40-ft trailer was an intermodal container on a chassis trailer.

Table 3-2. Trailer lengths during UMTRI drivers' travel in the MDGA.

Tractor	Trailer Length (ft)	Start Date	End Date	Distance (miles)
Blue	48	8/23/13	9/3/13	384
	40	9/3/13	10/29/13	1594
Red	53	8/23/13	10/29/13	2018
White	40	8/26/13	9/6/13	173
	48	9/6/13	10/29/13	885

UMTRI

Encounters during the Model Deployment

An encounter is the defined as the CCV-IT receiving multiple BSMs from a distinct remote vehicle in which the duration of the event is at least 0.5 s and the inter-message time-gap between any two successive messages is less than 5.0 s. Table 3-3 shows overall summary statistics of encounters as function of fleet, driver, and CCV-IT tractor during Model Deployment. The table is divided into three parts. The upper part shows statistics for all encounters. The middle part shows statistics for encounters within the Model Deployment Geographical Area (i.e., within 10 km of UMTRI). The lower part shows statistics for encounters outside the MDGA. In addition to the number and fraction of encounters, the table shows cumulative time and distance for all encounters and overall average duration and distance for each category.

The table illustrates that the majority of encounters (97 percent) occurred with UMTRI drivers in the MDGA. Of the CCV-IT tractors being driven by UMTRI drivers, the white High-roof sleeper had the fewest encounters. This is not surprising given the relative overall summary exposure statistics given in Table 3-1.

Table 3-3. The number of encounters during the Model Deployment.

All Encounters					**Total**		**Average**	
Fleet	Driver	Tractor	Count	Fraction	Time, hr	Dist, miles	Time, s	Dist. m
Rightaway	1	Blue	1171	0.021	15.9	235	49	323
	2	Blue	406	0.007	6.4	90	57	358
4H	1	Red	99	0.002	1.3	23	46	381
	2	White	40	0.001	0.1	6	12	246
UMTRI	1	Blue	22271	0.399	202.0	3004	33	217
	2	Red	20253	0.363	157.0	2423	28	193
	3	White	11609	0.208	95.7	1510	30	209
Total			55849	1.000	478	7292	36	275
Encounters in the MDGA					**Total**		**Average**	
Fleet	Driver	Tractor	Count	Fraction	Time, hr	Dist, miles	Time, s	Dist. m
Rightaway	1	Blue	981	0.018	14.7	170	54	280
	2	Blue	340	0.006	5.9	63	63	300
4H	1	Red	64	0.001	1.0	11	59	269
	2	White	18	0.000	0.1	3	12	306
UMTRI	1	Blue	22265	0.401	201.9	3003	33	217
	2	Red	20251	0.365	157.0	2422	28	193
	3	White	11589	0.209	95.7	1506	30	209
Total			55508	1.000	476	7179	40	253
Encounters not in the MDGA					**Total**		**Average**	
Fleet	Driver	Tractor	Count	Fraction	Time, hr	Dist, miles	Time, s	Dist. m
Rightaway	1	Blue	190	0.557	1.2	65	22	547
	2	Blue	66	0.194	0.5	27	25	659
4H	1	Red	35	0.103	0.2	13	23	585
	2	White	22	0.065	0.1	3	12	197
UMTRI	1	Blue	6	0.018	0.0	1	10	278
	2	Red	2	0.006	0.0	0	2	63
	3	White	20	0.059	0.1	5	14	373
Total			341	1.000	2	113	15	386

UMTRI

Number of Alerts Generated

This section presents the number of driver alerts generated by the safety applications onboard the integrated trucks. The alerts addressed include inform-level alerts (visual cues) and warning-level alerts (both audio and visual cues). The generated alerts are defined as those that the safety application requests from the DVI. Table 3-4 shows the travel distance of each fleet within the MDGA, as well as the number of each type of warning-level alerts. Curve speed warnings (CSWs) were generated on the DVI hardware (iPad), and those messages were not sent to the DAS, so there is no information on CSW alert experience. The next-to-bottom row of the table shows the percentage of all warnings that each fleet contributed to the CCV integrated truck total. The bottom row shows the ratio of each fleet's mileage within the MDGA to the number of warnings received within the MDGA by that fleet's drivers. This measure represents an average distance between warnings to give a sense of how often drivers experienced alerts.

Table 3-4 reiterates that UMTRI drivers accounted for 81 percent of the travel distance in the MDGA. That travel also accounted for 99 percent of warnings and 98 percent of inform-level alerts, as shown in the tables below. 4H had relatively little travel within the MDGA (428 miles) and their drivers also received zero warnings and only 13 inform-level alerts (three FCW and 10 BSW). Rightaway Delivery accounted for 2,292 miles of travel in the MDGA (16 percent of MDGA distance traveled), but only seven warnings and 27 inform-level alerts.

One comparison between the alert experiences of the fleets can be made by considering the bottom row of the table. There was an average of 327 miles between warnings for Rightaway, at least 428 miles for 4H, and 9.8 miles for the UMTRI drivers. The much higher rate of alerts for UMTRI drivers may be due to a combination of factors. The UMTRI drivers had presumably higher exposure to other BSM broadcasting vehicles since they operated only in rush hours and in the more concentrated areas of the MDGA. It is possible that although the UMTRI drivers were instructed to drive as they normally would, they may have been more prone to alerts. (Past field testing of crash warning systems shows that alerts vary substantially between drivers in similar operating environments.)

The EEBL and BSW warnings were relatively rare for the UMTRI drivers, compared with the much more common IMA and FCW warnings. Care is required when generalizing these results, given the small number of drivers and the possibility that they may not be representative of commercial carrier drivers. Yet the great difference suggests this would be possible in an actual deployment.

Table 3-5 is similar to Table 3-4, except inform-level alerts are addressed. The alert level represents 95 percent of all BSW messages because the BSW can occur on any multilane highway and not necessarily in a near-crash situation. FCW and IMA alerts were roughly evenly split between inform and warning level.

