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# Summary of NHTSA Heavy-Vehicle Vehicle-to-Vehicle Safety Communications Research

# DISCLAIMER

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16. Abstract

This report provides a complete summary of NHTSA's heavy-vehicle (trucks and buses over 10,000 pounds) V2V research activities and results to date, to facilitate access to results by researchers, developers, and others in a single source. The document consists of excerpts from and summaries of reports from projects in the heavy-vehicle V2V safety research program, and related research activities. Significant topics include development of integrated truck and Retrofit V2V systems, V2V and V2I applications for heavy trucks, testing and evaluation based on real-world (Safety Pilot Model Deployment) and controlled test-track experiences, and safety benefits estimation for heavy-truck V2V systems.

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## List of Acronyms

| | |
|---|---|
| ACAT | advanced crash avoidance technology |
| ANPRM | Advance Notice of Proposed Rulemaking |
| ASD | aftermarket safety device |
| BHI | bridge height inform |
| BSM | basic safety message |
| BSW | blind spot warning |
| CAE | crash avoidance effectiveness |
| CAMP | Crash Avoidance Metrics Partnership |
| CAN | controller area network |
| CCV-IT | Connected Commercial Vehicle – Integrated Truck |
| CDS | Crashworthiness Data System |
| CPM | crash problem measure |
| CS-SwRI | Cambridge Systematics – Southwest Research Institute Team |
| CSW | curve speed warning |
| CV | connected vehicle |
| DAC | Driver Acceptance Clinic |
| DAS | data acquisition system |
| DGPS | differential global positioning system |
| DNPW | do not pass warning |
| DSRC | dedicated short range communication |
| DVI | driver-vehicle interface |
| EEBL | emergency electronic brake light |
| FARS | Fatality Analysis Reporting System |
| FCW | forward collision warning |
| FMCSA | Federal Motor Carrier Safety Administration |
| FTA | Federal Transit Administration |
| GES | General Estimates System |
| GVWR | gross vehicle weight rating |
| HMI | human-machine interface |
| HT | heavy truck |
| HV | host vehicle |
| HVT | host vehicle truck |
| IMA | intersection movement assist |
| IMU | inertial measurement unit |
| IT | integrated truck |
| ITS | Intelligent Transportation Systems |
| IVBSS | Integrated Vehicle-Based Safety System |
| IVD | in-vehicle display |
| JPO | Joint Program Office |
| LCW | lane change warning |
| LTA | left turn assist |
| LTAP | left turn across path |
| LTAP/OD | left turn across path / opposite direction |
| LTCCS | Long-Term Crash Causation Study |
| LVD | lead vehicle decelerating |
| LVM | lead vehicle moving |
| LVS | lead vehicle stopped |

| | |
|---|---|
| MAIS | Maximum Abbreviated Injury Scale |
| MBRDNA | Mercedes-Benz Research & Development North America, Inc. |
| MD | Model Deployment |
| MITRP | Michigan Technical Research Park |
| NADS | National Advanced Driving Simulator |
| OBE | on board equipment |
| OEM | original equipment manufacturer |
| OSADP | Open Source Application Development Portal |
| PCW | pedestrian crosswalk warning |
| PDO | property damage only |
| PR | police-reported |
| RF | radio frequency |
| RSD | retrofit safety device |
| RSE | roadside equipment |
| RSU | roadside unit |
| RT | real-time |
| RV | remote vehicle |
| RVL | remote light vehicle |
| RVT | remote vehicle truck |
| SB | safety benefit |
| SCMS | Security Credential Management System |
| SCP | straight crossing paths |
| SD | standard deviation |
| SIM | Safety Impact Methodology |
| SPaT | signal phase and timing |
| SRI | Smart Roadside Initiative |
| TCD | traffic control device |
| TIM | Traveler Information Message |
| TRP | transit retrofit package |
| TT-BSM | truck trailer – basic safety message |
| TTC | time-to-collision |
| UMTRI | University of Michigan Transportation Research Institute |
| V2I | vehicle-to-infrastructure |
| V2P | vehicle-to-pedestrian |
| V2V | vehicle-to-vehicle |
| VAD | vehicle awareness device |
| VRTC | Vehicle Research and Test Center |
| VSC-A | vehicle safety communications - applications |
| VTRW | vehicle turning right warning |
| WAAS | wide area augmentation system |
| WSU | wireless safety unit |

# Executive Summary

The National Highway Traffic Safety Administration has been engaged in programs to research and assess vehicle-to-vehicle communications-based safety systems, as part of its mission to save lives, prevent injuries, and reduce economic costs due to road traffic crashes. These V2V safety systems transmit basic safety information between vehicles to enable warnings to drivers and help reduce the occurrence of and mitigate the impacts of motor vehicle crashes. By broadcasting real-time information on vehicle speed, heading, brake status, and other information, V2V systems can provide surrounding vehicles with critical information to assess and address scenarios where potential crash threats exist.

The objective of this report is to provide a synopsis of NHTSA's V2V research on a key segment of the vehicle fleet, heavy vehicles (trucks and buses over 10,000 pounds or 4,536 Kg). NHTSA has previously published *Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application* (V2V Readiness Report) [4], which included information on the light vehicle V2V research conducted over the last decade. Most of the research conducted under the light vehicle V2V research program is directly applicable to applications in heavy vehicles, including the foundational elements such as 5.9 GHz Dedicated Short Range Communications and the supporting security credential management system that enables trust for V2V basic safety messages. Additionally, continued research in areas such as cyber security is also expected to apply to heavy vehicles.

At the same time, there are certain aspects of heavy-vehicle V2V systems that differ significantly from light vehicles. A major distinction in the heavy-vehicle fleet is the widespread use of combination vehicles, (e.g., a tractor pulling a semitrailer) which articulate when turning. The prior research in light vehicle V2V systems used sedans and SUVs that act as a single rigid body, and were represented in BSM transmissions by a rectangle. While heavy-vehicle V2V safety applications such as Intersection Movement Assist and Lane Change Warning have been developed based on the light vehicle application prototypes, research has been underway to address the BSM representation for articulated vehicles, and the necessary message set adjustments have been developed. A related consideration for combination vehicles with V2V capability involves providing the ability for the tractor unit to broadcast BSMs that contain the necessary information (e.g., length) on the trailing unit. This topic is an area where active research continues.

Heavy-vehicle V2V systems have been prototyped and tested in controlled scenarios in track testing and driver clinics as well as in a real world environment, the United States Department of Transportation's Safety Pilot Model Deployment in Ann Arbor, Michigan. Testing of these heavy-vehicle V2V systems included a variety of prototypes with V2V capability, including class 8 tractors in an "integrated" configuration, retrofit safety devices designed to facilitate installation of V2V capability in existing trucks, and retrofitted local transit buses. Additional research is also being conducted to further explore V2V systems in single unit trucks.

Analysis of the potential safety benefits associated with heavy-vehicle V2V systems has shown good promise based on initial results. In 2013 there were 3,964 people killed and 95,000 people injured in crashes involving at least one large truck. Based on data from police-reported crashes, 70 percent of crashes involving trucks occurred in scenarios that could potentially be addressed by V2V systems. Refinement of these analyses is continuing, using a Safety Impact Methodology to identify estimated benefits from heavy-vehicle V2V safety systems, based on results from individual V2V application testing and other supporting information. While efforts continue to address specific remaining areas of research in heavy-vehicle V2V safety systems, results from NHTSA’s research program have been supportive of the potential for V2V implementation in heavy vehicles, with no unsolvable obstacles identified to date.

# I. Introduction

In August 2014 the National Highway Traffic Safety Administration released an Advance Notice of Proposed Rulemaking [1] stating its intent to propose to require vehicle-to-vehicle safety capability in new light-duty vehicles. NHTSA, in collaboration with industry and other partners, has been engaged in research, development, and demonstration of V2V communications to enable a new generation of safety technology, where vehicles cooperatively establish an awareness of surrounding vehicles to help drivers avoid potential crashes. In May 2015 U.S. Secretary of Transportation Anthony Foxx indicated the department's intent to accelerate the rulemaking process, and also noted the additional potential roles for automation and infrastructure communications [2]. Much of the research activity to date has therefore been focused on light-duty vehicles, but the role of V2V safety technology for heavy vehicles (trucks and buses with gross vehicle weight rating of 10,000 pounds or more) remains significant.

## I.A. Purpose of this document

This report provides a synopsis of NHTSA research, development, and testing associated with V2V technology for heavy vehicles. These activities have been conducted as part of a larger plan to conduct comprehensive V2V safety research to determine if V2V safety systems meet a safety need, are practicable, meet driver acceptance, and are effective [3]. Significantly, the safety research plan incorporates a specific program track to focus on identifying and addressing issues associated with heavy vehicles, in coordination with the NHTSA's light-vehicle V2V activities and cross-cutting connected vehicle research being conducted by USDOT's Intelligent Transportation Systems Joint Program Office. The objective in publishing this report is to complement the light-vehicleV2V Readiness Report [4], which provided detailed information on V2V technology, and safety applications, supporting systems and policies, and potential costs and benefits. The LV V2V Readiness Report was also written to support the ANPRM, covering for example NHTSA's legal authority to require V2V technology in new vehicles. This heavy-vehicle report represents an orientation toward establishing a base for understanding the progress made in V2V technology in heavy vehicles, and attempts to minimize duplicative content already covered by the LV V2V Readiness Report. Notably, **the primary intent of this report is to cover an overview of research results to date, including summaries and excerpts from the full research reports** (see References, Section VI). Readers interested in additional detail on a specific topic are directed to the original source document.

## I.B. Background of V2V communication research program

Early research in V2V technology started in the late 1990s with the Federal Communications Commission allocating wireless spectrum at 5.9 GHz to enable Dedicated Short Range Communications between vehicles and between vehicles and infrastructure to support Intelligent Transportation Systems, including vehicle safety applications. Several NHTSA projects have played a prominent role in bringing V2V from concept to development. From 2002-2005, the Vehicle Safety Communications project [5], conducted by a consortium organized by the Crash Avoidance Metrics Partners in partnership with NHTSA, engaged in exploratory work to identify and assess potential communications-based applications, tested the underlying communications technology, and participated in standards development activities to propose standards content to support vehicle DSRC communications and applications. A follow-on project from 2006-2009, Vehicle Safety Communications-Applications [6], conducted with a slightly different CAMP consortium, developed prototype V2V applications and the supporting relative positioning and communications capabilities between vehicles. Since 2009, CAMP has been conducting further work in the area of interoperability, scalability, and security to enable multiple devices and systems to support V2V, and also to build standards content and performance requirements to ensure common V2V capability. As the maturity of the technology increased, in 2012-2013, USDOT engaged in a Safety Pilot [7] to test V2V technology under controlled conditions (driver clinics, where drivers could experience scenarios being targeted by V2V applications) as well as in a real-world environment (Model Deployment in the Ann Arbor area).

## I.C. Studies related to V2V light-vehicle research

Most of the V2V research activity has been conducted on light vehicles, with significant involvement by carmakers. However, USDOT has also engaged in research planning to investigate how the communications that makes V2V possible can be applied to vulnerable road users such as pedestrians and cyclists through vehicle-to-pedestrian communications. Additionally, early stage research on equipping motorcycles with V2V technology was conducted in the Safety Pilot environment, largely to gather data and identify needed research on aspects of V2V systems that are unique to motorcycles. Further discussion of these research plans may be found in the LV V2V Readiness Report [4].

## I.D. Areas of light-vehicle V2V common for implementation on all vehicle types

This report largely discusses aspects of V2V technology where heavy vehicles differ from light vehicles. However, there are many areas where light and heavy vehicles are similar with respect to V2V. Fundamentally, the basic premise of V2V technology is for vehicles to broadcast, via standardized 5.9 GHz DSRC messages, their real-time position and movement-related information to surrounding vehicles, thereby enabling equipped vehicles to identify and mitigate (e.g., alerting drivers) potentially hazardous scenarios. This is the case for both light and heavy vehicles, and vehicles of any type need to be interoperable and able to understand and act upon the information transmitted by other vehicles. In order to trust the information received, a common security credential management system, including a means for establishing certificate definition and usage, common methods for signing and validating messages, and supporting minimum performance requirements and associated testing, needs to be in place so that a vehicle can verify the integrity of messages and trust that the message came from a valid source.

### *I.D.1. Technical practicability, DSRC standards, spectrum, interoperability, policy, and security approach*

The technical practicability of V2V technology in heavy vehicles has been explored during the course of several research projects, clinics, and field trials, discussed further in Sections IV and

V. Based on the results of these efforts, research needs and implementation issues have been identified for further action. For example, the need to represent the articulation behavior of combination vehicles resulted in a set of proposed modifications to the SAE J2735 basic safety message , and work is ongoing to assess changes needed for the associated draft J2945 Minimum Performance Requirements document in development. This may also entail interoperability-related changes in how light vehicles interpret the new BSM content.
With regard to the 5.9 GHz DSRC spectrum, heavy vehicles are expected to conform to the channel usage allocations established for light vehicles.

Policy considerations for heavy vehicles can differ from light vehicles, as the regulatory framework is not the same. NHTSA and the Federal Motor Carrier Safety Administration share regulatory oversight for heavy vehicles and their safe operation. USDOT has been engaged in the Smart Roadside Initiative [8] to explore how DSRC can be used to support commercial vehicle operations and enforcement. In addition, for transit buses, policies established by the Federal Transit Administration may be able to encourage the deployment of V2V safety systems. FTA provides capital funding, including funds for purchase of buses and associated equipment and systems, for the majority of transit agencies in the United States.

The security credentialing for all V2V systems is anticipated to be largely uniform across vehicle types with respect to how messages are signed and verified.

The remainder of this report provides a summary of research progress to address these and other issues to enable V2V safety systems in heavy vehicles.

## I.E. Special Considerations for Heavy Vehicles

Much of the prior V2V work documented in the Readiness Report [4] has focused on V2V safety systems oriented toward light vehicles. However, whereas light vehicles often have generally similar characteristics with respect to V2V design and performance considerations, V2V safety systems for heavy vehicles have unique issues that must be addressed. This section provides a summary of identified challenges in V2V safety systems associated with single-unit trucks and buses, and articulated vehicles.

Some limitations are common to both single-unit and combination-unit vehicles. For example, in heavy vehicles, DSRC can be more affected by line-of-sight obstructions than in light vehicles. It is possible to still receive a signal due to signal reflectivity but overall system performance can still be impacted by the presence of large commercial vehicles within the system. Antenna placement on heavy vehicles is key and even if optimized can still result in RF shadows around the vehicle, due to the presence of the large body profile, greater vehicle height, and trailers it may be hauling. Also, data elements used in the SAE J2735 standard sometimes lack sufficient representative power for heavy vehicles. For example, the current SAE J2735 definition for “Vehicle Mass” is insufficient for heavy vehicles. It currently only allows values up to 14,000 lbs., with greater values represented by a single placeholder value. This does not provide the ability to distinguish between trucks with differing weights, which can be up to 80,000 lbs. or more. A particular challenge for heavy vehicles is the range of vehicle weight (and associated vehicle dynamics) from an unloaded versus loaded state that is not captured by the VehicleMass data element.

### *I.E.1. Single-Unit Trucks and Buses*

NHTSA is currently engaged in an effort to study issues associated with single-unit trucks, with project results expected to be available by the end of 2016. With respect to transit buses, the Transit Safety Retrofit Project, described in more detail in Section IV.E, identified specific factors that are relevant in a transit bus environment. The DSRC antenna configuration selected for the transit buses used a combination of a whip-style antenna mounted on the driver mirror, along with a glass-mounted antenna installed on the front windshield [9]. These antennas were positioned in part to suit the applications being tested. BSMs from light vehicles passing the bus on the left were important to support the vehicle turning-right warning application, while the glass-mounted antenna was oriented toward receiving Signal Phase and Timing messages from infrastructure RSUs as the bus approached signalized intersections equipped with the pedestrian-in-crosswalk warning application. While most transit buses in the United States are single-unit (non-articulated), certain agencies in large metropolitan areas operate articulated transit buses which typically have a forward two-axle section with a permanently attached single-axle trailing section. As discussed further in Sections I.E.2 and IV.H, vehicle articulation can present challenges in accurately representing the location using the current SAE J2735 BSM.

### *I.E.2. Articulated Vehicles*

The primary issue with the current BSM that relates to heavy vehicles is the fact that the vehicle length and width in the BSM are used to define a simple rectangle. This results in a particular issue for heavy vehicle classes where combination units are prevalent (i.e., tractor-trailer combinations). Voluntary consensus industry standards use a static bounding box representation to define the length and width of all vehicles. This bounding box is transmitted as part of the BSM and used by remote vehicle V2V safety applications. This design is functionally limiting when combination-unit vehicles are introduced.

First, combination-unit vehicles contain a dynamic component that significantly affects the size and shape of the vehicle bounding box; i.e., the vehicle trailer (double and triple combinations). Within the trucking industry, it is not uncommon for a tractor trailer to drop off and pick up multiple loads over the course of a single day. These loads may change the vehicle’s length, width, or both.

Second, a tractor-trailer is an articulating unit that can significantly change its footprint geometry over the course of a turn. This articulation can have significant impact on safety applications in surrounding vehicles that may incorrectly discern roadway hazards based on an incorrect location of a trailer. Figure 1 provides a single example where a passenger vehicle could incorrectly detect a forward collision due to the rigid nature of how vehicle shape is defined and transmitted.

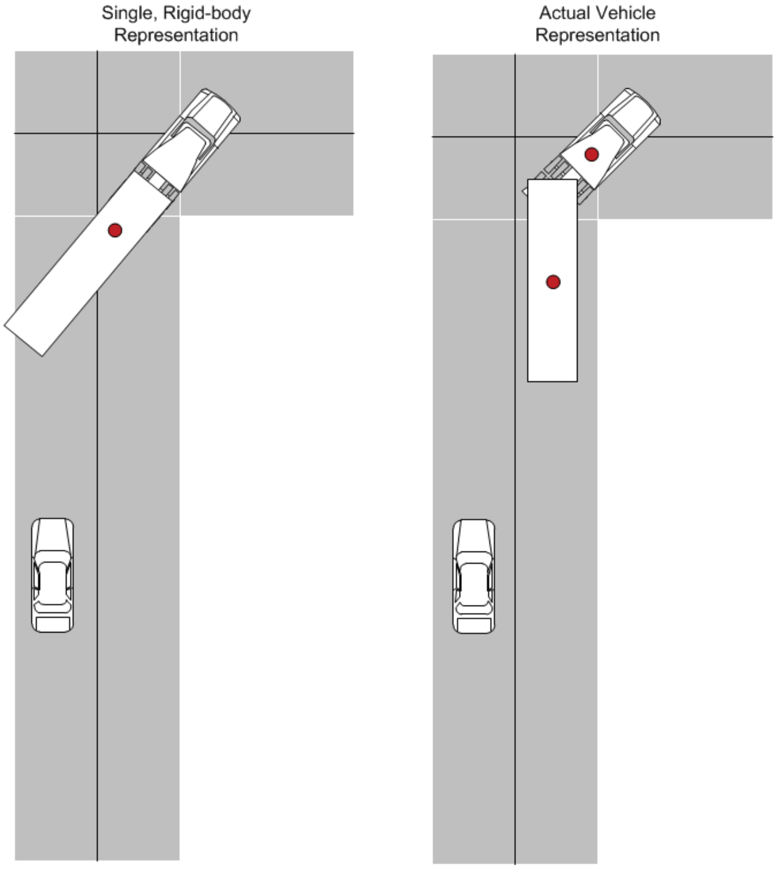


**Figure 1: Vehicle Representation**

Source: SwRI

NHTSA has engaged in the Tractor-Trailer BSM Development Project, discussed in Section IV.H, to develop and assess potential solutions to represent a more accurate BSM for articulated heavy vehicles given this issue. This includes both defining representation mechanisms for articulated vehicles as well as identifying any associated changes required for the receiving vehicle. Additionally, recent work in the SAE DSRC Technical Committee [10] has explored the potential for defining the representation of key attributes, such as the trailer pivot point, that can be applied to both the common cases (tractor-semitrailer, and light vehicle towing a trailer) as well as more complex configurations with multiple trailing units (e.g., doubles, triples). Research began in 2015 to determine processes and methods to efficiently populate the required data once a representation is developed, particularly with respect to size attributes for trailers of varying length.

# II. Safety Need

## II.A. Summary Focusing on Safety Need:

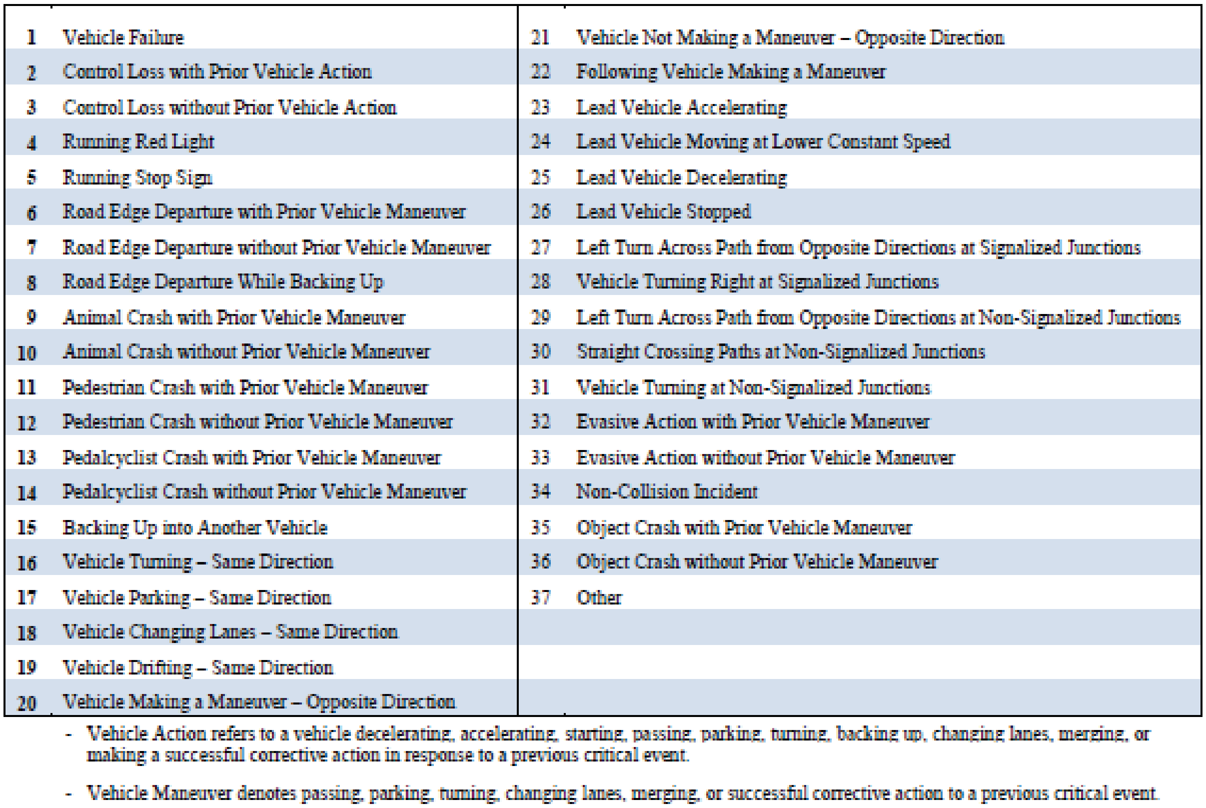
Crashes involving Heavy Vehicles frequently result in a significant impact in terms of fatalities, injuries, and property damage [14]. In 2013 there were 3,964 people killed and 95,000 people injured in crashes involving large trucks. In 2013 large trucks accounted for 4 percent of all registered vehicles and 9 percent of the total vehicle miles traveled [46]. In 2013 these large trucks accounted for 9 percent of all vehicles involved in fatal crashes and 3 percent of all vehicles involved in injury and property-damage-only crashes. In particular, large trucks were more likely to be involved in a fatal multiple-vehicle crash as opposed to a fatal single-vehicle crash than were light vehicles. In 2013 80 percent of fatal crashes involving large trucks were multiple-vehicle crashes, compared with 58 percent for fatal crashes involving passenger vehicles, and in 17 States, over 10 percent of fatal crashes involved large trucks. V2V technologies focus on preventing and mitigating multiple-vehicle crashes such as these and reducing associated fatalities, injuries, and property damage.

## II.B. Heavy-vehicle crashes potentially addressed by V2V technology

Calculating the target potential crashes that V2V-based safety applications could address helps provide a starting point for estimating the magnitude of the problem in terms of the number and severity of crashes and injuries, the number of fatalities, and the societal cost of vehicle crashes. Dividing up the potential target crashes by pre-crash scenario also helps to understand how different V2V-based safety applications can address different kinds of safety problems. USDOT conducted a preliminary analysis in 2009 of the estimated annual number of crashes that could be addressed by V2V technology [15]. The identified applicable crashes are based on the USDOT-developed pre-crash scenario typology [16], which is in turn primarily based on pre-crash variables recorded in the National Automotive Sampling System General Estimates System and Crashworthiness Data System.

In 2014 NHTSA published an analysis [17] of pre-crash scenarios applicable to heavy trucks, following a similar pre-crash scenario typology (see Table 1). As with the LV crash scenario analysis, some selected scenarios are not within the target of V2V crash avoidance system. Of the 37 pre-crash scenarios, 22 were considered to be potentially addressable by V2V technology (see Table 2). Of the 22 pre-crash scenarios, five scenarios (control loss/no vehicle action, control loss/vehicle action, parking, backing, and other) were not included in the set analyzed for V2V, since these scenarios are likely to draw upon other vehicle-based systems or provide advisories rather than crash-imminent warning systems.

**Table 1: 37 Pre-Crash Scenario Typology**

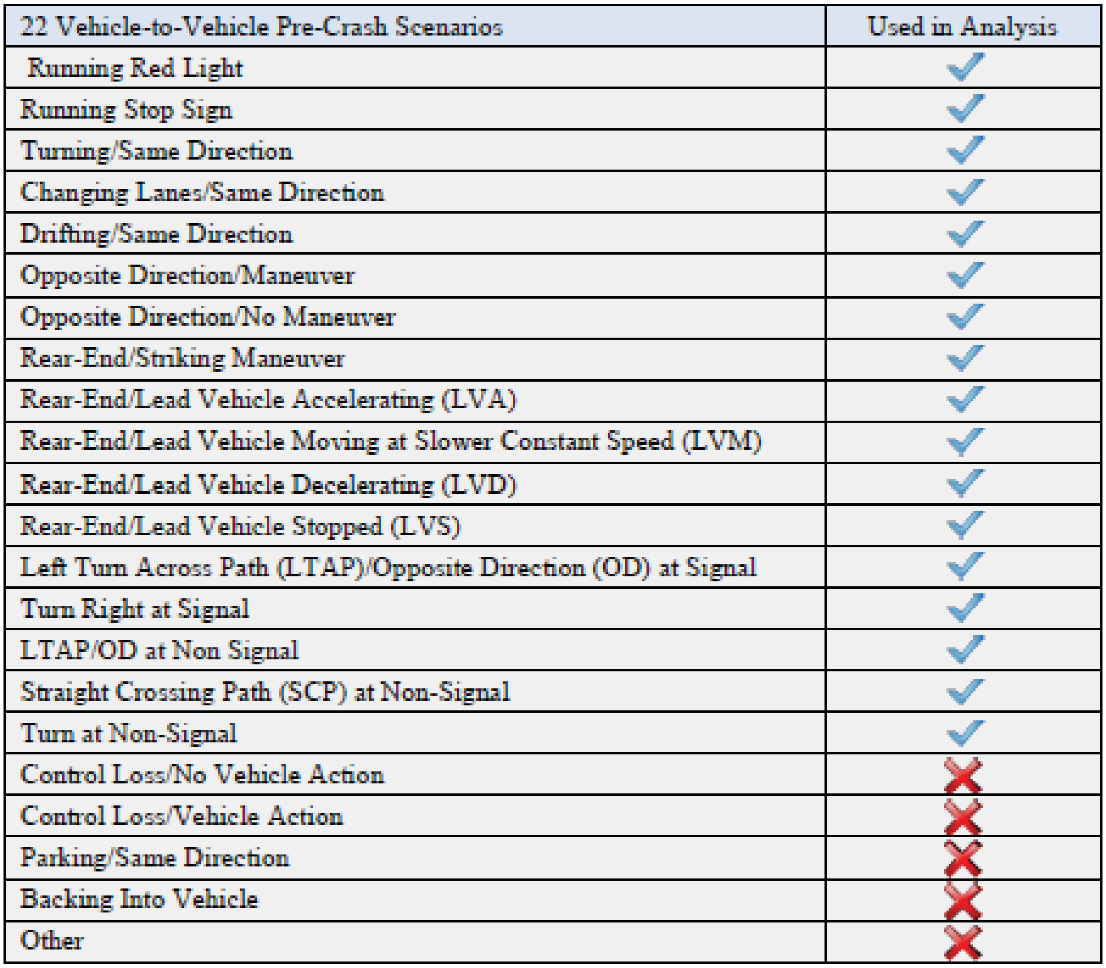


| | | | |
|---|---|---|---|
| 1 | Vehicle Failure | 21 | Vehicle Not Making a Maneuver – Opposite Direction |
| 2 | Control Loss with Prior Vehicle Action | 22 | Following Vehicle Making a Maneuver |
| 3 | Control Loss without Prior Vehicle Action | 23 | Lead Vehicle Accelerating |
| 4 | Running Red Light | 24 | Lead Vehicle Moving at Lower Constant Speed |
| 5 | Running Stop Sign | 25 | Lead Vehicle Decelerating |
| 6 | Road Edge Departure with Prior Vehicle Maneuver | 26 | Lead Vehicle Stopped |
| 7 | Road Edge Departure without Prior Vehicle Maneuver | 27 | Left Turn Across Path from Opposite Directions at Signalized Junctions |
| 8 | Road Edge Departure While Backing Up | 28 | Vehicle Turning Right at Signalized Junctions |
| 9 | Animal Crash with Prior Vehicle Maneuver | 29 | Left Turn Across Path from Opposite Directions at Non-Signalized Junctions |
| 10 | Animal Crash without Prior Vehicle Maneuver | 30 | Straight Crossing Paths at Non-Signalized Junctions |
| 11 | Pedestrian Crash with Prior Vehicle Maneuver | 31 | Vehicle Turning at Non-Signalized Junctions |
| 12 | Pedestrian Crash without Prior Vehicle Maneuver | 32 | Evasive Action with Prior Vehicle Maneuver |
| 13 | Pedalcyclist Crash with Prior Vehicle Maneuver | 33 | Evasive Action without Prior Vehicle Maneuver |
| 14 | Pedalcyclist Crash without Prior Vehicle Maneuver | 34 | Non-Collision Incident |
| 15 | Backing Up into Another Vehicle | 35 | Object Crash with Prior Vehicle Maneuver |
| 16 | Vehicle Turning – Same Direction | 36 | Object Crash without Prior Vehicle Maneuver |
| 17 | Vehicle Parking – Same Direction | 37 | Other |
| 18 | Vehicle Changing Lanes – Same Direction | | |
| 19 | Vehicle Drifting – Same Direction | | |
| 20 | Vehicle Making a Maneuver – Opposite Direction | | |

- Vehicle Action refers to a vehicle decelerating, accelerating, starting, passing, parking, turning, backing up, changing lanes, merging, or making a successful corrective action in response to a previous critical event.
- Vehicle Maneuver denotes passing, parking, turning, changing lanes, merging, or successful corrective action to a previous critical event.

Source: Table 1 from [17]

**Table 2: Target V2V Pre-Crash Scenarios**



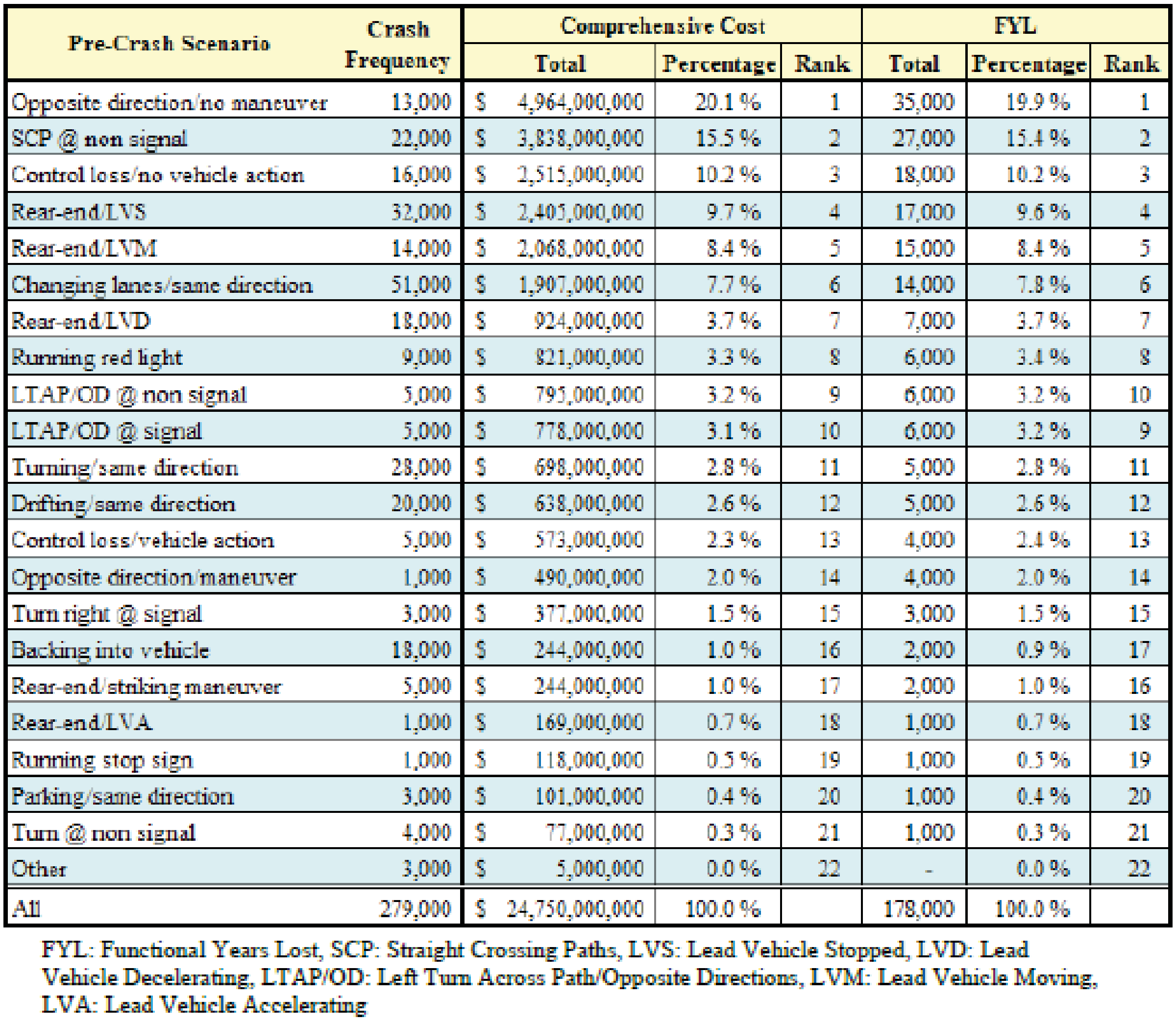
| 22 Vehicle-to-Vehicle Pre-Crash Scenarios | Used in Analysis |
|---|---|
| Running Red Light | ✓ |
| Running Stop Sign | ✓ |
| Turning/Same Direction | ✓ |
| Changing Lanes/Same Direction | ✓ |
| Drifting/Same Direction | ✓ |
| Opposite Direction/Maneuver | ✓ |
| Opposite Direction/No Maneuver | ✓ |
| Rear-End/Striking Maneuver | ✓ |
| Rear-End/Lead Vehicle Accelerating (LVA) | ✓ |
| Rear-End/Lead Vehicle Moving at Slower Constant Speed (LVM) | ✓ |
| Rear-End/Lead Vehicle Decelerating (LVD) | ✓ |
| Rear-End/Lead Vehicle Stopped (LVS) | ✓ |
| Left Turn Across Path (LTAP)/Opposite Direction (OD) at Signal | ✓ |
| Turn Right at Signal | ✓ |
| LTAP/OD at Non Signal | ✓ |
| Straight Crossing Path (SCP) at Non-Signal | ✓ |
| Turn at Non-Signal | ✓ |
| Control Loss/No Vehicle Action | ✗ |
| Control Loss/Vehicle Action | ✗ |
| Parking/Same Direction | ✗ |
| Backing Into Vehicle | ✗ |
| Other | ✗ |

Source: Table 2 from [17]

Based on crash data (from 2005-2008 GES databases) for the targeted scenarios, a fully mature V2V system could potentially address 267,000 police-reported crashes involving at least one heavy truck annually. This corresponds to 70 percent of all annual crashes involving at least one heavy truck if V2V systems were considered the primary countermeasure. Of the remaining crashes, about half are considered addressable by vehicle-to-infrastructure and/or autonomous vehicle-based systems, and the other half of this group was not assigned a specific countermeasure due to lack of sufficient information [17].

