Connected Commercial Vehicles—Retrofit Safety Device Kit 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. Cooperative vehicle-to-vehicle (V2V) safety applications will be effective only if a high fraction of vehicles are equipped. Deployment of V2V technology will be enhanced if it is available not only for manufacturing in new vehicles but also for retrofit to existing vehicles. The objective of the Connected Commercial Vehicles—Retrofit Safety Device (CCV-RSD) Kit Project was to develop complete hardware and software that can be used in various brands and models of heavy trucks. The RSD kits provide the functionality needed for cooperative V2V and vehicle-to-infrastructure (V2I) safety applications to support the model deployment and other USDOT connected vehicle projects. This project included testing and documentation needed for installation, operation, enhancement, and maintenance of the units. These retrofit kits were built so they could be installed in existing class 6, 7, or 8 trucks. The RSD kits achieved a V2V and V2I functionality similar to that of the Connected Commercial Vehicles—Integrated Truck vehicles, where onboard equipment was integrated with newly manufactured truck tractors.

This document describes the operational experience of commercial vehicles with the RSD kits 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.

17. Key Words
Commercial vehicle, connected vehicle, commercial motor vehicle, CMV, dedicated short-range communication, retrofit, DSRC, V2V, RSD

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS AND ABBREVIATIONS

ASD	Aftermarket Safety Device
BSM	Basic Safety Message
BSW	Blind Spot Warning
CAMP	Crash Avoidance Metrics Partnership
CAN	Control and Navigation [bus]
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
MDGA	Model Deployment Geographic Area
MBRDNA	Mercedes-Benz Research & Development North America, Inc.
OTA	Over the Air
RSD	Retrofit Safety Device
SAE	SAE International
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

EXECUTIVE SUMMARY

Connected vehicle telecommunications for vehicle data can transform travel in North America, enabling major reductions in crashes, injuries, and fatalities on our highways, as well as enabling reductions in traffic congestion and effects on the environment. This project demonstrated the technical viability of equipping an in-service truck tractor with connected vehicle safety applications. Furthermore, this “retrofit safety device” or RSD can be manufactured as a kit that can be installed by technicians and is not limited to a particular make of tractor. By providing not only newly manufactured tractors but also previously manufactured tractors, it is possible to accelerate capturing the benefits of connected commercial vehicle safety applications. The project provided information and data needed to assess the applications’ safety benefits and support regulatory decision processes.

Eight fleet-owned trucks were equipped with an RSD and participated in the safety pilot model deployment. For more than one year, approximately 2800 light, commercial, and transit vehicles with V2V collision avoidance technology drove in the Ann Arbor, Michigan, area. The eight tractors with RSD kits operated their normal routes in revenue service. They exchanged Basic Safety Messages (BSMs) with the other vehicles and alerts were generated.

Nearly 31,171 miles of data was collected as the tractors drove within a 6-mile radius, and they logged more than 60,880 encounters with other vehicles. More than 1,263 driver alerts were generated by the V2V applications, an average of approximately one alert every twenty-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 60 m ahead of the instrumented tractor were recorded by the tractor. In encounters where an RSD tractor received messages from another vehicle, communication was almost always maintained as long as the two vehicles were near each other. In 98 percent of these encounters, any interruption lasted less than a period of 0.3 s, the equivalent of dropping only one or two BSMs.

CHAPTER 1. INTRODUCTION

As part of the Connected Commercial Vehicles—Retrofit Safety Device (RSD) Kit Project, eight existing truck tractors operated by Sysco Foods were retrofit with safety equipment. The equipment broadcasts radio signals via Dedicated Short-Range Communication (DSRC) 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 these eight tractors drove in and around Ann Arbor, Michigan in revenue service. The tractors were among approximately 2800 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 retrofit to existing commercial vehicles. The RSD trucks were equipped with four V2V safety applications:

- Forward Collision Warning (FCW).
- Emergency Electronic Brake Lights (EEBL).
- Blind Spot Warning (BSW).
- Intersection Movement Assist (IMA).

The RSD kits also implemented one V2I safety application:

- Curve Speed Warning (CSW) and

This report presents a summary of the RSD truck experience in the model deployment, including:

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

CHAPTER 2. DESCRIPTION OF THE EXPERIMENT

An RSD kit consisting of a computer, specialized radio, global positioning device (GPS) receiver, and specialized antennas was installed on eight existing truck tractors. The computers had software that implemented five collision-avoidance safety applications. Four of the applications communicated with other vehicles to avoid vehicle-to-vehicle crashes (V2V), and one of the applications communicated with the fixed infrastructure for avoiding single-vehicle crashes (V2I). In addition to the equipment to implement the safety applications, the tractors were equipped with a Data Acquisition System (DAS) 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.

TEST FLEET AND TRUCKS

The eight trucks used in this study were model year 2012 and 2013 Freightliner Cascadia tractors operated by Sysco Foods LLC. Seven of the tractors were single drive axle and one was tandem drive. They were outfitted in the course of this project with prototype RSD 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 RSD system. One of the tractors is shown in figure 1.

The RSD 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 signal drive-axle units was more suited to the urban routes than the tandem drive unit.

The safety pilot test conductor sought fleets in the area that could use the RSD during their normal operations. Of the many fleets considered, Sysco was selected for the following reasons:

- Sysco is the prime food supplier to the University of Michigan Hospitals and Residential Halls.
- Sysco is a prime food supplier to many restaurants in the city of Ann Arbor and the surrounding area.
- Sysco operates newer equipment.
- Sysco's drivers agreed to participate in the study and have their driving behavior monitored.
- Sysco assigns drivers to a particular tractor, and each driver stayed with the same tractor for the duration of the model deployment.

Table 1 shows the make, device number (the unique broadcast identification number), installation date of the RSD equipment, and the last trip date for the eight Sysco tractors and their associated drivers. The date of the last trip was chosen to provide approximately a year of exposure by these eight tractors. The model deployment was originally planned to be from August 2012 to August 2013, but it was extended by USDOT for six more months of operation following. The safety pilot test conductor provided the resources to continue data collection in these tractors beyond the original end date of the CCV-RSD project.

Table 1. Make, Device Number, Install Date and Last Trip Date for the RSD Tractors

Make	Device	Install Date	Last Trip
Freightliner-130900	13106	October 22, 2012	October 31, 2013
Freightliner-130905	13101	October 24, 2012	October 31, 2013
Freightliner-130903	13107	October 29, 2012	October 30, 2013
Freightliner-130902	13103	November 1, 2012	October 31, 2013
Freightliner-130904	13109	November 6, 2012	October 31, 2013
Freightliner-130901	13110	November 9, 2012	October 31, 2013
Freightliner-129724	13105	November 14, 2012	October 31, 2013
Freightliner-129199	13108	November 19, 2012	October 31, 2013

UMTRI

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Figure 1. Photo. A CCV-RSD tractor used in the Safety Pilot Model Deployment. The arrow points to one of DSRC antennas.

RSD KIT

The safety applications were developed by DENSO using the DENSO wireless safety unit (WSU), which provides the DSRC communications with other vehicles, in addition to other support functions. The equipment in the kit and the nature of the safety applications are explained more fully in the final report for this project.(2) The five safety applications were

- **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.