Finally, note that only a small fraction of vehicles in the MDGA were equipped with V2V equipment, so that this measure would need to be scaled up in order to compute an approximate rate of alerts for a hypothetical deployment in which larger numbers of vehicles are equipped. That is out of scope for this report.

Table 3-4. Warning-level alerts generated by the safety applications during travel in the MDGA.

Fleet	Rightaway	4H Transp.	UMTRI	Total in MDGA
Miles in MDGA	2292	428	11237	13957
FCW warnings	2	0	323	325
EEBL warnings	0	0	14	14
BSW warnings	1	0	24	25
IMA warnings	4	0	782	786
BHI warnings	(BHI did not have a warning-level alert.)			
CSW warnings	(CSW was not recorded in the DAS.)			
All warnings	7	0	1143	1150
Fleet fraction of all warnings	1%	0%	99%	100%
Miles / Warnings	327.4	N/A	9.8	12.1

UMTRI

Table 3-5. Inform-level alerts generated by the safety applications during travel in the MDGA.

Fleet	Rightaway	4H Transp.	UMTRI	Total in MDGA
Miles in MDGA	2292	428	11237	13957
FCW informs	3	3	276	279
EEBL informs	2	0	8	10
BSW informs	11	10	498	519
IMA informs	11	0	921	932
BHI informs	0	0	33	33
CSW informs	(CSW was not recorded in the DAS.)			
Total informs	27	13	1736	1776
Fleet fraction of all informs	2%	0%	98%	100%
Miles / Informs	84.9	32.9	6.5	7.9

UMTRI

Integrated Truck Communication

The focus in this section is to present how successfully BSMs were received during exchanges with the integrated trucks. The intention is to get a sense for whether trucks may have communication performance issues due to their unique physical properties, including large trailers. This topic can get involved and the analyses below only begin to address these concerns by presenting some basic results. Further analysis of communication between all vehicle platforms involved in the Safety Pilot Model Deployment is certainly possible given the comprehensive data resources collected during the project.

BSM Data Processing Methodology

To begin the discussion of CCV-IT communication some background material outlining the analysis approach is necessary. This serves two purposes: a) to provide an understanding of how the results shown below were derived from the data archive, and b) to scope the content and complexity of the data archive prompting additional inquiries that might be addressed by data collected in this project.

A broad outline of the steps involved in this methodology includes:

- Using received BSM from remote vehicles (uniquely identified in every BSM) logged by the UMTRI DAS, create a set of interaction events for every trip on all three CCV-IT tractors.
- For all CCV-IT trips with at least one interaction event, search the OTA Sent BSM archive and save all broadcasted BSM from all remote vehicles (regardless of location) between the start and end time of the CCV-IT trip.
- At every time step (0.1 s) in a given CCV-IT trip find all the remote vehicle BSM that were broadcast at that same time (temporal alignment of data) and calculate the geographical distance between the CCV-IT and remote vehicle based on their GPS coordinates. Save the results if the distance between the host and remote vehicle is less than 1000 m.

Compare and flag every sent BSM from each remote vehicle that matches the list of received messages recorded by the CCV-IT. Figure 3-3 and Table 3-6 shows an example of this method. The table shows the vehicle data involved, while Figure 3-3 shows the details pictorially. The map in Figure 3-3 is an instant in time when a CCV-IT (15101/Blue) tractor was surrounded by eight remote vehicles (within 1000 m).

- Calculate the East and North vectors of the remote vehicle location, using derived gain values specific to the Model Deployment area to convert latitude and longitude coordinates (degrees) to a relative East/North distance (m) from the GPS location of the CCV-IT.

Perform a coordinate transformation rotating the CCV-IT and all remote vehicle vectors to a Cartesian X/Y coordinate system. An illustration of the coordinate transformation, using heading angle, to rotate the East/North GPS coordinates to a conventional Cartesian system is shown in Figure 3-3 in the boxes below the map.

- Bin longitudinally (X) and laterally (Y) and aggregate all received (flagged) OTA sent BSM under a variety of conditions for both the CCV-IT and remote vehicles.

The dimensions of the data that can be explored at this stage include:

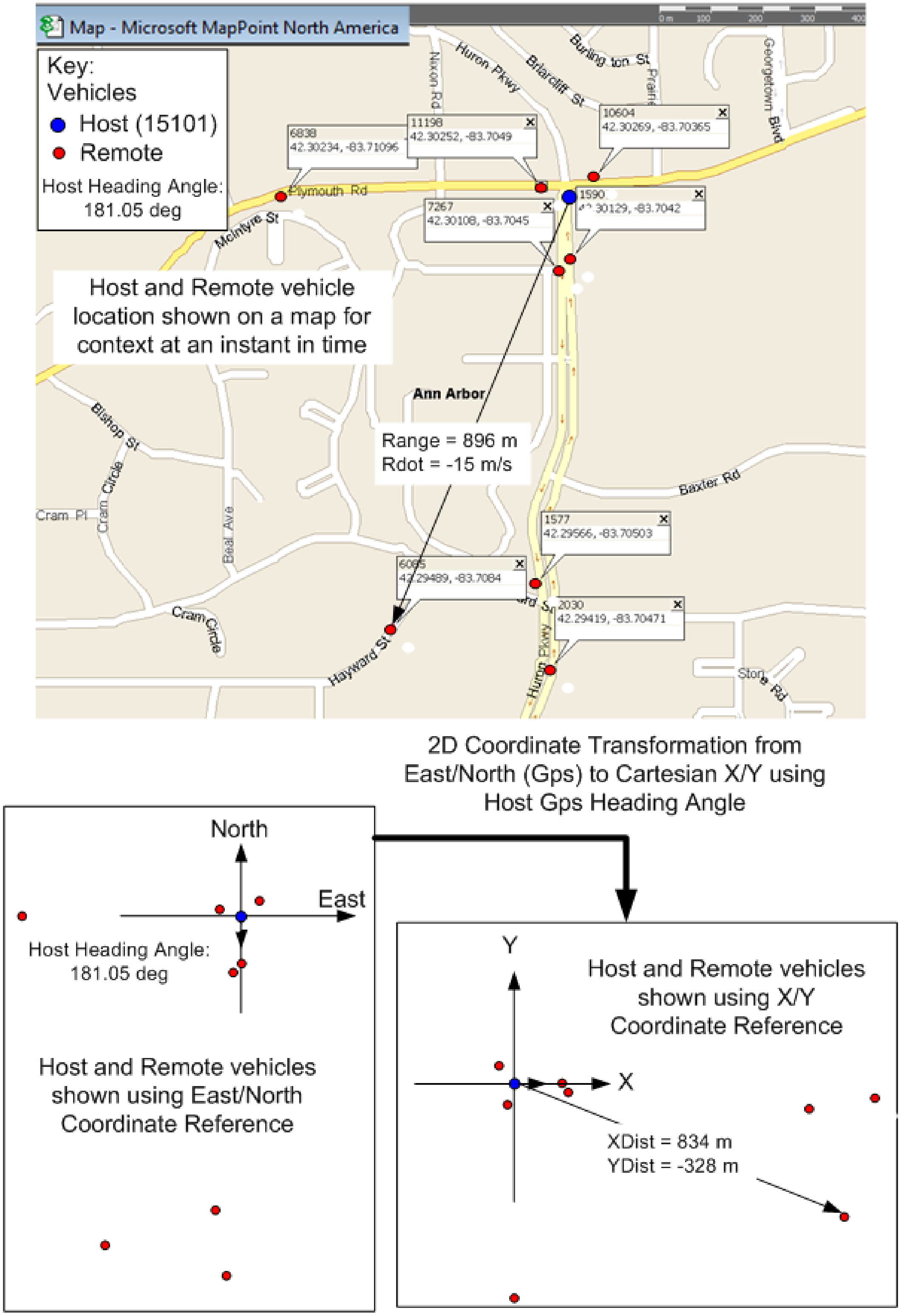
- The location, speed, and relative motion of all vehicles
- Vehicle platform effects (bus, truck, car, motorcycle)
- Variation among types of light vehicles (Vans, SUV, sedan, compact, sport)
- DSRC radio suppliers
- Installation variation in the fleet of vehicles
- DSRC antenna location and model
- City, urban and rural communication effects
- Road type effects (surface versus limited access)
- Seasonal variation and weather effects
- Line-of-sight considerations

Table 3-6. Example CCV-IT and remote vehicle data used in the BSM communication analysis.

CCV-IT Vehicle							
DeviceId	**Trip**	**DasTime, cs**	**Lat., deg**	**Long., deg**	**Heading, deg**	**XDist, m**	**YDist, m**
15101	821	27030	42.302	-83.704	181.05	0.0	0.0
Remote Vehicle							
DeviceId	**Lat., deg**	**Long., deg**	**Head, deg**	**Range, m**	**Rdot, m/s**	**XDist, m**	**YDist, m**
1198	**42.3025208**	**-83.7049026**	**87.2**	**57.9**	**-5.5**	**-19.0**	**-54.9**
10604	**42.3026886**	**-83.7036514**	**267.8**	**62.1**	**-7.7**	**-39.5**	**48.0**
15901	**42.3012886**	**-83.7042007**	**359.3**	**117.1**	**-12.4**	**116.8**	**5.5**
7267	**42.3010788**	**-83.7044983**	**140.4**	**141.9**	**2.7**	**140.6**	**-18.6**
6838	42.3023376	-83.7109604	79.0	552.5	-15.0	10.5	-554.0
1577	42.2956619	-83.7050323	172.4	745.5	9.8	743.0	-51.7
6085	42.2948875	-83.7083969	32.7	896.5	-14.9	834.0	-327.6
2030	42.2941933	-83.7047119	12.0	906.8	-13.5	905.6	-22.3

UMTRI

Bold indicates the CCV-IT V2V radio received BSMs from the remote vehicle.



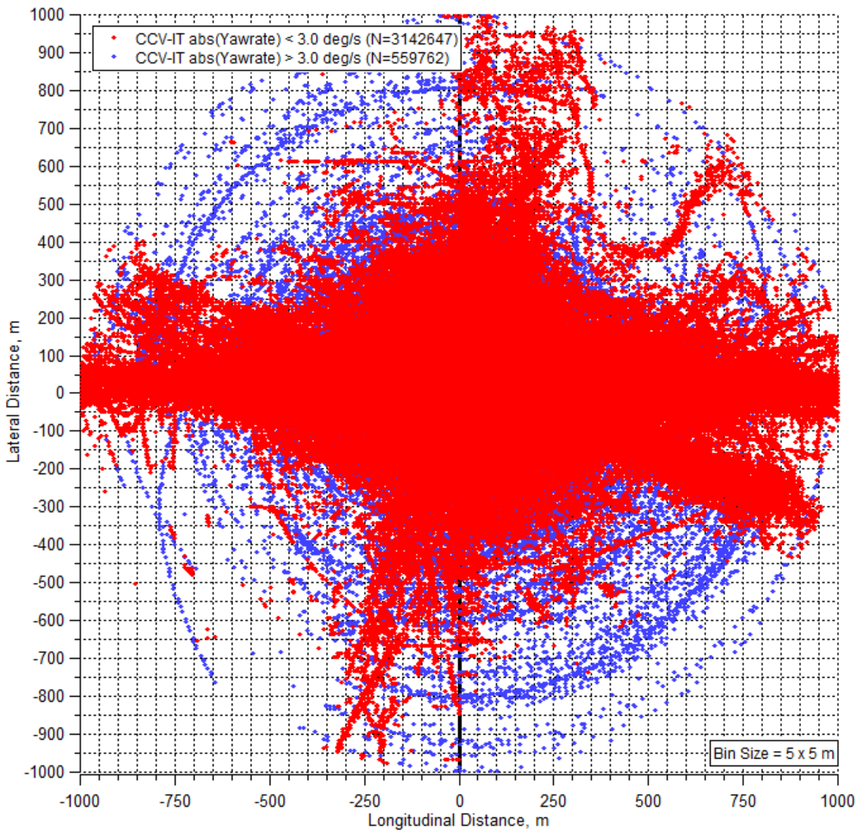
UMTRI

Figure 3-3. Example showing process for calculating the Cartesian distances from the host to remote vehicles for the BSM communication analysis.