Based on data from 2004-2008 GES and 2001-2003 Large Truck Crash Causation Study crash databases, the target V2V pre-crash scenarios for heavy truck may be measured in terms of societal cost through comprehensive costs and functional years lost. Comprehensive economic costs account for goods and services that must be purchased, or productivity that is lost as a result of crashes, and quality-of-life valuations [18]. Functional years lost is another measure that captures the years of life lost to fatal injury and years of functional capacity lost to non-fatal injury [19]. Table 3 shows the comprehensive costs and functional years lost corresponding to the pre-crash scenarios being targeted.

**Table 3: Frequency, Societal Cost, and Rank of Target Heavy-Truck Pre-Crash Scenarios**



| Pre-Crash Scenario | Crash Frequency | Comprehensive Cost | | | FYL | | |
|---|---|---|---|---|---|---|---|
| | | Total | Percentage | Rank | Total | Percentage | Rank |
| Opposite direction/no maneuver | 13,000 | $ 4,964,000,000 | 20.1 % | 1 | 35,000 | 19.9 % | 1 |
| SCP @ non signal | 22,000 | $ 3,838,000,000 | 15.5 % | 2 | 27,000 | 15.4 % | 2 |
| Control loss/no vehicle action | 16,000 | $ 2,515,000,000 | 10.2 % | 3 | 18,000 | 10.2 % | 3 |
| Rear-end/LVS | 32,000 | $ 2,405,000,000 | 9.7 % | 4 | 17,000 | 9.6 % | 4 |
| Rear-end/LVM | 14,000 | $ 2,068,000,000 | 8.4 % | 5 | 15,000 | 8.4 % | 5 |
| Changing lanes/same direction | 51,000 | $ 1,907,000,000 | 7.7 % | 6 | 14,000 | 7.8 % | 6 |
| Rear-end/LVD | 18,000 | $ 924,000,000 | 3.7 % | 7 | 7,000 | 3.7 % | 7 |
| Running red light | 9,000 | $ 821,000,000 | 3.3 % | 8 | 6,000 | 3.4 % | 8 |
| LTAP/OD @ non signal | 5,000 | $ 795,000,000 | 3.2 % | 9 | 6,000 | 3.2 % | 10 |
| LTAP/OD @ signal | 5,000 | $ 778,000,000 | 3.1 % | 10 | 6,000 | 3.2 % | 9 |
| Turning/same direction | 28,000 | $ 698,000,000 | 2.8 % | 11 | 5,000 | 2.8 % | 11 |
| Drifting/same direction | 20,000 | $ 638,000,000 | 2.6 % | 12 | 5,000 | 2.6 % | 12 |
| Control loss/vehicle action | 5,000 | $ 573,000,000 | 2.3 % | 13 | 4,000 | 2.4 % | 13 |
| Opposite direction/maneuver | 1,000 | $ 490,000,000 | 2.0 % | 14 | 4,000 | 2.0 % | 14 |
| Turn right @ signal | 3,000 | $ 377,000,000 | 1.5 % | 15 | 3,000 | 1.5 % | 15 |
| Backing into vehicle | 18,000 | $ 244,000,000 | 1.0 % | 16 | 2,000 | 0.9 % | 17 |
| Rear-end/striking maneuver | 5,000 | $ 244,000,000 | 1.0 % | 17 | 2,000 | 1.0 % | 16 |
| Rear-end/LVA | 1,000 | $ 169,000,000 | 0.7 % | 18 | 1,000 | 0.7 % | 18 |
| Running stop sign | 1,000 | $ 118,000,000 | 0.5 % | 19 | 1,000 | 0.5 % | 19 |
| Parking/same direction | 3,000 | $ 101,000,000 | 0.4 % | 20 | 1,000 | 0.4 % | 20 |
| Turn @ non signal | 4,000 | $ 77,000,000 | 0.3 % | 21 | 1,000 | 0.3 % | 21 |
| Other | 3,000 | $ 5,000,000 | 0.0 % | 22 | - | 0.0 % | 22 |
| All | 279,000 | $ 24,750,000,000 | 100.0 % | | 178,000 | 100.0 % | |

FYL: Functional Years Lost, SCP: Straight Crossing Paths, LVS: Lead Vehicle Stopped, LVD: Lead Vehicle Decelerating, LTAP/OD: Left Turn Across Path/Opposite Directions, LVM: Lead Vehicle Moving, LVA: Lead Vehicle Accelerating

Source: Table 7 from [17]

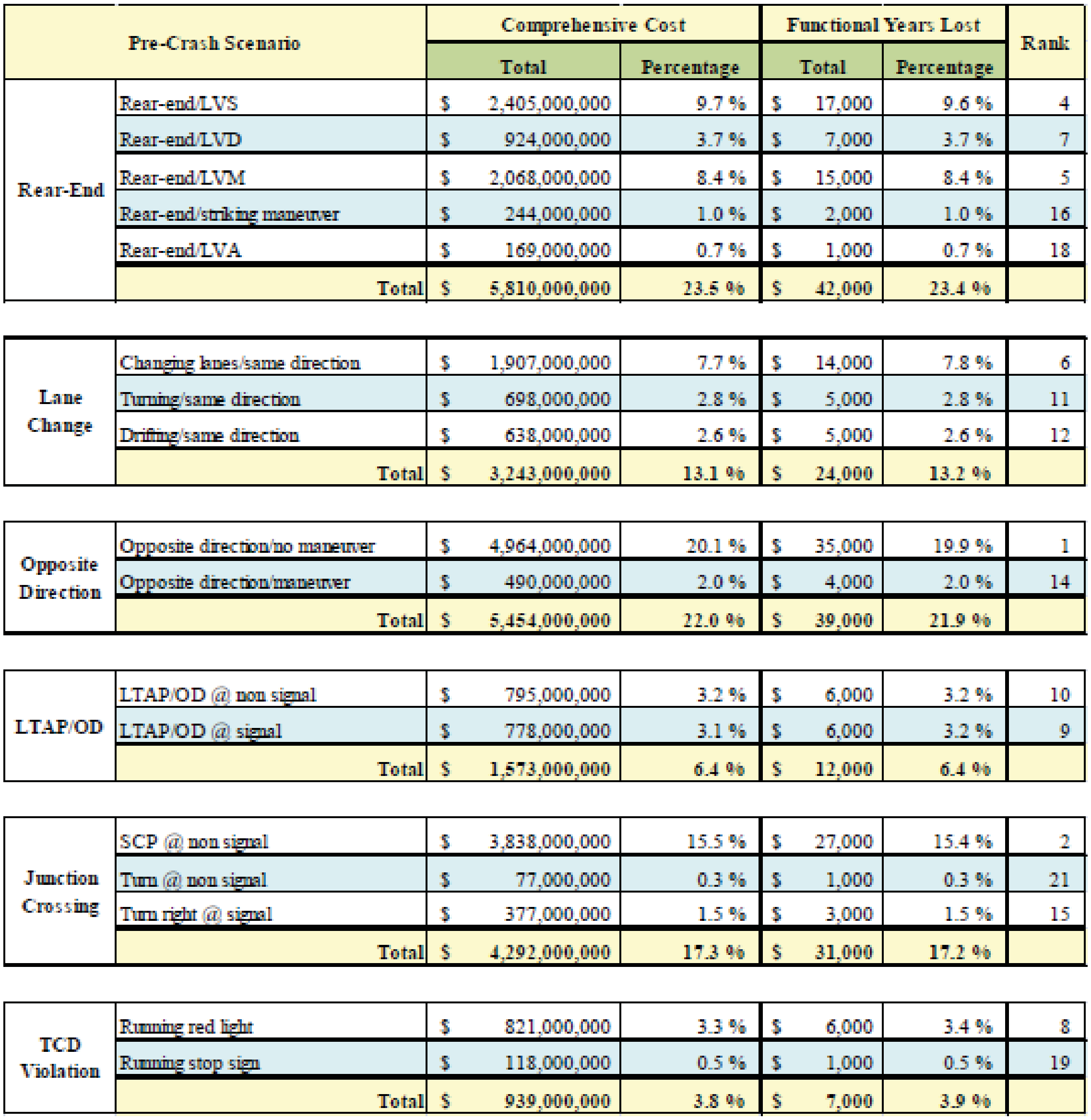
As the table indicates, several pre-crash scenarios account for a large proportion of the total comprehensive cost associated with the targeted scenarios. The top six scenarios, accounting for $17.7 billion or 72 percent of the $24.8 billion annual comprehensive cost, are:

1. Opposite direction/no maneuver,
2. Straight Crossing Paths (SCP) @ nonsignalized road junctions,
3. Control loss/no vehicle action,
4. Rear-end/Lead vehicle stopped,
5. Rear-end/Lead vehicle moving, and
6. Changing lanes/same direction.

As discussed previously, the “control loss/no vehicle action” scenario may potentially be addressed by autonomous crash avoidance systems and since the crash risk may or may not be imminent, the scenario is not included in the set of crashes potentially addressed by V2V-based crash-imminent warning applications.

Those scenarios considered potentially addressable by V2V crash avoidance applications may be grouped into six major categories: rear-end, lane-change, opposite-direction, left turn across path/opposite-direction (LTAP/OD), junction crossing, and traffic control device violation (see Table 4).

**Table 4: Groups and Societal Cost of Target V2V Pre-Crash Scenarios Involving Heavy Trucks**



| Pre-Crash Scenario | | Comprehensive Cost | | Functional Years Lost | | Rank |
|---|---|---|---|---|---|---|
| | | Total | Percentage | Total | Percentage | |
| Rear-End | Rear-end/LVS | $ 2,405,000,000 | 9.7 % | $ 17,000 | 9.6 % | 4 |
| | Rear-end/LVD | $ 924,000,000 | 3.7 % | $ 7,000 | 3.7 % | 7 |
| | Rear-end/LVM | $ 2,068,000,000 | 8.4 % | $ 15,000 | 8.4 % | 5 |
| | Rear-end/striking maneuver | $ 244,000,000 | 1.0 % | $ 2,000 | 1.0 % | 16 |
| | Rear-end/LVA | $ 169,000,000 | 0.7 % | $ 1,000 | 0.7 % | 18 |
| | **Total** | **$ 5,810,000,000** | **23.5 %** | **$ 42,000** | **23.4 %** | |
| Lane Change | Changing lanes/same direction | $ 1,907,000,000 | 7.7 % | $ 14,000 | 7.8 % | 6 |
| | Turning/same direction | $ 698,000,000 | 2.8 % | $ 5,000 | 2.8 % | 11 |
| | Drifting/same direction | $ 638,000,000 | 2.6 % | $ 5,000 | 2.6 % | 12 |
| | **Total** | **$ 3,243,000,000** | **13.1 %** | **$ 24,000** | **13.2 %** | |
| Opposite Direction | Opposite direction/no maneuver | $ 4,964,000,000 | 20.1 % | $ 35,000 | 19.9 % | 1 |
| | Opposite direction/maneuver | $ 490,000,000 | 2.0 % | $ 4,000 | 2.0 % | 14 |
| | **Total** | **$ 5,454,000,000** | **22.0 %** | **$ 39,000** | **21.9 %** | |
| LTAP/OD | LTAP/OD @ non signal | $ 795,000,000 | 3.2 % | $ 6,000 | 3.2 % | 10 |
| | LTAP/OD @ signal | $ 778,000,000 | 3.1 % | $ 6,000 | 3.2 % | 9 |
| | **Total** | **$ 1,573,000,000** | **6.4 %** | **$ 12,000** | **6.4 %** | |
| Junction Crossing | SCP @ non signal | $ 3,838,000,000 | 15.5 % | $ 27,000 | 15.4 % | 2 |
| | Turn @ non signal | $ 77,000,000 | 0.3 % | $ 1,000 | 0.3 % | 21 |
| | Turn right @ signal | $ 377,000,000 | 1.5 % | $ 3,000 | 1.5 % | 15 |
| | **Total** | **$ 4,292,000,000** | **17.3 %** | **$ 31,000** | **17.2 %** | |
| TCD Violation | Running red light | $ 821,000,000 | 3.3 % | $ 6,000 | 3.4 % | 8 |
| | Running stop sign | $ 118,000,000 | 0.5 % | $ 1,000 | 0.5 % | 19 |
| | **Total** | **$ 939,000,000** | **3.8 %** | **$ 7,000** | **3.9 %** | |

Source: Table 16 from [17]

As part of the Safety Pilot Model Deployment, several of the Safety Applications were prototyped in heavy trucks, either as part of the integrated trucks or Commercial Vehicle Retrofit Safety Devices, and discussed in Section IV. Specifically, prototype V2V applications consisted of FCW, IMA, EEBL, and BSW+LCW [20]. Table 5 summarizes the crash population associated with these four V2V applications, which cover 63 percent of the comprehensive costs associated with the 17 pre-crash scenarios and 76 percent of the injuries. In addition, some prototypes included functionality to use messages from the infrastructure to support V2I applications such as CSW. These applications represented a significant effort to exercise V2V applications at a prototype stage, both in real-world driving and in controlled driving clinics, and gather data and information to permit assessment and further development of V2V safety systems in heavy vehicles.  Work continues to address characteristics unique to heavy trucks, such as representing the dynamic configurations of tractor semi-trailer combinations in the BSM.

**Table 5: Societal Impacts Associated with Heavy-Truck FCW, IMA, EEBL, and BSW+LCW Pre-Crash Scenarios**

| Pre-Crash Scenario / Safety Application | | Annual injuries | MAIS 2+ | MAIS 3+ | Comprehensive Costs |
|---|---|---|---|---|---|
| Rear End / Forward Collision Warning, EEBL | Rear-end/LVS | 17687 | 2058 | 773 | $ 2,405,000,000 |
| | Rear-end/LVD | 9468 | 1077 | 364 | $ 924,000,000 |
| | Rear-end/LVM | 8898 | 1397 | 633 | $ 2,068,000,000 |
| | Rear-end/striking maneuver | 1566 | 216 | 81 | $ 244,000,000 |
| | Rear-end/LVA | 702 | 117 | 54 | $ 169,000,000 |
| | Total | 38321 | 4865 | 1905 | $ 5,810,000,000 |
| | | | | | |
| Lane Change / Blind Spot + Lane Change Warning | Changing lanes/same direction | 12909 | 1734 | 682 | $ 1,907,000,000 |
| | Turning/same direction | 6503 | 746 | 266 | $ 698,000,000 |
| | Drifting/same direction | 4560 | 586 | 222 | $ 638,000,000 |
| | Total | 23972 | 3066 | 1170 | $ 3,243,000,000 |
| | | | | | |
| Opposite Direction | Opposite direction/no maneuver | 7802 | 1878 | 1131 | $ 4,964,000,000 |
| | Opposite direction/maneuver | 708 | 182 | 115 | $ 490,000,000 |
| | Total | 8510 | 2060 | 1246 | $ 5,454,000,000 |
| | | | | | |
| LTAP/OD | LTAP/OD @ non-signal | 3309 | 483 | 217 | $ 795,000,000 |
| | LTAP/OD @ signal | 3733 | 604 | 260 | $ 778,000,000 |
| | Total | 7042 | 1087 | 477 | $ 1,573,000,000 |
| | | | | | |
| Junction Crossing / Intersection Movement Assist | SCP @ non-signal | 10929 | 1958 | 992 | $ 3,838,000,000 |
| | Turn @ non-signal | 458 | 52 | 20 | $ 77,000,000 |
| | Turn right @ signal | 450 | 96 | 68 | $ 377,000,000 |
| | Total | 11837 | 2106 | 1080 | $ 4,292,000,000 |
| | | | | | |
| TCD Violation | Running red light | 6609 | 909 | 338 | $ 821,000,000 |
| | Running stop sign | 1259 | 169 | 56 | $ 118,000,000 |
| | Total | 7868 | 1078 | 394 | $ 939,000,000 |

Source: Table 7 from [17], Section V.A

## II.C. Scenarios addressed uniquely by vehicle-to-vehicle communications

The safety benefits of V2V technology that addresses the target crash scenarios are heavily dependent upon the penetration of V2V safety applications into the vehicle fleet. The LV V2V Readiness report [4] provides an overview of the V2V applications that have been tested thus far and describe how they address the targeted pre-crash scenarios. The report also describes the various types of V2V devices and covers the device configurations tested in the Safety Pilot Model Deployment, which incorporated heavy trucks in both an integrated OEM style and retrofit configuration.

# III. Types of V2X Devices for Heavy Vehicles

NHTSA’s heavy-vehicle V2V safety research program, conducted in conjunction with the ITS JPO, FMCSA, and FTA, has engaged in prototyping of two classes of V2V safety devices for heavy trucks, an integrated design and a retrofit package design (RSD), and a transit retrofit package. The integrated truck design was intended to represent the system as it would be installed in a truck during manufacture. The retrofit package represented a set of equipment that could be installed on existing vehicles of different makes and models by a qualified installer, similar to how other types of supplemental equipment (e.g., fleet tracking / telematics gear, etc.) are currently installed on trucks today. Both the Integrated trucks and RSDs are able to receive and process incoming BSMs which are broadcast from devices in other surrounding vehicles; it is envisioned that minimum performance standards such as those currently being developed in the SAE DSRC technical committee (e.g., J2945/1) would govern the nature of BSMs that would be accepted by either an Integrated truck or RSD. The Integrated trucks and RSDs would also need to meet the same set of performance standards when broadcasting BSMs.

## III.A. Integrated devices

Integrated truck V2V systems are defined by tight integration of V2V components with truck body, electronics, and driver interfaces by the OEM at or closely related to manufacture. Since there are often customizations that occur in the heavy-truck market based on customer needs, the distinction between an integrated truck design and retrofit design may sometimes appear to be minor, but primarily the integrated nature is reflected in the installation, which is customized to the specific tractor model and configuration. For example, factors such as location of specific V2V system hardware and wiring would be expected to be incorporated into the vehicle design, with appropriate connections to the vehicle data bus present at time of manufacture. It is expected that the primary components of the integrated truck system would consist of:

- DSRC OBE and GPS receiver,
- Connection to vehicle data bus (SAE J1939),
- Cabling between components / supporting wiring harnesses,
- DSRC antennas,
- GPS antenna, and
- Driver vehicle interface.

An integrated truck installation [21] would mount the equipment so as not to affect normal vehicle operations or electrical system functions, and include secure mounting designs to withstand the expected heavy-vehicle operating environment (e.g., vibration tolerant). Driver vehicle interfaces could be integrated with other vehicle-based safety systems to manage visual, auditory, and other feedback to the driver. In this sense, while the integrated truck project (see Section IV.A) was not a true full factory production implementation, the design provided the envisioned functionality for an integrated V2V system and maintained a reasonably integrated appearance (see Figure 2) for a prototype.

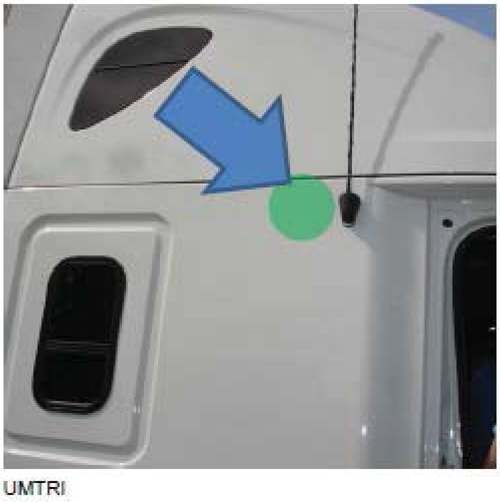


**Figure 2: Illustration of DSRC Antenna on Integrated Truck**

Source: Figure 3-6 from [21]

## III.B. Retrofit safety devices

The heavy-truck RSDs, as implemented in the two USDOT projects [22][23], consist of a set of equipment and software to implement V2V safety technology in existing trucks. The kits were designed to be installed on Class 6, 7, and 8 commercial vehicles with a GVWR greater than 19,500 lbs. that have completed their build process at their OEM facilities and are already in service. While the RSD kits may be considered aftermarket [4](p. 30), the level of capability provided by a RSD is significantly greater than that of aftermarket safety devices, (as tested on light vehicles) since a RSD connects to the vehicle data bus, defined by SAE J1939 on heavy-vehicles, and is able to access vehicle-based data such as turn signal status.

Each of the two RSD project teams conducted their own design and implementation. While functionally, the RSD capabilities have many similarities with the integrated trucks, the equipment used varied, as the intent of the RSD kit was to support an installation by a qualified installer on an existing truck, with a minimum of modification required. The specific details of each RSD project are described in Section IV.B. In addition, a transit vehicle-specific (bus) implementation of a retrofit safety device was conducted as a separate project, and is described in Section IV.E.

While all the RSD implementations received and broadcast BSMs, the set of V2V applications implemented in each project varied somewhat. In addition, the projects also provided support for a limited set of V2I safety applications (see Section IV.D). The differences in the set of applications implemented in a specific device are reflective of the nature of V2V safety systems. The core functionality exists in the transmission and reception of BSMs via 5.9 GHz DSRC. V2V applications use this core functionality to implement driver advisories and warnings such as FCW, and may supplement these capabilities with reception of infrastructure-based DSRC messages to provide V2I safety applications such as CSW. The following section provides further detail on the specific applications implemented in the USDOT research.

# IV. Development of V2V Safety Applications on Heavy Vehicles

USDOT engaged in a set of related projects to design, build, test and operate V2V safety technology in heavy vehicles. These projects included both an integrated truck implementation as well as RSD implementation in heavy trucks by two different project teams, and a single transit retrofit package. The following sections provide a synopsis of the projects' implementations. Full details are available in the published project reports (see References, Section VI).

## IV.A. Connected Commercial Vehicle Team Project

The Connected Commercial Vehicle - Integrated Truck project [20] was conducted over 2 ½ years by a project team led by Battelle and which included University of Michigan Transportation Institute; Mercedes-Benz Research & Development North America, Inc.; DENSO International America, Inc./North America Research and Development, California Office; Daimler Trucks North America; and Meritor WABCO. The project team built upon prior work on light vehicle V2V systems (e.g., VSC-A [6]) and developed an integrated system for use in three Class 8 tractors. An additional tractor was also outfitted for use by a different USDOT project.

In addition to the V2V implementation on the three tractors, the project also included several activities to support the overall USDOT connected vehicle research program. The major project activities consisted of:

- **Design/Application Development** – Building upon the prior light vehicle V2V research, determine necessary revisions for heavy-vehicle operation, and design additional V2I safety applications (CSW and Bridge Height Inform). Develop driver-vehicle interface for all implemented applications. See [21] for details.
- **Vehicle Builds –** Identify, install, and test required hardware to support V2V systems, as well as testing and evaluation (data acquisition systems) on three Class 8 tractors. See [21] for details.
- **World Congress Support** [24] **–** Conduct outreach and demonstration at the 2011 ITS World Congress in Orlando, FL. Due to the timing of the conference, instead of using the integrated trucks, the demonstration used a comparable tractor-trailer equipped with DSRC equipment, used as a stopped forward vehicle (broadcasting BSMs) to enable a light vehicle FCW demonstration.
- **Driver Acceptance Clinics** [25] **–** Conduct trials with selected V2V scenarios using naive drivers on a closed course to identify driver opinions on the technology and applications. See Section IV.F.1 for more details.
- **DSRC Performance Testing** [25] **–** Gather related performance data (DSRC BSMs, GPS data) from a variety of geographic/travel conditions while on route to and from Driver Acceptance Clinic sites.
- **Application Objective Testing –** Design and test V2V application performance in defined scenarios on a closed test track. See Section V.B.2 for more details. In contrast to

the Driver Acceptance Clinics, the vehicles in the objective tests were driven by trained staff executing precise maneuvers.

- **Safety Pilot Model Deployment Support** [26] – Provide support for operation and maintenance of the integrated trucks during the year-long Safety Pilot Model Deployment in Ann Arbor. See Section IV.F.2 for details.

The CCV-IT project implemented and tested an integrated V2V system on three new 2012 Freightliner Cascadia tractors, comprising day cab, mid-roof sleeper, and high-roof sleeper configurations (an additional tractor was also included to support another USDOT project). Figure 3 illustrates the overall architecture for the V2V system developed by the project team, including the independent DAS used for system monitoring, testing, and evaluation support.

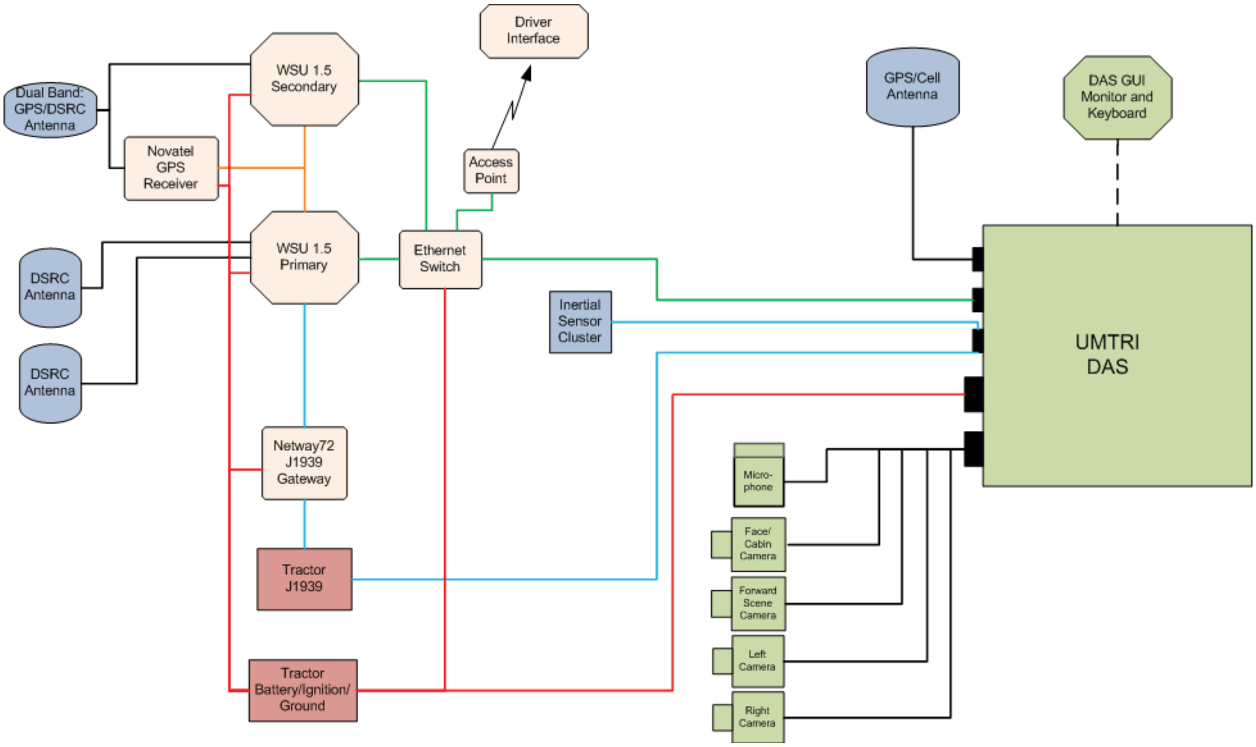


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**Figure 3: CCV-IT System Architecture**

Source: Figure 2-2 from [21]

The primary components for the integrated truck V2V system were as follows:

- **Wireless Safety Unit** – This comprises the main component of the OBE. In this design, two DENSO WSU devices (see Figure 4) were used as primary, and secondary electronic control units. These devices host the V2V applications and associated DSRC-related components to broadcast and receive messages. The primary unit was configured to host the V2V applications and BSM broadcast and reception. The secondary unit was connected to a separate antenna and supported additional applications as well as access to the Safety Pilot security credential management system.

- **DPGS Receiver –** A differential GPS receiver provided access to GPS position and timing data for both WSU units.
- **Vehicle Bus Gateway –** This device acted as a gateway to the SAE J1939 vehicle data bus, and permitted real-time access to the truck’s internal data available on the bus, such as turn signal, brake status, etc.
- **Driver Vehicle Interface –** The DVI was implemented on a tablet computer, connected to the other components via a wireless connection.
- **Associated DSRC and GPS Antennas –** Multiple antennas were installed to support the V2V system operation. The primary WSU was connected to a pair of DSRC antennas mounted on the sides of the cab. The secondary WSU was connected to a single combined roof-mounted DSRC/GPS antenna that also provided GPS satellite reception for the DGPS receiver. In order to support short, relatively straight cable runs between the DSRC antennas and WSU, the mounting locations for the WSU units were selected to best accommodate this factor, and were placed in existing storage compartments above the windshield.

**Figure 4: WSU unit installed in Integrated Truck**

Source: Figure 2-3 from [21]

Additionally, a DAS (see Figure 5) was installed and configured to allow access to relevant V2V system data, as well as to independently record audio, video, and other vehicle data to support later analysis of application performance by the USDOT independent evaluator (The Volpe National Transportation Systems Center [Volpe]). The DAS also provided the ability for the Model Deployment test conductor to remotely monitor location and potential system issues via a cellular modem interface.

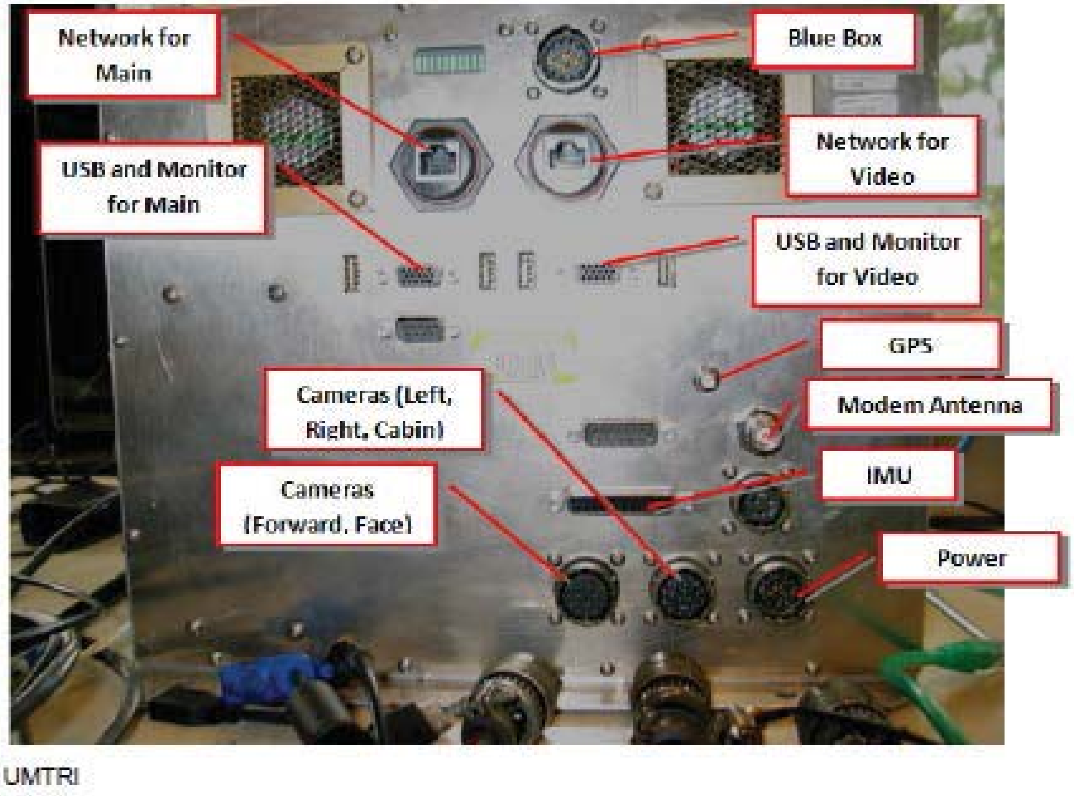
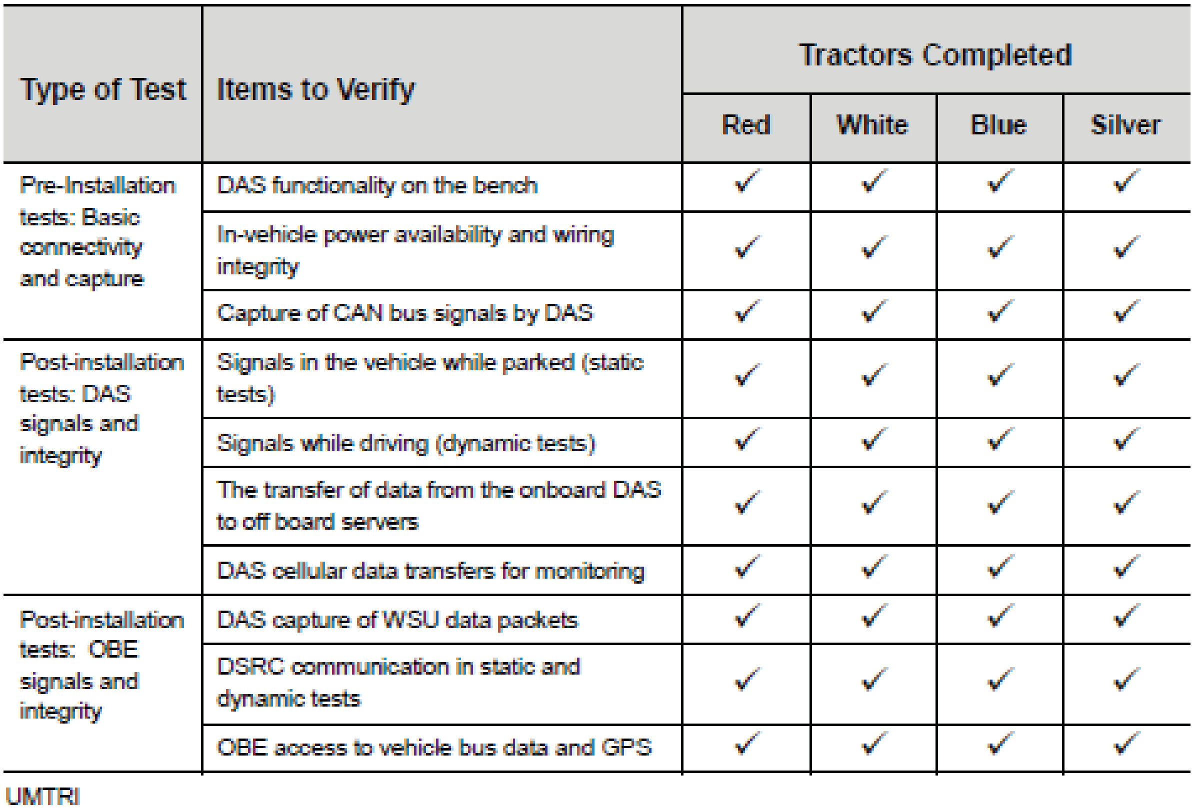


**Figure 5: Integrated Truck Data Acquisition System**

Source: Figure 4-2 from [27]

After the V2V system and DAS components were installed, the project team executed a series of tests to check the operation of the system, and performed remediation as required to correct any problems. Table 6 illustrates the vehicle build test results as verified by the project team.

**Table 6: Integrated Truck Vehicle Build Verification Test Results by Project Team**



| Type of Test | Items to Verify | Tractors Completed | | | |
|---|---|---|---|---|---|
| | | Red | White | Blue | Silver |
| Pre-Installation tests: Basic connectivity and capture | DAS functionality on the bench | ✓ | ✓ | ✓ | ✓ |
| | In-vehicle power availability and wiring integrity | ✓ | ✓ | ✓ | ✓ |
| | Capture of CAN bus signals by DAS | ✓ | ✓ | ✓ | ✓ |
| Post-installation tests: DAS signals and integrity | Signals in the vehicle while parked (static tests) | ✓ | ✓ | ✓ | ✓ |
| | Signals while driving (dynamic tests) | ✓ | ✓ | ✓ | ✓ |
| | The transfer of data from the onboard DAS to off board servers | ✓ | ✓ | ✓ | ✓ |
| | DAS cellular data transfers for monitoring | ✓ | ✓ | ✓ | ✓ |
| Post-installation tests: OBE signals and integrity | DAS capture of WSU data packets | ✓ | ✓ | ✓ | ✓ |
| | DSRC communication in static and dynamic tests | ✓ | ✓ | ✓ | ✓ |
| | OBE access to vehicle bus data and GPS | ✓ | ✓ | ✓ | ✓ |

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Source: Table 6-1 from [28]

In addition to the vehicle build, the project team also conducted V2V safety application development, largely based on prior work on the LV platform [6]. The software architecture (see Figure 6) selected was largely the same as was used on the LV platform, with a common set of functionality to monitor and track surrounding vehicles. Each application used the processed information to identify specific hazards for corresponding scenarios, and an overall threat arbitration subsystem determined which if any alerts to provide to the driver via the DVI. The integrated truck team implemented four V2V applications (FCW, EEBL, IMA, and BSW/LCW) as well as two V2I applications (CSW and BHI). Sections IV.C and IV.D describe the various applications in further detail.