- **Blind Spot Warning (BSW):** provides the driver with a visual cue when there is a vehicle present in the space adjacent to the tractor or trailer.

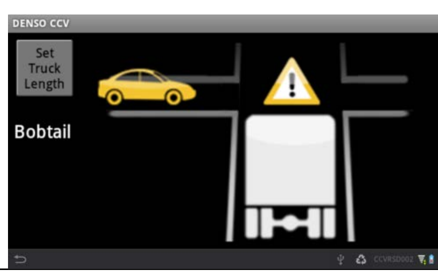
- **Intersection Movement Assist (IMA):** provides the driver with audible and visual cues if the driver begins to accelerate from rest on a side road or driveway onto a roadway, and there is cross-traffic nearby.

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

Table 2 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 a tablet mounted on the instrument panel, which has 1024 x 600 pixels on a 7.0-in. diagonal screen. Applications except BSW 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 IMA images in the table show a remote light vehicle approaching from the left. Mirror images with the vehicle approaching from the right were shown when appropriate.

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. The images in this table were displayed on the tablet when an alert occurred.

Safety Application	Inform	Warning (FCW, EEBL, and IMA were accompanied by audible tones.)
Forward Collision Warning (FCW)		
Emergency Electronic Brake Light (EEBL)		
Blind Spot Warning (BSW)		(There was no warn-level blind spot alert.)
Curve Speed Warning (CSW)		
Intersection Movement Assist (IMA)		

DENSO

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 licenced CDL 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 Michigan. The Model Deployment Geographic 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 eight tractors with RSD kits operated in revenue service in their normal routes during the model deployment.

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 RSD operations during model deployment, not all data sources listed below were used in these findings.

Over-the-Air Transmitted 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 RSD team. (Note that UMTRI was part of the RSD team and was also the safety pilot test conductor under a separate contract.)

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 bytes 3 and 4 are fixed to represent a unique ID (a.k.a. Device 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 randomly change periodically, as normal.

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, antilock brake, or airbag 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 BSMs 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 the eight CCV Retrofit Safety Device (RSD) heavy vehicles, three CCV integrated tractors, three Transit Safety Retrofit Package (TRP) transit buses, and 100 aftermarket safety device (ASD) passenger vehicles. Data from the integrated passenger vehicles from Crash Avoidance Metrics Partnership (CAMP) and the RSD vehicles from Southwest Research Institute was not available to the RSD team. The DAS units recorded the following data, generally at 10 Hz

- **Vehicle CAN.** Signals obtained from the vehicles' Control and Navigation (CAN) bus include accelerator pedal, brake pedal, cruise control status, engine speed, fuel use, head lamp state, odometer, speed, turn-signal, and wiper setting. 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 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 description of data from the DAS was provided in a previous RSD report.(1)

Other Data Archives

In addition to the databases for roadside equipment, OTA sent BSMs, and Driving, 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. Also included are data related to weather, traffic (counts from the City of Ann Arbor), and special applications like a V2V bicycle and V2I ice warning. 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.

CHAPTER 3. ANALYSIS OF DATA

This chapter presents the amount of time and distance that the RSD tractors traveled during the model deployment and also analyzes the exchange of BSMs with other vehicles.

MODEL DEPLOYMENT GEOGRAPHIC AREA

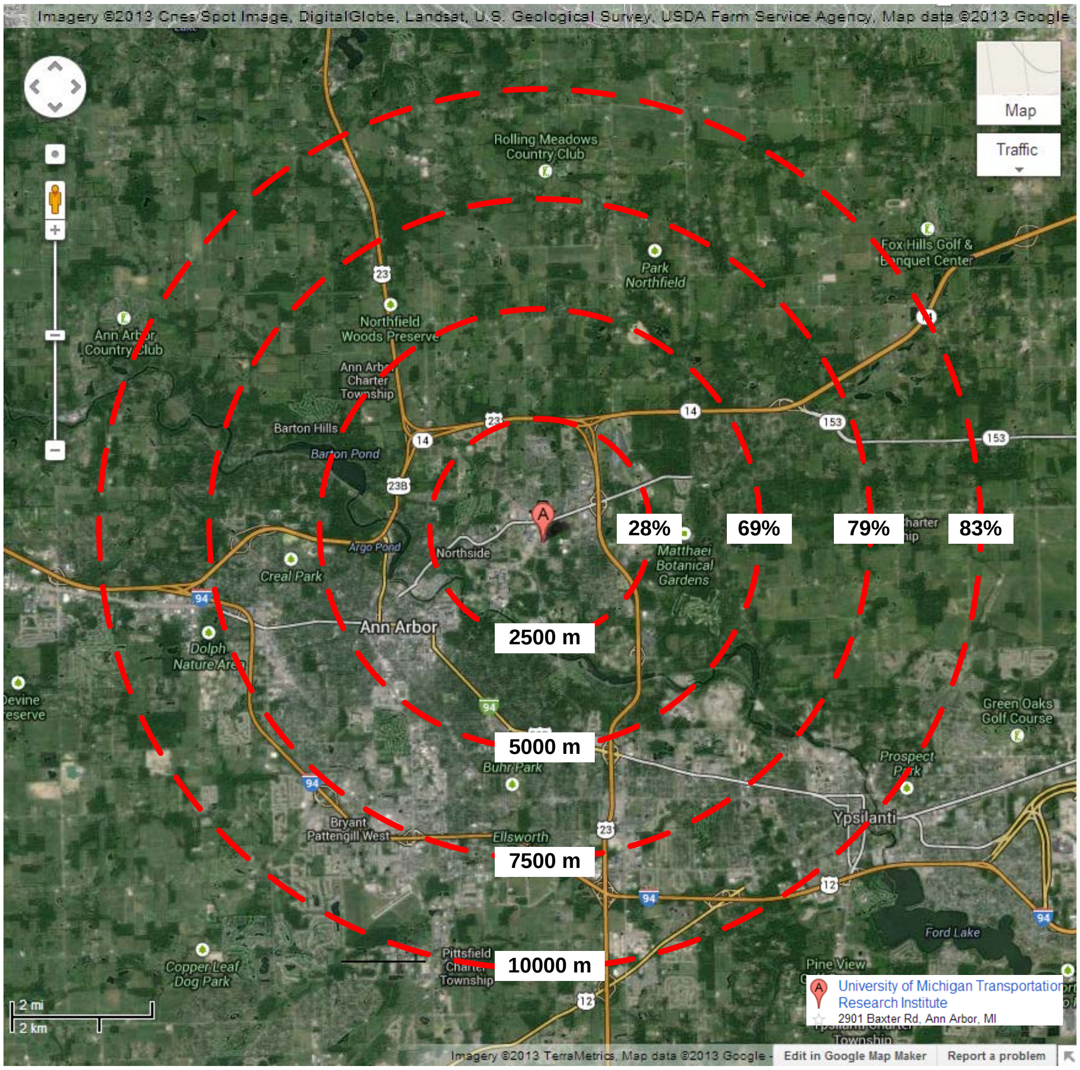
The Model Deployment Geographic Area (MDGA) is defined as a circle with a radius of 10 km (approximately 6 miles) centered at UMTRI, as shown in figure 2. UMTRI is within 800 m of the geometric center of the roadside installations of model deployment and has latitude of 42.298351 degrees and a longitude 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 RSD vehicles away from Ann Arbor that did not include any interactions with other model deployment vehicles. Figure 2 shows the cumulative fraction of V2V interactions as a function of distance from the MDGA center. The MDGA contains over 83 percent of all interactions between a RSD 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 driving, as vehicles and systems are tested before and after installation, and as researchers continue development of broadcasting devices.