BSM Coverage during Model Deployment

To illustrate the coverage and communication between CCV-IT and other vehicles in Model Deployment consider Figure 3-4. The figure shows the locations of remote vehicles at the time of BSM capture by all three CCV-IT tractors. The figure was created by grouping the X and Y values into bins five meters square and then counting the number of pairs in each bin. The plot is separated into two sets of data based on the CCV-IT yaw rate value at the time the BSM was received.

For CCV-IT yaw rate values between -3 and 3 deg/s (which accounts for 85 percent of all received BSMs) the coverage shape is principally along the longitudinal and lateral axis out-side of the central region with a radius of approximately 500 m. The general shape of this coverage map is most likely a result of orthogonal nature of the roadway system in Model Deployment (most roads run North/South or East/West) and line-of-sight obstruction of vehicles on different roads.

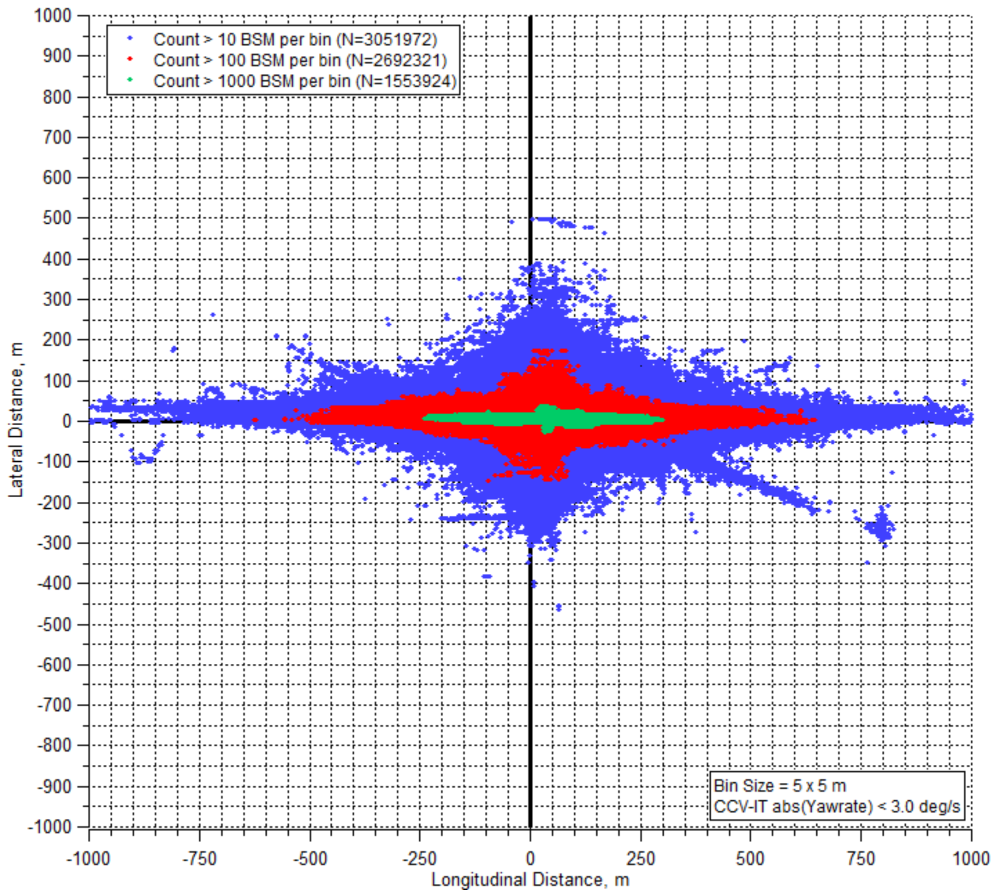


UMTRI

Figure 3-4. BSM coverage map showing effect of host yaw-rate as a function of distance from the CCV-IT.

The second scatter plot for yaw rate values not between -3 and 3 deg/s shows a distinct circular pattern that is the result of the heading change of the CCV-IT and the coordinate transformation from an East-North GPS coordinate to an X-Y Cartesian system. This transformation effectively rotates the location of the remote vehicle around the host using the changing heading angle of the CCV-IT vehicle. During this rotation the overall range between the vehicles is not likely to change much, so the patterns appear circular. In reality what's happening is the CCV-IT vehicle is rotating locally (turning right or left) while receiving messages from an essentially fixed remote vehicle. That is, since the rate of rotation of the CCV-IT vehicles is much greater than changes in the relative distance between the vehicles, the traces appear to be constant radius circles.

A different representation of the BSM coverage map is shown in Figure 3-5. This figure illustrates the relative number of (or density) received BSM as function of location from the CCV-IT vehicle. Unlike Figure 3-4 which shows all possible remote vehicle locations, this figure requires the number of remote vehicle X/Y pairs to be above distinct thresholds of 10, 100, and 1000 counts. More than anything this figure illustrates that proximity and relative location of the remote vehicle makes a difference in the number of messages that are received by the CCV-IT. It also illustrates that coverage along the longitudinal axis is always considerably better than in the lateral direction. The antenna configuration on CCV-IT is partially responsible for this, since the fore/aft direction has clear line-of-site to both antennas, but only one antenna has direct line-of-site to remote vehicles to the side.