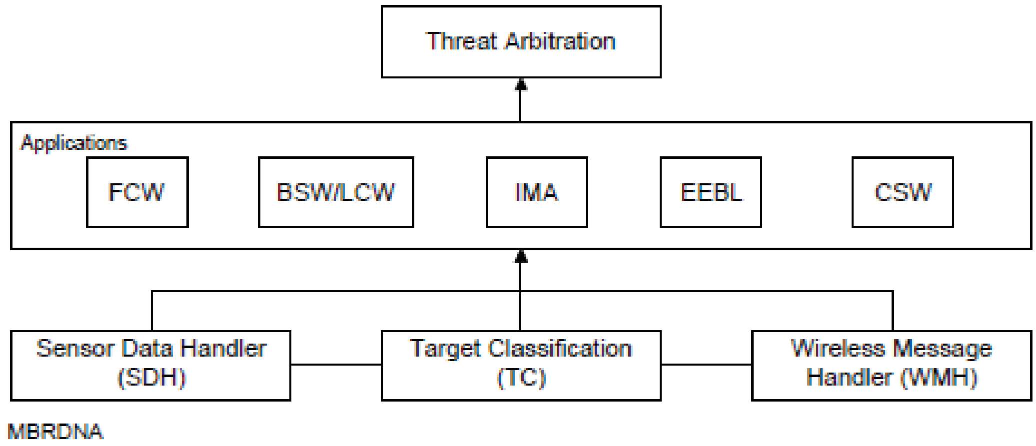

**Figure 6: Integrated Truck Software Architecture**

Source Figure 2-1 from [29]

However, although the overall V2V system operation was similar to the LV implementation, many parameters needed adjustment to reflect heavy-vehicle operation. Table 7 illustrates the parameters customized by the project team for the integrated truck.

### Table 7: Integrated Truck Modification to WSU Configuration Parameters

| Parameter Name | Parameter Description | Implications |
|---|---|---|
| BSWLCWHorizonTimeS | A time horizon in which a closing vehicle must enter the blind spot zone to be considered "Will be in Blind Spot" | Increase default value to account for CCV longer lane change time |
| BSWLCWBsLengthLeftM | Length of the left blind spot zone | A CCV has a longer blind spot zone than LVs |
| BSWLCWBsLengthRightM | Length of the right blind spot zone | A CCV has a much longer blind spot zone on the right |
| EEBLMaxLongOffsetDistM | Longitudinal length of the EEBL zone | A longer EEBL zone is needed when CCV is the host vehicle |
| FCWMaxRangeM | Maximum longitudinal range for FCW application | Increase default value to account for longer CCV stopping distance |
| FCWDriverReactionTimeS | Assumed driver reaction time in s | May need longer reaction time for CCV drivers |
| FCWCaFollowCeilingFactor | Maximum host vehicle deceleration | Need to adapt to CCV braking |
| FCWCaFollowFloorFactor | Minimum host vehicle deceleration | Need to adapt to CCV braking |
| IMAMinCrossPathS | Minimum acceptable separation time (in seconds) between an HV and RV below whose absolute value a collision is possible | May need more time buffer for CCV in crossing paths |
| IMAMaxRvRangeM | Maximum range to intersection point that IMA considers RVs for warning or informing | May need longer default range to account for longer CCV stopping distance |
| IMABrakingSystemDelayS | Estimated response time for a braking system from brake pedal press to brake application | Adapt to CCV braking profile |
| IMABrakingConstant | A unitless braking parameter representing a fraction of gravitational acceleration | Need to adapt to CCV braking system |
| IMAInformMultiplier | A unitless multiplier used to determine the size of the inform zone based on the size of the warn zone | May need to adjust default value |
| COMMONAntAdjXm | Longitudinal offset adjustment if GPS antenna is not installed at the center of the vehicle | Need to allow for CCV size and changes in configuration |
| COMMONAntAdjYm | Lateral offset adjustment if GPS antenna is not installed at the center of the vehicle | Need to allow for CCV size and changes in configuration |
| COMMONMultiRadioEnable | Enable/Disable simultaneous dual radio use for WMH/VSC-A | May adjust for dual WSUs |

Source: Appendix A from [29]

## IV.B. Development of Retrofit Safety Devices

In addition to the CCV-IT project, USDOT conducted two RSD projects for heavy trucks, each led by a separate project team. The Battelle team included DENSO International North America Research Laboratory, UMTRI, Daimler Trucks North America, and Meritor WABCO. The other RSD team was comprised of Cambridge Systematics and Southwest Research Institute (SwRI). Each developed and implemented a set of equipment and software to provide an existing truck tractor with V2V safety capability. In addition, supporting capabilities for testing and evaluation, such as DAS, were included in the packages. Each team produced RSD "kits" to enable both testing and installation and operation during the Safety Pilot Model Deployment. The intent of the kits was to enable a knowledgeable installer to take an existing truck tractor and implement the V2V system in a fairly independent fashion. The two project teams each developed an independent implementation, using different hardware vendors and including a similar but not identical set of applications. In this manner, the ability for cross-vendor interoperability in V2V systems and applications could be tested.

### *IV.B.1. Battelle RSD Team*

As with the integrated truck project, the Battelle RSD team implemented V2V system functionality building upon the previously conducted light vehicle V2V efforts. In the case of the RSD, the design was developed to facilitate the installation in an existing truck, and consisted of the elements depicted in Figure 7 The primary component of the RSD consisted of a DENSO miniWSU, which includes an integrated GPS receiver and DSRC radio, and performed most of the processing necessary to support the V2V applications. The miniWSU was connected to multiple DSRC antennas, a combined DSRC/GPS antenna, the SAE J1939 vehicle data bus, and the DVI (a tablet computer, see Figure 8) via a wireless interface. In addition, as with the integrated truck, a separate DAS was installed to independently record data to support later evaluation of the system and application performance.

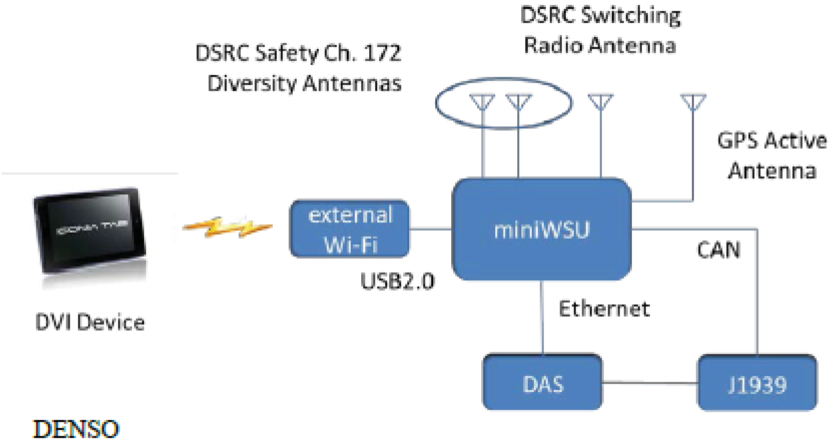

**Figure 7: Battelle Team RSD Architecture**

Source: Figure 1 from [22]

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**Figure 8: Battelle Team RSD Driver Vehicle Interface Tablet**

Source: Figure 4 from [22]

In order to facilitate installation on a variety of trucks, the miniWSU was installed inside a weatherproof enclosure atop a mounting bracket which was installed behind the tractor cab. The mounting hardware incorporated a horizontal bar to allow the cables for the DSRC antennas (mounted on each end of the bar) to remain at a pre-configured length so as not to require any field modification (see Figure 9). The project team developed detailed installation instructions [22] (Appendix A) to enable an independent installer to add the RSD to an existing truck.

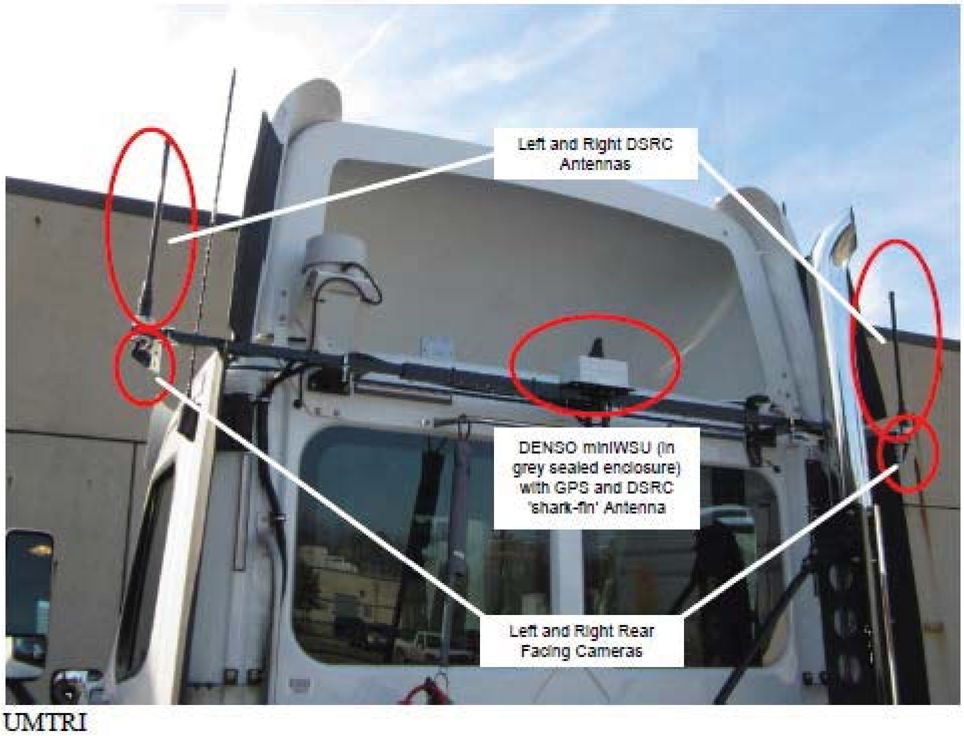


**Figure 9: Battelle Team RSD Mounting Configuration**

Source: Figure 7 from [22]

The Battelle RSD implemented four V2V (FCW, EEBL, IMA, and BSW/LCW) applications and one V2I (CSW) application, using a similar software architecture (see Figure 10) as used in the integrated truck project. Sections IV.C and IV.D provide detail on each V2V and V2I application. Before the applications can be exercised, configuration of the system is necessary, given both the retrofit nature of the kit as well as the dynamic configuration present in tractor combination units. Appendix D of the final project report [22] consists of a user's guide to the retrofit system and includes guidance on necessary configuration steps. The initial setup of the RSD kit after physical installation includes establishing values for parameters such as GPS antenna location, which must be measured according to established conventions (see Figure 11). Other configuration parameters such as the length of the trailer are set at every vehicle start, using the DVI (see Figure 12), with a default value of the last entered length used if no selection is made by the driver within a certain amount of time.

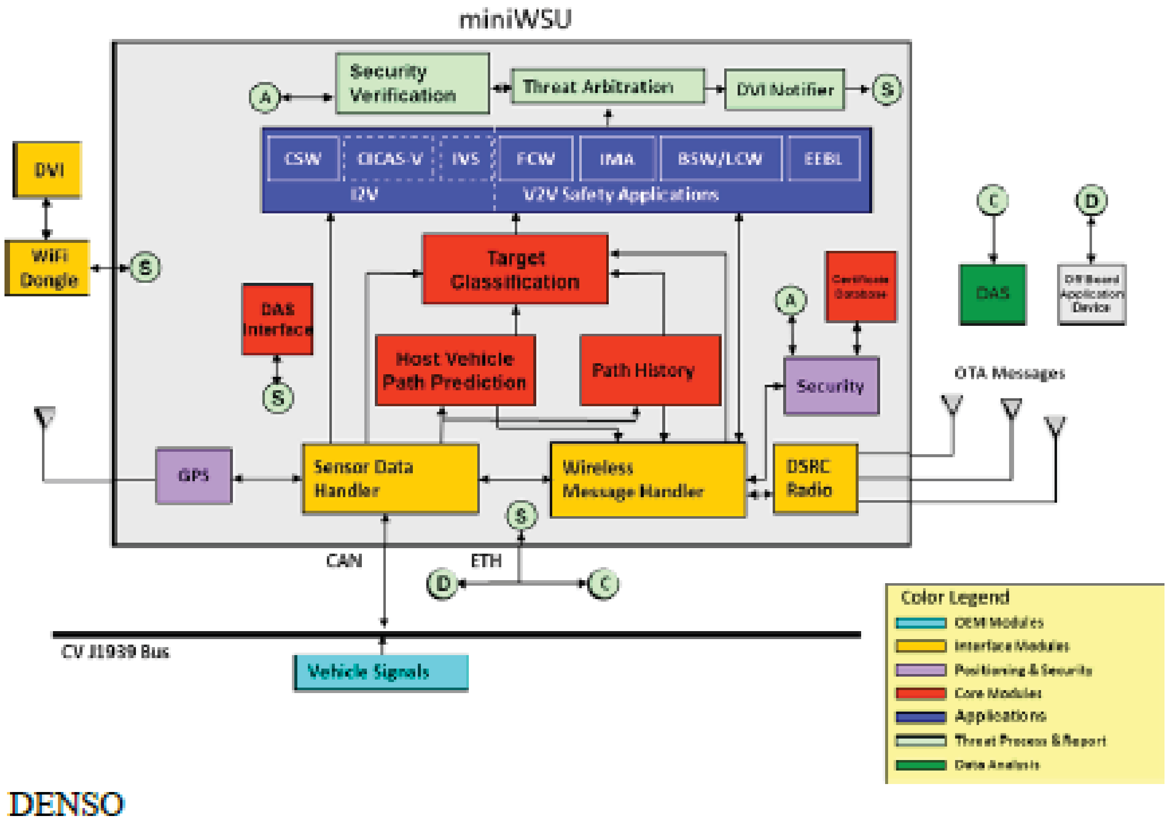


**Figure 10: Battelle Team RSD Software Architecture**

Source: Figure 3 from [22]

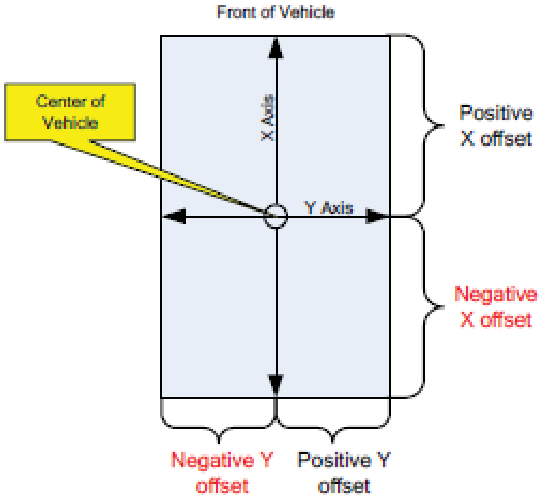
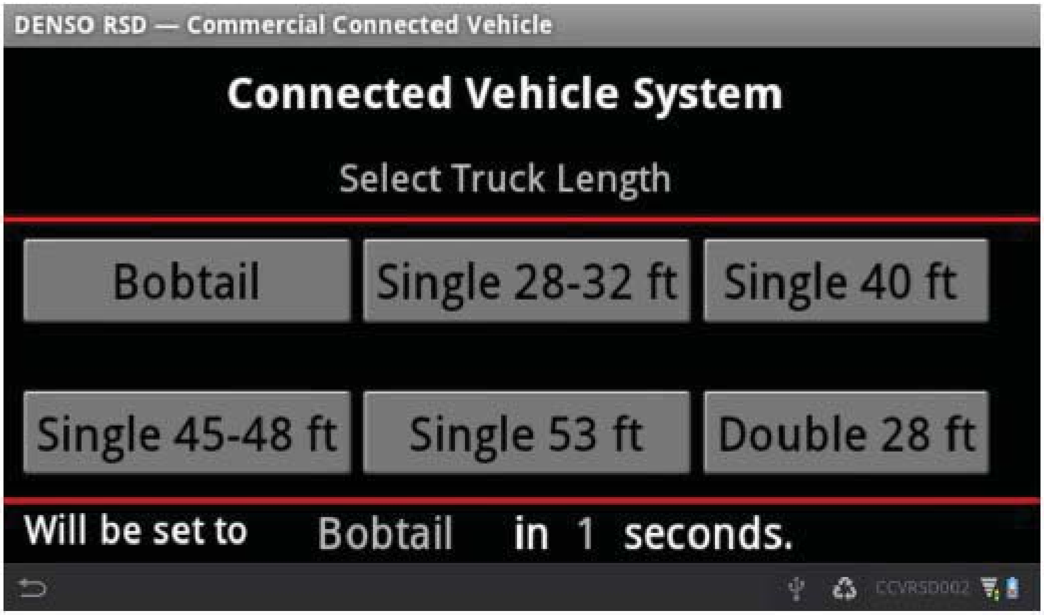


**Figure 11: Battelle Team RSD GPS Antenna Location Configuration Parameters**

Source: Figure 49 from [22]



DENSO RSD — Commercial Connected Vehicle

Connected Vehicle System

Select Truck Length

Will be set to Bobtail in 1 seconds.

**Figure 12: Battelle Team RSD Trailer Length Configuration in DVI**

Source: Figure 54 from [22]

### *IV.B.2. Cambridge Systematics RSD Team*

The team led by Cambridge Systematics and Southwest Research Institute, developed retrofit safety devices [23] for installation on operational commercial vehicles in the Ann Arbor area for inclusion in the Safety Pilot Model Deployment. The units included cooperative V2V and V2I safety applications and were tested against devices from other manufacturers to ensure standards compliance and interoperability in the deployment.

The development of the RSD kits focused on creating a robust, reliable implementation of three connected vehicle safety applications, including EEBL, FCW, and CSW, each tailored to the specific needs and requirements related to their use on a commercial vehicle platform. The kits were designed to be installed on Class 6, 7, and 8 commercial vehicles with a GVWR greater than 19,500 lbs. that have completed their build process at their OEM facilities and are already in service. For this project, eight complete RSD kits (including hardware, software, and applications) were designed, tested, and integrated onto commercial vehicles (see Figure 13). These kits were specifically designed and built to be vehicle-agnostic and capable of retrofit integration with all participating cooperative vehicles in the Safety Pilot Program. Once installed, the RSD kits provided the host vehicles with V2V and V2I safety application capability.

**Figure 13: CS-SwRI Retrofit Installation in Conway Truck**

Source: SwRI

With regard to overall RSD design, an integrated system design was chosen (see Figure 14). Specifically, safety applications were integrated directly into the DSRC radios. This design had the advantages of reducing hardware, minimizing vehicle installation complexity, and reducing both the development and build cost.

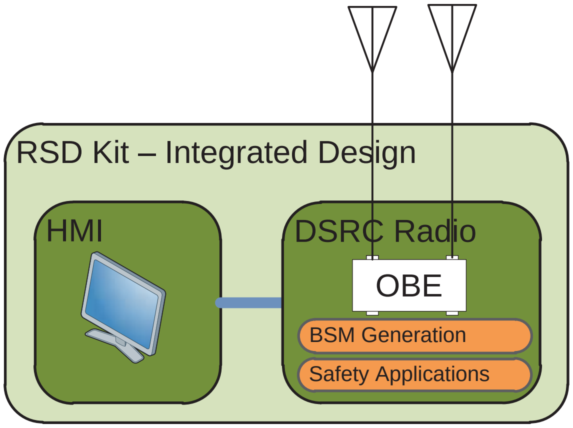


**Figure 14: CS-SwRI RSD Kit Integrated System Design**

Source: SwRI

**Hardware**

Each of the RSD kits includes a DSRC radio and antennas, GPS receiver and antenna, embedded gyroscope, J1939 CAN interface, DVI, and interface to a DAS. The primary hardware components included in the kit, as well as their respective connections and relation to the overall system, are shown in Figure 15. Hardware was selected such that there are standardized interfaces between components, allowing individual pieces to be upgraded or replaced as necessary without requiring changes to other components. The two main components of the RSD kit are the DSRC radio and the DVI.

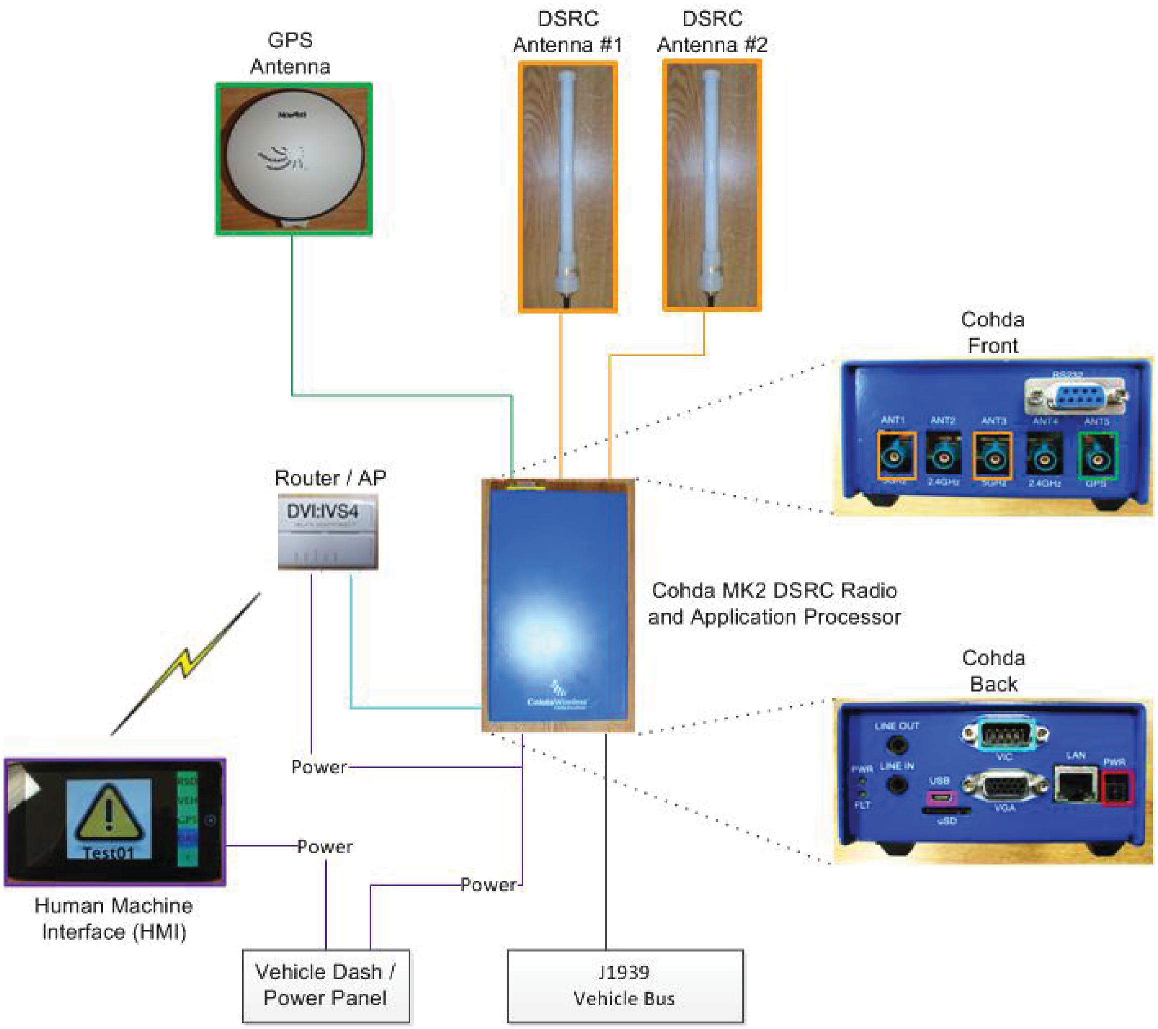


**Figure 15: CS-SwRI RSD Equipment**

Source: SwRI

**DSRC Radio**

The main component of the RSD Kit is the DSRC radio. “DSRC radio” can refer both to the embedded chipset that enables 802.11p wireless communications, as well as the entire hardware unit that encloses the chipset and provides additional lower level hardware components and interfaces.

The radio contains the majority of the interfaces required for the complete kit, including two wireless communications modules (DSRC radios), an embedded GPS receiver, a CAN interface to receive data from the vehicle’s J1939 bus, and an Ethernet connection to provide data to the DVI and DAS (if installed).

Although the radio is configurable for either single antenna or dual antenna operation, the physical configuration of typical commercial vehicles creates line of sight occlusion issues. As such, it was necessary to have both DSRC antennas installed on the vehicle to provide sufficient communications coverage with nearby vehicles. More specifically, DSRC antennas were installed on each side of the vehicle, mounted on custom-fabricated mounts near the edge of the cab's roof fairing. This configuration provided sufficient coverage along both sides of the vehicle and to the front. While communications coverage directly behind the vehicle still contains small areas of limited coverage, the majority of typical vehicle locations behind the commercial vehicle are still covered to a sufficient extent to enable safety applications to function as designed.

## Safety Applications

The safety applications incorporated into the Cambridge/SwRI RSD Kit include EEBL, FCW, and CSW. Each safety application generates a distinct warning message to the driver via the HMI tablet. In the event that multiple applications are triggered simultaneously, the highest priority warning will be displayed to the driver. Figure 16 details a high level operational flow chart of the incorporated safety applications.

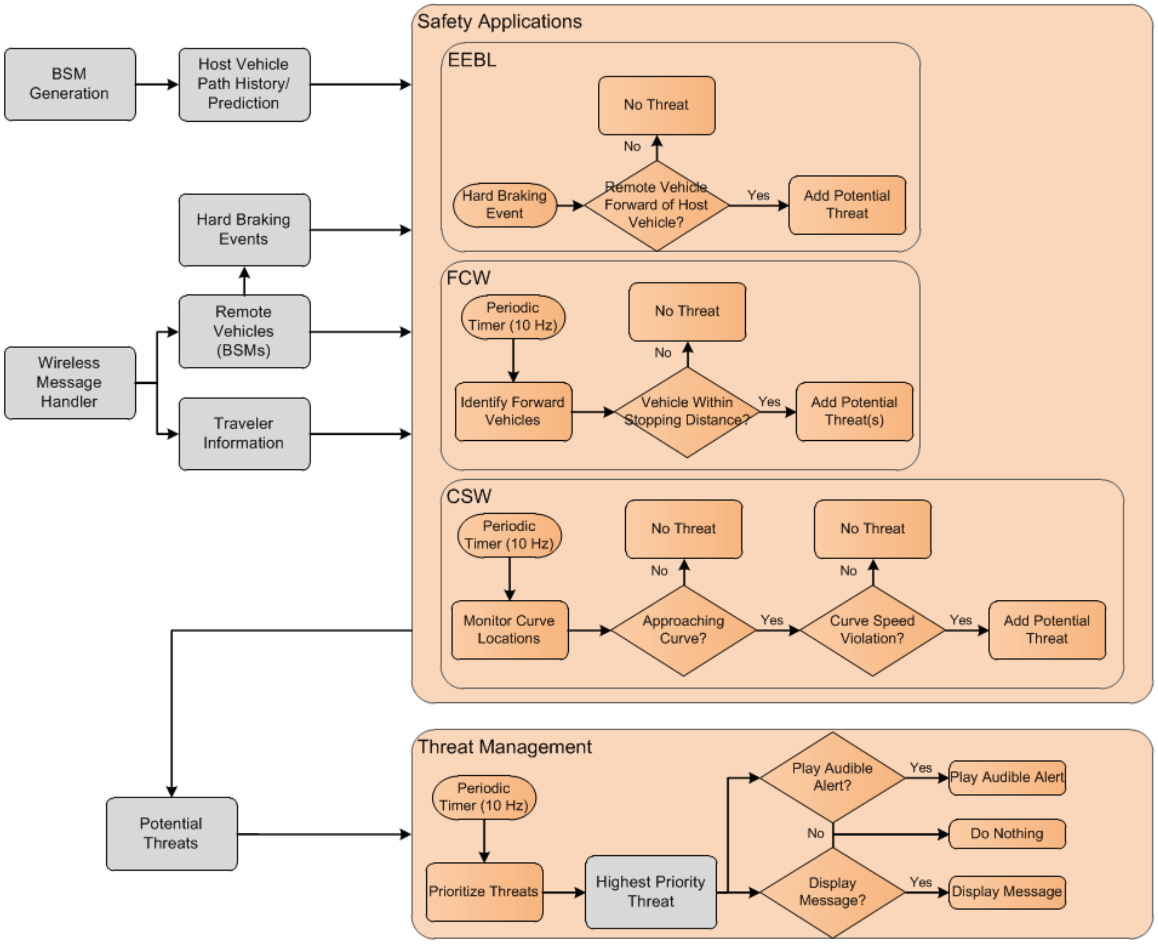


**Figure 16: CS-SwRI RSD Safety Applications**

Source: SwRI

**Driver-Vehicle Interface**
The DVI provides a medium for communicating visual and auditory warnings to the driver and allows the driver to input any required configuration information, discussed in the next section. This DVI is implemented with a 7” dash-mounted Android tablet, as shown in Figure 17. This tablet is mounted in such a way as to be easily visible to the driver but not impede or obstruct the driver’s view of the roadway. The tablet communicates wirelessly, via IEEE 802.11g, with the DSRC radio and its respective safety applications.

**Figure 17: CS-SwRI DVI Tablet**

Source: SwRI

The DVI is the central interface to the driver and is implemented as a 7-inch Android tablet mounted to the dash of the vehicle. The interface is capable of presenting both auditory and visual warnings and additionally serves as the interface for the driver to enter required configuration information.

In order to prevent misuse of the tablet interface, the Android tablet operating system was modified to start the DVI’s RSD safety application immediately upon boot. Additionally, there is no direct way for the operator to minimize or exit the program. In order to support basic maintenance, the RSD safety application can be closed using a designated set of motion swipes. This “back door” only exists for development and initial installation and configuration purposes and can be disabled when necessary.

When the DVI starts the first time (after initial installation and configuration are complete), the driver will be presented with a set of instructional slides that detail input requirements and describe each of the alerts that may be seen during normal operation. Once the slides have been completed, the driver can opt not to see the instructional slides again by making a selection on the final slide.

The normal boot up procedure will ask the driver to designate the current configuration of the vehicle. This is implemented by presenting the driver with four images representing the most common vehicle configurations anticipated for this vehicle's installation (see Figure 18, which shows no trailer, 25 ft. trailer, 28 ft. trailer, and 38 ft. trailer configurations, from left to right). The options presented are defined in a configuration file on the DSRC radio during installation. The selected configuration information will be transmitted back to the DSRC radio and used by the safety applications. If the driver does not select a configuration before the vehicle begins to move, the DVI will default to the last known configuration and will continue to ask the driver for configuration information each time the vehicle comes to a complete stop. When the vehicle is in motion, all user input is disabled on the device and the screen is blank unless a safety application generates an alert.

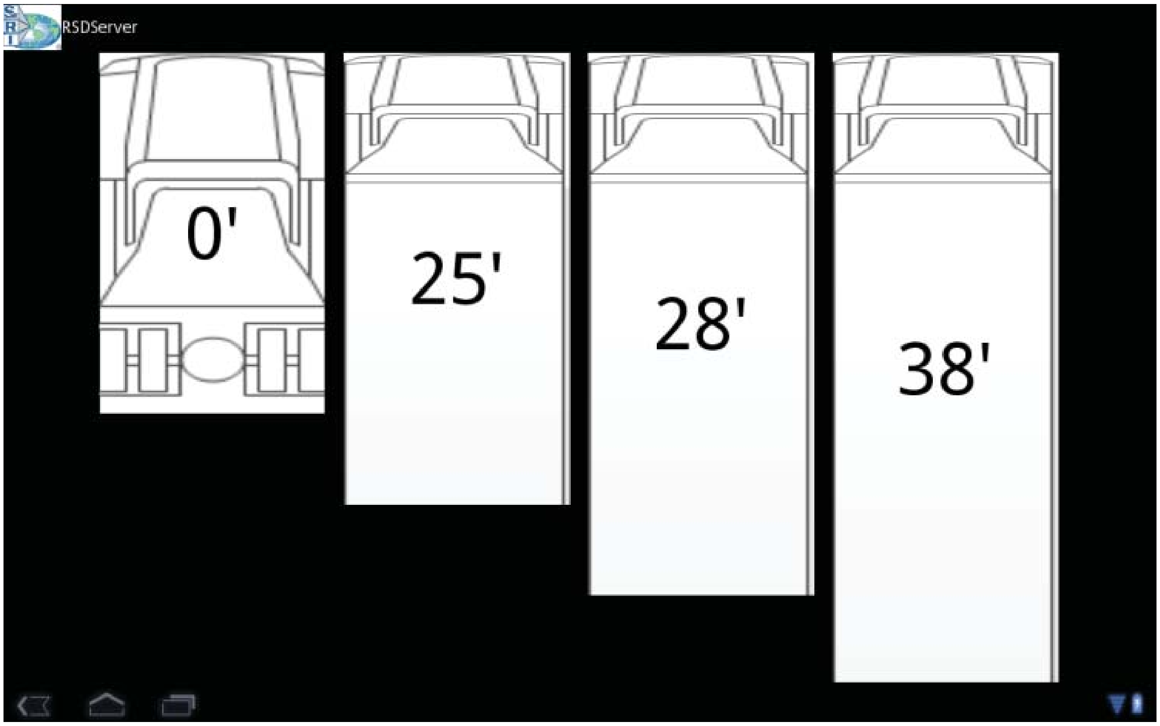


**Figure 18: CS-SwRI RSD DVI Vehicle Configuration Screen**

Source: SwRI

The vehicle configuration is the only input required from the user and once completed, the DVI operates only to provide warning messages (both auditory and visual) to the user. DVI visual warnings for EEBL, FCW, and CSW can be seen in Figure 19. Figure 20 illustrates the overall appearance of the DVI in a test scenario. Note that there is a comparable CSW warning for "right hand" curves as well.

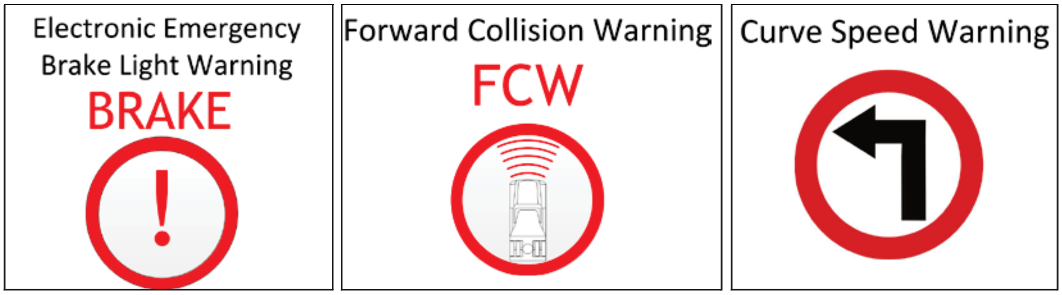


**Figure 19: CS-SwRI RSD HMI Visual Warning Messages (EEBL, FCW, and Left CSW)**

Source: SwRI

**Figure 20: CS-SwRI V2V Application Testing at SwRI Test Track**

Source: SwRI

Once installed in the vehicles, the RSD kits communicated with other devices deployed in vehicles and as part of the infrastructure in the Ann Arbor region for the USDOT Safety Pilot. This communication included the BSM transmitted by vehicles and multiple infrastructure-oriented messages, including traveler information messages containing CSW alerts and various messages related to device’s security credential management. All messages transmitted and received by the RSD kits followed a common set of SAE and IEEE standards, including SAE J2735-200911 and IEEE 1609.2-4.