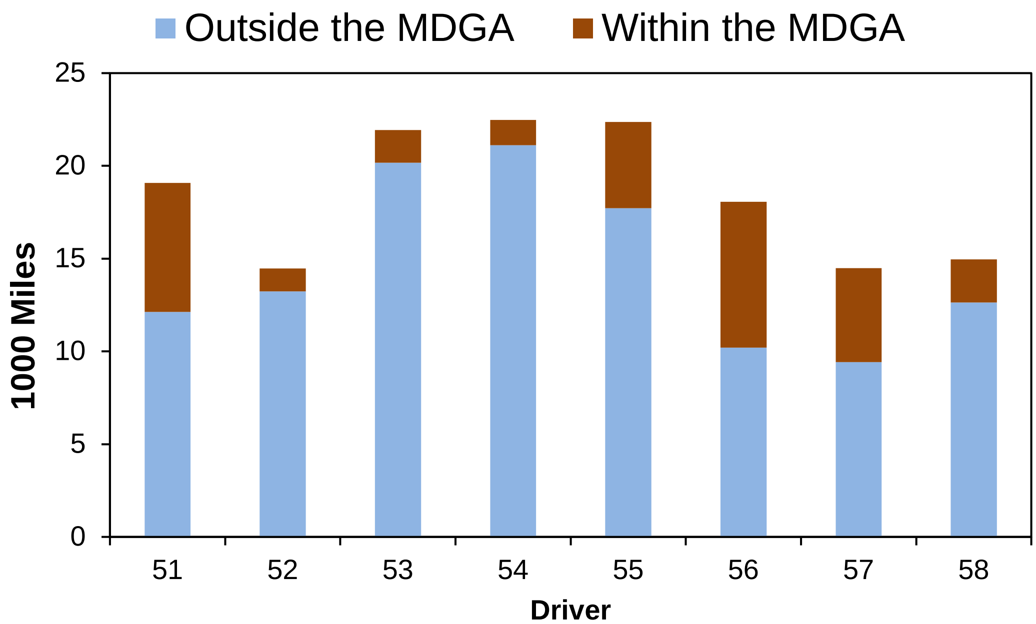
TRAVEL DURING THE MODEL DEPLOYMENT

A total of 147,839 miles (approximately 237,000 km) traveled by the eight CCV-RSD 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-RSD tractors was 194,235 miles in 35,654 trips. Figure 3 shows the number of miles driven by the Sysco tractors. It distinguishes between miles in the MDGA and those outside the area.



UMTRI

Figure 2. Diagram. RSD message interactions (cumulative fraction) as a function of distance from UMTRI.



UMTRI

Figure 3. Graph. Distances traveled by the eight drivers during model deployment.

Travel by three Sysco drivers was mostly outside the MDGA, as table 3 shows. This was expected, given that only four to five tractors are needed to service customers in the MDGA. Approximately 21 percent of all miles traveled were within the MDGA. The Sysco distribution terminal is 20 miles from Ann Arbor, and routes are optimized to reduce the time between deliveries. When not en route to and from the MDGA, the tractors spent most of their time and distance within the MDGA.

Table 3. Travel in Safety Pilot by driver and device for the Sysco fleet.

Fleet	Driver	Device	All Travel			Travel in MDGA		Percent Travel within MDGA	
			Trips	Hours	Miles	Hours	Miles	Hours	Miles
Sysco	51	13107	3,829	690	19,076	316	6,941	46%	36%
Sysco	52	13106	2,817	466	14,477	59	1,239	13%	9%
Sysco	53	13110	3,609	646	21,933	78	1,759	12%	8%
Sysco	54	13105	4,027	732	22,478	61	1,363	8%	6%
Sysco	55	13103	4,328	685	22,360	195	4,634	28%	21%
Sysco	56	13101	4,466	726	18,060	310	7,853	43%	43%
Sysco	57	13109	3,192	601	14,495	248	5,069	41%	35%
Sysco	58	13108	2,854	617	14,959	107	2,314	17%	15%
Totals			29,122	5,164	147,839	1,375	31,171	27%	21%

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The tractors were hitched to trailers of different lengths during the model deployment, or were running bobtail with no trailer. The driver-vehicle interface asked that the driver enter the length of the trailer.The RSD needs to know the length of the vehicle so it can properly report the location of the vehicle's geometric center in the BSM. This setting was held across ignition cycles until it was changed by the driver.

Since the DAS did not record the trailer length setting, the overall length of the vehicle was captured from the vehicle length value broadcast as part of the BSM. This value was not always available, and the length of the trailer was unknown for 31,452 miles or approximately 21 percent of the travel distance. Table 4 shows that for most trips a 32-ft. trailer was specified by the driver.

Table 4. Trailer lengths for all travel in the safety pilot.

Trailer Length (ft)	Travel		Percent	
	Hours	Miles	Hours	Miles
Unknown	1,076	31,452	21%	21%
No Trailer	745	21,635	14%	15%
28	615	16,792	12%	11%
32	2,672	76,609	52%	52%
40	51	1,237	1%	1%
45	5	114	0%	0%
53	0	0	0%	0%
Total	5,164	147,839	100%	100%

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ENCOUNTERS DURING THE MODEL DEPLOYMENT

An encounter is defined as the RSD 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 5 shows summary statistics of encounters as functions of the driver and tractor during the 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 MDGA (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 (83 percent) occurred with drivers in the MDGA. This is not surprising given the relative overall summary exposure statistics given in table 3.

Table 5. 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
Sysco	51	13107	16,662	0.235	113.9	1,477	25	143
	52	13106	2,773	0.039	36.0	240	47	139
	53	13110	4,161	0.059	47.3	456	41	176
	54	13105	5,079	0.071	77.9	676	55	214
	55	13103	9,780	0.138	66.9	896	25	147
	56	13101	9,898	0.139	99.8	1,072	36	174
	57	13109	16,508	0.232	159.7	1,912	35	187
	58	13108	6,189	0.087	69.8	618	41	161
Total			71,050	1.000	671	7,348	38	168
Encounters in the MDGA					**Total**		**Average**	
Fleet	Driver	Tractor	Count	Fraction	Time, hr	Dist, miles	Time, s	Dist. m
Sysco	51	13107	15,394	0.217	96.0	1,323	22	138
	52	13106	1,805	0.025	8.4	119	17	106
	53	13110	3,102	0.044	17.2	258	20	134
	54	13105	3,453	0.049	25.5	371	27	173
	55	13103	8,604	0.121	46.8	731	20	137
	56	13101	7,957	0.112	43.8	813	20	165
	57	13109	15,316	0.216	125.3	1,636	29	172
	58	13108	5,249	0.074	36.4	465	25	143
Total			60,880	1.000	399	5,717	22	146
Encounters not in the MDGA					**Total**		**Average**	
Fleet	Driver	Tractor	Count	Fraction	Time, hr	Dist, miles	Time, s	Dist. m
Sysco	51	13107	1,268	0.018	17.9	154	51	195
	52	13106	968	0.014	27.6	121	103	201
	53	13110	1,059	0.015	30.1	197	102	300
	54	13105	1,626	0.023	52.5	305	116	302
	55	13103	1,176	0.017	20.1	165	62	226
	56	13101	1,941	0.027	56.0	259	104	215
	57	13109	1,192	0.017	34.4	276	104	373
	58	13108	940	0.013	33.4	152	128	261
Total			10,170	1.000	272	1,631	96	259