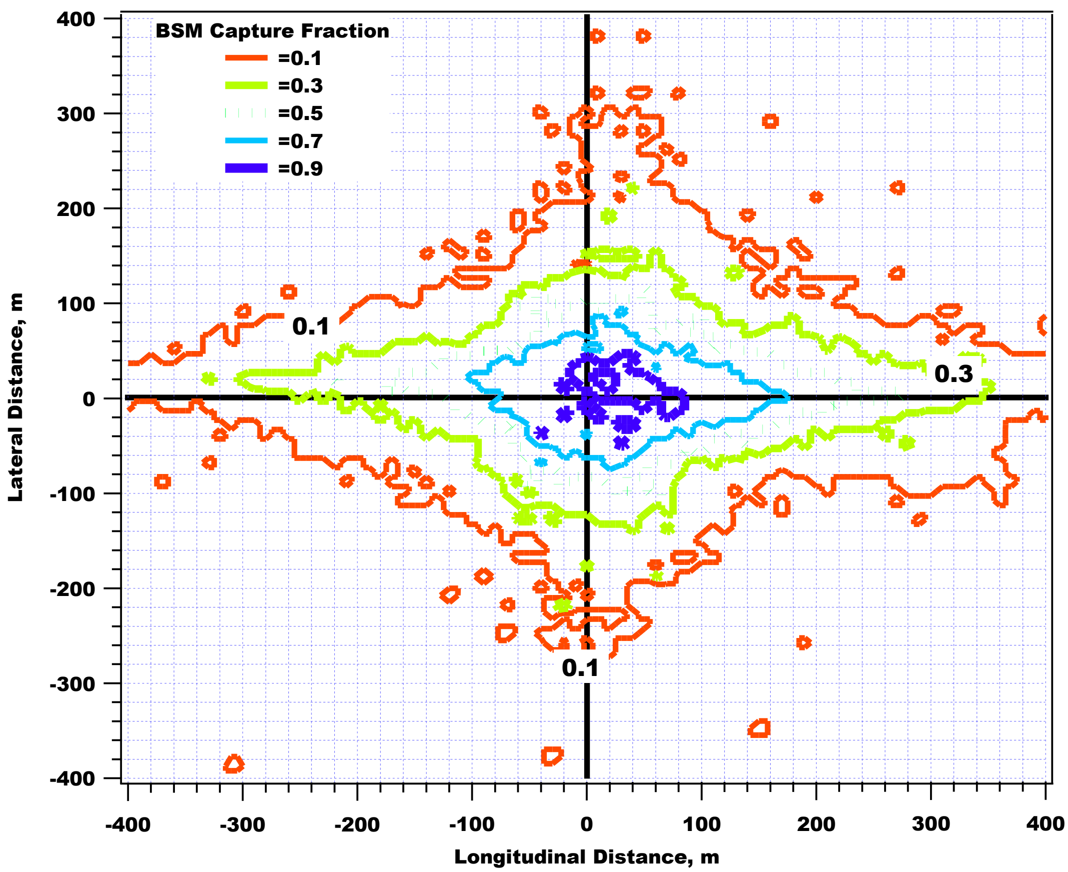


UMTRI

Figure 3-5. BSM coverage map showing effect of message density as function of distance from the CCV-IT.

BSM Capture Fraction

To further explore the capture of BSM from remote vehicles by CCV-IT consider Figure 3-6. This figure shows the fraction of all BSM that were processed by the DSRC radio on-board the CCV-IT tractor. These results are derived from the OTA Sent BSM database and the UMTRI DAS Driving database. The OTA Sent BSM database is a collection of all transmitted BSM by all vehicles in Model Deployment. The UMTRI DAS Driving database for CCV-IT contains records of all BSM processed by the DSRC radio as they pertained to various safety applications on-board the vehicle. The contour plot shown in Figure 3-6 is generated by building a sub-set of all the BSM messages sent by all remote vehicles during all trips by the CCV-IT tractors that are within a 1000 m of each other. This set of messages are then matched to the set of BSM collected by the CCV-IT radio and logged in the driving database. All matches in the sub-set are then flagged. The BSM Capture fraction is sum of all matched BSM records to the total number of BSM messages for a given location relative to the CCV-IT. The data are grouped in to 10 x 10 m bins and the fraction calculated for each bin. The contour plot interpolates between given fraction values to show boundaries where the fraction changes. To keep the figure uncluttered, only five boundary values where selected.



UMTRI

Figure 3-6. BSM capture fraction (integrated trucks receiving broadcast BSMs from other vehicles) for all vehicle platforms and device categories.

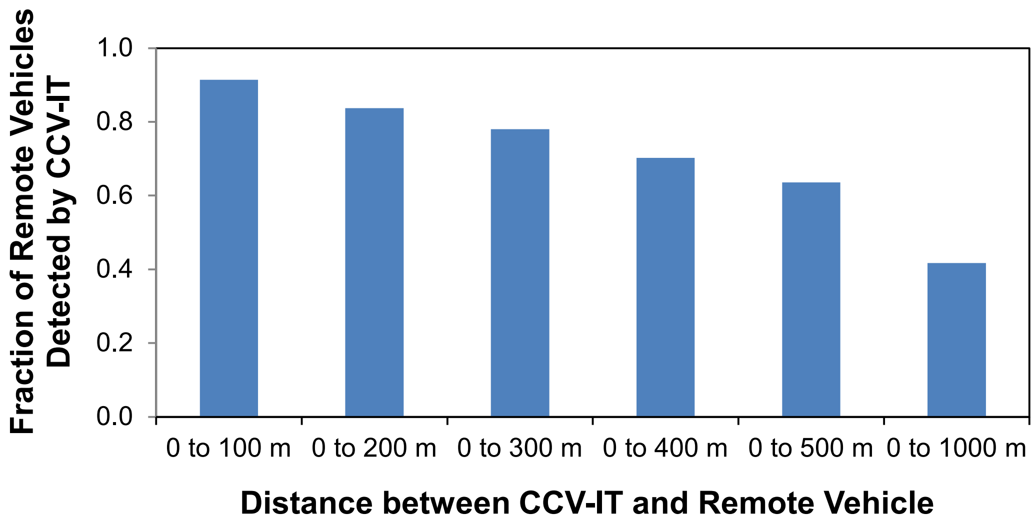
The outer red contour shows that the tractors were capturing ten percent of the BSMs from remote vehicles several hundred meters away. The inner dark blue contour shows that more than 90 percent of the BSMs were captured from vehicles up to 80 m in front of the tractor. Other observations from the figure are