A subset of the vehicles on which an RSD kit was installed also had a DAS that was developed to record data from several sources including the DSRC radio and safety applications, GPS, the vehicle’s J1939 CAN bus, video cameras, and a forward-facing radar.  The DAS (see Figure 21) is a stand-alone system from the RSD kit and includes sensor and video recording capabilities to provide data for assessing the safety applications operating on the RSD kit.  The DAS records data from the vehicle’s J1939 CAN interface and a forward-facing radar mounted on the vehicle, information about DSRC equipped vehicles within communications range of the host vehicle, and safety application alert information. Data was recorded to a removable storage device to facilitate easy retrieval of data.

When an alert is triggered, the DAS also records video from three cameras installed inside the cab of the vehicle, recording a view of the driver's area, a view of the dash – including the DVI, and a forward view of the roadway ahead of the vehicle as shown in Figure 22.

**Figure 21: SwRI Data Acquisition System**

Source: SwRI

**Figure 22: CS-SwRI RSD DAS Video Snapshots**

Source: SwRI

This data was subsequently shared with the Safety Pilot Independent Evaluator for performance measure purposes. The RSD software and associated documentation has been submitted to the Open Source Application Development Portal and is currently being made available for research purposes to be used across the connected-vehicle research community.

## IV.C. V2V Safety Applications Developed

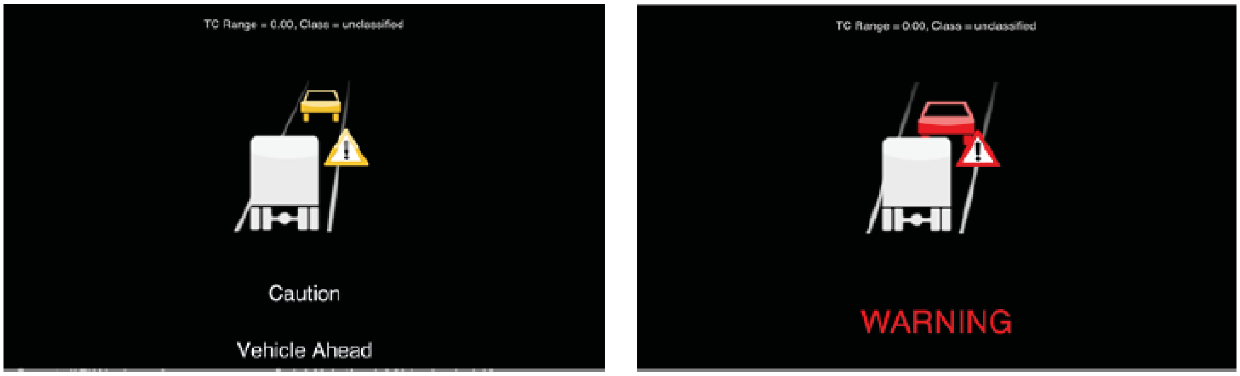
The integrated truck and two retrofit safety device projects all supported the common V2V safety functionality with respect to broadcasting BSMs to surrounding vehicles. Specific V2V applications supported by each project varied (see Table 8), with all implementing a core set including FCW, EEBL, and V2I-based CSW. The Battelle team RSD project implementation also included IMA and BSW. The integrated truck project added support for IMA and BSW+LCW as well as an additional V2I application, BHI.

**Table 8: V2V / V2I Heavy-Truck Applications Implemented by Project**

| | FCW | EEBL | CSW(V2I) | IMA | BSW only | BSW+ LCW | BHI (V2I) |
|---|---|---|---|---|---|---|---|
| Integrated Truck | X | X | X | X | | X | X |
| Battelle RSD | X | X | X | X | X | | |
| CS-SwRI RSD | X | X | X | | | | |

### *IV.C.1. Forward Collision Warning*

The V2V FCW application has previously been tested as part of NHTSA's light-vehicle research program [4]. The basic functionality of FCW is to provide a driver with an alert or warning when, based on the current speed of the vehicle, a potential for collision with a forward vehicle in the same lane is identified, using the BSM information from the forward vehicle. The classification of lane is based on the relative position of the two vehicles, and the risk of collision is based on factors such as longitudinal distance between vehicles, speed of each vehicle, and acceleration/deceleration. For heavy trucks, the braking performance cannot match that of light vehicles, and therefore the implementation in both the IT and RSDs were not the same as the light vehicle implementation. Specific implementation details may vary depending on the design. For example, the Battelle team design monitors farther ahead for stopped vehicles as compared to the light vehicle implementation, and uses a lower deceleration and longer reaction time. The CS-SwRI design requires the forward vehicle to be within 300 m and the host vehicle to be traveling at least 11.4 m/s for a FCW alert to be provided to the driver. Additional design variations such as minimum speed difference for an alert and specific alert modality and displays/sounds depended on the implementation (see Figure 23, Figure 24, and Figure 25).



MBRDNA

**Figure 23: Battelle Team Integrated Truck Visual Images for FCW Inform and Warn**

Source: Battelle Team

DENSO

**Figure 24: Battelle Team RSD Visual Images for FCW Inform**

Source: Battelle Team

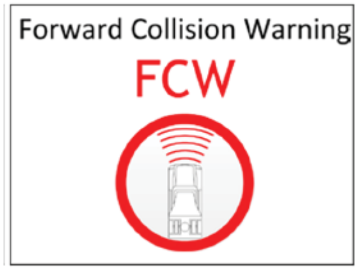


**Figure 25: CS-SwRI Visual Image for FCW Warning**

Source: SwRI

### *IV.C.2. Emergency Electronic Brake Lights*

The EEBL safety application is designed to help drivers avoid or mitigate rear-end collisions with vehicles that are braking in their forward path. This application is implemented as a Part II element of the BSM, with the braking vehicle responsible for recognizing the “hard” braking event and transmitting a notification. This requires the vehicle to calculate or directly sense its current accelerations and monitor those values for decelerations that constitute a “hard” braking event. As with FCW, the specific implementations may vary (see Figure 26, Figure 27, and Figure 28). In the CS-SwRI RSD, EEBL hard braking events used a minimum threshold of 0.3 g for commercial vehicles as compared to 0.4 g for passenger vehicles, and required the vehicle to be traveling between 11.4 and 30 m/s (25-67 mph) in order for the BSM Part II element flag to be set.

For the following vehicle, the EEBL application must receive the hard braking event flag and determine whether an alert or warning should be given to the driver. Every vehicle within receiving range of the EEBL event will first calculate its relative position to the event using BSM Part I data. Once calculated, each vehicle determines if the message warrants a warning (and what type) be presented to the driver. This is accomplished by checking factors (which may vary by implementation) such as:

- Direction – EEBL warnings are only applicable to vehicles traveling in the same direction as the vehicle that generated the EEBL event.
- Distance – EEBL warnings are only applicable to vehicles within 300 meters (longitudinally) of the EEBL event and within one lane width (laterally) of the EEBL event.
- Host Deceleration – EEBL alerts can be suppressed if the host vehicle is already decelerating at the time the EEBL message is received from the braking vehicle. Assumed deceleration may be lower in commercial vehicles than in light vehicles.

In the IT implementation, the EEBL alert modality varied depending on the lane position of the braking vehicle, with audible part of alerts suppressed if not in the same lane. In the CS-SwRI RSD, EEBL messages can be suppressed if the host vehicle is already decelerating at the time the EEBL message is handled by the host vehicle.

MBRDNA

**Figure 26: EEBL Warning for Integrated Truck**

Source: Battelle Team

DENSO

**Figure 27: EEBL Inform-level Alert in Battelle Team RSD**

Source: Battelle Team

**Figure 28: CS-SwRI EEBL Visual Alert Image**

Source: SwRI

### *IV.C.3. Intersection Movement Assist*

IMA is another application previously tested on light vehicles which was included in the IT and Battelle team RSD implementations. IMA provides a driver of a vehicle stopped at an intersection with an alert or warning when a potential conflict with crossing traffic, based on reception of BSMs, is predicted.

The light vehicle implementation was designed to issue a warning as soon as the brake pedal was released if a crossing vehicle was a threat. In the integrated truck (see Figure 29) and Battelle team RSD (see Figure 30) implementations, the warning is only issued when the accelerator is pressed and the vehicle speed begins to increase. Also, assumed heavy-truck acceleration is lower than the light vehicle implementation, and a greater response time is given.

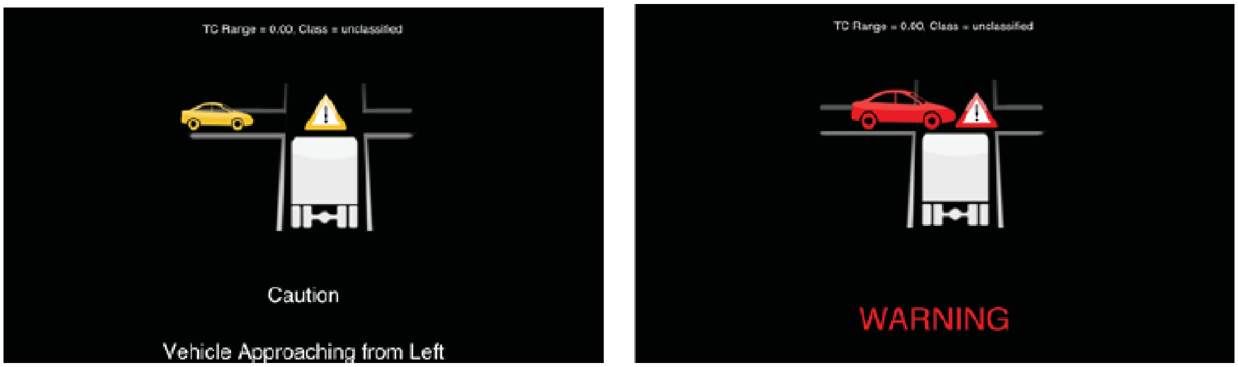


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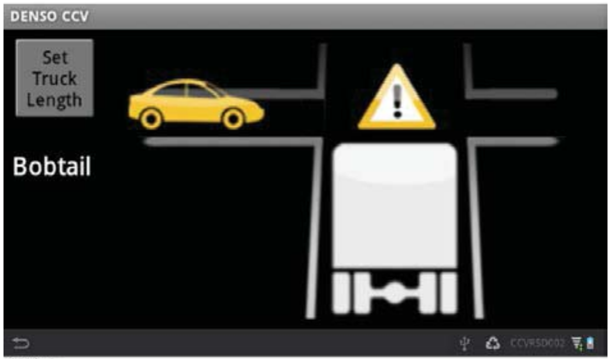
**Figure 29: Integrated Truck Inform and Warn Alert Images for IMA**

Source: Battelle Team



DENSO

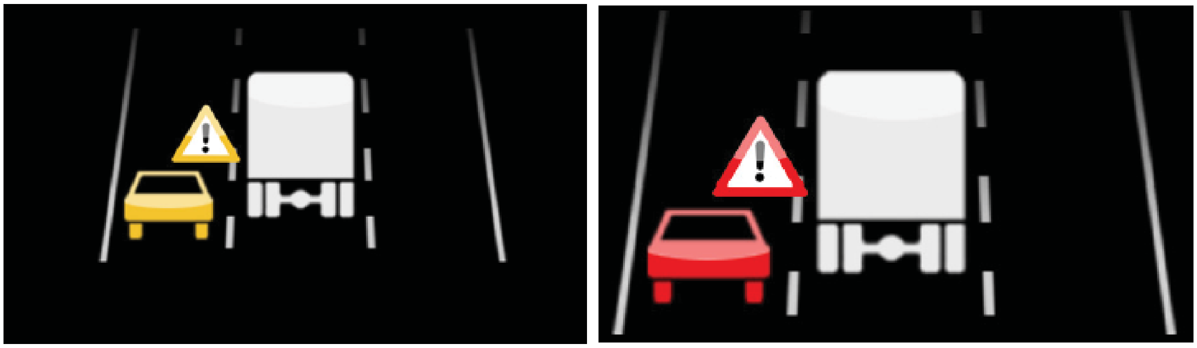
**Figure 30: Battelle Team RSD Inform-level IMA Alert Image**

Source: Battelle Team

### *IV.C.4. Blind Spot and Lane Change Warning*

BSW and LCW, also previously tested in light vehicles, are complimentary applications based on advising and warning the driver of potential conflicting vehicles in the adjacent lane, using BSMs received from surrounding vehicles. BSW provides an advisory alert to drivers when a BSM from a vehicle in the blind spot is received. LCW builds upon the BSW by providing a warning to the driver when a lane change is signaled and a conflicting vehicle is present.

In the integrated truck implementation (see Figure 31), both BSW and LCW were included, and when the turn signal was activated to indicate a lane change in the direction of a vehicle in the blind spot, an audible alert was activated in addition to the warning-level visual display. Since the BSW zone in the adjacent lane is different in a heavy truck than a light vehicle, the system was designed to permit configurable blind spots, with a zone behind the driver on the left side, and a zone from the front of the truck rearward on the right side. In the Battelle team RSD, only BSW was implemented, and the driver alert was limited to an inform-level alert with no auditory feedback (see Figure 32).



MBRDNA

**Figure 31: Integrated Truck BSW (left image) and LCW (right image) Visual Alerts**

Source: Battelle Team

**Figure 32: Battelle Team RSD Inform-Level Alert Image for BSW**

Source: Battelle Team

## IV.D. V2I uses for heavy-vehicle DSRC

In addition to the V2V safety applications described in Section IV.C, prototype versions of two V2I safety application concepts were also implemented in the heavy trucks. CSW was implemented in the integrated truck platform, both retrofit safety device truck packages, and the transit bus retrofit package. While each project used the same DSRC-based infrastructure messages, provided by the Safety Pilot test conductor, teams were not required to produce the same implementation. The BHI application concept was only implemented in the integrated trucks, and was tested using a static stored message in the OBE, since the field infrastructure was not set up to broadcast this message.

### *IV.D.1. V2I safety applications*

Excessive vehicle speed in curves often leads to lane departure, collision, loss of vehicle control, and/or road departure, any of which may result in some combination of vehicle or property damage or loss, injury, and death. The CSW safety application is intended to target crashes approaching horizontal curves on segments or interchange ramps that are speed-related. The application provides a warning to drivers approaching a curve or ramp at an unsafe speed or decelerating at insufficient rates to safely maneuver the curve, using information provided by connected vehicle field infrastructure.

The prototype version of CSW is implemented using TIMs that are transmitted periodically (at 1 Hz) by static infrastructure-based roadside unit devices to 5.9 GHz DSRC equipped vehicles as they approach and traverse the curve (see Figure 33). These messages contain a list of locations with associated advisory speeds and direction. These data sets identify roadway areas with reduced speed requirements due to the curvature of the road. These data sets can also be logged for long-term usage by equipped vehicles.

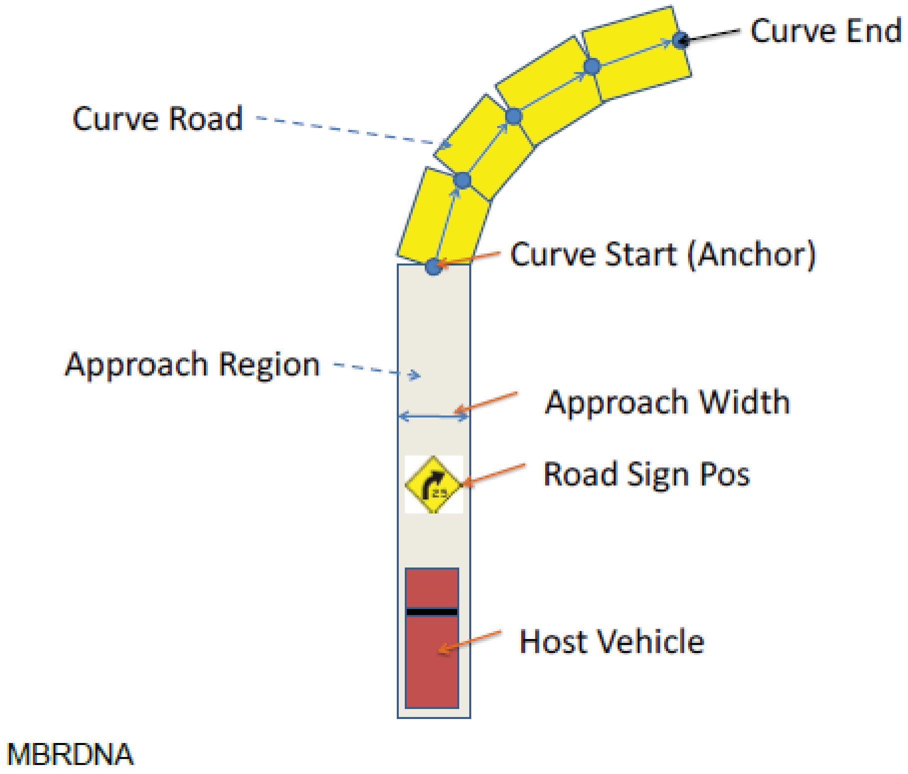


Figure 33: Illustration of CSW Scenario

Source: Figure 3-6 from [29]

At a typical rate of 10Hz, all reduced speed data sets stored on the host vehicle are evaluated by the on-board CSW application. The CSW application evaluates three States to determine if a CSW advisory or alert should be activated and presented to the host driver:

- **Location –** Reduced speed regions, defined within the context of the Safety Pilot, are represented as connected line segments that follow the path of the curve with a corresponding lane width. If the host vehicle's position is within this geometry, a CSW alert may be issued, while if the host vehicle is approaching, some implementations include the capability to provide the driver with an informational advisory.
- **Direction –** In addition to position, the current heading of the vehicle must be within a known threshold of the directions stated in the data sets. This ensures that only vehicles traveling toward the reduced speed area will receive the warning.
- **Speed –** If the host vehicle is determined to be within the active range and direction of the reduced speed area, as determined above, the current speed of the vehicle is compared against the designated curve speed. If the vehicle's current speed is found to be in excess of the designated curve speed a CSW alert is given to the driver if the vehicle is in the curve area, or in some implementations, within a calculated distance of the curve, defined by "emergency braking distance." If the host vehicle has not reached the curve, but is

within a “comfortable braking distance” of the curve, the alert in some implementations consists of an informational advisory rather than a warning.

CSW alerts can be suppressed if the driver has recently received a warning for the given curve, or based on other customizable parameters (see Table 9). When a CSW is warranted, the event is transmitted to the DVI which displays the appropriate informational advisory or warning message to the vehicle driver and may generate an audible alert. Again, the implementation varied among the different heavy-vehicle packages. Figure 34 and Figure 35 depict some of the CSW driver interface designs.

**Table 9: Example Parameters to Customize CSW Application Implementation**

| **Parameter** | **Use by Application** |
|---|---|
| **CSW minimum speed threshold** | Warning and advisories are suppressed if vehicle speed is below threshold |
| **CSW maximum assumed braking factor** | Assumed deceleration value used in calculation of braking distance |
| **CSW advisory speed adjustment** | Adjustment, if any, applied to the advisory speed given by the TIM for use by the host vehicle application |

Source: [29], p. 23

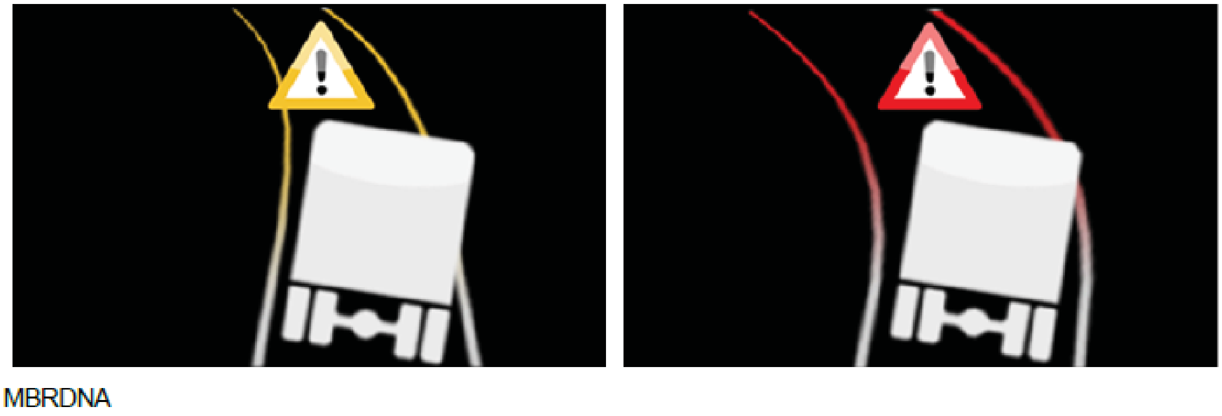


**Figure 34: Battelle Team CSW Inform Advisory (left image) Versus Warning (right image)**

Source: Figure 2-22 from [20]

**Figure 35: CS-SwRI CSW Left Curve Warning Image**

Source: Figure 2-7 from [23]

**TIM Location Limitations**

Implementation of the CSW prototype led to two primary recommendations relating to the use of the TIM:

1. Improved TIM location representation over the current circle, region, and shape point set options.
2. Improved TIM direction representation, perhaps by removing the overall “direction of use” attribute and adding direction as an inherent attribute of each segment within the vehicle path.

Traveler Information Messages, as defined in the SAE J2735-200911 DSRC Message Set Dictionary, contain information to be presented to a driver and a definition of when, where, and under what circumstances it should be presented. Options for where information should be displayed include:

- Circle - a center point and radius, generally used for very large areas;
- Region - a sequence of vertices that define a polygon, generally used to isolate stretches of a highway or a particular jurisdiction; and
- Shape point set - a sequence of points that define a path with a particular width.

While the shape point set seems the obvious choice for a message that should be displayed in a relatively small area along an approach to and through the path of a given curve, there are a couple of key limitations with its usage. For instance, attempting to define the path of a road around a curve requires a dense set of path points. Unfortunately these path points will not fully cover a particular lane, as seen in Figure 36. Although using a geometry that is wider than a lane width will capture the missing sections of the lane, the extended geometry may cover unintended and non-applicable lanes.

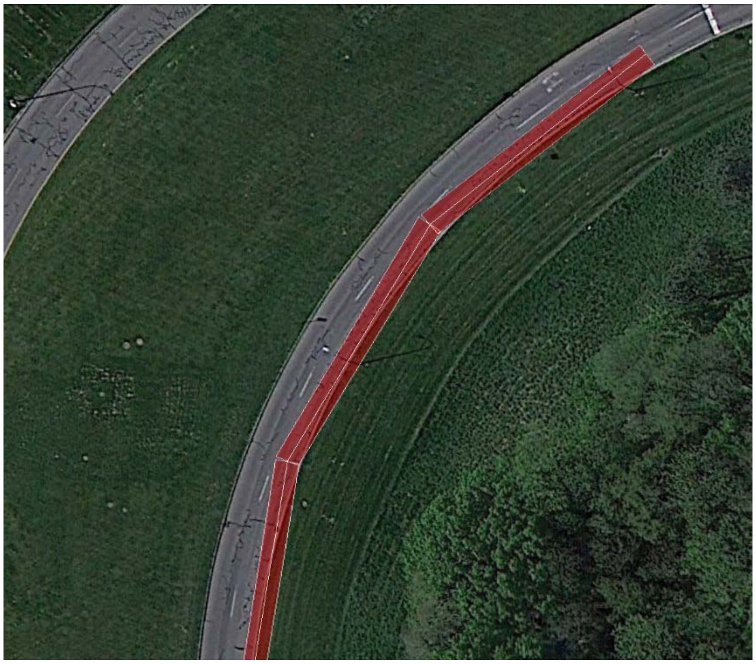


**Figure 36: Example Curve Speed Warning Definition**

Source: SwRI

**TIM Direction Limitations**

An additional limitation related to TIM that was noted during the course of the testing was the applicable heading associated with TIM regions. The current standard uses a single 'direction-of-use' element that is applied over the entire list of segments. This implementation has led to issues when applied to longer curves and especially those at highway interchanges such as a cloverleaf (see Figure 37). By including a sufficient range of directions to cover all of the segments (white arrows), those segments must be very strictly defined such that they do not include adjacent roads that are not applicable (red arrows) which increases the complexity of the region structure and thus increases the processing requirements and load on the OBE. One project team recommended that the overall "direction of use" attribute should be removed from that region type and instead to include the direction as an inherent attribute of each segment within the path.

**Figure 37: Example Curve Speed Warning Direction Issue**

Source: SwRI

### *IV.D.2. V2I safety applications (BHI)*

The integrated truck project also implemented an additional V2I safety application, BHI. The purpose of the BHI application was to provide information to the truck driver about bridge or overpass heights in the area where the vehicle is operating to assist the driver in avoiding structures which cannot be cleared by the truck. The information provided is the same as a static roadside sign, but is not subject to being obscured by other vehicles or otherwise missed by the driver. The application was designed only to provide an informational advisory message (see Figure 38) providing the clearance height of the bridge, and did not issue warnings.

Bridge Ahead

Clearance 14' 6"

UMTRI

**Figure 38: Integrated Truck Bridge Height Inform Message Displayed to Driver**

Source: Table 2-1 from [26]

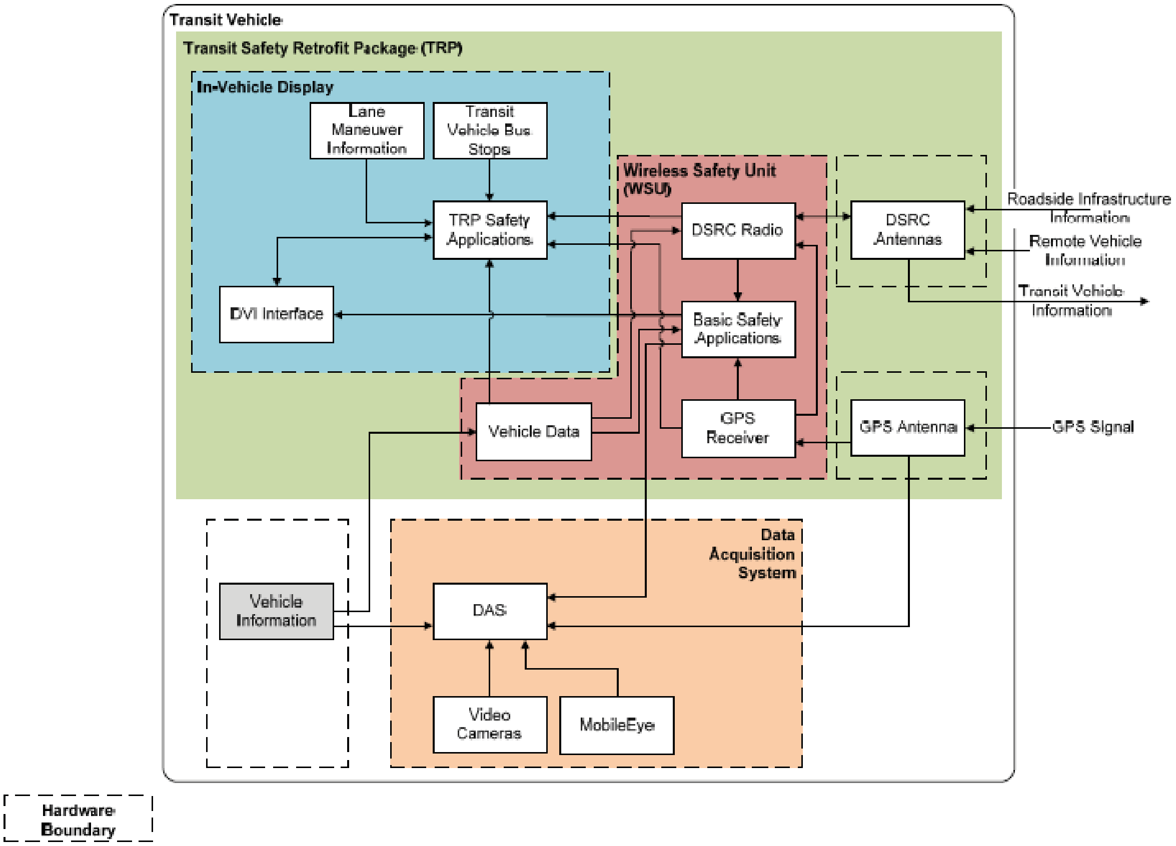
The prototype BHI application in the integrated truck platform was designed to receive bridge clearance information via a TIM message broadcast from an infrastructure Roadside Equipment (RSE), or could use the same information stored in the OBE. The BHI application was not evaluated in the driver clinics or functional tests, but during the model deployment in Ann Arbor, MI, clearance information for a pedestrian bridge was stored in the OBE ahead of time, and provided the ability to demonstrate the application capability. However, no RSE was located at the pedestrian bridge location, and so the BHI application was not tested by infrastructure-based messages.

## IV.E. Transit Bus V2V Development - Transit Retrofit Package Safety Applications

The Battelle team conducted a project known as the Transit Retrofit Package (TRP) [9] to prototype connected vehicle capabilities for transit buses and to support testing of those capabilities in the Safety Pilot Model Deployment. The project included development of transit-vehicle specific communications and processing components including 5.9 GHz DSRC, five safety applications and associated components. The TRP project included operation of the equipped buses by University of Michigan Transit within the Safety Pilot Model Deployment, which was conducted by UMTRI in Ann Arbor. The TRP deployment included one V2I safety application, the newly-developed transit-specific pedestrian in signalized crosswalk Warning, and four V2V safety applications: a newly-developed VTRW safety application as well as the EEBL, FCW, and CSW basic safety applications, which had been previously prototyped on light vehicles. Live testing commenced in August 2012, with final refinement testing occurring in February 2014.

### Development of the TRP device and the deployed safety applications

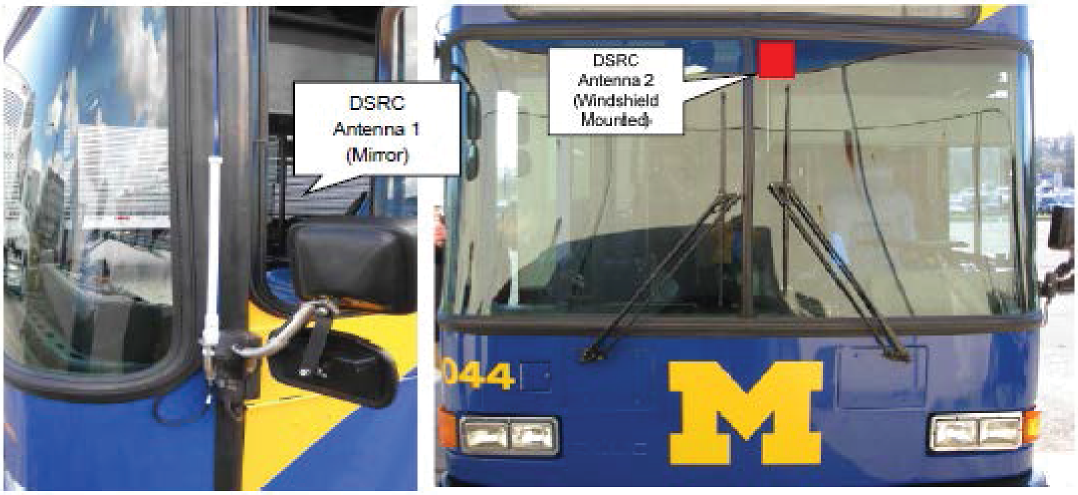
The TRP project included the development of system requirements, listed in the final report, that were developed through both stakeholder input and an evaluation of constraints and assumptions. System requirements include warnings for transit drivers when pedestrians or BSM-equipped vehicles are in the vicinity, latency and timing requirements, and the installation, location, and interface design of TRP equipment. The contractor team developed a TRP system design, depicted in Figure 39 a visual schematic of the high-level system architecture. The architecture includes the components of the TRP: the in-vehicle display, the wireless safety unit, DSRC antennas (see Figure 40, GPS antenna, and a DAS, a supplementary component that records events and data for evaluation purposes. One part of the design specific to transit buses is the interface between the system and the transit driver. The team developed a design of the tablet-based in-vehicle display, and its various components, including the message broker, application-specific modules, the alert manager (including auditory and visual warnings), and the user interface (see Figure 41) for example warnings provided to the driver). The project team, working with the transit operator, established a process of installing the TRP system and each of its components in participating transit buses, and conducted pre-deployment testing of the TRP system, including the installation and functional testing steps. Initial functional testing was unsuccessful due to a malfunctioning RSE unit that failed to properly transmit SPaT and other critical information, as well as several issues with the onboard WSU, including inaccuracies in properly classifying the locations of nearby vehicles. These issues were addressed by UMTRI and a successful functional re-test occurred in January 2013.



Source: Battelle

**Figure 39: Transit Retrofit Package Architecture**

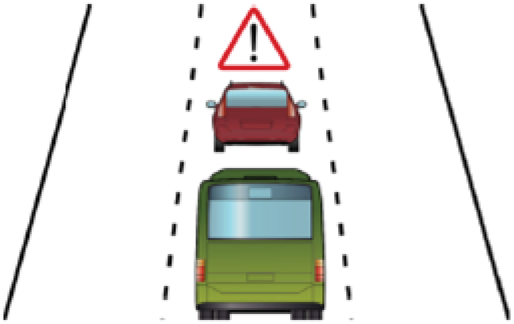
Source: Figure 3-3 from [9]



Source: Battelle

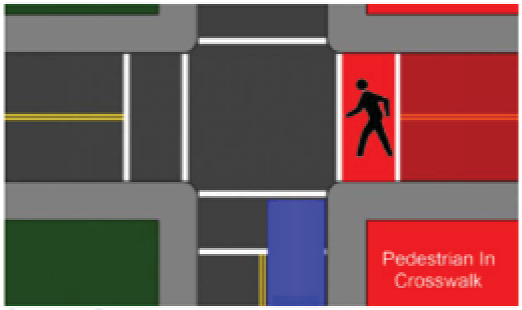
**Figure 40: DSRC Antenna Placement on Transit Bus**

Source: Figure 3-25 from [9]



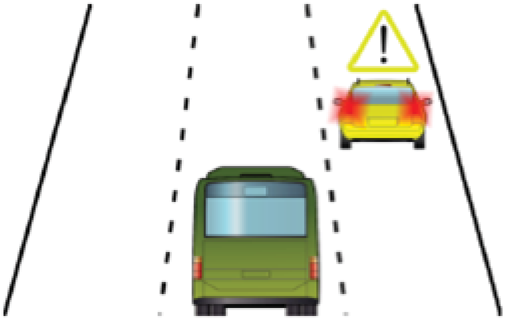
Source: Battelle

FCW Warning Display



Source: Battelle

PCW Warning Display



Source: Battelle

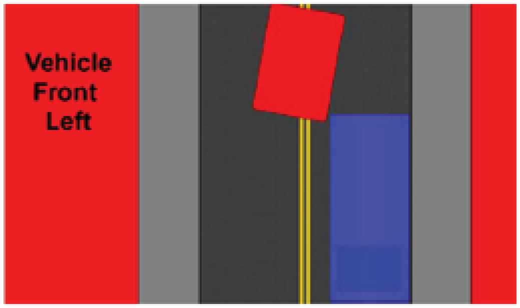
EEBL Inform Display

Source: Battelle

VTRW Inform Display

Source: Battelle

CSW Inform Display



Source: Battelle

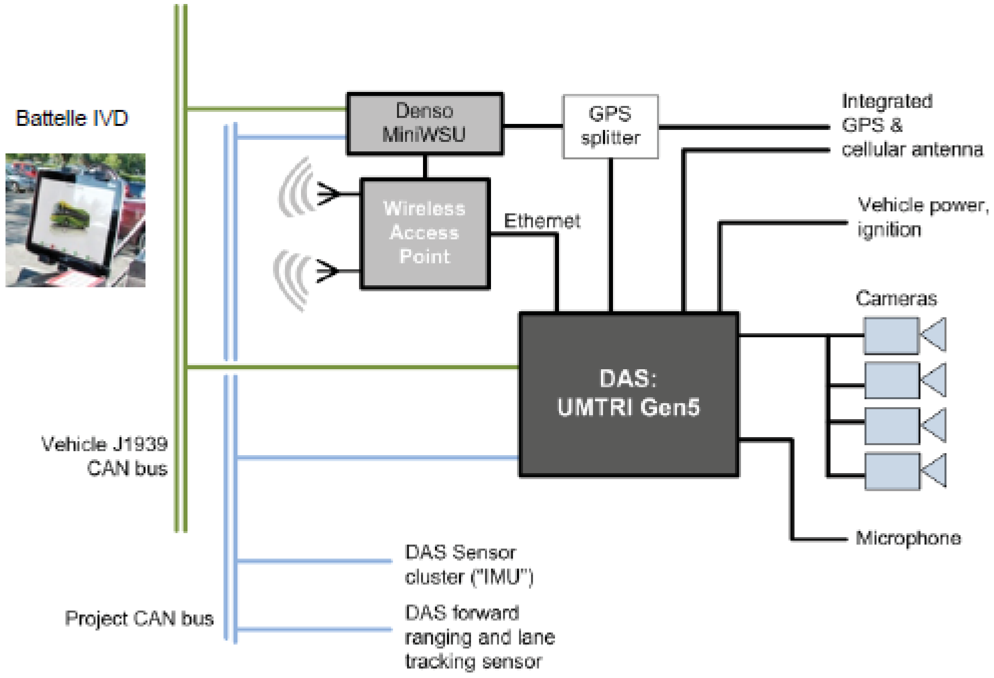
VTRW Warning Display

**Figure 41: Transit Retrofit Package In-Vehicle Display Images**

Source: Figures 3-12 through 3-17 from [9]

## In-vehicle data acquisition system

In order to support evaluation of the TRP system performance, the project team included an in-vehicle data acquisition system in the design. The DAS serves as a data collection mechanism during vehicle operation and gathers information such as safety application alerts, sensor inputs, vehicle travel and driver action data, and other metrics. Note that the DAS is distinct from and not connected to the IVD. Figure 42 depicts a visual schematic of the DAS and its feeder components, including the WSU, GPS and cellular antennas, and onboard cameras. The project report also includes in-depth descriptions of individual DAS system components (including the project and factory-installed data buses, Ethernet connection, GPS and cellular modem antennas, cameras, vehicle power and ignition indicators, and a microphone to verify audio warnings) as well as a discussion of the role of DAS data (vehicle speed, distance, braking, "target" acquisition, forward objects, alerts, GPS location, other devices encountered, and vehicle diagnostics, among other metrics). The collected data was downloaded by UMTRI, and the resulting data set recorded metrics concerning vehicle performance and diagnostics, trips, forward objects, alerts, and other connected vehicles and RSE units encountered.