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NUMBER OF ALERTS GENERATED

This section presents the number of driver alerts generated by the safety applications onboard the retrofit trucks. The alerts addressed include inform-level alerts (visual cues) and warning-level alerts (both audio and visual cues). Table 6 shows the travel distance of each driver within the MDGA, as well as the number of each type of warning-level alerts. Blind Spot Warnings (BSWs) were generated only at the Inform level because turn signal state was not available to the WSU. The next-to-bottom row of the table shows the percentage of all warnings that each driver contributed to the CCV-RSD truck total. The bottom row shows the ratio of each driver's mileage within the MDGA to the number of warnings received within the MDGA by each driver. This measure represents an average distance between warnings to give a sense of how often drivers experienced alerts.

One comparison between the alert experiences of the drivers can be made by considering the bottom row of the table. There was an average of 76.4 miles between warnings for drivers overall with driver 57 having the most frequent alerts at 47.8 miles per warning while driver 55 had an alert every 159 miles while in the MDGA.

The EEBL and CSW warnings were relatively rare for the 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 7 is similar to table 6, except inform-level alerts are addressed. BSW alerts are included at this alert level. Across all drivers the number of BSW Left inform alerts is larger compared to alerts on the right. This is not surprising since heavy truck drivers are trained to stay in the right-hand lane (understood to be the slower lane) of multilane roads, which means they are more likely to be passed by an instrumented remote vehicle on the left. 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 extrapolation is beyond the scope of this report.

Table 6. Warning-level alerts generated by the safety applications during travel in the MDGA.

Driver	51	52	53	54	55	56	57	58	Total in MDGA
Miles in MDGA	6,941	1,239	1,759	1,363	4,634	7,853	5,069	2,314	31,171
FCW warning	46	4	11	9	6	19	48	1	144
EEBL warning	4	0	1	1	0	2	2	0	10
IMA Left warning	28	3	7	4	12	26	33	8	121
IMA Right warning	31	6	4	8	10	24	13	6	102
BSW Left warning		(BSW Left did not have a warning-level alert)							
BSW Right warning		(BSW Right did not have a warning-level alert)							
CSW warning	2	0	2	0	1	1	10	15	31
All warnings	111	13	25	22	29	72	106	30	408
Driver Percent	27%	3%	6%	5%	7%	18%	26%	7%	100%
Miles / Warning	62.5	95.3	70.4	62.0	159.8	109.1	47.8	77.1	76.4

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Table 7. Inform-level alerts generated by the safety applications during travel in the MDGA.

Driver	51	52	53	54	55	56	57	58	Total in MDGA
Miles in MDGA	6,941	1,239	1,759	1,363	4,634	7,853	5,069	2,314	31,171
FCW inform	44	4	14	11	11	20	48	0	152
EEBL inform	2	0	2	2	1	2	4	1	14
IMA Left inform	52	5	17	26	27	62	65	19	273
IMA Right inform	17	3	6	12	7	26	25	10	106
BSW Left inform	71	5	9	28	13	36	41	17	220
BSW Right inform	33	1	2	3	9	14	11	5	78
CSW inform	1	0	1	0	0	0	4	6	12
All informs	220	18	51	82	68	160	198	58	855
Driver Percent	26%	2%	6%	10%	8%	19%	23%	7%	100%
Miles / Inform	31.6	68.8	34.5	16.6	68.2	49.1	25.6	39.9	36.5

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RETROFIT TRUCK COMMUNICATION

The focus in this section is to present how successfully BSMs were received during exchanges with the CCV-RSD trucks. The intention is to get a sense for whether trucks may have communication performance difficulties due to their unique physical properties, including large trailers. This topic can get involved the basic results and analysis begin to address these concerns. Further analysis of communication between all vehicle platforms involved in the safety pilot model deployment is certainly possible given the comprehensive data collected during the project.

BSM Data Processing Methodology

To begin the discussion of RSD communication some background material outlining the analysis approach is necessary. This serves two purposes: a) to provide an understanding of how the results 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 DAS, create a set of interaction events for every trip on all eight RSD tractors.

- For all RSD trips with at least one interaction event, search the OTA sent BSM archive and save all broadcasted BSM from each remote vehicle (regardless of location) between the start and end time of the trip.

- At every time step (0.1 s) in a given RSD trip, find all the remote vehicle BSM that were broadcast at that same time (temporal alignment of data) and calculate the straight-line distance between the RSD 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 RSD DAS. Figure 4 and table 8 show an example of this method. The table shows the vehicle data involved, while figure 4 shows the details pictorially. The map in figure 4 is an instant in time when an RSD 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 RSD.

- Perform a coordinate transformation rotating the RSD 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 4 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 RSD 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 8. Example RSD and remote vehicle data used in the BSM communication analysis.

RSD Vehicle							
DeviceId	**Trip**	**DasTime, cs**	**Lat., deg**	**Long., deg**	**Heading, deg**	**XDist, m**	**YDist, m**
13110	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