- The general shape of the contours shows that reception is better in the fore-aft direction than to the sides of the tractor. The two DSRC antennas were mounted on each side of the tractor so two antennas have visibility of vehicles ahead and behind the tractor, but only one is available for vehicles to the side. A vehicle more than 40 m to the left or right may be obscured by a building or trees along the road.
- The capture fraction was better than 90 percent for vehicles 20 m behind to 80 m ahead of the CCV-IT and approximately 50 m to each side. This is the important region for the FCW and BSW safety applications.
- The dotted green contour represents the 50 percent capture fraction. Half of the BSMs broadcast by remote vehicles on the line were recorded by the CCV-IT tractors. The contour line extends from 180 m behind to 280 m ahead of the CCV-IT and approximately 100 m to each side. Reliability to the sides affects the IMA application. For example, a vehicle approaching at 20 m/s (slightly more than 40 mph) is 5 s away at a range of 100 m.
- In the case of EEBL, only a single remote vehicle's hard braking event flag needs to reach the CCV-IT. This safety application an effective range of approximately 300 to 400 m or about 0.25 mile.
- This installation and antenna location provide better remote vehicle detection in the forward direction than behind the CCV-IT tractor. This effect is most pronounced at distances up to 200 m. Beyond 200 m the capture fraction is symmetrical both forward and aft.

The fraction of BSMs that were captured is important from an engineering perspective for antenna performance. More important for crash avoidance is the fraction of remote vehicles whose BSMs were detected by the CCV-IT tractor. Figure 3-7 is a histogram showing the fraction of vehicles that were detected as a function of distance from the CCV-IT tractor. Better than 90 percent of vehicles within 100 m of the tractor were recognized by the tractor. In other words, the tractor failed to record any BSMs from a small number of vehicles within 100 m, but those vehicles represented less than 10 percent of the Model Deployment vehicles within that radius.

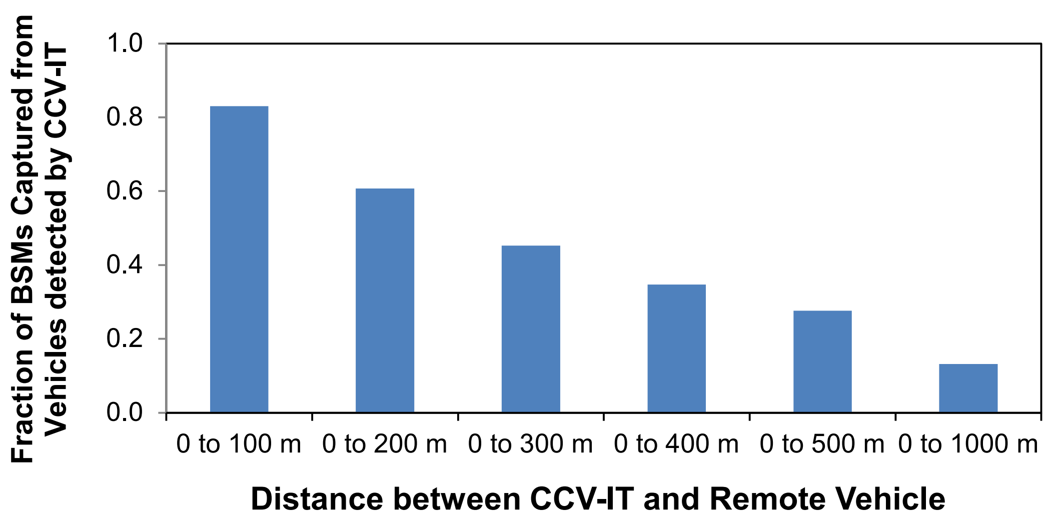
Further analysis is necessary to learn why some of the vehicles were missed. The figure is based on BSMs that were recorded on the transmitting vehicles' DAS; if certain vehicles are found to be frequently missed by CCV-IT and others, then they may have had a weak signal. Another possibility is that certain locations have obstacles that impair communication; this could be tested by mapping the locations of the vehicles whose BSMs were missed by the CCV-IT.

Limiting the analysis to only those remote vehicles from which at least one BSM was recorded, the results in Figure 3-8show the fraction of BSM that were recorded as a function of distance to the remote vehicle. Approximately 83 percent of all BSMs were captured by the CCV-IT when the remote vehicle was within 100 m.



UMTRI

Figure 3-7. The majority of remote vehicles were sensed by the CCV-IT.



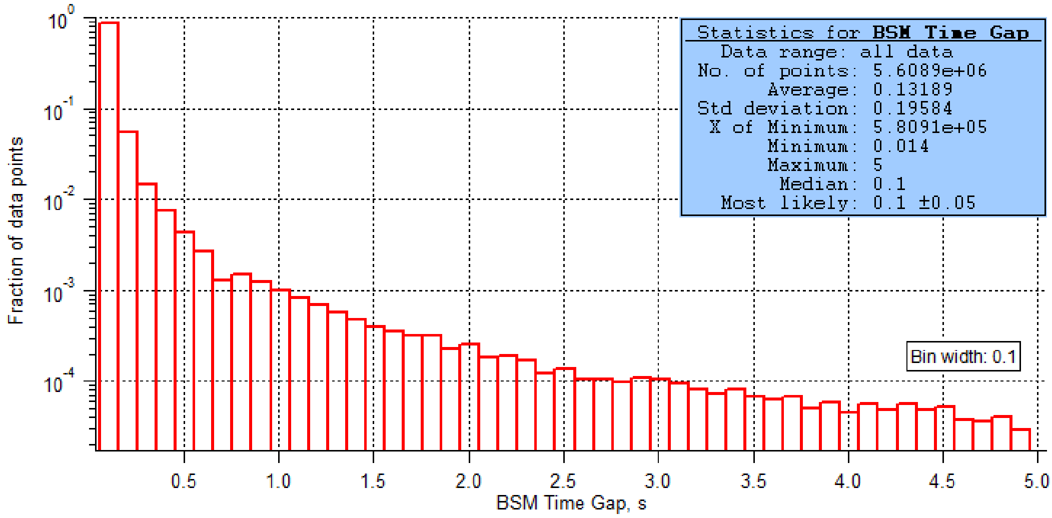
UMTRI

Figure 3-8. BSM capture fraction as a function of distance, limited to vehicles from which the CCV-IT captured at least one BSM.