Source: UMTRI

**Figure 42: DAS Components and Connections with TRP**

Source: Figure 3-34 from [9]

### Transit driver training process

As the TRP system was a newly developed prototype, the project team used a driver training process to assure that drivers are capable of correct TRP operation and interpretation. Participating operators first underwent a series of hour-long classroom instruction sessions, which included an overview presentation of the TRP, introduction to TRP operations, and the role of data in the deployment. A total of 61 drivers were trained during the original training period in December 2012 and a supplemental training period in January 2013. Of the 61 participants, 32 were full-time transit drivers, while 29 were part-time. A total of 35 drivers received training for the 2014 redeployment.

**Summary of the TRP deployment in Safety Pilot**

The deployment of the three TRP-equipped buses occurred over the following four phases and resulted in the collection of numerous data points:

- Phase 1: Basic integration and deployment of FCW, EEBL, and CSW (August 2012);
- Phase 2: DAS integration and deployment (October 2012);
- Phase 3: Integration and deployment of PCW and VTRW (January 2013); and
- Phase 4: Integration of TRP revisions (January 2014) and follow-up testing (February 2014).

From February to September 2013, the TRP IVDs on board the three buses captured 23,211 events, including 1,995 warnings and 1,720 cautions. A large majority of the collected events (19,496) were "no alerts" for the PCW and VTRW applications, signifying that the application was active but not in alert state (for example, the transit bus was in the turn lane with no pedestrians in the crosswalk). The redeployment captured 4,730 total events, of which 294 were warnings, 262 were cautions, and 4,174 constituted "no alert" events. The final portion of this section provides a summary of transit driver feedback. The original deployment featured a focus group composed of five drivers that accounted for 46 percent of the total hours of operation. The initial focus group offered the following observations:

- IVD: participants suggested that the display should be more centered, so operators do not have to look to the side to such a degree. The group expressed a mixed opinion regarding the utility of the audio beeps, with one participant suggesting that they be replaced with narrated warnings.
- PCW: the operators expressed concern for the number of system false positives, as well as the possibility that bicyclists move too rapidly to be accurately identified and tracked by the current system.
- VTRW: participants stated their belief that this application could prove to be the most useful if properly implemented, particularly in the case of rear vehicles pulling out from behind and attempting to pass the bus, but none of the five participants received an actual VTRW warning.

A follow-up focus group consisting of three operators (44 percent of total re-deployment operator hours) convened following the 2014 re-deployment following implementation of TRP system refinements. These participants stated that:

- The new IVD location offers an improvement over the original deployment
- Increased length of warning and caution display were likewise useful
- The refinement resulted in a decrease in false positive events
- Overall, however, this small sample size of operators did not report any tangible benefit of the TRP system as currently implemented, nor would they recommend installing it throughout the bus fleet. The operators stated that they were aware of conditions regardless of TRP warnings and cautions, and in fact TRP operation caused additional distraction. The participants did state, however, that the system might prove useful for inexperienced drivers or in areas with greater congestion and pedestrian traffic.

**Analysis of the original deployment**

Observations from the original deployment include:

- PCW: 97 invalid and 23 valid warnings (40 unsure);
    - Root causes: crosswalk detectors could not accurately distinguish pedestrians from vehicles, application settings allowed warnings for a straight travel lane, GPS inaccuracy;
- VTRW: 31 valid and 7 invalid warnings (5 unsure);
    - Incorrect target classification caused by GPS inaccuracy led to invalid warnings;
- Some warnings logged in the IVD could not be matched with DAS data;
    - Root causes: WSU unit reset and battery depletion.

Following the initial analysis, the project team executed the following revisions.

- Verbal notifications instead of beeps
- Longer display of cautions and warnings
- Position IVD closer to the driver
- Power cable replacement and improvement
- Decrease crosswalk detection speed threshold from 7 to 5 miles per hour and increase verification time to 3.5 seconds (PCW)
    - Result: 38 percent decrease in invalid warnings caused by lack of pedestrian
- Modify settings so no alerts displayed when in straight lane (PCW)
    - Result: 76 percent decrease in invalid warnings caused by bus path
- No longer display warnings when bus is not in forward gear (VTRW)
    - Result: mitigation of VTRW “nuisance” alerts

The research team’s overall findings, as documented in the final report, include:

- The TRP on-bus software was effective at providing alerts to transit drivers.
- The transit drivers expressed acceptance of the TRP concept.
- There was a high rate of false alerts for the PCW application due primarily to a combination of GPS limitations and pedestrian detector limitations.
- There was a high rate of false alerts for the VTRW application due to GPS limitations.
- Wide Area Augmentation (WAAS)-enabled GPS accuracy is insufficient for the PCW and VTRW applications. Typical lane width is 3.35 meters, thus accuracy within 1.675 meters is required, which cannot reliably be achieved with WAAS-enabled GPS. A more precise technology, such as Differential GPS, should be employed to achieve expected performance levels.
- The Doppler microwave-based crosswalk detectors are insufficient for the PCW application. They cannot adequately discern between pedestrians and slow moving vehicles in the crosswalks. A more discerning technology, such as high-speed imaging, should be employed to achieve expected performance levels.
- DSRC radio technology performed well – there were no TRP problems traced to DSRC radio communications.
- The short-term system revisions yielded expected performance improvements.

**Project Team Recommendations for Next Generation System**

Based on their experience, the project team recommended the following next steps, which are further developed in the final Vision for the Next Generation.

- Improved locational accuracy technology
- Conduct a human factors assessment to improve IVD and other system aspects
- Improved and ruggedized IVD cables
- Review of budget and possible re-design of power source
- Additional logging and monitoring capacity
- Improved pedestrian detection technology (PCW)
- Extend area of application to anywhere RSE units could be located (PCW and VTRW)
- Software design modifications to reduce nuisance alerts (PCW and VTRW)

The strategies presented are designed to ameliorate known weaknesses and to incorporate emerging technologies. The strategies presented:

- Vehicle positioning
    - Continuously Operating Reference Station-based differential GPS for improved transit vehicle location information
    - Improved collection of localized inertial measurement unit data, especially in areas of poor GPS reception
    - Vehicle CAN data to supplement GPS and IMU inputs
- Improved pedestrian detection
    - Investigate role of Bluetooth and Wi-Fi
    - Use the MobilEye 560 onboard sensor
- User interface improvements
    - Recommend conducting a thorough human factors assessment
    - Alternately, host the TRP presentation on existing mobile data terminal (MDT) or mobile digital computer units
- Repackaged and ruggedized hardware
    - Due to battery/power issues, move to a directly-powered and permanently attached power and data cable
    - Relocate a smaller TRP package to the overhead area behind the driver
- Software improvements
    - Investigate and fix WSU reset glitch within firmware
    - PCW: distance decrease will reduce number of alerts, proxy basic safety message data gathered by MobilEye will increase effective area
    - VTRW: Increased DGPS accuracy will lead to improved target classification performance, among other improvements

### IV.F. Heavy-Vehicle Participation in Safety Pilot

As described in Section IV, USDOT engaged several project teams to implement both Integrated Trucks and heavy trucks equipped with RSDs. These V2V systems were tested during the USDOT Safety Pilot, which consisted of both short-term driver clinics to evaluate driver acceptance, and a year-long model deployment which involved more than 2,000 other vehicles, with varying levels of V2V functionality, operating in the Ann Arbor area. In support of this effort, Volpe conducted evaluations of the driver clinics and model deployment results [30].

### *IV.F.1. Commercial Vehicle Driver Clinics*

The heavy-truck driver acceptance clinics were conducted on two closed course facilities, the TRC facility in East Liberty and the former Alameda Naval Air Station in Oakland, using a V2V-equipped tractor (an integrated truck) pulling a 53-foot semitrailer. Volunteer drivers were directed to drive this truck through pre-defined, scripted scenarios, with other vehicles in the scenarios driven by project team staff. The scenarios were designed to elicit specific V2V warnings based on the BSMs broadcast by the surrogate vehicles. Four different V2V application warnings were tested.

- **IMA** - Warning for an approaching conflicting vehicle while turning into an intersection (Figure 43)
- **FCW –** Warning for a stopped vehicle ahead (Figure 44)
- **EEBL –** Warning for hard braking in car ahead, with a single-unit truck in between blocking the view (Figure 45)
- **BSW/LCW –** Warning for a light vehicle in the truck's blind spot in adjacent lane (Figure 46)

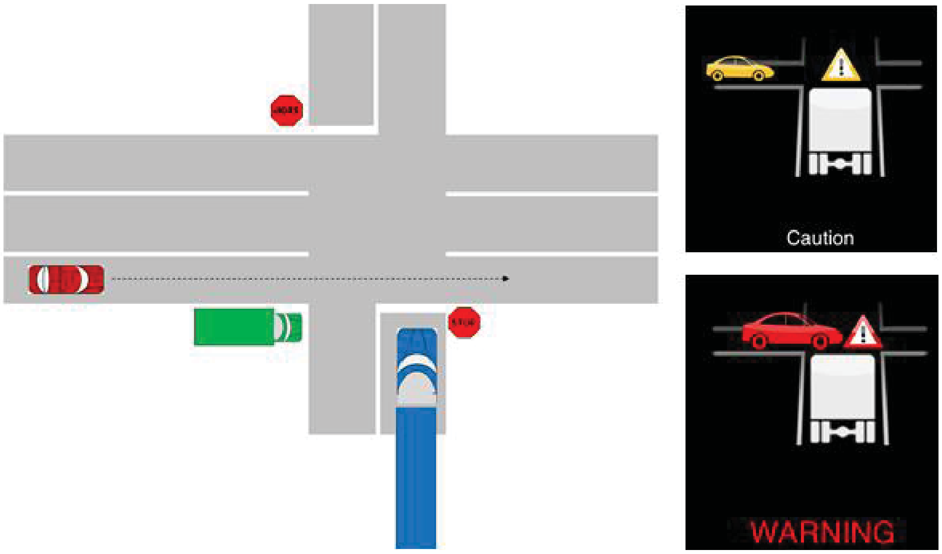


**Figure 43: IMA Scenario**

Source: Figure 3 from [30]

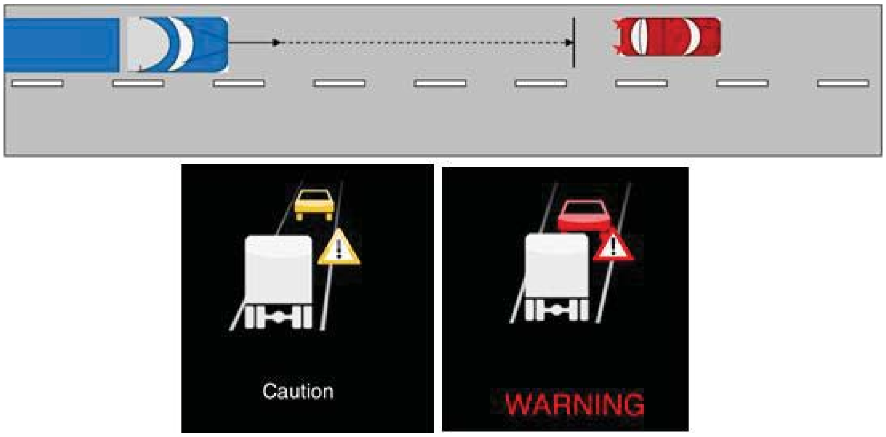


**Figure 44: FCW Scenario**

Source: Figure 4 from [30]

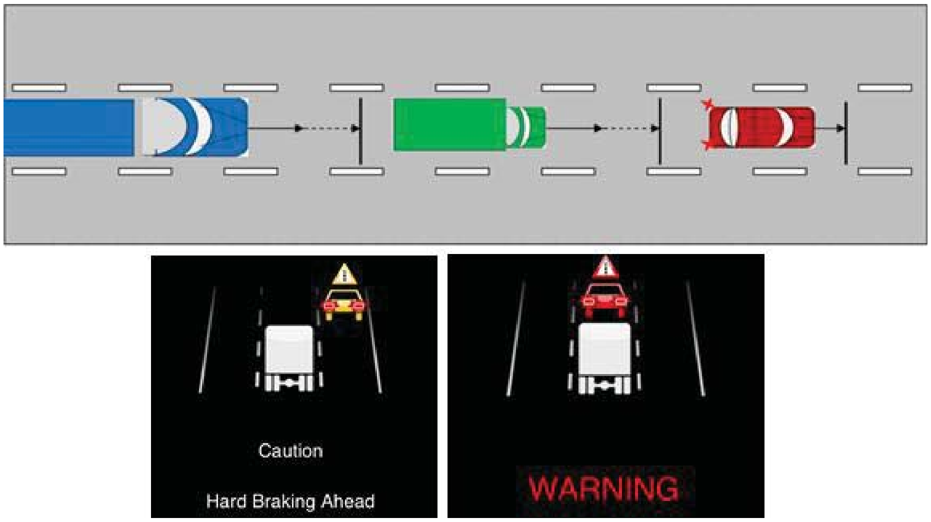


**Figure 45: EEBL Scenario**

Source: Figure 5 from [30]

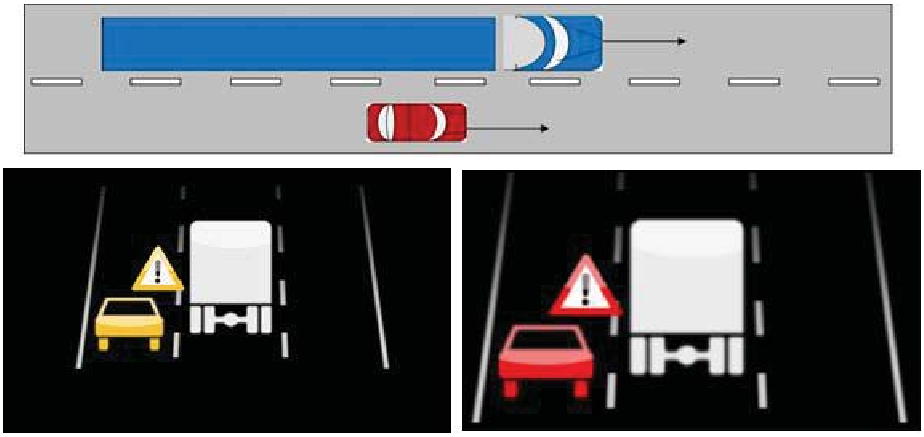


**Figure 46: BSW / LCW Scenario**

Source: Figure 6 from [30]

Based on the experience in the V2V scenarios, the volunteer subjects were assessed with respect to several key driver acceptance factors [30](p.7):

1. **Usability:** Do subjects think that the V2V safety features are easy to use?
2. **Perceived Safety Benefits:** Do subjects think that V2V technology will contribute to their driving safety?
3. **Understandability:** Are the V2V safety features easy to understand and learn to use?
4. **Desirability:** Do subjects want to have and use V2V safety features in their truck?
5. **Security and Privacy:** How do subjects feel about the security and privacy issues raised by V2V technologies?

A total of 112 truck drivers participated in the driver clinics. Each participant was given three different surveys, one before the driving started, one covering each V2V scenarios immediately after the experience, and one after the driving was complete. The surveys included both open ended questions and Likert-scale questions. In addition, over half of the drivers participated in a more detailed interview afterward to offer additional opinions and feedback.

Volpe analyzed the results from the surveys and driver feedback to identify the following results:

### Effect of Driver Clinic Location

It was possible that a factor associated with the clinic location (e.g., track layout, etc.) affected driver acceptance. After assessing the percent of positive responses in each location, no significant difference was found. As a result, the driver feedback from both clinic locations was pooled for further analysis.

### Usability

All safety features were rated as effective by the majority of subjects, although the sequence of how the scenarios were presented to drivers may have influenced the ratings. For all tested applications, over 80 percent of respondents rated the application as “very” effective, and nearly all considered the application to be at least moderately effective. In the clinics, all subjects experienced both auditory and visual warnings. Most respondents considered the combined auditory and visual alert was most useful, and most of the remaining respondents preferred the auditory only alert. Open-ended feedback often noted the desire to not require drivers to take their eyes off the forward road to view a visual alert.

### Perceived Safety Benefits

With respect to participants' view of real world usefulness, over 80 percent considered each application to be "extremely useful" (the highest option on the answer scale), with nearly all responding that each application would be at least moderately effective. After the subjects completed the driving, they also ranked the usefulness of each application tested. The average rank for each application is shown in Table 10.

**Table 10: Mean Rank of Application's Usefulness Among 4 Tested (1=Most Useful, 4=Least Useful)**

| Safety Feature | Mean Rank |
|---|---|
| **BSW/LCW** | 2.1 |
| **EEBL** | 2.2 |
| **IMA** | 2.7 |
| **FCW** | 3.0 |

Source: Table 1 from [30]

Subjects were asked about the perceived potential for driver distraction due to the applications. Overall, 75 percent of subjects considered the level of distraction to be comparable to a car radio, and 81 percent believed there was some likelihood of drivers becoming dependent on the warnings. Consistent with this result, over 90 percent of subjects thought that the V2V system should inform drivers when the feature becomes unavailable.

### Understandability

A large majority of subjects considered the warnings to be easy to understand, but more than half also thought that some confusion was likely when drivers would interpret which warning was provided by each safety feature. Although most drivers believed that they understood how the V2V technology worked, about a third still had some questions on the technology's operation.

### Desirability

Overall, over 90 percent of subjects indicated that they would like to have the V2V feature on their truck. When broken out by application, BSW/LCW was desired by the highest number of respondents, followed by EEBL, FCW and lastly IMA. V2V was also ranked highly when compared with other vehicle-based technologies.

### Security and Privacy

While no specific survey questions were asked directly relating to security and privacy, the responses to the open-ended questions were reviewed to identify subjects' concerns in this area. Only one of the 112 subjects raised security as an issue.

### Environmental Concerns

Subjects were asked for their opinions on the specific environmental conditions (with multiple responses permitted) in which each application would be most beneficial. The responses corresponding to each application are depicted in Figure 47 through Figure 50.

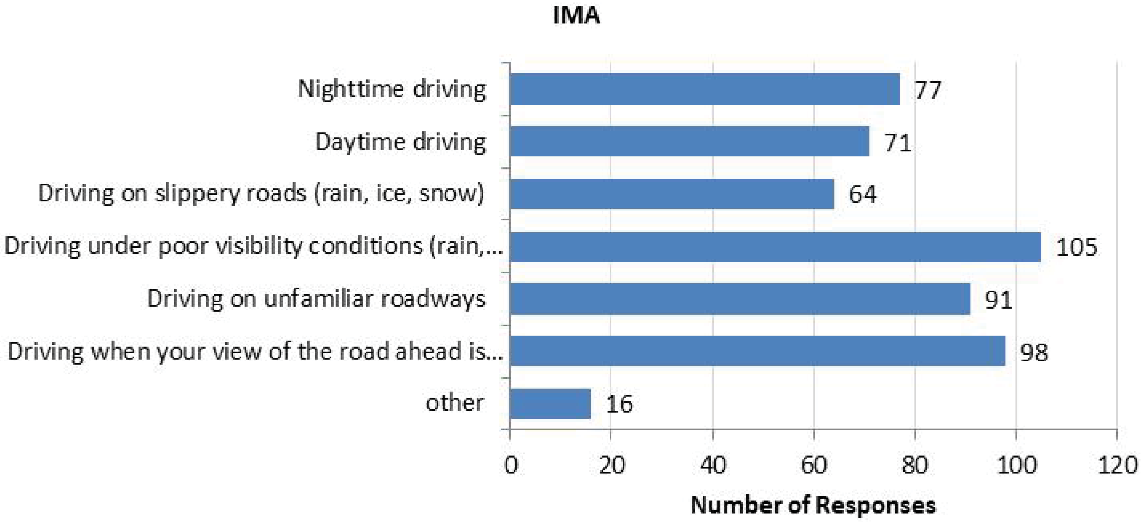


**Figure 47: Environmental conditions where IMA was considered most useful**

Source: Figures 20-23 from [30]

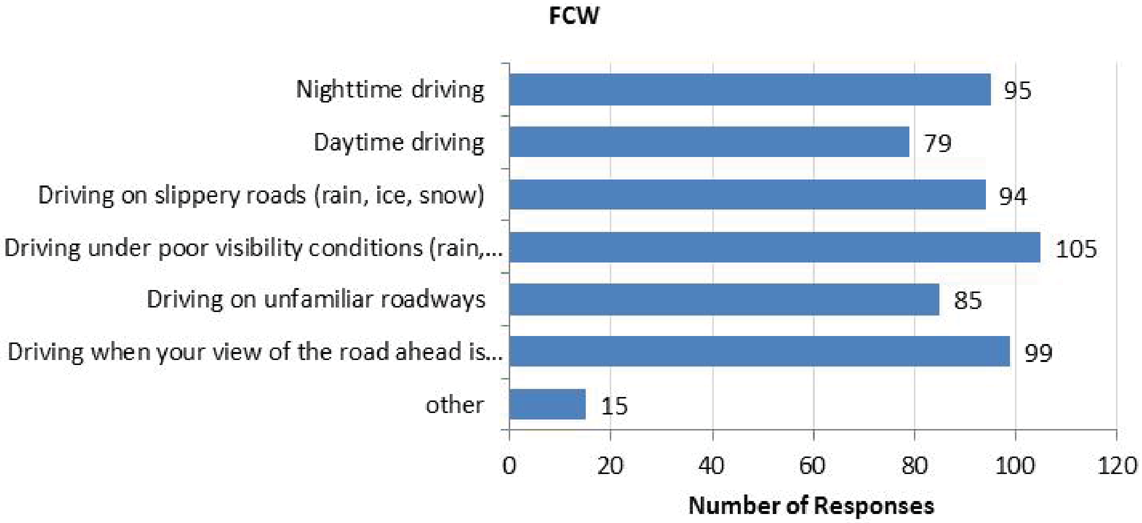


**Figure 48: Environmental conditions where FCW was considered most useful**

Source: Figure 21 from [30]

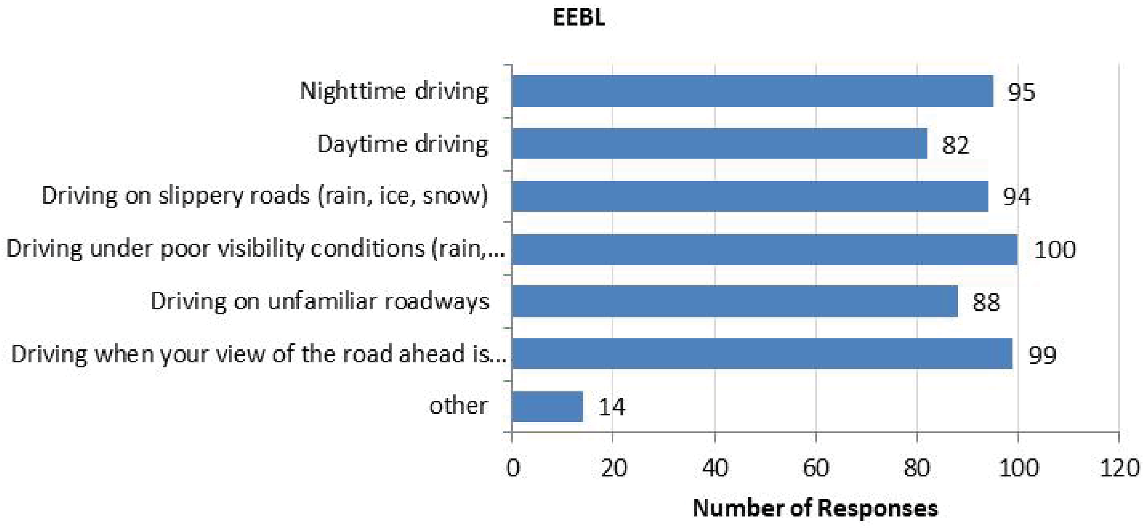


**Figure 49: Environmental conditions where EEBL was considered most useful**

Source: Figure 22 from [30]

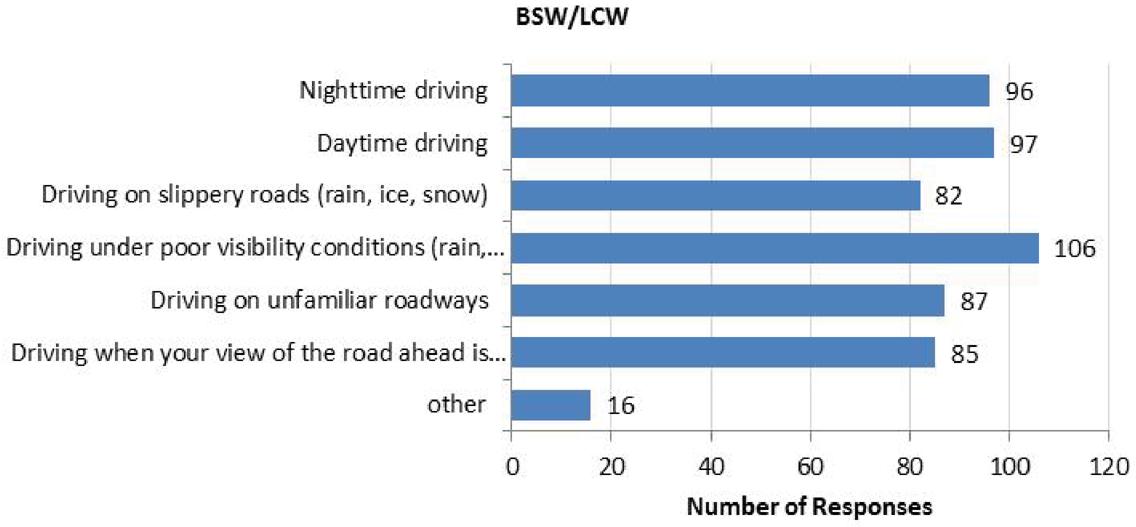


**Figure 50: Environmental conditions where BSW/LCW was considered most useful**

Source: Figure 23 from [30]

### Age Effect

Across all participants, the mean age was 47.2 years old, with a range of 28 to 66 years old. Correlations between the survey responses with age were investigated. Overall, there did not appear to be strong relationship between responses and age.

### Previous Driving Experience

The mean number of years of CDL-A driving experience in the subject population was 18.6 years, with a range of 5 months to 41 years. With respect to line-haul versus pick-up-and-delivery driving experience, there was limited data to support the analysis, but results suggested that line-haul experience was associated with higher ratings for EEBL effectiveness and understandability of BSW / LCW.

Overall, the participants in the driver acceptance clinics found their experience with the V2V safety systems to be very positive. However, it was noted that since the scenarios were carefully designed to demonstrate the value of each V2V application under ideal conditions, real world considerations, such as false alerts and nuisance alerts, could not be evaluated in the clinics.

### *IV.F.2.Heavy Vehicles in Model Deployment*

The Model Deployment in Ann Arbor served as the second, and primary, part of the Safety Pilot. The Model Deployment involved approximately 2,800 vehicles equipped with varying levels of V2V capability, ranging from integrated light vehicles with a variety of V2V applications to vehicles equipped with vehicle awareness devices, which would only transmit BSMs and did not include application interactions with drivers.

The heavy trucks that participated in Safety Pilot Model Deployment included three implementations of V2V capability.

- Integrated Trucks – 3 trucks
    - 2 participants from 4H Transportation in 2 trucks, driven for 5 months
    - 2 participants from Rightaway Delivery in 1 truck, driven for 3 months
    - 5 participants from UMTRI in 3 trucks, driven for 5 months
- Retrofit Safety Devices (Battelle Team, referred to as “RSD1”) – 8 trucks
    - 8 participants in 8 trucks from Sysco Foods, LLC, driven for 17 months
- Retrofit Safety Devices (Cambridge Systematics/SwRI, referred to as “RSD2”) – 8 trucks
    - 16 participants in 8 trucks from Con-way, driven for 11 months
- Vehicle Awareness Devices – 100 medium/heavy trucks
    - Only broadcast BSMs to enable other vehicles’ V2V applications

The Model Deployment supported the independent evaluation conducted by Volpe [31], further described in Section V.A. Each category of truck had variations in the specific V2V and V2I applications implemented (see Table 11). In the integrated truck and RSD1 implementation, both cautionary and imminent alerts had a visual and auditory component with the exception of BSW, which displays a visual warning only with no audio. The RSD2 implementation provided crash-imminent warnings only with both visual and auditory components, and did not use cautionary alerts.

**Table 11: Heavy-Truck Safety Applications in Model Deployment Assessment**

| Platform | Safety Applications | | | | |
|---|---|---|---|---|---|
| | FCW | IMA | BSW/LCW | EEBL | CSW |
| Integrated Safety Systems | C/I | C/I | C/I | C/I | C/I |
| RSD1s | C/I | C/I | C | C/I | C/I |
| RSD2s | I | | | I | I |

C= Cautionary alert  I = Imminent alert  C/I = Cautionary and imminent alert

Source: Table 1 from [31]

UMTRI, in its role as the test conductor for Safety Pilot, recruited the participants for the heavy-trucks. The goal was to recruit drivers who would drive the trucks in the Model Deployment area and therefore maximize interactions with the other V2V-equipped vehicles. UMTRI selected trucking companies that would make local deliveries in the area; however, the actual exposure during Model Deployment varied significantly. Table 12 shows the demographics for the drivers using the integrated trucks and RSD-equipped trucks who received alerts (drivers who did not experience alerts were not required to submit questionnaires).

**Table 12: Demographics for Heavy-Truck Driver Respondents**

| Truck Fleet | Total No. of Drivers | Sex | Age Category | | | | |
|---|---|---|---|---|---|---|---|
| | | | 18-24 | 25-34 | 35-44 | 45-54 | 55-64 |
| Con-way | 16 | M | | 1 | 3 | 7 | 5 |
| Sysco | 8 | M | | 2 | 4 | 1 | 1 |
| Rightaway | 1 | F | | | | 1 | |

Source: Table 2 from [31]

### Model Deployment Data

In aggregate, the drivers in the heavy trucks experienced a total of 1,089 crash-imminent alerts during Model Deployment.  Figure 51 depicts the number of alerts presented for each application.

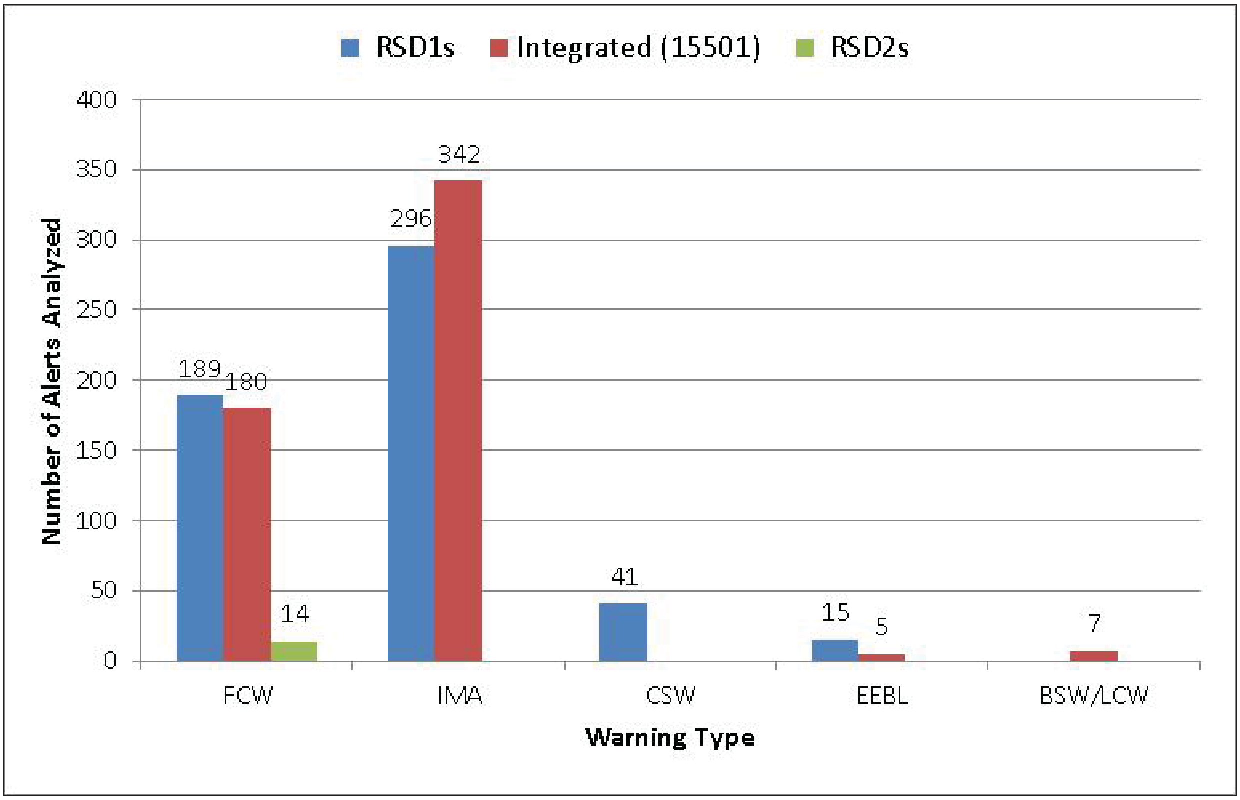


**Figure 51: Number of Crash-imminent Alerts Presented for Each Safety Application**

Source: Figure 1 from [31]

Volpe conducted an analysis of the alerts presented to drivers based on available data from vehicle-based data acquisition systems. Table 13 summarizes the percentage of valid alerts for each safety application, based on their analysis. Section V.A provides additional information based on the Volpe analysis of the data.

**Table 13: Percentage of Valid Alerts**

| Percentage of Valid Alerts by Safety Application and Device | | | |
|---|---|---|---|
| | **Integrated Truck (15501)** | **RSD1** | **RSD2** |
| **FCW** | 32% | 12% | 43% |
| **IMA** | 63% | 37% | n/e[1] |
| **BSW/LCW** | 71% | 88%[2] | n/e |
| **EEBL** | 100% | 73% | n/d[3] |
| **CSW** | n/d | 91%[4] | n/d |

Source: Table 9 from [31]

The specific findings on alert validity in Model Deployment from the Volpe report are as follows (excerpted from [31]):

**FCW**

- The percentage values of FCW alerts issued for in-path RVs were 12 percent and 43 percent for RSD1s and RSD2s respectively, and 32 percent for the integrated truck (15501). The remaining alerts were false.
- The in-path alert percentage of FCW alerts issued for stopped RVs was lower than for moving RVs for both RSD1s and integrated truck (15501). Due to the small number of alerts issued by the RSD2s, this data was not included in the analysis.
- The majority of in-path alerts were issued during lead vehicle decelerating (LVD) scenarios for both RSD1s and integrated truck (15501). Limited numerical data collected from the RSD2s precluded this information from being obtained.
- The percentages of in-path alerts issued on curves was greater when the HV was located at curve entry and in the curve compared to being located on the straight road approaching the curve. The percentages of alerts issued when the HV was approaching on a straight road were approximately the same for both RSD1s and integrated truck (15501). There were no alerts issued on curves by the RSD2s.
- Alert performance by RV range showed similar results for both RSD1s and the integrated truck (15501). Alerts issued for RVs between 30 and 60 m away had the highest in-path percentages for both the RSD1s and integrated truck (15501). Limited numerical data collected from the RSD2s precluded this information from being obtained.
- In regards to alert performance by RV device type, similar trends were observed between the RSD1s and the integrated truck (15501). There was a large disparity (78 percent compared to 9%) in percentages of RSD1 in-path alerts triggered by RSD1 equipped trucks compared to in-path alerts triggered by ASDs and VADs combined. There was

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[1] Denotes RSD2 not equipped with safety feature
[2] Denotes percentage of valid BSW (cautionary alert with no audio) alerts
[3] Denotes no data collected
[4] The percentage is the sum of valid alerts (curve entry and in-curve) at both Plymouth Road and Bonisteel Boulevard

also a large difference (94% compared to 25%) in percentages of integrated truck (15501) in-path alerts triggered by remote integrated trucks compared to in-path alerts triggered by ASDs and VADs combined. Limited numerical data collected from the RSD2s precluded this information from being obtained.