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

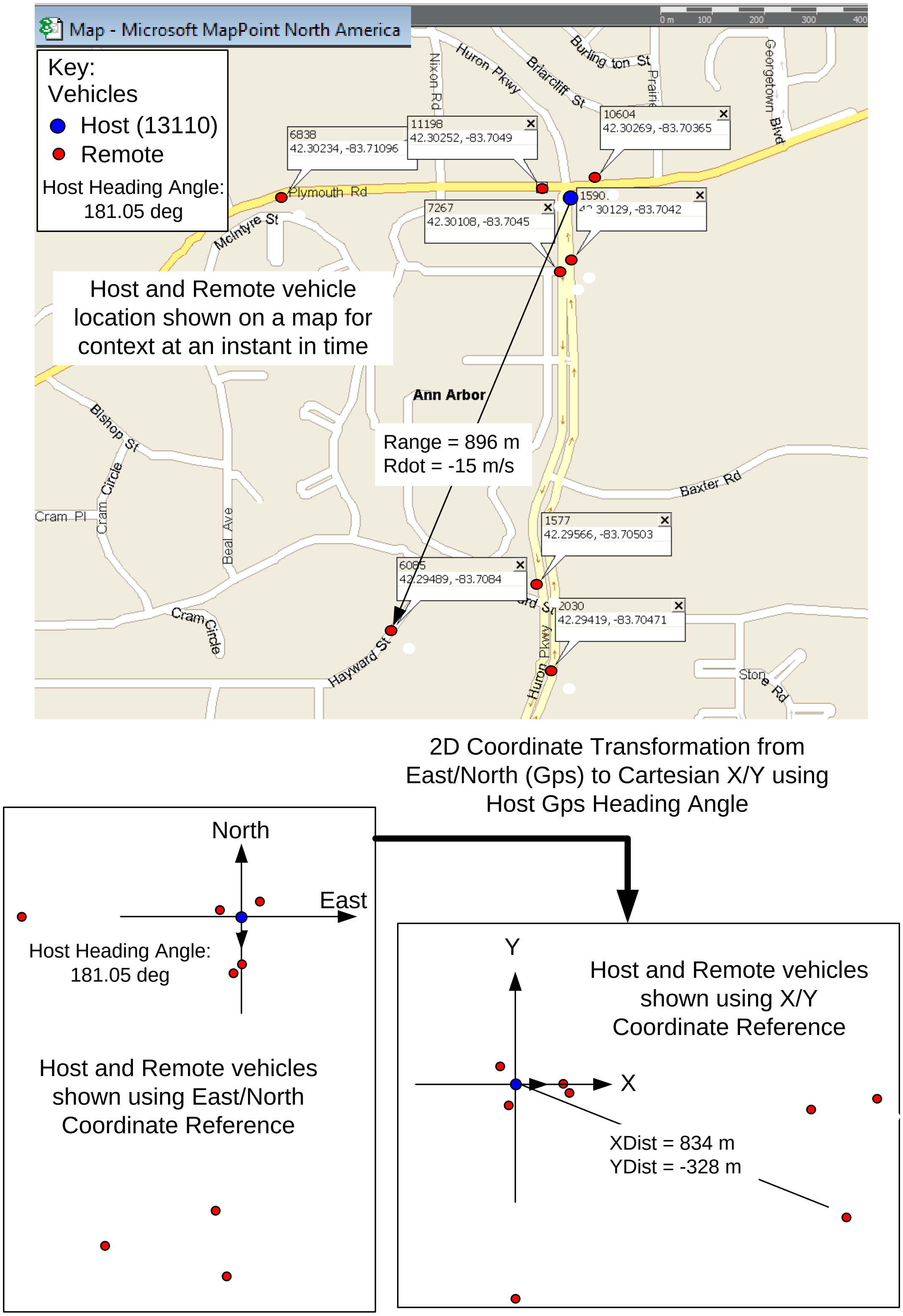

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Figure 4. Diagram. Example showing process for calculating the Cartesian distances from the host to remote vehicles for the BSM communication analysis.

BSM Coverage during Model Deployment

To illustrate the coverage and communication between CCV-RSD and other vehicles in the model deployment, consider figure 5. The figure shows the locations of remote vehicles at the time of BSM capture by all eight CCV-RSD 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-RSD yaw rate value at the time the BSM was received.

For CCV-RSD yaw rate values between -3 and 3 deg/s (which accounts for 81 percent of all received BSMs), the coverage shape is principally along the longitudinal and lateral axis outside 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.

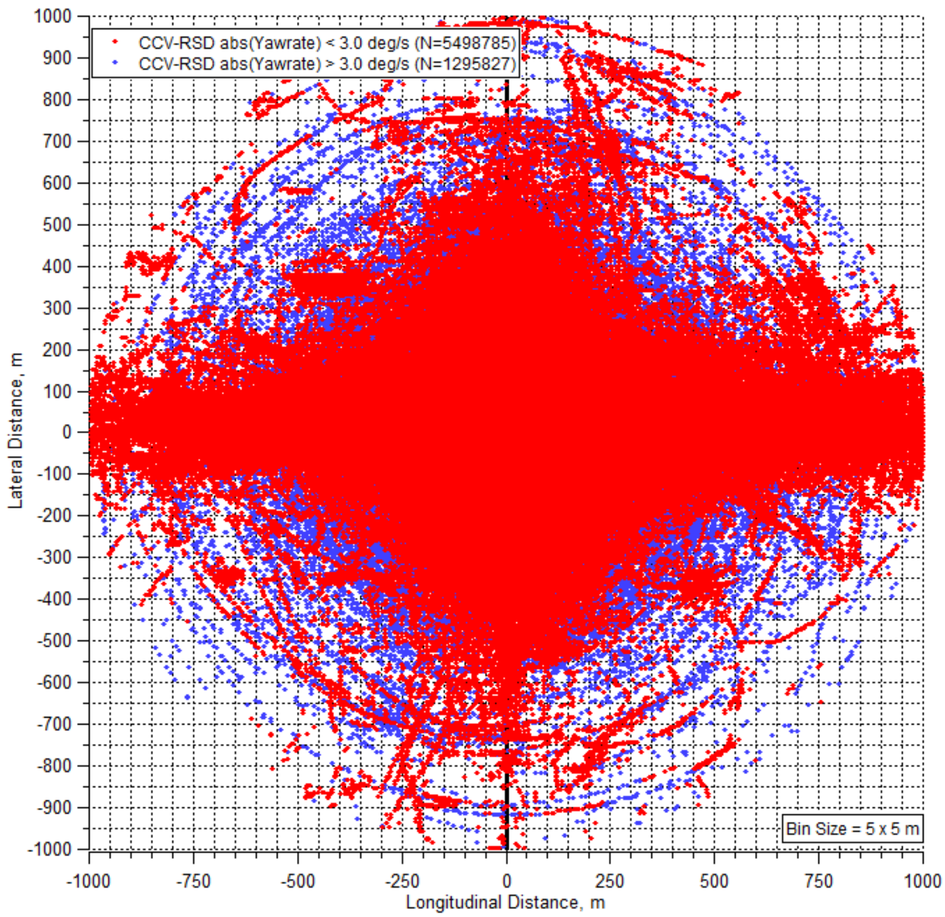

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Figure 5. Graph. BSM coverage map showing effect of host yaw-rate as a function of distance from the CCV-RSD.

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-RSD 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-RSD vehicle. During this rotation the overall range between the vehicles is not likely to change much, so the patterns appear circular. In reality what is happening is the CCV-RSD 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-RSD 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 6. This figure illustrates the relative number of (or density) received BSMs as function of location from the CCV-RSD vehicle. Unlike figure 5, 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-RSD. It also illustrates that coverage along the longitudinal axis is always considerably better than in the lateral direction. The antenna configuration on CCV-RSD 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.