BSM Inter-packet Time Gap

Figure 3-6 plotted the capture fraction for all BSMs as a function of range and azimuth but without regard to time or originating vehicle. Figure 3-7 and Figure 3-8 grouped BSMs by the remote vehicle that transmitted them. This section explores the messages from individual remote vehicles during an encounter. The measure of V2V communication performance is the time gap between successive messages received by the CCV-IT tractors.

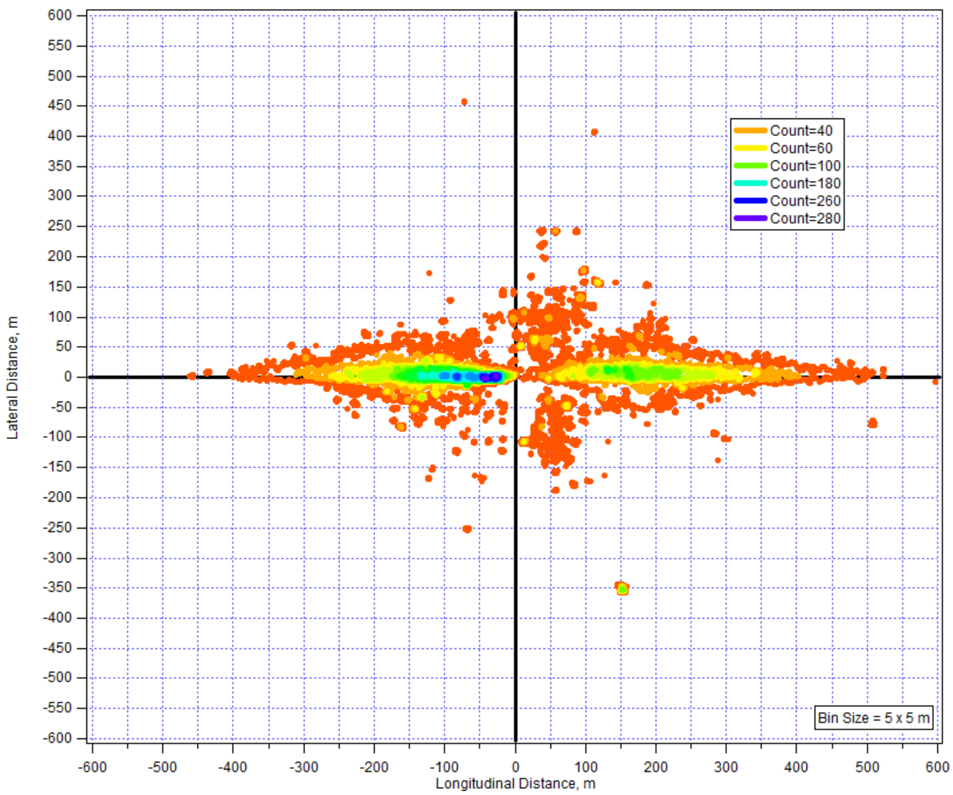
Figure 3-9 is a histogram of the elapsed time between successive messages received by the CCV-IT tractors during Model Deployment. The left axis shows the fraction of points as a function of the time gap between messages. Ninety percent of the time gap values are 0.1 s, which was the nominal broadcast interval in Model Deployment, and 97 percent are less than 0.3 s. In other words, of the 55,849 encounters of CCV-IT vehicles listed in Table 3-3, only 1675 had an internal gap of more than 0.3 s.



UMTRI

Figure 3-9. Histogram of the time between successive BSM messages received by CCV-IT.

Figure 3-10 shows the count of time gap events between 0.3 and 5.0 s as a function of remote vehicle location. Interestingly, this figure has two distinct regions with higher counts of gap events. Both regions are centered at 0 m laterally relative to the CCV-IT tractors, with one extending forward longitudinally between 50 and 300 m and a second region extending rearward from about -20 to -250 m.