- There was one observed instance of missed FCW alert in the RSD1 dataset.

**IMA**

- The percentage values of IMA alerts that occurred at intersections were 37 percent and 63 percent for the RSD1s and integrated truck (15501) respectively.
- The majority of the false alerts (50% of all IMA alerts) issued by the RSD1s occurred at an overpass. These false alerts represent opportunities for software refinement to account for elevation in the GPS data. The percentage of false alerts issued at an overpass by the integrated truck (15501) was small (7%). This could be attributed to the UMTRI drivers driving in areas where there were no overpasses. It could also be that the integrated truck (15501) system accounts for elevation in the GPS data.
- The majority of the RSD1 and integrated truck (15501) IMA alerts issued at intersections were triggered by VADs and ASDs.
- One potential missed IMA stopped event was identified in the RSD1 dataset.
- There were no observed instances of missed IMA moving alerts in the Safety Pilot MD.

**BSW/LCW**

- Eighty-eight percent of BSW alerts issued by the RSD1s were for RVs in the adjacent lane. None of the events involved a steering response from the driver. It should be noted here that the RSD1s were equipped with BSW only (cautionary alert with no audio).
- Seventy-one percent of BSW/LCW alerts issued by the integrated truck (15501) were for vehicles in the adjacent lane. None of the events involved a steering response from the driver.
- There was one observed missed LCW alert in the integrated truck (15501) dataset.

**EEBL**

- The majority of the alerts (73%) issued by the RSD1s were for in-path and adjacent lane RVs. Two of the 11 events involved an obstructing LV.
- All 5 alerts issued by the integrated truck (15501) were for in-path RVs. One of the 5 events involved an obstructing LV.
- There was no EEBL data collected from the RSD2s.

**CSW**

- All CSW alerts were issued by RSD1s. The majority of the alerts were issued at the entry points to equipped curves located on Plymouth Road (71%) and Bonisteel Boulevard (65%). The percentage values of alerts issued in the equipped curves located on Plymouth Road and Bonisteel Boulevard were 12 percent and 35 percent respectively. The percentage of CSW alerts issued at curve entry and in the equipped curve on both Plymouth Road and Bonisteel Boulevard combined is 91 percent.
- All CSW alerts were issued at or above the threshold speeds. None of the CSW alert events involved the driver braking when the alert was issued.
- There were two observed instances of missed CSW alerts.

- There was no CSW data collected from the RSD2s.

### Driver Acceptance

In addition to the objective data, all 24 drivers of the RSD-equipped trucks and one driver of the integrated trucks completed a questionnaire designed to assess the driver's opinion of the V2V safety systems. Given the limited response from the integrated truck drivers, most analysis results were based on the RSD-equipped truck drivers. As with the driver acceptance clinics, a Likert scale was used to gauge agreement with questions, and the scale was further converted into positive, neutral, and negative responses. However, since the Model Deployment was conducted under naturalistic driving conditions and not scripted scenarios, the amount of experience with the alerts was significantly different. Figure 52 quantifies the experience with each safety application.

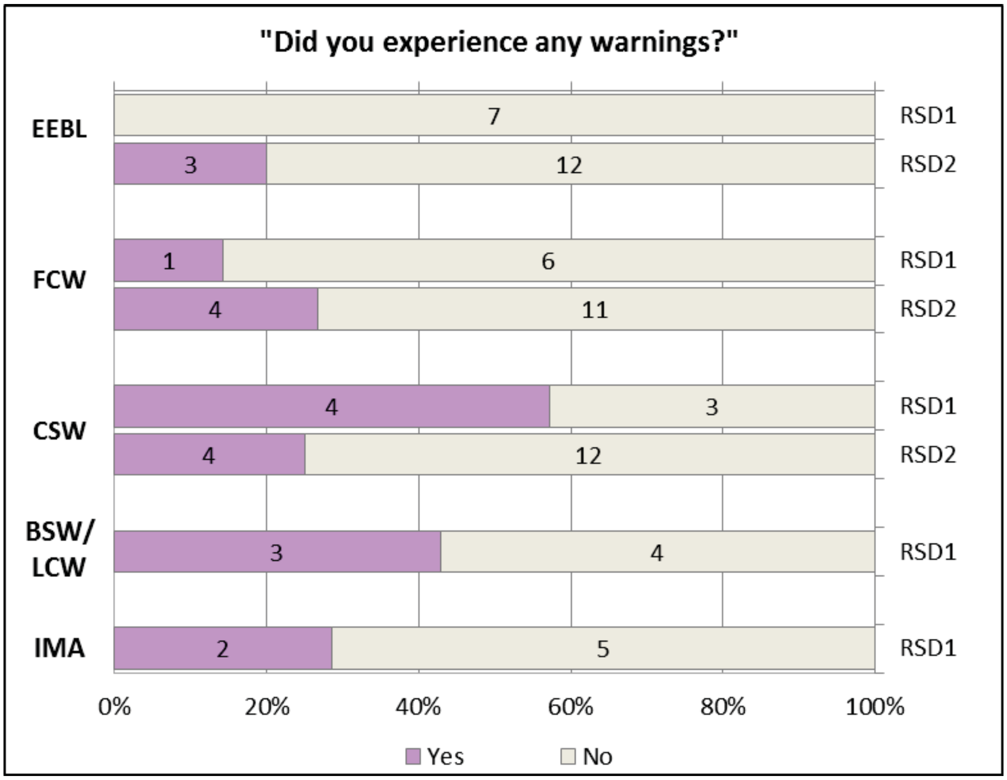


**Figure 52: Participant Exposure to Safety Application Alerts**

Source: Figure 31 from [31]

Overall satisfaction with the connected vehicle system is presented in Figure 53. Most respondents had a neutral response, with one dissatisfied participant.

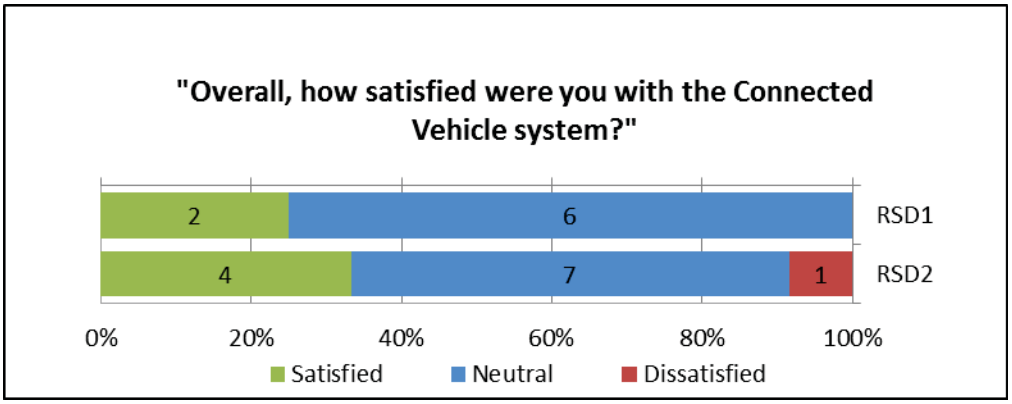


**Figure 53: Overall Driver Satisfaction with System**

Source: Figure 32 from [31]

With respect to usability, neutral responses were prevalent, with a few exceptions. In the RSD 1 implementation, over half of the respondents considered the CSW warning to be clear, while none considered the EEBL or IMA alert to be clear. Results on drivers' view of whether the warnings were trusted varied by application and sometimes by implementation (see Figure 54). Overall CSW had the highest proportion of positive scores. CSW also had the best results with respect to the perception of false alerts (see Figure 55).

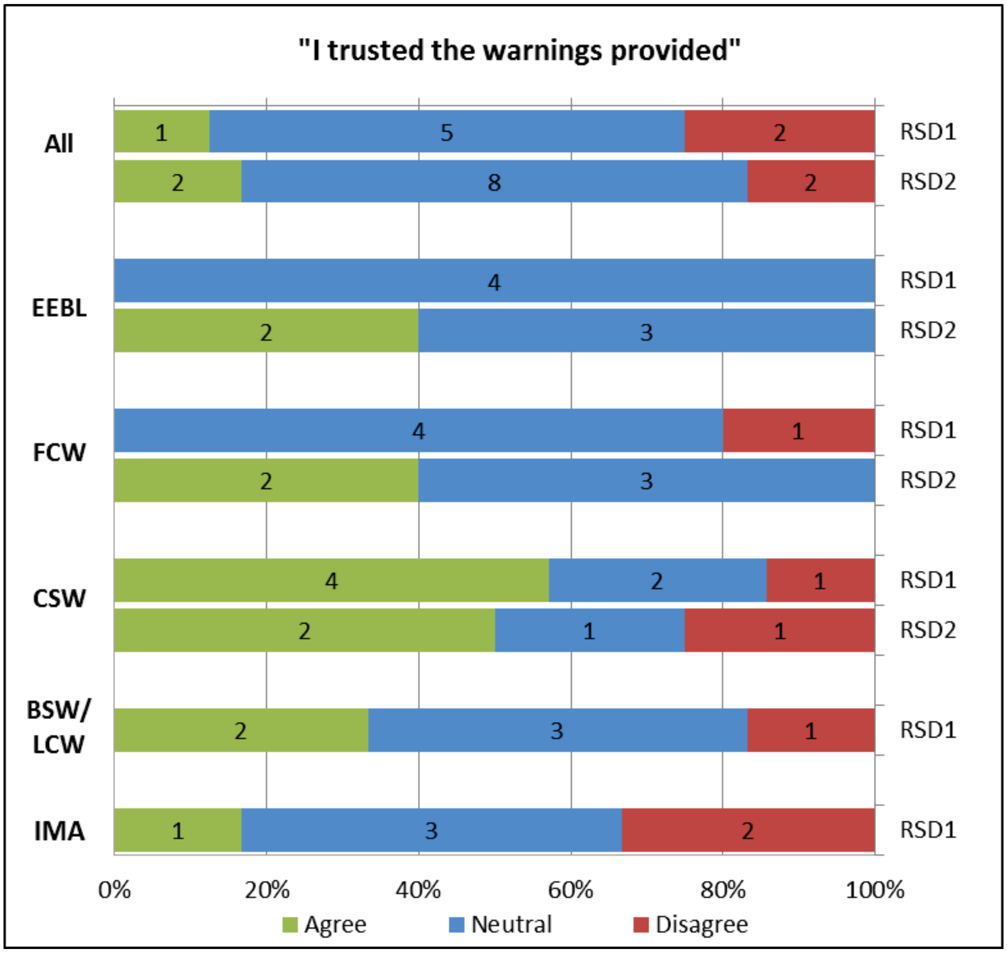


**Figure 54: Respondents' Trust in Alerts Received**

Source: Figure 35 from [31]

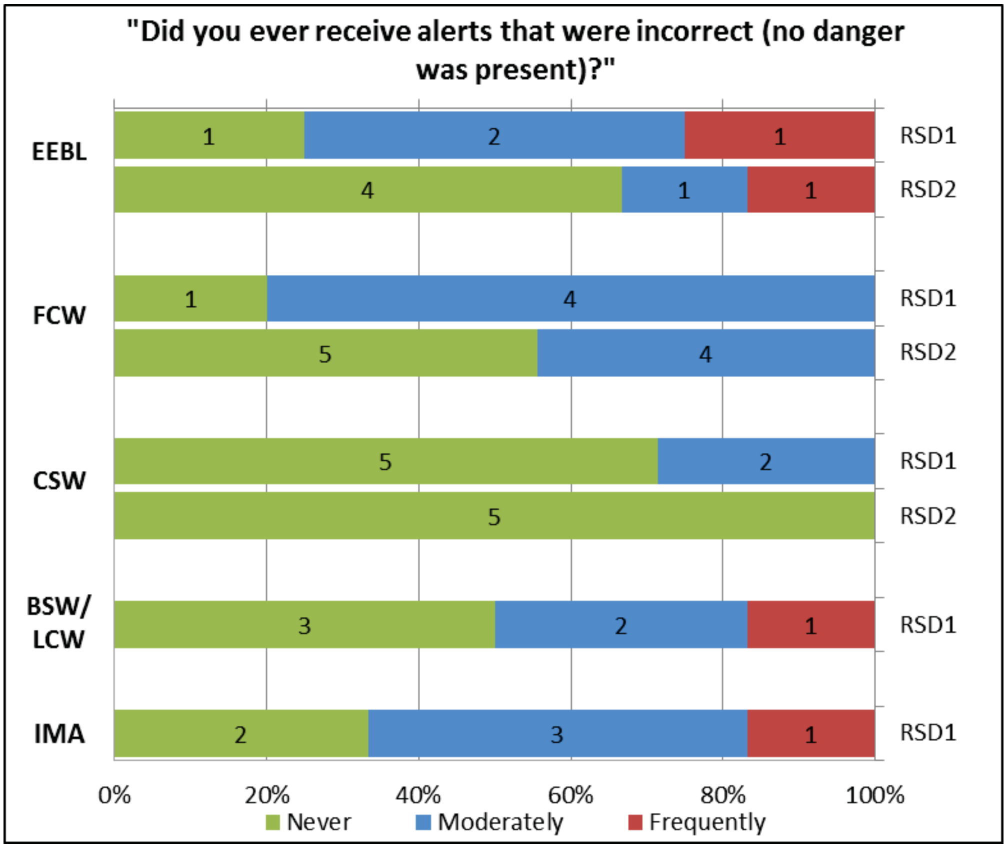


**Figure 55: Respondents' Perception of False Alerts**

Source: Figure 36 from [31]

Results from the analysis of perceived effectiveness and safety benefit, shown in Figure 56 and Figure 57, were similarly mixed from one application to the next.

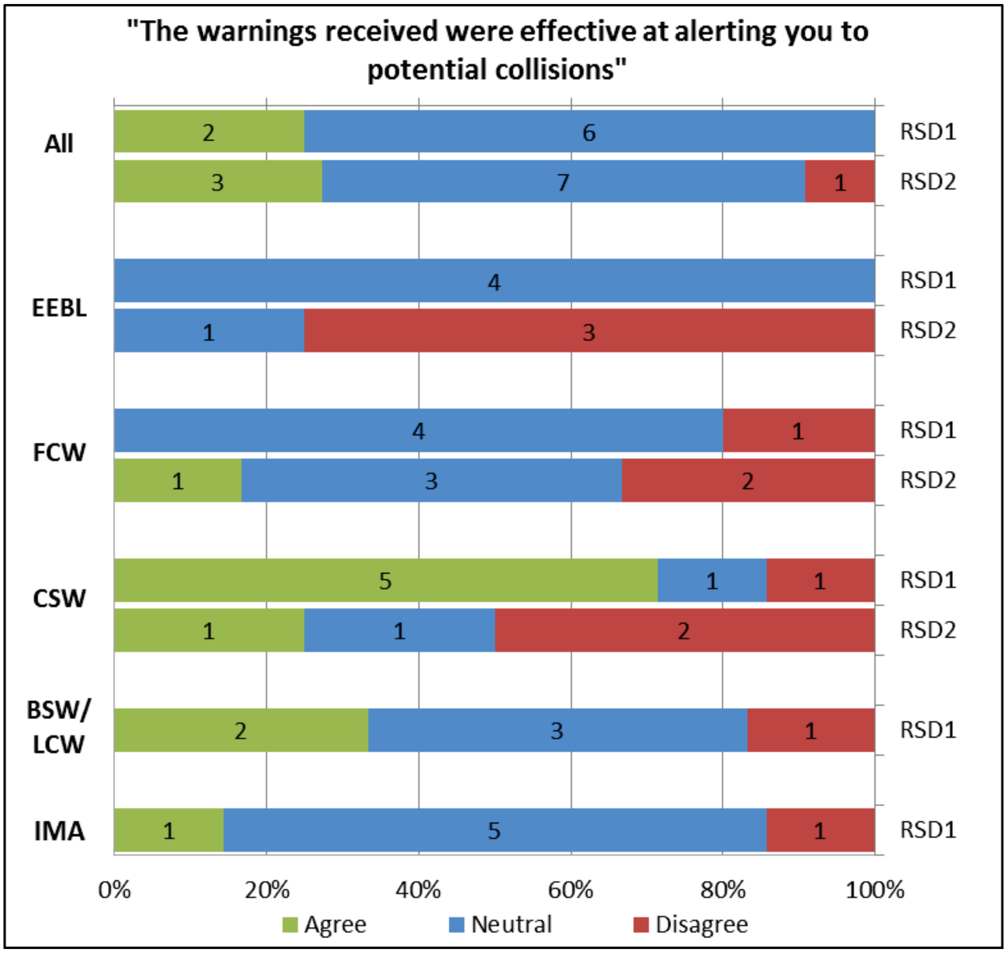


**Figure 56: Perceived Effectiveness of Alerts**

Source: Figure 37 from [31]

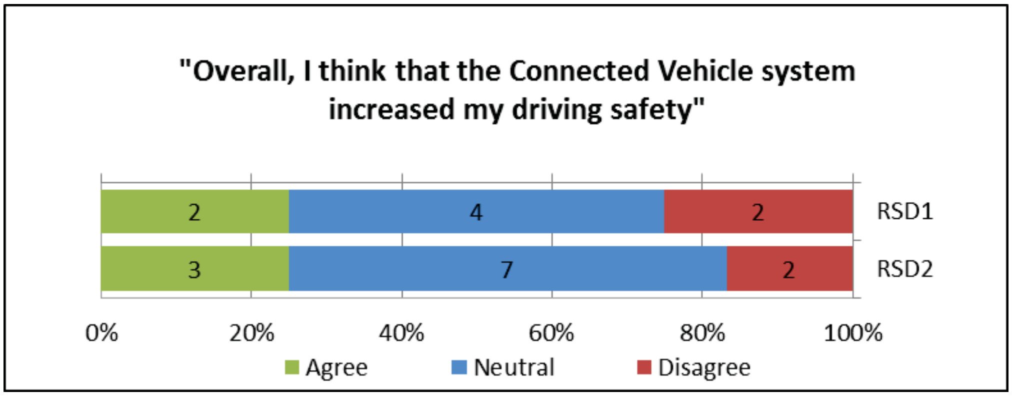


**Figure 57: Perceived Safety Benefit**

Source: Figure 38 from [31]

Unlike in the driver acceptance clinics, the surveys given to Model Deployment drivers included questions on the potential privacy impact of connected vehicle systems. Figure 58 illustrates the significant negative opinions held by participants if the system allowed privacy to be compromised.

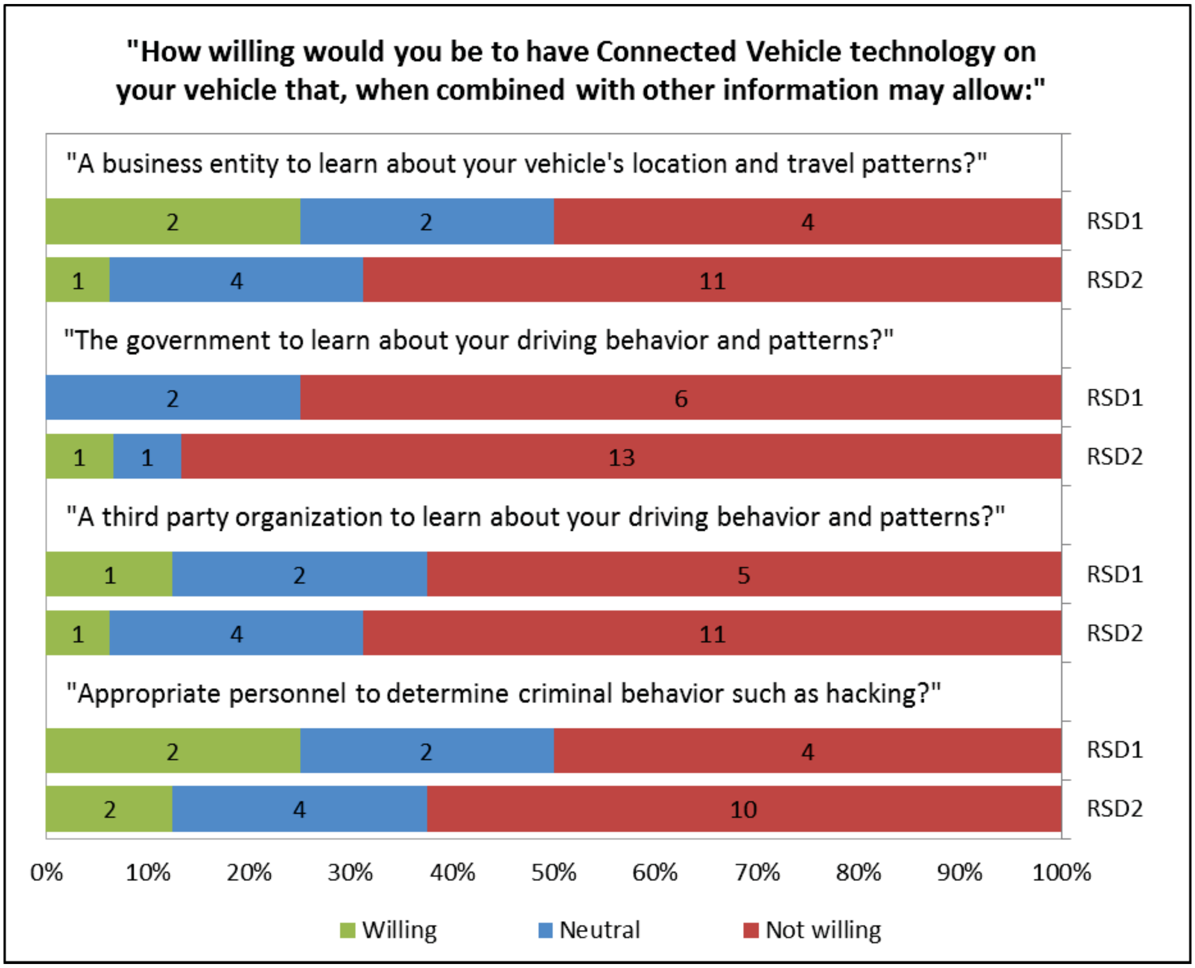


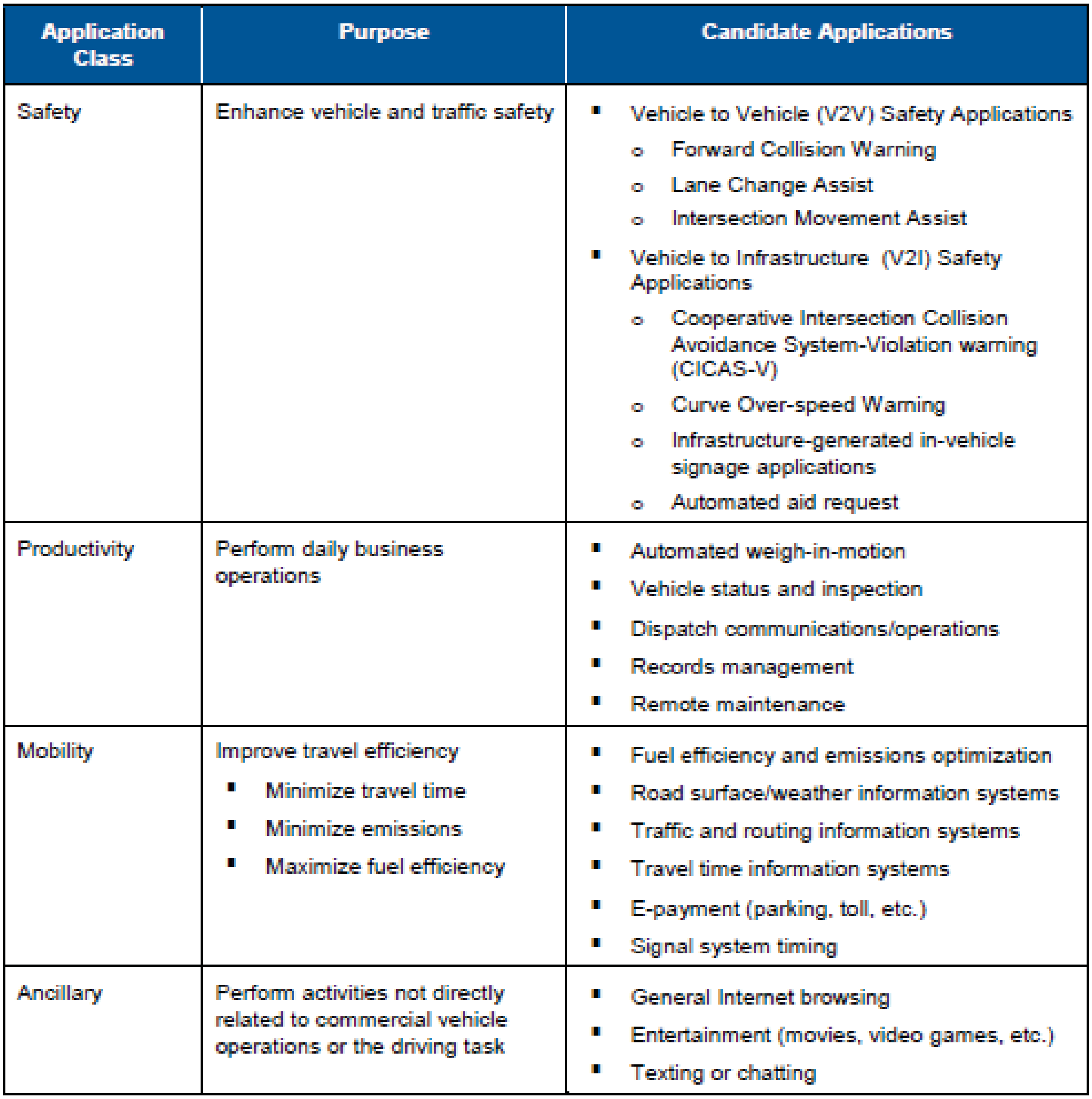
**Figure 58: Privacy-related Impacts on Willingness to Use**

Source: Figure 45 from

## IV.G. Driver Vehicle Interface

In 2010, NHTSA engaged in an effort [32] to identify and document available information on the human interface needs for heavy-vehicle drivers. This effort was conducted in part to support the need to understand how drivers would engage with V2V safety systems which may vary in implementation and undergo updates on a periodic basis, unlike most traditional vehicle-based autonomous crash avoidance systems (e.g., radar-based). The project team conducted a literature review and supplemented the information through interviews with subject matter experts. The resulting information was refined into a framework to allow flexibility in applying to a variety of applications, including safety and non-safety applications (see Table 14).

**Table 14: Application Categories Framework for Needs Specification**



| Application Class | Purpose | Candidate Applications |
|---|---|---|
| Safety | Enhance vehicle and traffic safety | ▪ Vehicle to Vehicle (V2V) Safety Applications<br>o Forward Collision Warning<br>o Lane Change Assist<br>o Intersection Movement Assist<br>▪ Vehicle to Infrastructure (V2I) Safety Applications<br>o Cooperative Intersection Collision Avoidance System-Violation warning (CICAS-V)<br>o Curve Over-speed Warning<br>o Infrastructure-generated in-vehicle signage applications<br>o Automated aid request |
| Productivity | Perform daily business operations | ▪ Automated weigh-in-motion<br>▪ Vehicle status and inspection<br>▪ Dispatch communications/operations<br>▪ Records management<br>▪ Remote maintenance |
| Mobility | Improve travel efficiency<br>▪ Minimize travel time<br>▪ Minimize emissions<br>▪ Maximize fuel efficiency | ▪ Fuel efficiency and emissions optimization<br>▪ Road surface/weather information systems<br>▪ Traffic and routing information systems<br>▪ Travel time information systems<br>▪ E-payment (parking, toll, etc.)<br>▪ Signal system timing |
| Ancillary | Perform activities not directly related to commercial vehicle operations or the driving task | ▪ General Internet browsing<br>▪ Entertainment (movies, video games, etc.)<br>▪ Texting or chatting |

Source: Table 1 from [32]

Based on the results of the literature review and subject matter expert interviews, the project team developed a series of draft functional requirements relating to the DVI, System Integration, and Automation. Each functional requirement identified the following.

- Relevant Design Factors
- Relevant Driver Factors/Behaviors
- Supporting Source Documents
- Additional Relevant Information/Notes

Table 15 documents the categorized functional requirements as identified by the project team.

Table 15: Summarized Needs/Requirements From Project Report

| Category | Title | Need/Requirement |
|---|---|---|
| **DVI Interfaces:** | | |
| **General Requirements** | Adherence to Existing Standards or Practices | DVI design elements should conform to available standards or recognized industry practices |
| | Consistency | Consistency (i.e., similar "look and feel") in the DVI should be maintained across applications with respect to presenting information to drivers and inputs to the system provided by drivers. |
| | Customization | DVI characteristics should be customizable to reflect driver preferences. |
| | Distraction and Workload | The DVI should not contribute to driver distraction or unnecessary workload. |
| **Driver Needs** | Accuracy | Information provided to drivers should be as accurate and reliable as possible. |
| | False or Nuisance Warnings | Applications that provide warnings or alerting information should minimize the occurrence of false or nuisance warnings. |
| | Timeliness | Time sensitive information should be presented far enough in advance of related events to give drivers adequate time to respond. |
| | System Status | The DVI should provide system status information to drivers. |
| | Conspicuity | DVI displays should capture drivers' attention in a manner appropriate for the application. |
| **Message Characteristics** | Non-Critical Information | The presentation of non-critical information should be minimized while the vehicle is in motion. |
| | Complexity | Information presented while the vehicle is in motion should be presented in the simplest form that can be readily understood and acted upon. |
| | Sensory Modality – Compatibility of Modality | Display modalities should be compatible with driver tasks, needs, and expectations. |
| | Sensory Modality – Hands-Free Interactions | The use of modalities that support hands-free interaction with the DVI is encouraged when appropriate for the application. |
| | Sensory Modality – Redundant Modality Coding | Applications that require immediate driver attention or action should present messages using redundant modalities. |
| **Visual Interfaces** | Display Type | The type of visual display or displays used should convey information in a way that is consistent with the functional requirements of the application. |
| | Location – Placement | The primary visual interface should be placed in a location that minimizes eye-off-the-road time. |
| | Location – Visual Obstruction | The DVI should not obstruct the driver's field of view of key portions of the roadway or occlude the |

| Category | Title | Need/Requirement |
|---|---|---|
| | | visibility of other displays. |
| | Location – Display Glare | DVI displays should be located and oriented to minimize glare. |
| | Visibility – Contrast | Visual displays should have sufficient contrast that messages are visible under an expected range of environmental conditions. |
| | Visibility – Glare From the Display Under Nighttime Driving Conditions | Illumination from visual displays should not present a significant source of glare during nighttime driving. |
| | Legibility | Text, icons, and other symbols presented on visual displays should be clearly legible from the driver's viewpoint. |
| **Auditory Interfaces** | Display Type | The type of auditory display used should convey information in a way that is most consistent with the functional requirements of the application. |
| | Compatibility | Auditory information should be presented in a way that is compatible with drivers' expectations. |
| | Auditory Signal Characteristics – Distinctiveness | Auditory messages should be distinguishable from other auditory signals in the cab. |
| | Auditory Signal Characteristics – Loudness | Auditory signals should be loud enough to overcome masking sounds from road noise, the cab environment, and other equipment. |
| | Auditory Signal Characteristics – Urgency | Auditory signal characteristics should convey a level of urgency that is consistent with the functional requirements of the application. |
| | Auditory Signal Characteristics – Localization | Localized auditory signals should elicit a response that is consistent with the functional requirements of the application. |
| | Auditory Signal Characteristics – Speech | Speech messages used to convey information should be presented in a way that is consistent with the functional requirements of the application. |
| **Haptic Interface** | Display Type | Haptic displays should convey information in a way that is consistent with the functional requirements of the application. |
| | Compatibility | Haptic information should elicit a response that is compatible with the functional requirements of the application. |
| | Distinctiveness | Haptic signals should be presented in a way that distinguishes them from other vibrations in the cab. |
| **Driver Inputs** | DVI-Driver Interactions | The DVI should minimize the frequency and complexity of driver interactions when the vehicle is moving. |
| | Control Design Characteristics – Control Movement Compatibility | Operation of controls, whether physical or virtual, should be compatible with drivers' expectations. |
| | Control Design Characteristics – Coding | The design characteristics of controls should readily identify the control and its related function. |
| | Control Design Characteristics – Labeling | Controls should be clearly labeled using either text or symbols to identify their functions and settings. |

| Category | Title | Need/Requirement |
|---|---|---|
| | Voice Recognition Inputs | Voice recognition should be used for DVI inputs only if recognition accuracy supports an acceptable level of error. |
| | Virtual Controls | Virtual controls should be developed using the same functional principles as their physical counterparts. |
| | | |
| **System Integration:** | | |
| **General Requirements** | Systems Integration | Safety, productivity, and mobility systems should be integrated whenever possible. |
| | DVI Integration Support for Aftermarket Devices | The DVI should support system integration approaches where possible, including integration with aftermarket and/or nomadic devices. |
| | Ancillary Information | An integrated DVI should not present ancillary information while the vehicle is in motion. |
| **Prioritization** | Systems Priority | Safety-relevant information should be given priority over other types of information. |
| | Message Priority | Messages within and across systems should be prioritized to provide the most important information at the appropriate time. |
| **Feedback** | Immediate Feedback to the Driver | Immediate driver feedback should be provided in a manner that does not interfere with the primary driving task. |
| | | |
| **Automation:** | | |
| | Automated Functions | V2V and V2I systems should implement automated functions in a manner that supports accurate understanding of the system by the driver, accurate awareness of the driving situation, and, overall, safe operation of the vehicle. |

Source: [32]

## IV.H. Truck Trailer BSM Development

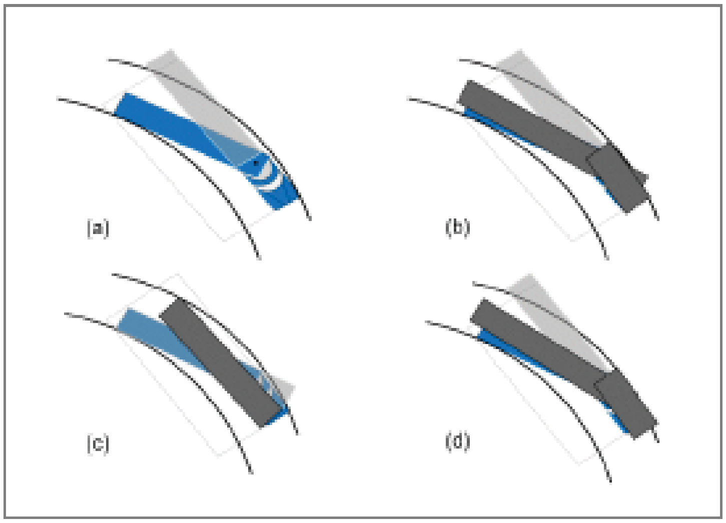
In order to conduct further research on the use of BSMs in articulated vehicles such as tractor-trailer combinations, NHTSA sponsored the Tractor Trailer Basic Safety Message Development (TT-BSM) project [33] conducted by MBRDNA under the CAMP Cooperative Agreement. During Safety Pilot Model Deployment, participating heavy-truck tractor-trailers broadcast BSMs similar to those developed for light vehicles. This BSM was a simple rigid body model to represent the tractor-trailer as a single body. However, because of the articulated behavior inherent in a tractor-trailer, this approach did not always accurately identify the trailer position or space occupied by the truck to support V2V safety applications in light vehicles under certain situations (particularly when the truck is turning). This can lead to an unacceptable number of false and missed warnings to drivers in surrounding connected vehicles. The TT-BSM project was conducted to develop technical solutions to this issue.