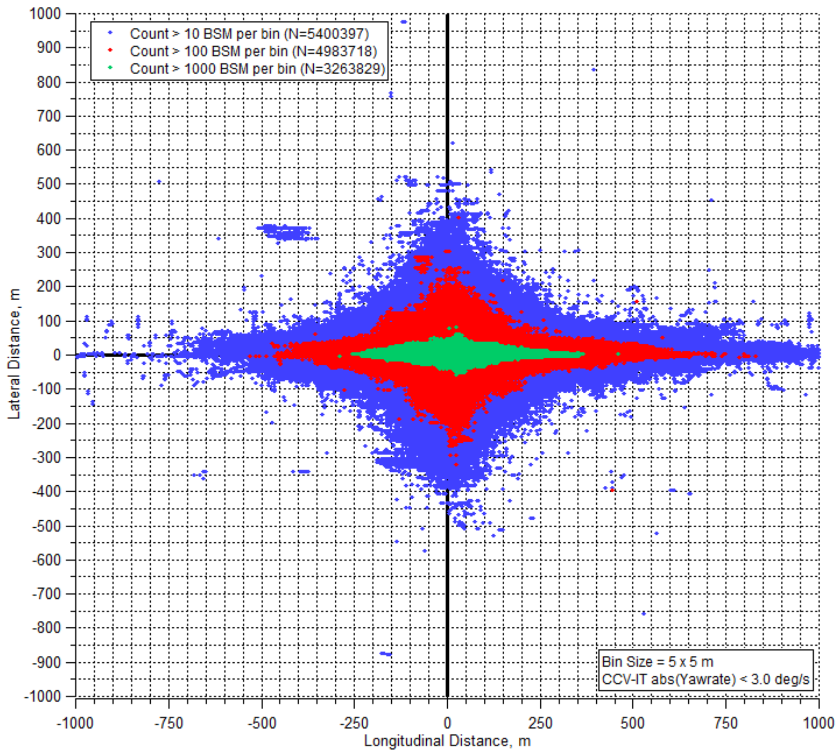

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Figure 6. Graph. BSM coverage map showing effect of message density as function of distance from the CCV-RSD.

BSM Capture Fraction

To further explore the capture of BSM from remote vehicles by CCV-RSD, consider figure 7. This figure shows the fraction of all BSM that were processed by the DSRC radio on-board the CCV-RSD 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-RSD 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 7 is generated by building a sub-set of all the BSM messages sent by all remote vehicles during all trips by the CCV-RSD tractors that are within a 1000 m of each other. This set of messages are then matched to the set of BSMs collected by the CCV-RSD radio and logged in the driving database. All matches in the subset 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-RSD. The data are grouped in to 10 x 10 m bins and the fraction is 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.

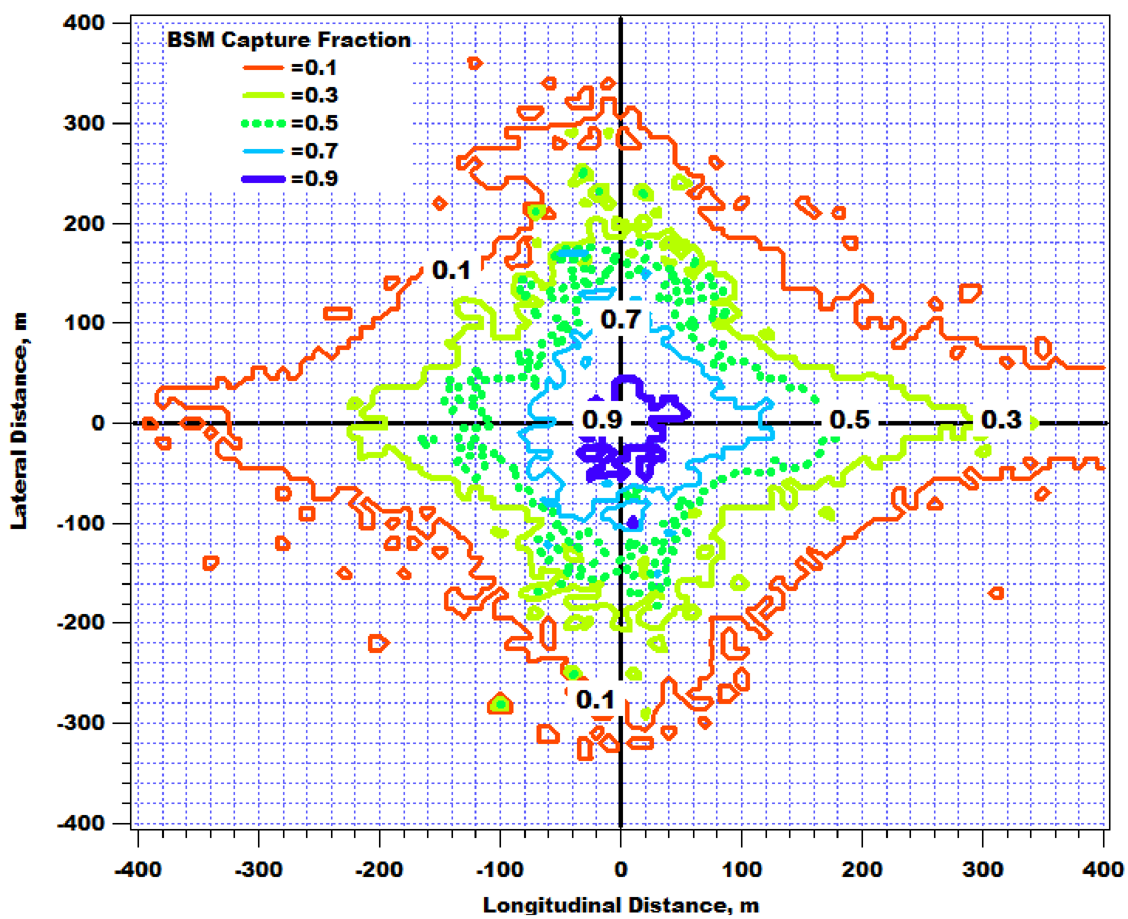

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Figure 7. Graph. BSM capture fraction (integrated trucks receiving broadcast BSMs from other vehicles) for all vehicle platforms and device categories.

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 40 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 RSD captured better than 90 percent of the BSMs from vehicles 40 to 60 m in front of the vehicle. This is the important region for the FCW safety application.

- 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-RSD tractors. The contour line extends from 120 m behind to 180 m ahead of the CCV-RSD and approximately 150 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-RSD. This safety application had an effective range of approximately 300 to 400 m or about 0.25 mile.

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-RSD tractor. Figure 8 is a histogram showing the fraction of vehicles that were detected as a function of distance from the CCV-RSD tractor. Better than 80 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 20 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 more frequently missed by CCV-RSD than 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-RSD.

Limiting the analysis to only those remote vehicles from which at least one BSM was recorded, the results in figure 9 show the fraction of BSM that were recorded as a function of distance to the remote vehicle. Approximately 70 percent of all BSMs were captured by the CCV-RSD when the remote vehicle was within 100 m.