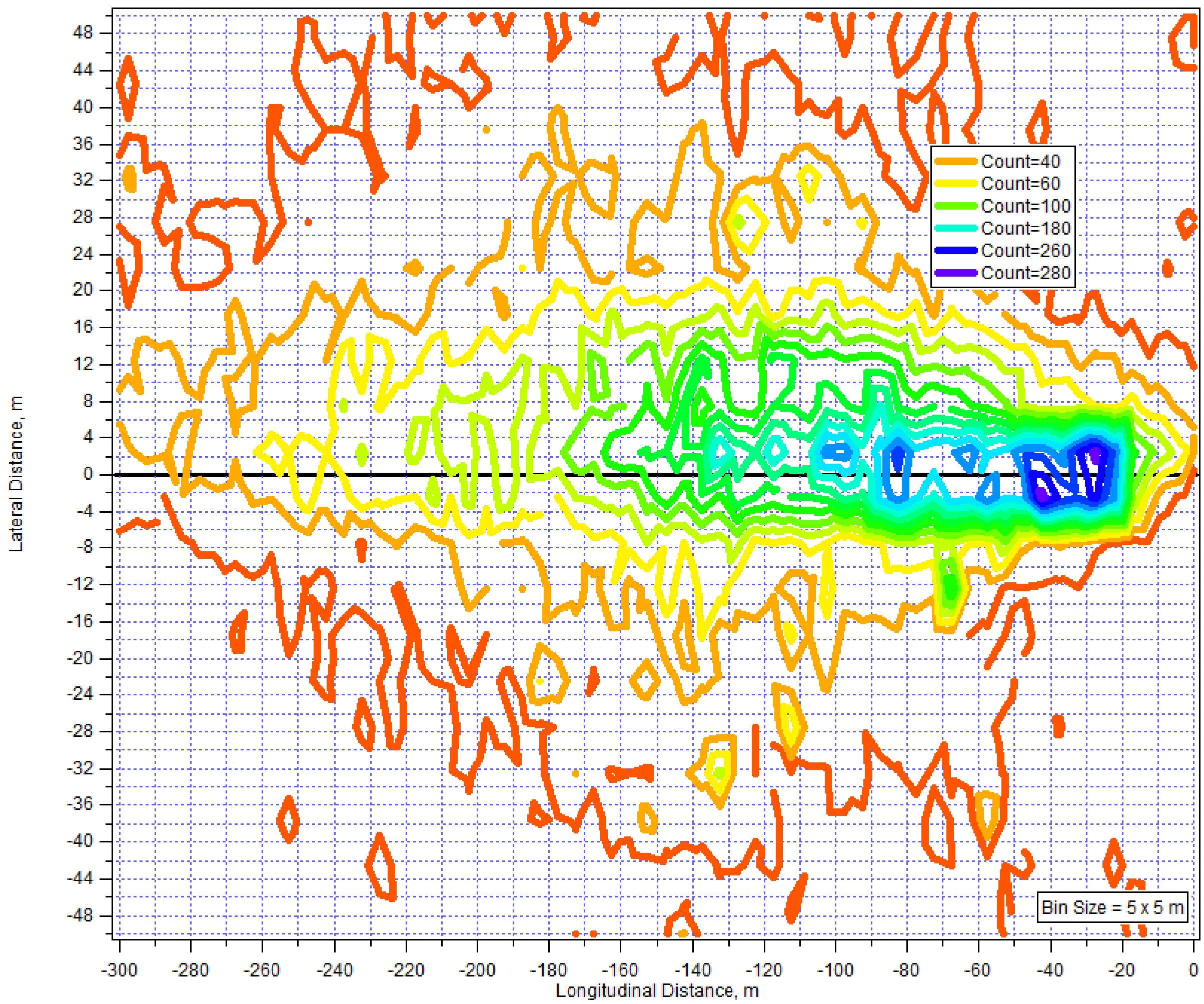


UMTRI

Figure 3-10. Contour plot showing relative count of time gap events greater than 0.3s as a function of location relative to the CCV-IT.

The rearward region with higher counts could be the result of obstruction by the CCV-IT trailer. Remote vehicles located behind the tractor-trailer do not have line-of-sight communication with the CCV-IT DSRC antennas due to obstruction by the trailer. It is possible that this obstruction is a major cause of larger time-gap events between messages received from remote vehicles. Figure 3-11 below is an expanded view of the region behind the trailer. This figure further illustrates that region just behind the trailer from -20 to -45 m (65 to 150 ft) had the highest concentration of events with longer time gaps between BSMs.

These findings represent communication from the remote vehicle to the CCV-IT. In rear-crash scenarios, the communication from the CCV-IT to the remote vehicle is what matters for issuing a meaningful alert to the driver of the following vehicle. Although not addressed in this report, the dataset collected on ASD equipped vehicles in Safety Pilot Model Deployment can address this communication issue as well, since these vehicles logged both sent and received BSM from remote vehicles.



UMTRI

Figure 3-11. Contour plot showing relative count of time gap events greater than 0.3 s for the region immediately behind the CCV-IT.

Chapter 4 Summary

This report summarizes the operational experience of the Connected Commercial Vehicle integrated trucks in the Safety Pilot Model Deployment. The three tractors were each equipped with a set of crash warning safety applications and a data acquisition system. Two commercial fleets each used vehicles in service during parts of the Model Deployment period; later professional drivers from UMTRI drove the vehicles on fixed routes within the Model Deployment Geographic Area.

Communication of Basic Safety Messages from other vehicles to the integrated trucks was excellent in the region ahead of the truck, where they are needed for forward collision warnings and emergency electronic brake light warnings. The tractors received BSMs from more than 90 percent of the remote vehicles within a radius of 100 m. Reception was good along the side of the truck for blind spot and lane change warnings. At greater distances to the left and right needed to support an intersection movement safety application, more messages were missed but overall reception was satisfactory. These results were accomplished with a 53- or 48-ft van trailer or a 40-ft intermodal container in combination with the equipped tractor.

References

[1] Bogard, S., LeBlanc, D., and Gilbert, M. (UMTRI) (January 31, 2014) "Connected Commercial Vehicles—Integrated Truck Project: Data Acquisition System (DAS) Documentation." (Report from the University of Michigan Transportation Research Institute to Battelle for ITS JPO) Battelle document 10003838-302. Contract No. DTFH61-06-D0007/ORDER T11004/WO BA07-092. Publication Number FHWA-JPO-13-105.

[2] Stephens, S., Pape, D., LeBlanc, D., Bogard, S., Peredo, G., Berg, R., and Wells., B. (January 31, 2014) "Connected Commercial Vehicles—Integrated Truck Project: Final Report." (Report from Battelle to the ITS JPO) Battelle document 10003838-1102. Contract No. DTFH61-06-D0007/ORDER T11004/WO BA07-092. Publication Number FHWA-JPO-13-112.

APPENDIX A. Glossary of Terms and Abbreviations

BHI	Bridge Height Inform
BSM	Basic Safety Message
BSW	Blind Spot Warning
CAMP	Crash Avoidance Metrics Partnership
CAN	Controller Area Network
CCV	Connected Commercial Vehicle
CSW	Curve Speed Warning
DAS	Data Acquisition System
DSRC	Dedicated Short Range Communications
DVI	Driver-Vehicle Interface
EEBL	Emergency electronic brake lights
FCW	Forward Collision Warning
GPS	Global Positioning System
IMA	Intersection Movement Assist
IVBSS	Integrated Vehicle-Based Safety System
MDGA	Model Deployment Geographic Area
MDOT	Michigan Department of Transportation
MBRDNA	Mercedes-Benz Research & Development North America, Inc.
OBE	On-Board Equipment
OEM	Original Equipment Manufacturers
OTA	Over the Air
RSE	Road Side Equipment
SPaT	Signal Phase and Timing
TRP	Transit Safety Retrofit Package
UMTRI	University of Michigan Transportation Research Institute
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
WSU	Wireless Safety Unit

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