### *IV.H.1. Alternatives explored*

The TT-BSM project developed and investigated several BSM enhancement approaches to more accurately represent the tractor-trailer articulation. The project team also developed system and performance requirements and an assessment of the enhanced BSM's impact on internal vehicle platform (OBE necessary vehicle sensors on the tractor and the trailer) and external systems (e.g. communications channel loading, other OBE-equipped vehicles, and backend systems). The project reviewed data captured from Model Deployment in an attempt to identify problematic warnings associated with articulation. However, the project team was not able to find instances of false warnings associated with the trucks driving in the relatively small area of Ann Arbor truck routes for the Model Deployment. It was then determined that additional field testing using specific scenarios could readily create repeatable false warnings.

The project evaluated several enhancement approaches to reduce the potential for false warnings under the identified scenarios, and compared the representation to the baseline, single rigid body BSM representation. The alternative approaches evaluated, as depicted in Figure 59 were:

- Multi-DGPS - used distinct rigid body representations for the tractor and trailer where separate, independent rectangles represented the actual locations of each body of the articulated vehicle. A multi-DGPS receiver system was used to derive these locations.
- Best Fit Rigid Body - the length and width of the rigid body model was kept the same as the baseline approach, but translated its position laterally and longitudinally so that the rectangle is centered in a weighted average of the articulated tractor-trailer's planar area.
- Algorithmically Derived - used separate rectangles, as in the multi-DGPS approach, but no sensors were used to determine the actual position of the trailer. Rather, this is calculated through a kinematics algorithm, using the tractor yaw rate to estimate the trailer yaw angle.



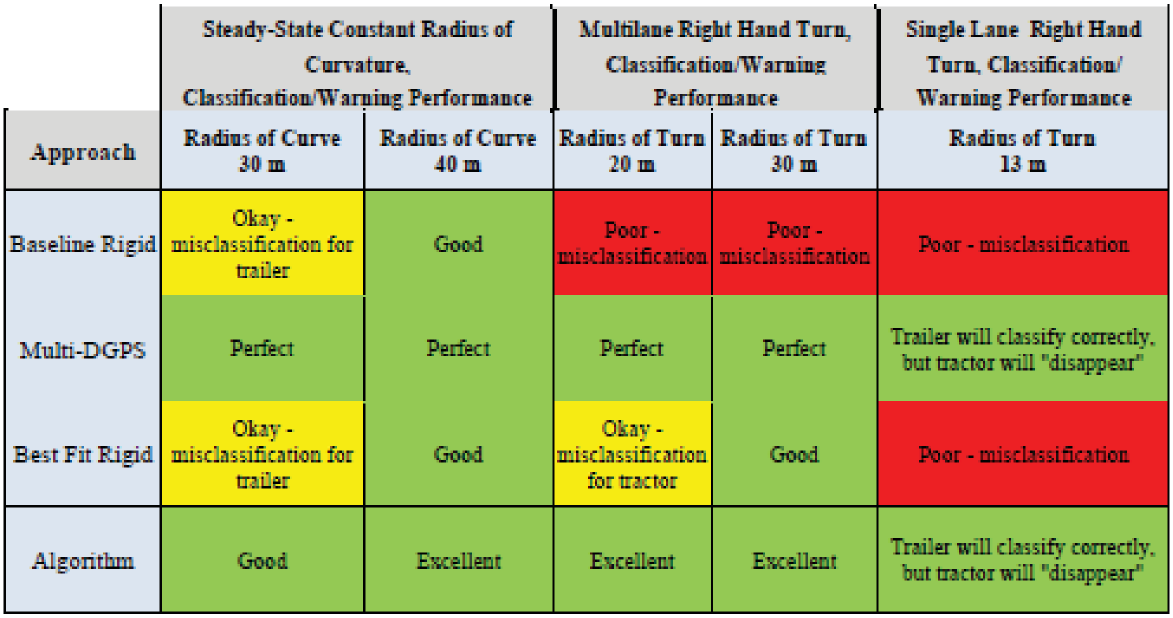
(a) Baseline Rigid Body (b) Multi-DGPS
(c) Best Fit Rigid Body (d) Algorithmically Derived

**Figure 59: TT-BSM Project Solution Set**
Source: Figure 2 from [33]

### *IV.H.2. Selected solution and requirements for modifications to BSM*

The performance of the BSM enhancement approaches was evaluated using a set of simulations (using TruckSim in conjunction with Matlab/Simulink) covering four representative scenarios of interest. These were: curved road, multi-lane right turn, single-lane right turn, and highway lane change. Based on the results, the project team recommended the algorithmically derived approach. Table 16 summarizes the classification performance of each approach in different scenarios.

**Table 16: Enhancement Approach Ratings by Scenario**

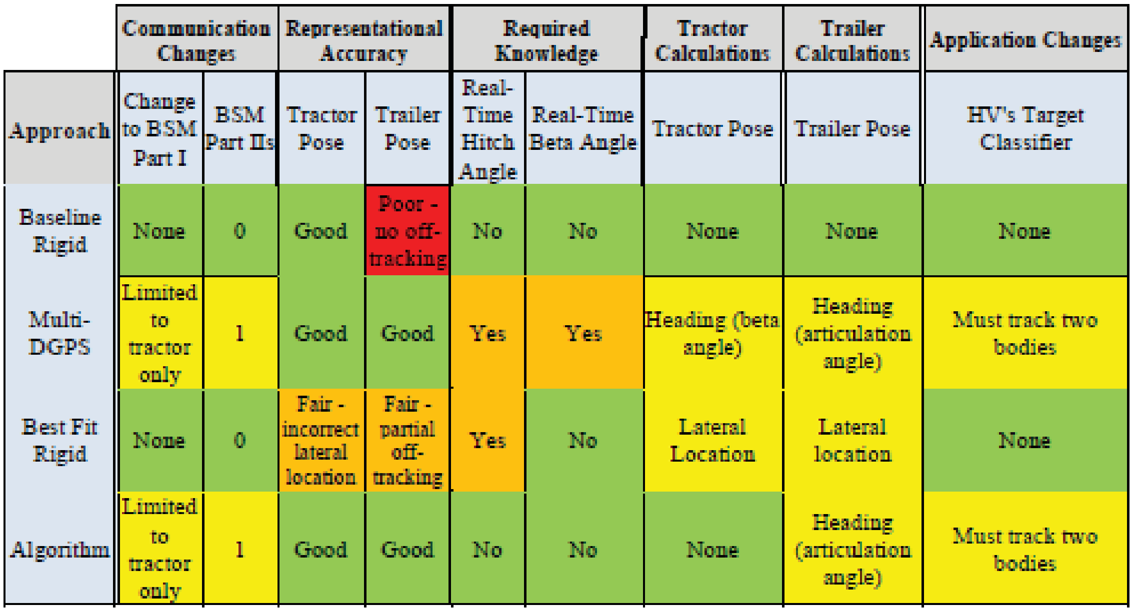


| | Steady-State Constant Radius of Curvature, Classification/Warning Performance | | Multilane Right Hand Turn, Classification/Warning Performance | | Single Lane Right Hand Turn, Classification/ Warning Performance |
|---|---|---|---|---|---|
| Approach | Radius of Curve 30 m | Radius of Curve 40 m | Radius of Turn 20 m | Radius of Turn 30 m | Radius of Turn 13 m |
| Baseline Rigid | Okay - misclassification for trailer | Good | Poor - misclassification | Poor - misclassification | Poor - misclassification |
| Multi-DGPS | Perfect | Perfect | Perfect | Perfect | Trailer will classify correctly, but tractor will "disappear" |
| Best Fit Rigid | Okay - misclassification for trailer | Good | Okay - misclassification for tractor | Good | Poor - misclassification |
| Algorithm | Good | Excellent | Excellent | Excellent | Trailer will classify correctly, but tractor will "disappear" |

Source: Table 1 from [33]

The project team proceeded to develop and test modifications to support this approach, including modifications to the software to generate and process BSMs. The prototype generates separate tracks for the tractor and trailer, and generates a modified BSM for transmission. The receiving vehicle then processes the modified BSM and treats it as two tracks, one for the tractor and one for the trailer. The proposed modifications provide for up to three trailers using this approach. Testing of the different representation approaches was conducted on a closed course, using the FCW application. While no approach worked perfectly in all the objective test scenarios, the project team concluded that the algorithmic approach was the best solution to use since it does not require a multi-DGPS receiver system as in the multi-DGPS solution. Additional factors considered in the relative assessment of the approaches are described in Table 17.

**Table 17: General Assessment of Approaches Relative to Implementation Factors**



| | Communication Changes | | Representational Accuracy | | Required Knowledge | | Tractor Calculations | Trailer Calculations | Application Changes |
|---|---|---|---|---|---|---|---|---|---|
| Approach | Change to BSM Part I | BSM Part IIs | Tractor Pose | Trailer Pose | Real-Time Hitch Angle | Real-Time Beta Angle | Tractor Pose | Trailer Pose | HV's Target Classifier |
| Baseline Rigid | None | 0 | Good | Poor - no off-tracking | No | No | None | None | None |
| Multi-DGPS | Limited to tractor only | 1 | Good | Good | Yes | Yes | Heading (beta angle) | Heading (articulation angle) | Must track two bodies |
| Best Fit Rigid | None | 0 | Fair - incorrect lateral location | Fair - partial off-tracking | Yes | No | Lateral Location | Lateral location | None |
| Algorithm | Limited to tractor only | 1 | Good | Good | No | No | None | Heading (articulation angle) | Must track two bodies |

Table 5: General Assessment of Approaches Relative to Implementation Factors

Source: Table 5 from [33]

### IV.H.3. *Changes in light-vehicle V2V applications to interpret enhanced BSM*

Finally, the project team developed a set of proposed modifications to the SAE J2735 standard and draft J2945 minimum performance requirements to reflect this approach. These modifications provide the ability to include the derived trailer information in BSM Part II, to be used when the truck is turning or otherwise experiences a non-negligible articulation angle. The proposed modifications to the BSM were presented to the SAE technical task force in April 2015.

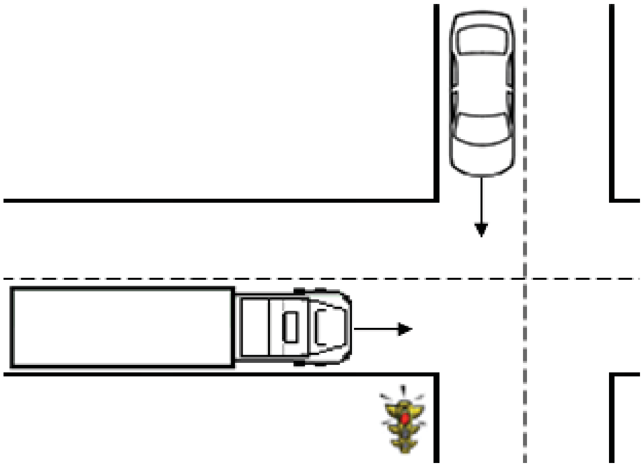
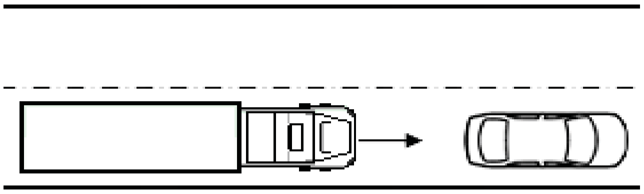
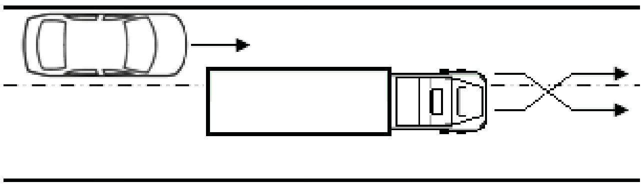
# V. Effectiveness and Benefits Estimates of V2V

Volpe, in support of NHTSA, conducted a project which applied a general methodology, developed by Volpe, to estimate the crash avoidance effectiveness of V2V safety applications for heavy vehicles and project their potential annual safety benefits. This section provides a summary of the analysis and results, which focused upon three V2V safety applications, IMA, FCW, and BSW/LCW. In addition, results from track testing, by both the integrated truck project team and VRTC, are included to illustrate the performance of the heavy-vehicle V2V applications under controlled test scenarios. The section also includes a brief overview of the SIM, which integrates factors such as testing results into a broader framework to estimate benefits of pre-production systems. As objective testing cannot always evaluate performance in crash-imminent scenarios, where safe staging may be impractical, an overview of a simulator-based project, currently in progress, is provided to illustrate how driver response in high-risk scenarios can be evaluated in a systematic manner.

## V.A. Volpe Analysis of benefits of V2V technology

This section delineates the approach and results of an analysis that was performed to estimate the crash avoidance effectiveness of V2V safety applications for heavy vehicles and project their potential annual safety benefits [31]. Heavy vehicles include medium and heavy trucks as well as buses with GVWR over 10,000 pounds. The focus of this analysis was on safety applications that could benefit the most from V2V technology that either enables or greatly improves the performance of crash warning applications, as opposed to autonomous vehicle-based sensor technologies (i.e., radar, lidar, or vision). Table 18 lists and defines the three V2V safety applications of interest, in terms of their high-level functionality and target pre-crash scenarios. These applications are adapted for heavy vehicles from the safety applications developed by the CAMP for light vehicles (e.g., passenger cars, vans and minivans, SUVs, and light pickup trucks with GVWR less than or equal to 10,000 pounds) [1].

**Table 18: Description of Heavy-Vehicle V2V Safety Applications**

| Application | Countermeasure | Target Scenario |
|---|---|---|
| Intersection Movement Assist (IMA) | Alerts drivers of lateral crossing traffic at a junction |  |
| Forward-Collision Warning (FCW) | Alerts drivers of slower moving, slowing, or stopped vehicles in their path of travel |  |
| Blind Spot Warning/Lane Change Warning (BSW/LCW) | Alerts drivers to the presence of vehicles in adjacent lanes when changing lanes |  |

Note that this analysis separates the IMA application into the following two distinct operating scenarios:

- IMA-Moving (IMA-M) which addresses all moving lateral-crossing traffic pre-crash scenarios. In this operating scenario, the heavy vehicle as the host vehicle is traveling at a constant speed (i.e., greater than or equal to 10 mph) as it approaches, and intends to continue through the road junction/intersection (e.g., a vehicle running a red light or stop sign).
- IMA-Stop/Proceed (IMA-S) which addresses all stopped lateral-crossing pre-crash scenarios. In this operating scenario, the HV is initially at a stop or moving at a very low speed (i.e., less than 10 mph), then accelerates at a constant level intending to go through the road junction/intersection.

This analysis determines the target crash problem for heavy vehicles that might be addressed by the three V2V safety applications, using statistics from national crash databases. Moreover, this analysis adopts estimates of crash avoidance effectiveness for each of the three applications from the National Advanced Driving Simulator (NADS - Refer to Section V.B.4) study (IMA-M) and the Integrated Vehicle-Based Safety System (IVBSS) field operational test (FCW). In addition, the crash avoidance effectiveness for IMA-S and BSW/LCW were obtained from the Safety

Impact Methodology (SIM) Tool using NADS data as input. Finally, safety benefits are projected based on the crash statistics and effectiveness estimates.

### V.A.1. Analysis overview

The safety benefits of the three V2V safety applications are calculated by the following equation:

$$\text{SB} = \text{Target CPM} \times \text{CAE} \qquad (\mathbf{1})$$

$\text{SB} \equiv$ Safety Benefit
$\text{CPM} \equiv$ Crash Problem Measure
$\text{CAE} \equiv$ Crash Avoidance Effectiveness

The measures of the target crash problem include the annual frequency of police-reported (PR) crashes, crash comprehensive cost, and equivalent lives lost. The basis of this analysis is to properly quantify the target crash problem using national crash statistics that are available from the GES [14] and Fatality Analysis Reporting System [35] crash databases. Appendix D of the GES manual identifies heavy vehicles from the Imputed Body Type variable (BDYTYP_IM):

- Large truck codes = 60-63, 64, 66, 67, 68, 71, 72, and 78.
- Bus codes = 50-58

Target crashes involve at least one heavy vehicle and encompass all the pre-crash scenarios addressed by the IMA, FCW, and BSW/LCW applications. The Crash Type (ACC-TYPE), Imputed Pre-Event Movement (PCRASH1_IM), and Critical Event (P_CRASH2) variables in the GES and FARS databases enable the identification of target pre-crash scenarios [4]. Furthermore, target crashes exclude those that involve alcohol use (PERALCH_IM variable – Police-Reported Alcohol Involvement), vehicle defect (P_CRASH2 variable), and vehicle control loss (P_CRASH2 and PCRASH4 – ‘Pre-Impact Stability’ variables). Furthermore, target crashes consist only of heavy vehicles that were either making the maneuver (i.e., changing lanes or merging) or, in the case of rear-end crashes, striking the lead vehicle; which correspond to the vehicle scenarios that V2V-based safety applications are designed to warn. The following section quantifies the target crash problem by querying the GES and FARS crash databases using these variables and codes.

Estimates of CAE values for the IMA, FCW, and BSW/LCW applications are obtained from prior studies as explained later in this section.

### *V.A.2. Target population for V2V technology*

#### Target Crash Problem Definition

This section quantifies the annual frequency of target police-reported crashes that involve at least one heavy vehicle, which the three V2V safety applications (IMA, FCW, and BSW/LCW) might potentially address. In addition, this section provides statistics on the distribution of injury levels and property damage that resulted from these target crashes for each of the three applications. Finally, this section expresses the target crash problem in terms of the annual comprehensive cost that includes both economic cost components[5] and quality-of-life valuations.[6]

#### Annual Target Crash Population

The annual target crash population amounts to approximately 92,875 police-reported crashes, based on crash statistics from the 2011-2013 GES databases. Figure 60 illustrates the breakdown of these target crashes by the three V2V safety applications. The IMA and FCW applications address approximately the same number of crashes.

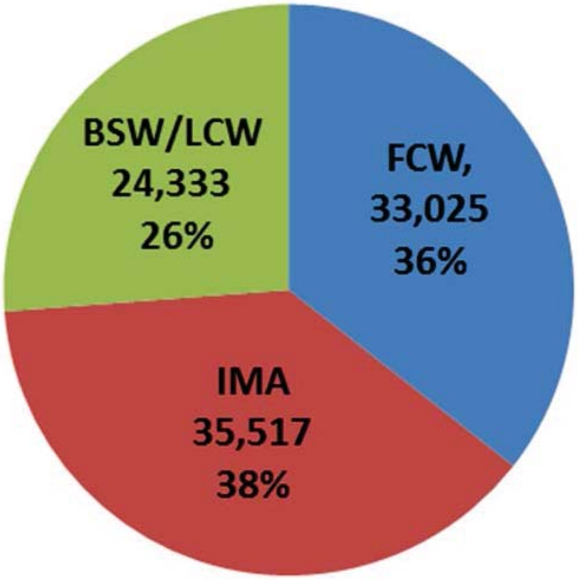


**Figure 60: Breakdown of Target Crashes by V2V Safety Application**

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[5] Economic cost components include productivity losses, property damage, medical costs, rehabilitation costs, congestion costs, legal and court costs, emergency services such as medical, police, and fire services, insurance administration costs, and the costs to employers.

[6] Quality-of-life valuations refer to intangible crash consequences such as physical pain or lost quality-of-life.

About 25,880 crashes (≅ 28%) result in at least one injured person (i.e., injury crash) and the remaining 73 percent of target crashes cause property damage only. Figure 61 provides statistics on target injury and PDO crashes for the three V2V safety applications. Injury crashes account for 34 percent of the IMA target crashes, 33 percent of the FCW target crashes, and 12 percent of the LCW target crashes.

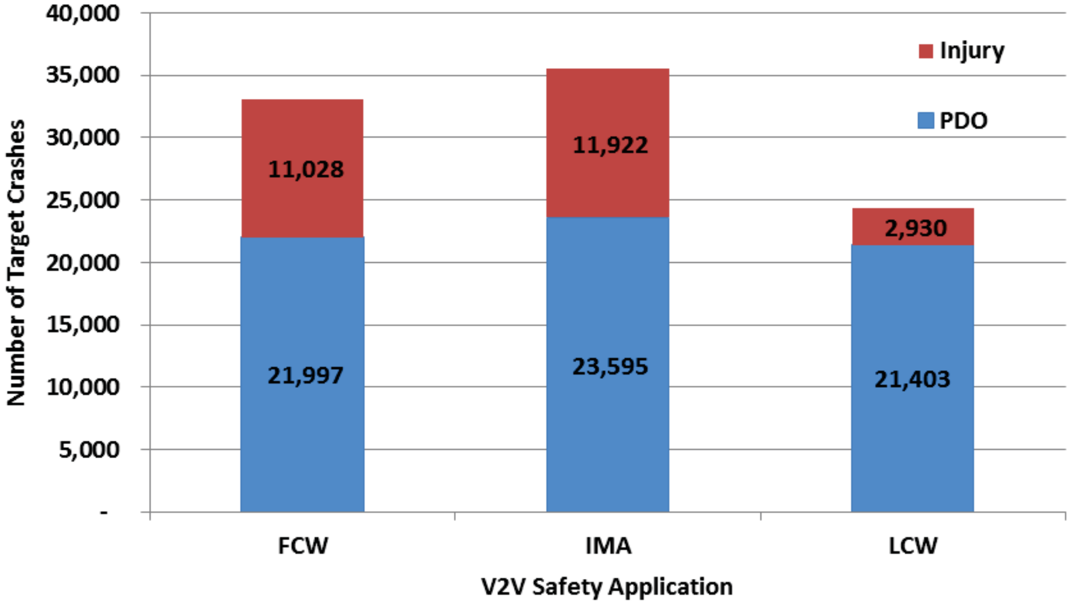

**Figure 61: Breakdown of Target Crashes by Injury and PDO Crashes by V2V Safety Application**

**Annual Target Injury Population**

The annual target injury population amounts to approximately 36,122 injured persons, based on crash statistics from the 2011-2013 GES and FARS databases. Figure 62 shows the distribution of injured persons in these target crashes by the three V2V safety applications. The IMA and FCW applications address approximately the same number of target injured persons.

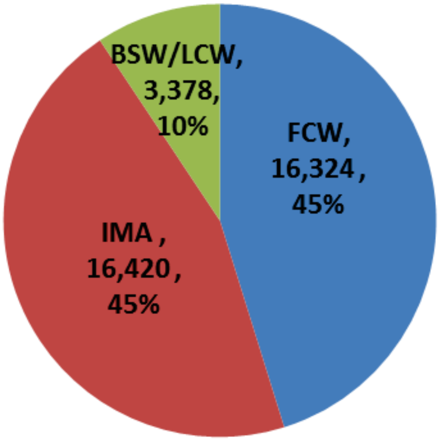

**Figure 62: Distribution of Injured Persons in Target Crashes by V2V Safety Application**

Table 19 provides the distribution of target injured persons by their injury level for the three V2V safety applications, based on the Maximum Abbreviated Injury Scale. It is noted here, that the GES crash database does not provide detailed information about injury severity based on the AIS coding scheme. Instead, the GES records injury severity by crash victim on the KABCO scale from police crash reports. To estimate injuries based on the MAIS coding structure, a translator derived from 1984–1986 NASS and 2008-2010 CDS data was applied to the GES police-reported injury profile. This table also presents statistics about the number of PDO vehicles in target crashes. A total of 921 persons (2.5%) of all injured persons died in target crashes. The number of fatalities accounts for about two percent (≅ 1.5%) of the FCW target injured persons, about four percent (≅ 3.9%) of the IMA target injured persons, and about one percent (≅ 0.9%) of the BSW/LCW target injured persons.

**Table 19: Distribution of Injured Persons by MAIS Level and V2V Safety Application**

| MAIS Injury | FCW | IMA | BSW/LCW | Total |
|---|---|---|---|---|
| 0 - No Injury | 23,689 | 19,531 | 4,668 | 47,888 |
| 1 - Minor | 13,965 | 13,438 | 2,890 | 30,293 |
| 2 - Moderate | 1,559 | 1,646 | 330 | 3,535 |
| 3 - Serious | 439 | 535 | 99 | 1,073 |
| 4 - Severe | 86 | 114 | 20 | 220 |
| 5 - Critical | 31 | 42 | 7 | 80 |
| 6 - Fatal | 244 | 645 | 32 | 921 |
| **Total MAIS 1-6** | 16,324 | 16,420 | 3,378 | 36,122 |
| **PDO Vehicles** | 48,028 | 47,541 | 43,971 | 139,540 |

### Annual Target Comprehensive Cost

The annual comprehensive cost of target crashes amounts to approximately $14,275M. This cost corresponds to about 1,561 equivalent lives[7] lost annually.

Figure 63 shows the distribution of the target annual comprehensive cost by the three V2V safety applications. The IMA application has the potential to address more than half of the comprehensive cost of target crashes (i.e., ≅ $9B and 937 lives lost).

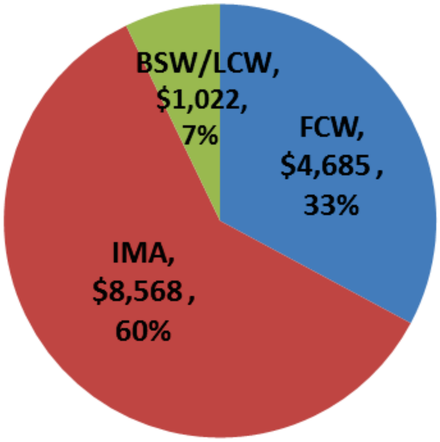

**Figure 63: Distribution of Target Crash Annual Comprehensive Cost by V2V Safety Application**

The comprehensive cost is calculated by multiplying the annual frequency of PDO vehicles and target injured persons at various MAIS levels in Table 19 with the respective comprehensive unit costs for police-reported crashes, expressed in year 2010 economic values as listed in Table 20 below [36].

**Table 20: Comprehensive Unit Costs for Police-Reported Crashes Based on 2010 Dollars**

| MAIS 0 | MAIS 1 | MAIS 2 | MAIS 3 | MAIS 4 | MAIS 5 | Fatal | PDO Vehicle |
|---|---|---|---|---|---|---|---|
| $4,380 | $43,942 | $399.626 | $992,825 | $2,432,091 | $5,579,614 | $9,145,998 | $6,076 |

---

[7] An equivalent life is worth $9,145,998.

### *V.A.3. Crash Avoidance Effectiveness of V2V Safety Applications*

This section explains the estimation of the crash avoidance effectiveness for IMA, FCW, and BSW/LCW safety applications for heavy vehicles.

**Intersection Movement Assist Crash Avoidance Effectiveness**

The crash avoidance effectiveness of the IMA V2V safety application in the IMA-M operating scenario, is estimated from a NADS driving simulator study that was designed for heavy vehicles. This study employed 40 participants between the ages of 22 and 55 years old. These participants held a valid, unrestricted Class A commercial driver’s license (corrected vision and/or hearing loss acceptable), had at least six months of driving experience with this license, drove an average of at least 2,000 miles per month over the last six months, and were in good general health. Since the population of commercial vehicle drivers is comprised of mostly males, no attempt was made to balance the test participants by gender.

The simulator study involved a straight-crossing-paths test scenario that occurs at a signalized, two-lane intersection with a green light in the direction of the host vehicle (HV) or truck driver and a red light in the direction of the remote vehicle. Both directions have a posted speed limit of 40 MPH. Both vehicles are traveling at constant speeds nominally at the speed limit. As the truck driver approaches the intersection with the green light, the RV approaches the intersection with the red light from the left. The initial approach of the RV from the left is obscured to the HV driver, and the RV becomes visible at 3.5 seconds away from the intersection. The HV driver was not asked to engage in any secondary task. Half (20) of the test participants experienced an IMA application alert (treatment group) and half did not (baseline group).

Table 21 presents the results of the IMA experiment for heavy vehicles. Almost all participants in the baseline condition ended up in a crash. In contrast, about half of the participants in the treatment condition collided with the RV. As a result, the crash avoidance effectiveness of the IMA-M application in this driving simulator experiment is calculated at 53 percent. This analysis assumes that this estimate of the IMA crash avoidance effectiveness applies to all travel speeds by the HV and RV in the SCP scenario.

**Table 21: Results of IMA Experiment for Heavy Vehicles**

| Scenario Outcome | Baseline | Treatment |
|---|---|---|
| **Crash** | 19 | 9 |
| **No Crash** | 1 | 11 |
| **Total** | 20 | 20 |
| **Crash Ratio** | 0.95 | 0.45 |
| **Crash Reduction** | 53% | |

The crash avoidance effectiveness of the IMA application in the IMA-S operating scenario was obtained from the SIM Tool using key input parameters obtained from the NADS data. This was due to the small number of crashes which occurred in the baseline and treatment conditions.

The SCP-S test scenario was similar to the SCP-M scenario with the exception that there was a stop sign in the direction of travel and no traffic control for cross traffic. The HV is initially stopped or moving at low speed (less than 10 mph). The initial approach of the RV from the left is obscured to the HV driver, and the RV becomes visible at 3.5 seconds away from the intersection. The HV driver was not asked to engage in any secondary task. Half (20) of the test participants experienced an IMA application alert and half did not.

The SIM tool yielded an effectiveness of 68 percent for the IMA-S application.

### Forward Collision Warning Crash Avoidance Effectiveness

Volpe estimated the crash avoidance effectiveness of the FCW V2V safety application from naturalistic driving data collected during the IVBSS field operational test. Eighteen volunteer drivers from a commercial fleet operated 10 IVBSS-equipped heavy trucks, accumulating 600,000 miles over a 10-month period. The test period consisted of 2 months of baseline driving, when the IVBSS was disabled, and an 8-month treatment period, when the IVBSS was enabled and alerts were presented to the drivers. Table 22 shows the results of the IVBSS data analysis. These figures are based on an analysis of rear-end near-crash encounters per 1,000 miles traveled. By comparing the whole treatment period versus the baseline period based on rear-end near crashes where the host truck (1) did not steer and (2) braked at an average deceleration value greater than 0.2g, there was a statistically-significant difference or drop (at the 98% confidence level) in the number of these events from the baseline to treatment periods. This analysis assumes that this reduction (41%) in rear-end near crashes represents a rough estimate of the potential crash avoidance effectiveness of the V2V FCW application in all three rear-end pre-crash scenarios (i.e., LVS, LVM, and LVM).

**Table 22. IVBSS Statistics of Rear-End Near-Crashes per 1,000 Miles Driven**

| Measure | Baseline | Treatment |
|---|---|---|
| Number of Participants | 9 | 9 |
| Mean | 1.9 | 1.1 |
| Standard Deviation | 1.4 | 0.9 |
| T-Test p-value | 0.023 | |
| Exposure Reduction | 41% | |

### Blind Spot Warning and Lane Change Warning Crash Avoidance Effectiveness

The crash avoidance effectiveness of the BSW/LCW application was estimated using the SIM Tool using key input parameters obtained from the NADS data. This was due to the small number of crashes which occurred in the baseline and treatment conditions.

The NADS study employed approximately 28 participants. The simulated left lane change event occurs on a 4-lane roadway with the HV in the right lane with a speed limit of 55 mph. Traffic periodically passes the HV. The HV is approaching a slower moving vehicle traveling at 40 mph. After the driver turns on the left turn signal, a vehicle traveling 10 mph faster than the driver appears next to the trailer, in the left adjacent lane.

The simulated right lane change event occurs on a 4-lane roadway with the HV in the left lane with a speed limit of 55 mph. The HV is moving with the flow of traffic in the left lane past slow moving traffic in the right lane with a car following close behind the truck. After the driver turns on the right turn signal, a vehicle traveling 10 mph faster than the driver appears next to the trailer, in the right adjacent lane. Half (14) of the test participants experienced a BSW/LCW alert in the above two simulated events and half did not.

The SIM Tool results yielded an average crash avoidance effectiveness of 39 percent for the BSW/LCW application.

### *V.A.4. Projected benefits of V2V technology - (IMA, FCW, BSW/LCW)*

#### Projected Safety Benefits of V2V Safety Applications

This section applies Equation (**1**) using the values of the target crash problem definition (Section V.A.2) and estimates of the crash avoidance effectiveness (Section V.A.3) to project the potential safety benefits for the IMA, FCW, and BSW/LCW safety applications. The safety benefits are expressed in terms of the number of heavy-vehicle, police-reported crashes that might be avoided and their comprehensive cost that might be saved with the full (100%) deployment of these V2V safety applications on board heavy vehicles. Also, all other motor vehicle body types (e.g., passenger cars, motorcycles, etc.) are assumed to be equipped with V2V devices that transmit basic safety information to heavy vehicles.

#### Annual Crashes Avoided

The IMA, FCW, and BSW/LCW V2V safety applications have the potential to avoid a total of 45,775 (≅ 49% of the total 92,875 target crashes) target heavy-vehicle police-reported crashes annually. Reference [16] presents the annual number of target crashes that might be avoided by each of the three V2V safety applications. The IMA application has the potential to prevent almost half of the total target crashes.

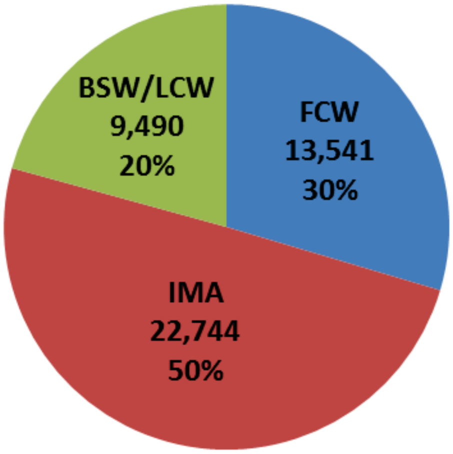

**Figure 64: Distribution of Annual Target Crashes Avoided by V2V Safety Application**

### Annual Comprehensive Cost Saved

The three V2V safety applications could save about $7,848M (≅ 55% of the total $14,275M comprehensive cost) in annual target crash comprehensive cost. This cost benefit translates into 857 equivalent lives saved. Figure 65 shows the annual crash comprehensive costs that might be saved by the full deployment of the IMA, FCW, and BSW/LCW safety applications. The IMA application alone could potentially save more than two thirds of the total target comprehensive cost. Moreover, the IMA application could potentially reduce equivalent lives lost by 604 while the FCW and BSW/LCW applications could avert the loss of 209 and 44 equivalent lives, respectively.

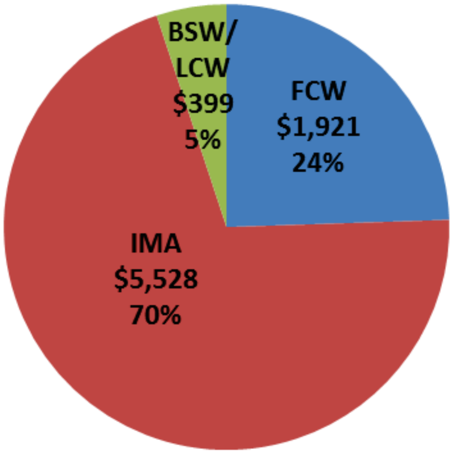

**Figure 65: Distribution of Annual Target Comprehensive Cost Saved by V2V Safety Application**

### *V.A.5. Summary of Target Crash Problem and Projected Safety Benefits*

Table 23 lists the key statistics of the target crash problem for the IMA, FCW, and BSW/LCW V2V safety applications in terms of the average annual number of police-reported crashes and comprehensive costs, based on 2011-2013 GES and FARS data and using 2010 economic values. In addition, Table 23 provides the individual estimates of the crash avoidance effectiveness and the projected safety benefits for each of the three safety applications in terms of crashes avoided, cost saved, and equivalent lives saved.