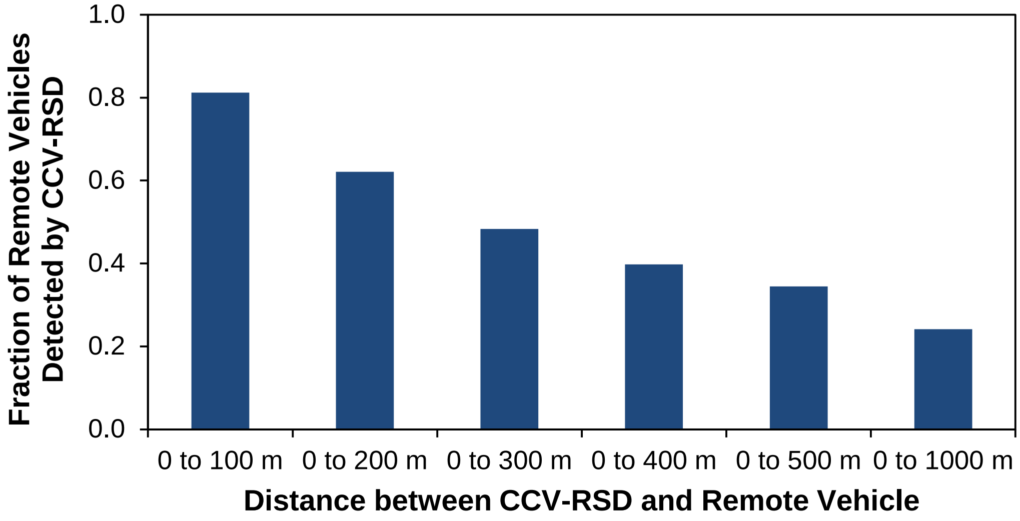

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Figure 8. Graph. The majority of remote vehicles were sensed by the CCV-RSD.

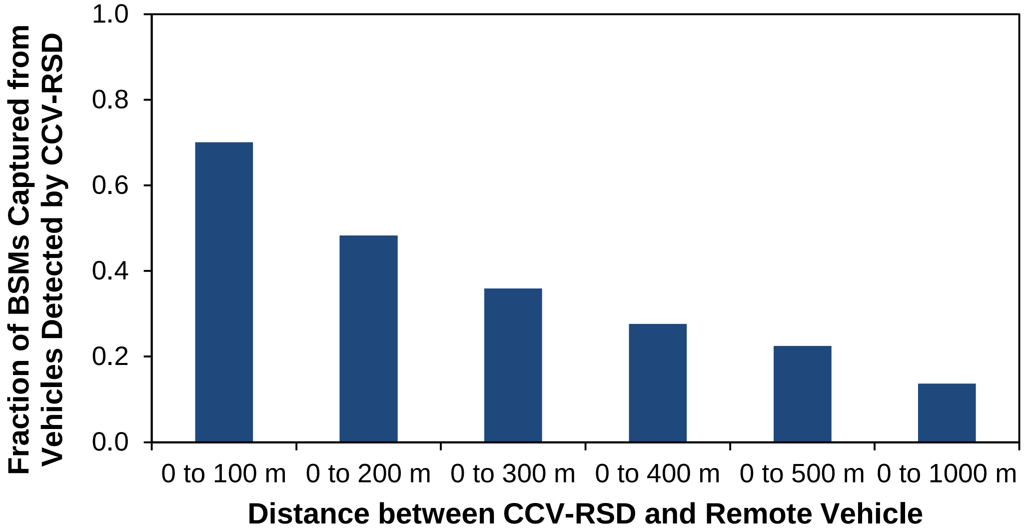

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Figure 9. Graph. BSM capture fraction as a function of distance, limited to vehicles from which the CCV-RSD captured at least one BSM.

BSM Inter-packet Time Gap

Figure 7 plotted the capture fraction for all BSMs as a function of range and azimuth but without regard to time or originating vehicle. Figure 8 and figure 9 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-RSD tractors.

Figure 10 is a histogram of the elapsed time between successive messages received by the CCV-RSD tractors during the 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 98 percent are less than 0.3 s. In other words, of the 71,050 encounters of CCV-RSD vehicles listed in table 5, only 1,389 had an internal gap of more than 0.3 s.

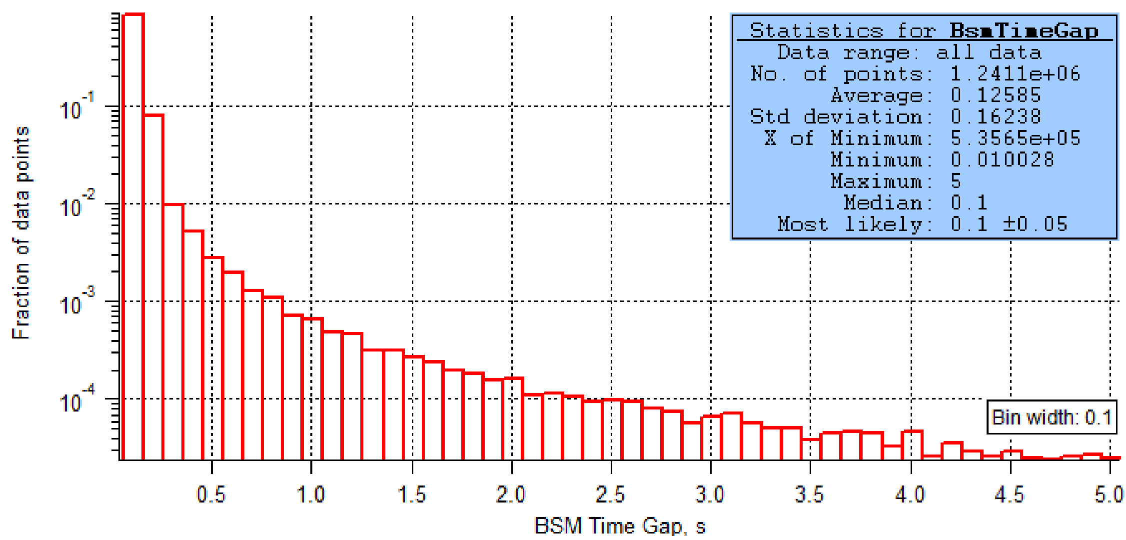

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Figure 10. Graph. Histogram of the time between successive BSM messages received by CCV-RSD.

Figure 11 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-RSD tractors, with one extending forward longitudinally between 50 and 300 m and a second region extending rearward from about -20 to -250 m.

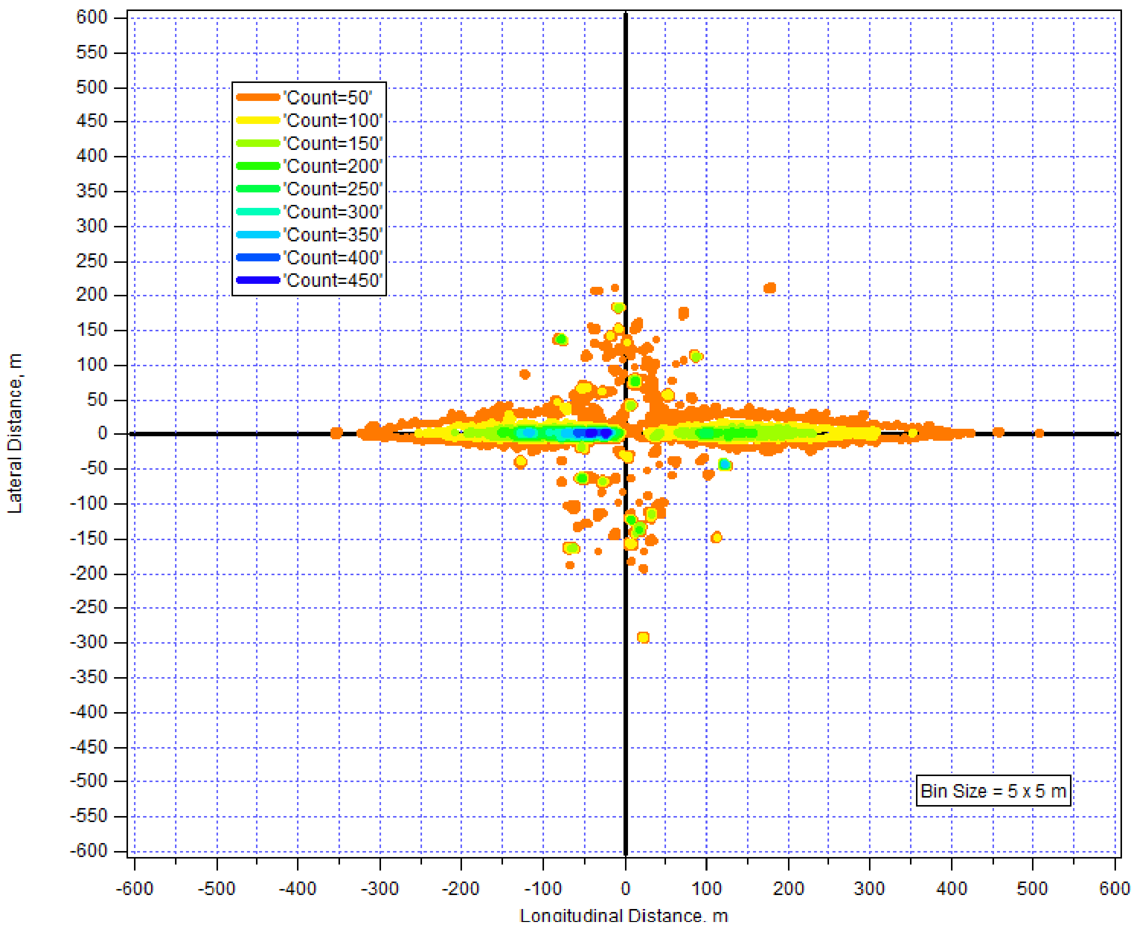

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Figure 11. Graph. Contour plot showing relative count of time gap events greater than 0.3 s as a function of location relative to the CCV-RSD.

The rearward region with higher counts could be the result of obstruction by the CCV-RSD trailer. Remote vehicles located behind the tractor-trailer do not have line-of-sight communication with the CCV-RSD 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 12 below is an expanded view of the region behind the trailer. This figure further illustrates that region just behind the trailer from -20 to -50 m (65 to 164 ft) had the highest concentration of events with longer time gaps between BSMs.

These findings represent communication from the remote vehicle to the CCV-RSD. In rear-crash scenarios, the communication from the CCV-RSD 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 BSMs from remote vehicles.

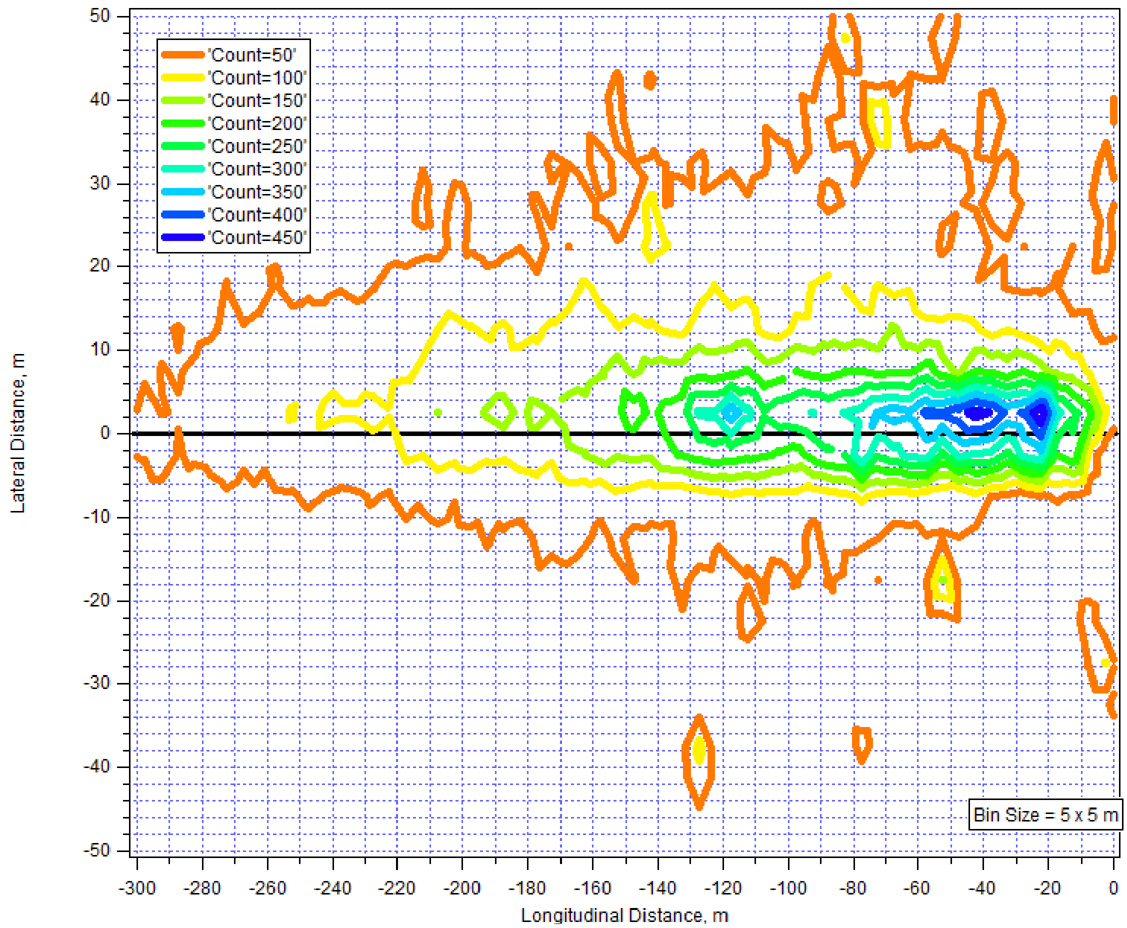

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Figure 12. Graph. Contour plot showing relative count of time gap events greater than 0.3 s for the region immediately behind the CCV-RSD.

CHAPTER 4. SUMMARY

Eight truck tractors that were already in fleet operation were equipped with Retrofit Safety Devices (RSDs). These devices provided crash warning safety applications using Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication. A commercial fleet used the vehicles in revenue service during the year-long model deployment in and around Ann Arbor, Michigan.

Communication of Basic Safety Messages (BSMs) from other vehicles to the RSD tractors 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 80 percent of the remote vehicles within a radius of 100 m. Reception was good along the side of the truck for blind spot 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.

The success in the model deployment demonstrated the interoperability of the RSD kits with light vehicles in a real-world setting. This project proved the technical viability of providing connected vehicle safety applications not only to newly manufactured tractors but also to previously manufactured tractors. Thus, it is possible to accelerate capturing the benefits of connected vehicle safety applications. The overall project provided information needed to assess the applications' safety benefits and support regulatory decision processes.

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