**Table 23: Summary of Crash Problem and Projected Safety Benefits for V2V Safety Applications**

| Application | Target Crashes | Comprehensive Cost ($M) | Effectiveness | Crashes Avoided | Cost Saved ($M) | Equivalent Lives Saved |
|---|---|---|---|---|---|---|
| **IMA-S** | 26,133 | 6,581 | 0.68 | 17,770 | 4,475 | 489 |
| **IMA-M** | 9,384 | 1,987 | 0.53 | 4,974 | 1,053 | 115 |
| **FCW** | 33,025 | 4,685 | 0.41 | 13,541 | 1,921 | 209 |
| **BSW/LCW** | 24,333 | 1,022 | 0.39 | 9,490 | 399 | 44 |
| Total | 92,875 | 14,275 | 🟥 | 45,775 | 7,848 | 857 |

## V.B. Additional Studies to Determine Effectiveness of V2V safety applications

### *V.B.1. Transit Retrofit Package Evaluation*

Volpe conducted an independent evaluation [40] of TRP applications installed on transit vehicles in the Safety Pilot Model Deployment. The goals of the independent evaluation were to assess system performance, safety impact, and driver acceptance of the vehicle-to-vehicle safety applications based on the naturalistic driving of 75 drivers who drove the equipped transit buses during the Model Deployment. The results of the analysis suggest that the TRP safety applications have the potential to improve driver behavior and increase driver safety, but improvements in accuracy are needed. The independent evaluation team established the following goals and objectives for their efforts:

- **Characterize system performance** by evaluating the ability of the safety applications to appropriately issue warnings within the Model Deployment Environment (objective)
- **Assess the safety impact of the deployed V2V and V2I safety applications** by evaluating their effects on bus driver behavior and performance (objective)
- **Determine bus driver acceptance of the deployed safety applications** by evaluating usability, perceived safety benefits, and security/privacy concerns from the driver's perspective (subjective)

The independent evaluation team used both objective and subjective data elements for their analyses. The objective data gathered includes over 330 million numerical records and 9,300 hours of video data. The team examined in-vehicle data collected from the CAN; V2V data concerning additional DSRC-equipped vehicles within the vicinity; external sensor data concerning locations of other objects and TRP bus locations within the lane; and application data detailing when and why alerts were issued. The subjective data sources included questionnaires completed by drivers of TRP-equipped buses and bus driver focus groups.

The evaluation team employed a classification matrix of alerts shown in Table 24.

**Table 24: Evaluation Team's Classifications of Alerts**

| | **Target, In Position** | **Target, Out of Position** | **No Target** |
|---|---|---|---|
| **Alert** | True Alert | False Alert | False Alert |
| **No Alert** | Missed Alert | Valid Rejection | Valid Rejection |

Source: Table 2-1 from [40]

The evaluation team used a video tool to analyze application alerts. The video tool displayed footage from ten seconds before and five seconds after each alert notification. The evaluation team also analyzed a random sample of approximately 50 percent of the alerts for each application, with the exception of the EEBL and VTRW applications, which had a much smaller total pool of alerts. Lastly, the team performed select, in-depth evaluations of instances of missed alerts.

The primary findings of the evaluation of the applications, described here and excerpted from the report conclusion, are:

- FCW
  - 41 percent of alerts issued for in-path targets (valid alerts);
- CSW
  - 57 percent of alerts issued when TRP was approaching or in the curve (valid alerts);
  - Accuracy much higher for north approach than for east approach;
  - 22 potential missed alerts observed;
- EEBL
  - Over 90 percent of alerts issued for targets on same road (valid alerts);
- PCW
  - Accuracy of PCW doubled from model deployment to redeployment (12 percent valid to 24 percent valid);
  - The percent of alerts that were potentially helpful to the driver doubled from the Model Deployment to the Redeployment (9 percent to 18%);
- VTRW
  - In the model deployment, 14 percent of cautionary and 22 percent of imminent alerts were issued when the target followed the prescribed path (valid alerts); and
  - VTRW performance improved during the redeployment in terms of alerts being issued when drivers were intending to proceed.

The evaluation assessed two areas pertinent to safety impacts: driver response to alerts and driver attention and the possibility of negative unintended consequences. Driver behavior metrics used to evaluate driver response include brake reaction time (FCW, CSW); time-to-collision at brake onset (FCW); peak and average deceleration (FCW, CSW, EEBL); minimum TTC (FCW); and response rate (PCW, VTRW). The evaluation team analyzed data from both the model deployment and the redeployment. Additionally, the team used video data analysis and facial recognition coding to evaluate changes in driver attention.

The primary findings of the evaluation of the applications, described here and excerpted from the report conclusion, are:

- FCW
    - Trend toward faster driver reaction time when alerts were issued compared to the baseline period;
- CSW
    - Higher rate of driver response rate to alerts during the redeployment, suggesting that the changes in the TRP DVI impacted driver behavior;
    - Drivers braked harder in response to CSW alerts between the baseline and model deployment, and between the model deployment and redeployment;
- EEBL
    - No significant differences in driver behavior were observed between the baseline and the model deployment and redeployment periods combined;
- PCW
    - Drivers braked in response to 4 of 37 valid PCW Alerts (in the other 33 events, the driver was either stopped, already braking, braking in response to a red light or to initiate the turn to the intersection, or did not break because no braking was required to avoid the pedestrian);
- VTRW
    - No changes in driver behavior observed in response to VTRW alerts;
- Driver Attention
    - Drivers rarely engaged in secondary tasks, and generally only did so when the bus was stopped; and
    - No negative behavior adaptations observed as a result of driving with the TRP.

The evaluation team aimed to ascertain bus driver opinions and attitudes within five areas: usability, perceived safety benefits, unintended consequences, desirability, and privacy/security. The findings were recorded separately for the top seven drivers (86% of total hours) and the other, less-active twenty-five drivers. The driver survey included both open-ended and Likert-scale (approval/agreement scale of 1-7, with 1-2 expressing disagreement, 3-5 neutral, and 6-7 agreement) question types. The team executed survey efforts during both the deployment (32 respondents) and redeployment (27 respondents) phases.

The primary findings of the driver evaluation described here and in the report conclusion:

- Usability
    - Easy to use (CSW rated the highest, FCW the lowest)
    - Alerts easy to see and read (particularly during redeployment)

    - Despite incorrect alerts, applications rated understandable and alerts distinguishable
- Perceived safety benefits
    - Safety benefits rated low (already good, careful drivers, already aware of situation). Perhaps better suited for inexperienced drivers in big cities with more traffic
    - Low trust in alerts (due to incorrect alerts). Perception of safety increase did go up with redeployment (possible experimental effect as they were aware that improvements were being tested)
- Unintended consequences
    - Risk for unintended consequences mostly neutral: some complaints of distraction, inadequate for overreliance
- Desirability
    - Little desire for system overall
    - CSW desired most for accuracy/usefulness
    - FCW desired least for false alerts and distraction
    - PCW liked for accuracy but still regarded neutrally for desirability
    - Very little feedback for the VTRW and EEBL and largely neutral
- Privacy
    - Concern for privacy mixed, largely neutral (expectations of privacy different for bus drivers—they're on the job, not driving personal vehicle)
    - One driver concerned that system hacking could leak driving info to insurance companies who would raise their rates
    - Passenger opinion matters for drivers and could affect job security; one participant embarrassed by alerts visible to passengers

In overall terms, the TRP deployment demonstrated that safety applications can operate in a real-world environment. Like the Transit Safety Retrofit Package Development Final Report [9] prepared by Battelle, the authors identified issues with false warnings and inaccuracies in relative lane positioning, with improvements observed in the redeployment phase following system adjustments. While the TRP drivers recognized the system's inaccuracies, they felt that the system was easy to use and understand, and could potentially provide a safety benefit.

### *V.B.2. Test Track Evaluation*

#### Integrated Truck Project Track Testing

The integrated truck project included designing and conducting a series of track tests of the V2V applications under controlled conditions, in order to evaluate correct functioning and performance of the implementation in the integrated truck. During June 2012, the integrated truck team conducted a series of tests using two of the Freightliner integrated trucks (host vehicle truck "HVT" and remote vehicle truck "RVT") as well as a remote light vehicle ("RVL", a Honda Accord, equipped to broadcast BSMs) used as a remote vehicle in testing. [21] Testing was conducted at Michigan Technical Research Park in Ottawa Lake, using drivers from the project team. Testing of V2I applications (i.e., CSW, BHI) was not conducted during these tests due to lack of supporting messages from RSEs at the time. The V2V scenarios and applications tested are listed in Table 25, along with the type of test: a threat scenario designed to elicit a warning (test to detect a true positive), or a similar but non-targeted scenario where no warning should be given (test to detect a false positive).

**Table 25: V2V Scenarios Tested on Test Track**

| Scenario | Name | Type |
|---|---|---|
| EEBL-1 | HVT Drives Behind Braking RVL | True positive |
| EEBL-2 | HVT Drives Behind RVT Which Drives Behind Braking RVT | True positive |
| EEBL-3 | HVT Drives Behind Mildly Braking RVT | True positive |
| EEBL-4 | HVT Drives Behind Braking RVT in Left Adjacent Lane | False positive |
| FCW-1 | HVT Drives Behind Stopped RVL | True positive |
| FCW-2 | HVT Drives Behind RVT Which Drives Behind Stopped RVL | True positive |
| FCW-3 | HVT Tailgates RVT | False positive |
| FCW-4 | HVT Drives Behind Braking RVT | True positive |
| FCW-5 | HVT Changes Lanes Behind Stopped RVL | True positive |
| FCW-6 | HVT Passes a Stopped RVL on a Curve | False positive |
| FCW-7 | HVT Drives on a Curve Behind RVT Stopped in the Curve | True positive |
| FCW-8 | HVT Drives Behind Moving RVT in Left Adjacent Lane and Passes it in a Curve | False positive |
| BSW+LCW-1 | RVL Passes HVT on the Left | True positive |
| BSW+LCW-2 | RVL Passes HVT on the Right | True positive |
| BSW+LCW-3 | Two RVLs Pass HVT on the Left and Right | True positive |
| BSW+LCW-4 | HVT Passes RVL on the Left and Pauses | True positive |
| BSW+LCW-5 | RVT Passes HVT in a Curve | True positive |
| BSW+LCW-6 | RVT Tailgates HVT | False positive |

| Scenario | Name | Type |
|---|---|---|
| BSW+LCW-7 | RVT and HVT Separated by One Lane | False positive |
| IMA-1 | Approaches with Moving HVT and RVL | True positive |
| IMA-2 | Stopped HVT, Moving RVL, Obstructing Parked RVT | True positive |

Source: Table 2-1 from [21]

The project team developed a series of criteria for successful execution of a given test run, with typical pass criteria established as 6 out of 8 runs successfully issuing or not issuing a warning as specified using one of three metrics [21] (p. 4-5):

- Latency – time between trigger activation (e.g., activating turn signal) and warning issuance; the project team selected a maximum latency of 0.5 s in some scenarios and 0.6 s in others
- TTC when warning given – estimated time for two vehicles to make contact if no action were taken, based on current speed ; the project team selected a range of minimum and maximum TTC based on the scenario (e.g., for a low-speed scenario, TTC between 4 and 6 s at warning, or between 5 and 7 s, or 5.5 and 7.5 s in other scenarios)
- Required Deceleration when warning given – the calculated required deceleration for the host vehicle in order not to collide with the remote vehicle; the project team used this metric in scenarios where both vehicles were decelerating

As the project team evaluated and refined the scenarios in pre-testing rehearsals, sometimes the metrics were revised or adjusted to better distinguish correct application behavior in each scenario. In addition, due to problems with some data sent from the remote vehicle, a subjective assessment was made by the project team in affected scenarios.

Results from the project team’s testing for each scenario are summarized in Table 26.

**Table 26: Summary Results from V2V Warning Scenarios Tested at MITRP Track**

| Scenario | Conditions | Summary Results |
|---|---|---|
| EEBL-1: HVT Drives Behind Braking RVL | Host and remote vehicles traveling at 35 mph (15.7 m/s), 200 m apart. Remote vehicle brakes at 0.4 g | Latency between remote vehicle braking at 0.4 g and host vehicle warning averaged 0.19 s and all runs less than 0.6 s. 8/8 runs passed |
| EEBL-2: HVT Drives behind RVT Which Drives Behind Braking RVL | Host, remote truck (middle) and remote light vehicle (front) traveling at 35 mph (15.7 m/s), with 240 m between host and front remote vehicle. Front remote vehicle brakes at 0.4 g | Latency between front remote vehicle braking at 0.4 g and host vehicle warning averaged 0.13 s, but only 2 runs completed due to technical issues invalidating other runs. |

| Scenario | Conditions | Summary Results |
|---|---|---|
| EEBL-3: HVT Drives behind Mildly Braking RVL (false positive) | Host and remote vehicles traveling at 35 mph (15.7 m/s), approximately 180 m apart. Remote vehicle brakes at less than 0.4 g | Remote vehicle braking was checked to be below 0.4 g, based on speed history and DAS accelerometer, and no warning was issued in host vehicle. 5/5 runs passed. |
| EEBL-4: HVT Drives Behind Braking RVL in Left Adjacent Lane | Host and remote vehicles traveling at 35 mph (15.7 m/s) on curve in adjacent lanes, approximately 200 m apart. Remote vehicle brakes at 0.4 g | Latency between remote vehicle braking at 0.4 g and host vehicle warning averaged 0.35 s, with 7 of 8 runs below 0.6 s. 7/8 runs passed. |
| FCW-1: HVT Drives behind Stopped RVL | Host vehicle approaches stopped remote vehicle at 40 mph (17.9 m/s). | TTC at warning issuance averaged 6.9 s, and all six runs had TTC in the specified range, 5.5 to 7.5 s. 6/6 runs passed |
| FCW-2: HVT Drives behind RVT Which Drives Behind Stopped RVL | Host and remote truck (middle) approach stopped remote vehicle at 35 mph (15.7 m/s). Remote truck changes lane to reveal stopped remote vehicle. | TTC at warning issuance averaged 6.6 s, and all eight runs had TTC in the specified range, 5.5 to 7.5 s. 8/8 runs passed. |
| FCW-3: HVT Tailgates RVT (False Positive Test) | Host vehicle follows remote truck traveling at 60 mph (26.8 m/s), with a gap of approximately 15 m (0.5 s). | Platoon traveled for 36 s without FCW warning (though inform advisory was issued), checked by verifying range and range-rate. |
| FCW-4: HVT Drives behind Mildly Braking RVL | Host follows remote vehicle traveling at 35 mph (15.7 m/s) with 65 m or 90 m between vehicles. Remote vehicle brakes at 0.2 g. | Required deceleration at warning issuance averaged 2.1 m/s$^2$ in 65 m scenario, within the 2.0 – 2.4 m/s$^2$ specified range. 6/6 runs within criteria. Required deceleration at warning issuance averaged 2.6 m/s$^2$ in 90 m scenario, within the 2.3 – 2.7 m/s$^2$ specified range. 6/6 runs within criteria. |
| FCW-5: HVT Changes Lanes behind Stopped RVL | Host vehicle traveling at 35 mph (15.7 m/s) changes lane to approach stopped remote vehicle from behind, approximately 100 m away. | TTC at warning issuance averaged 6.6 s, and all runs within the 5.5 – 7.5 s specified range. 8/8 runs within criteria. |
| FCW-6: HVT Passes a Stopped RVL on a Curve<br>(False Positive Test) | Host vehicle traveling at 35 mph (15.7 m/s) approaches stopped remote vehicle in adjacent lane in curve. | Four passes made without FCW warn or inform alerts. Fifth run invalid. |
| FCW-7: HVT Drives on a Curve behind Stopped RVL | Host vehicle traveling at 45 mph (20.1 m/s) approaches stopped remote vehicle in same lane in curve. | TTC at warning issuance averaged 7.0 s, with all runs within the 5.5 – 7.5 s specified range. 8/8 runs passed |

| Scenario | Conditions | Summary Results |
|---|---|---|
| FCW-8: HVT Passes Moving RVL on Left Side in a Curve (False Positive Test) | Host vehicle traveling at 35 mph (15.7 m/s) passes remote vehicle traveling in adjacent lane at 30 mph (13.4 m/s). | One pass made on left and one on right, without FCW warn or inform alerts being issued. |
| BSW-1: RVL Passes HVT on the Left | Remote vehicle traveling at 35 mph (15.7 m/s) in left adjacent lane passes host vehicle traveling at 30 mph (13.4 m/s). | Inform-level alert confirmed when remote vehicle past rear of trailer. Warn-level alert issued when turn signal activated with less than 0.5 s latency. 6/6 runs passed |
| BSW-2: RVL Passes HVT on the Right | Remote vehicle traveling at 35 mph (15.7 m/s) in right adjacent lane passes host vehicle traveling at 30 mph (13.4 m/s). | Inform-level alert confirmed when remote vehicle past rear of trailer. Warn-level alert issued when turn signal activated with less than 0.5 s latency. 5/6 runs passed |
| BSW-3: Two RVs Pass HVT on the Left and the Right | Host vehicle traveling in center lane passed by remote vehicles on left and right. | Problems with GPS elevation and DVI caused inability to successfully execute scenario |
| BSW-4: HVT with RVL in Right Side Blind Spot | Host vehicle traveling at 30 mph (13.4 m/s) passed by remote vehicle which stays in front blind spot. | Inform and warn alerts confirmed with latency averaging 0.21 s. All runs had less than 0.5 s latency. 7/7 runs passed. |
| BSW-5: RVL Passes HVT in a Curve | Host vehicle traveling at 30 mph (13.4 m/s) passed in curve by remote vehicle traveling at 35 mph (15.7 m/s) | Inform and warn alerts confirmed with latency averaging 0.22 s. All runs had less than 0.5 s latency. 8/8 runs passed. |
| BSW-6: RVL Tailgates HVT (False Positive Test) | Host vehicle followed closely by remote vehicle in same lane. | No BSW inform or warn alerts issued over 54 s. |
| BSW-7: RVL and HVT Separated by One Lane (False Positive Test) | Host vehicle traveling at 35 mph (15.7 m/s) while remote vehicle travels alongside two lanes over. | No BSW inform or warn alerts issued. |
| IMA-1A: 15 mph (6.7 m/s) HVT and 15 mph (6.7 m/s) RVL | Host and remote vehicle traveling on perpendicular paths at 15 mph (6.7 m/s). | TTC when warning issued of 4.3 s, within the 4 – 6 s specified criteria. 1/1 run passed. |
| IMA-1B: 15 mph (6.7 m/s) HVT and 30 mph (13.4 m/s) RVL | Host traveling at 15 mph (6.7 m/s) and remote vehicle traveling on perpendicular path at average of 25 mph (11.2 m/s). | TTC when warning issued averaged 5.9 s, with all runs within the 5.0 – 7.0 s specified criteria. 4/4 runs passed. |
| IMA-1C: 30 mph (13.4 m/s) HVT and 15 mph (6.7 m/s) RVL | Host traveling at 30 mph (13.4 m/s) and remote vehicle traveling on perpendicular path at 15 mph (6.7 m/s). | TTC when warning issued averaged 5.1 s, with 3 of 4 runs within the 5.0 – 7.0 s specified criteria. 3/4 runs passed. |
| IMA-1D: 30 mph (13.4 m/s) HVT and 30 mph (13.4 m/s) RVL | Host traveling at 30 mph (13.4 m/s) and remote vehicle traveling on perpendicular path at average of 25 mph (11.2 m/s). | TTC when warning issued averaged 6.4 s, with all runs within the 5.0 – 7.0 s specified criteria. 4/4 runs passed. |

| Scenario | Conditions | Summary Results |
|---|---|---|
| IMA-2A: HVT Stopped; RVL Approaches at 20 mph (8.9 m/s) | Host vehicle stopped at intersection, remote vehicle traveling at 20 mph (8.9 m/s) on perpendicular path. Host vehicle releases brake pedal. | Latency between host vehicle brake release and warning issuance averaged 0.33 s when remote vehicle approached from left, with 3 of 4 runs within the latency criteria of below 0.5 s. Latency when remote vehicle approached from the right averaged 0.53 s with 3 of 4 runs within the latency criteria. 6/8 runs passed. |
| IMA-2B: HVT Stopped; RVL Approaches at 40 mph (17.9 m/s) | Host vehicle stopped at intersection, remote vehicle traveling at 40 mph (17.9 m/s) on perpendicular path. Host vehicle releases brake pedal. | Latency between host vehicle brake release and warning issuance averaged 0.16 s when remote vehicle approached from left, with 4 of 4 runs within the latency criteria of below 0.5 s. Latency when remote vehicle approached from the right averaged 0.32 s with 3 of 4 runs within the latency criteria. 7/8 runs passed. |

Source: [25]

Overall, the project team reviewed the results from the test runs and concluded that the system passed 24 of 25 test scenarios. In 2 of the 24 passing scenarios, fewer valid runs were conducted than intended by the testing procedures, but the completed runs were considered to warn properly. The one test scenario that was not passed was BSW+LCW-3, and not passing the test was due to technical issues.

In addition, while the test scenarios focused on issuance of V2V warnings within specified criteria, the project team also executed runs to assess “inform-level” advisories provided to the driver. Combining the inform and warn tests, a total of 218 runs were conducted, of which 40 were found to be invalid due to various technical issues, such as a cable to the DAS becoming disconnected, or the DVI tablet becoming unresponsive.

### VRTC Testing of BSW/LCW

Subsequent to the development and testing by the integrated truck team, VRTC staff conducted a study with additional scenario development and testing activity for the BSW/LCW application at the TRC facility. [42] Analysis of some of the initial results raised questions about how the system was operating, and led to a literature review of BSW/LCW recommended/proposed capabilities and performance measures. Based on the literature review, the BSW/LCW test procedures were modified and re-evaluated based on recommended changes. The investigation included the scenarios described in Table 27 and depicted in Figure 66 and Figure 67.

**Table 27: Original Scenarios and Test Conditions**

| Scenario | Conditions | Original Pass Criteria |
|---|---|---|
| BSW/LCW-1 - RV Passes HV on Left, Straight Road<br>BSW/LCW-2 - RV Passes HV on Right, Straight Road | RV at 40 mph (17.9 m/s) passes 35 mph (15.7 m/s) HV at constant rate. HV waits for “inform” alert and then activates turn signal. | HV issues inform alert when RV enters blind zone, and extinguishes alert when RV exits blind zone. Activation of turn signal in proper direction converts inform to warn-level alert. |
| BSW/LCW-3 - HV Passes RV on Left, Straight Road<br>BSW/LCW-4 - HV Passes RV on Right, Straight Road | HV at 40 mph (17.9 m/s) passes 35 mph (15.7 m/s) RV at constant rate. HV waits for “inform” alert and then activates turn signal. | HV issues inform alert when RV enters blind zone, and extinguishes alert when RV exits blind zone. Activation of turn signal in proper direction converts inform to warn-level alert. |

Source: [42]

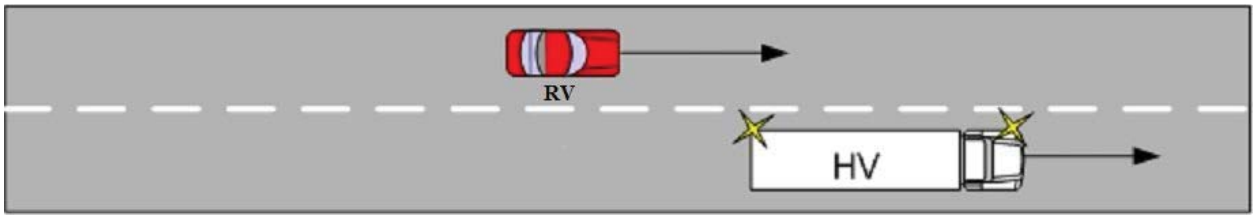

**Figure 66: BSW/LCW-1 Scenario**

Source: [42]

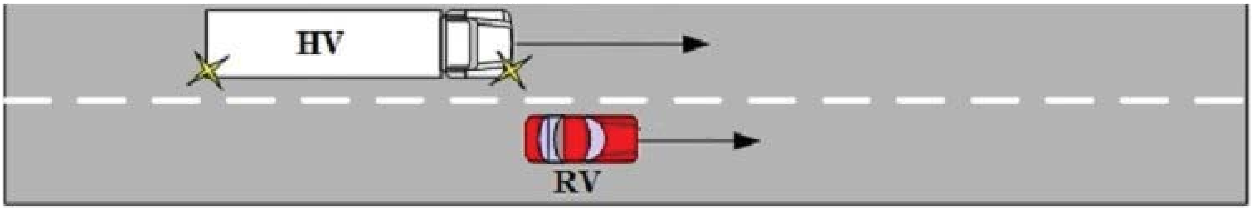

**Figure 67: BSW/LCW-3 Scenario**

Source: [42]

During the testing, issues were encountered with the connection between the OBE and the SAE J1939 vehicle bus. As a result, some tests were run with the CAN bus connection and others were run without. Various combinations of trailers and bobtail configurations were also used for the host and remote vehicles. Table 28 through Table 31 provide a summary of the preliminary BSW/LCW scenario results, noting the relative position of the vehicles at inform-level (since turn signal was not activated) alert onset and “offset” (when alert transitioned to off status) for each combination tested. Negative distances for HV rear to RV front at onset (e.g., -3.8 m) represent cases where there was no overlap between the vehicles at onset (e.g., there was 3.8 m between the vehicles). Positive distances for this metric indicates that the vehicles were already overlapping when the inform alert was given.

**Table 28: BSW/LCW-1 Average Warning Onset and Offset Range Metrics**

| HV Trailer | RV Trailer | CAN | No. of Trials | HV Rear to RV Front at Onset (m) | | | HV Front to RV Front at Offset (m) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | RT | GPS | WSU | RT | GPS | WSU |
| Bobtail | Bobtail | Off | 5 | -3.8 | -4.0 | -4.1 | 2.0 | 1.8 | 2.9 |
| Bobtail | Bobtail | On | 4 | -6.2 | -6.1 | -6.1 | 0.4 | 0.6 | 1.7 |
| Bobtail | 2x28' | On | 2 | -6.7 | -6.9 | -5.6 | 1.6 | 1.6 | 2.1 |
| 40’ | 2 x 28’ | Off | 10 | -0.7 | -1.0 | -0.2 | 8.3 | 7.9 | 10.2 |
| 2 x 28’ | Bobtail | On | 2 | 2.1 | 2.4 | 2.3 | -1.2 | -1.6 | 0.6 |
| 2 x 28’ | 40’ | Off | 7 | 5.9 | | 4.9 | 6.7 | | 7.3 |

Source: Table 8 from [42]

**Table 29: BSW/LCW-2 Average Warning Onset and Offset Range Metrics**

| HV Trailer | RV Trailer | No. of Trials | HV Rear to RV Front at Onset (m) | | | HV Front to RV Front at Offset (m) | | |
|---|---|---|---|---|---|---|---|---|
| | | | RT | GPS | WSU | RT | GPS | WSU |
| Bobtail | Bobtail | 4 | -5.8 | -6.0 | -4.5 | 0.7 | 0.6 | 2.5 |
| Bobtail | Bobtail | 3 | -6.1 | -5.8 | -6.1 | 1.6 | 1.7 | 2.4 |
| 40 ft. | 2x28 ft. | 5 | 4.2 | 3.9 | 4.3 | 4.3 | 4.1 | 4.9 |
| 2x28 ft. | 40 ft. | 6 | 7.2 | 7.2 | 6.8 | -0.9 | -1.1 | -0.9 |

Source: Table 14 from [42]

**Table 30: BSW/LCW-3 Average Warning Onset and Offset Range Metrics**

| HV Trailer | RV Trailer | CAN | No. of Trials | HV Front to RV Rear at Onset (m) | | | HV Rear to RV Front at Offset (m) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | RT | GPS | WSU | RT | GPS | WSU |
| Bobtail | Bobtail | Off | 5 | -7.3 | -7.3 | -6.7 | -6.4 | -6.5 | -6.7 |
| Bobtail | Bobtail | On | 5 | -8.8 | -8.6 | -8.1 | -7.8 | -7.5 | -7.9 |
| 40' | 2x28' | Off | 10 | -15.9 | -16.1 | -14.0 | -1.8 | -1.9 | -2.0 |
| 2x28' | Bobtail | On | 2 | -10.9 | -10.1 | -8.7 | 0.8 | 1.1 | 0.4 |
| 2x28' | 40' | Off | 8 | -11.9 | | -11.5 | 4.5 | | 2.9 |

Source: Table 21 from [42]

**Table 31: BSW/LCW-4 Average Warning Onset and Offset Range Metrics**

| HV Trailer | RV Trailer | CAN | No. of Trials | HV Front to RV Rear at Onset (m) | | | HV Rear to RV Front at Offset (m) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | RT | GPS | WSU | RT | GPS | WSU |
| Bobtail | Bobtail | Off | 5 | -7.7 | | -7.6 | -6.9 | | -7.7 |
| Bobtail | Bobtail | Off | 3 | -8.5 | -8.4 | -7.0 | -7.0 | -6.9 | -6.2 |
| Bobtail | Bobtail | On | 3 | -8.5 | -8.5 | -7.5 | -7.2 | -6.5 | -6.9 |
| Bobtail | Bobtail | On | 3 | -8.4 | -8.0 | -7.6 | -8.3 | -7.8 | -8.1 |
| 40' | 2x28' | Off | 6 | -19.9 | -19.8 | -20.2 | 3.7 | 3.8 | 3.1 |
| 2x28' | 40' | On | 5 | -20.1 | -20.0 | -20.3 | 6.5 | 6.6 | 5.2 |

Source: Table 29 from [42]

Since the preliminary results sometimes varied significantly when different trailer combinations were used, a review of literature was conducted by the study team to identify objectives and performance characteristics associated with BSW and LCW operation in heavy trucks. The review identified variations in the zone definitions (see Figure 68 and Figure 69) and the need to consider that the LCW application includes not just vehicles in the blind zone but also cases where the blind zone will be occupied by a vehicle in the near future. For example, there may be a remote vehicle behind the blind zone that is overtaking the host vehicle at a high closing rate.

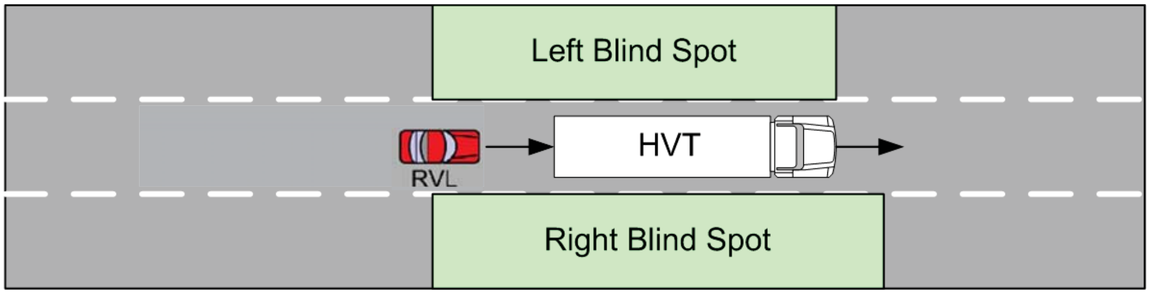

**Figure 68: Blind Zone Depiction (CCV-IT)**

Source: [42]

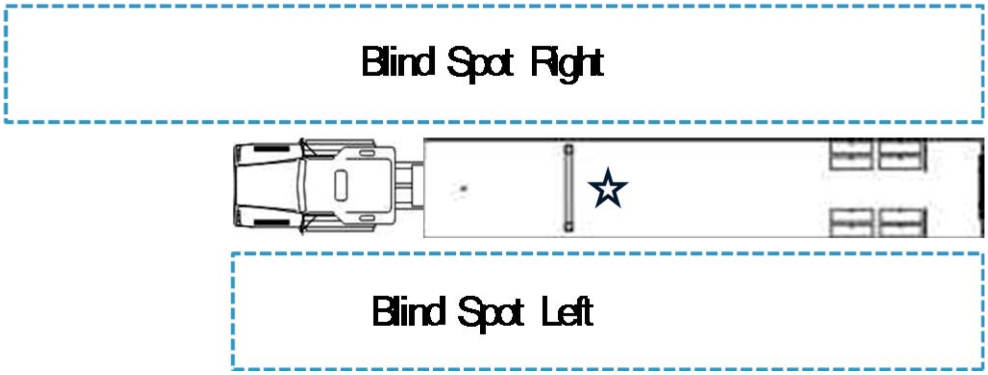

**Figure 69: Alternate Blind Zone Depiction (CS-SwRI RSD)**

Source: [43]

Based on the literature review, the study team concluded that a properly designed BSW/LCW V2V system will have a larger blind zone for LCW, and that BSW/LCW test procedures that rely upon initial activation of BSW before testing LCW will not adequately test the LCW capability. Instead, the LCW should be tested separately, with the HV turn signals on before conducting the passing maneuver. The study team also concluded that although definitive blind zone definitions were lacking, the zone should at least run the length of the tractor trailer combination.

The study team conducted additional testing based on a revised procedure to include testing where the HV turn signal was activated ahead of time. Three scenarios were run, BSW/LCW-1, BSW/LCW-2, and BSW/LCW-3. Summary results indicating average warning onset and offset metrics are depicted in Table 32 through Table 34.

**Table 32: BSW/LCW-1 Average Warning Onset and Offset Range and Overlap Metrics for HV = Red Cascadia Bobtail, RV = Blue Cascadia Bobtail**

| Turn Signal | HV/RV RT Speeds (mph) | | No. of Trials | HV Rear to RV Front at Onset (m) | | HV Front to RV Front at Offset (m) | | Overlap in HV/RV at Offset (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | HV | RV | | RT | WSU | RT | WSU | RT | WSU |
| Off | 35.1 | 40.8 | 6 | -4.7 | -6.0 | 1.8 | 1.6 | 5.4 | 5.7 |
| On | 35.0 | 40.8 | 8 | -19.1 | -18.8 | 0.1 | 1.6 | 7.0 | 5.7 |
| On | 35.2 | 45.9 | 8 | -30.2 | -29.3 | 1.5 | 5.0 | 5.4 | 2.2 |

Source: Table 34 from [42]

**Table 33: BSW/LCW-2 Average Warning Onset and Offset Range and Overlap Metrics for HV = Red Cascadia With 28-Foot Tandems, RV = Blue Cascadia Bobtail**

| Turn Signal | HV/RV RT Speeds (mph) | | No. of Trials | HV Rear to RV Front at Onset (m) | | HV Front to RV Front at Offset (m) | | Overlap in HV/RV at Offset (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | HV | RV | | RT | WSU | RT | WSU | RT | WSU |
| Off | 35.2 | 41.0 | 8 | 5.0 | 5.9 | -7.5 | -5.6 | 7.2 | 7.2 |
| On | 35.1 | 41.2 | 6 | -7.4 | -7.7 | -5.2 | -4.9 | 7.2 | 7.2 |
| On | 35.2 | 45.9 | 7 | -18.4 | -18.0 | -4.8 | -2.2 | 7.2 | 7.2 |

Source: Table 39 from [42]

**Table 34: BSW/LCW-3 Average Warning Onset and Offset Range and Overlap Metrics for HV = Red Cascadia Bobtail, RV = Blue Cascadia Bobtail**

| Turn Signal | HV/RV RT Speeds (mph) | | No. of Trials | HV Front to RV Rear at Onset (m) | | Overlap in HV/RV at Onset (m) | | HV Rear to RV Front at Offset (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | HV | RV | | RT | WSU | RT | WSU | RT | WSU |
| Off | 40.1 | 35.6 | 6 | -8.4 | -8.0 | 6.6 | 7.2 | -7.7 | -7.9 |
| On | 40.1 | 35.8 | 7 | -9.4 | -8.1 | 5.9 | 7.2 | -7.8 | -7.6 |
| On | 45.2 | 35.8 | 6 | -9.0 | -8.1 | 6.3 | 7.1 | -10.1 | -10.0 |

Source: Table 44 from [42]

Based on the literature review and revised testing results, the study team concluded that the LCW likely considered the TTC between the vehicles as a factor in the warning issuance, with approximately a 5 s additional margin added to the blind zone in the tested scenarios (35/40 mph). In addition, the performance of BSW with long trailer combinations warranted further investigation. The study team concluded its activity by identifying the following conclusions and recommendations [42] (p. 70-71):

1. The currently evaluated BSW/LCW test procedures do not properly evaluate V2V systems with blind zone extension capabilities for LCW. This can be easily remedied by adding a second test with the HV turn signals applied prior to the HV or RV starting the passing maneuver.
2. A base blind zone for tractor/trailer combination needs to be determined, but it should at least run the full length of the combination.
3. The Freightliner Cascadia WSU units do a good job of extending the base BSW blind zone for LCW conditions. The blind zone is essentially extended by a TTC of 5 seconds.
4. The base BSW blind zone for the Freightliner Cascadia WSU units when the tractor is running bobtail seem appropriate. There is no overlap in the HV and RV at warning onset for the BSW/LCW-1 and -2 test procedures or at warning offset for the BSW/LCW-3 and -4 test procedures.
5. The Freightliner Cascadia WSU units do not properly extend the base BSW blind zone for trailer length. This was especially true for longer trailer lengths. There was overlap in

the HV and RV at warning onset for BSW/LCW-1 and -2 test procedures and at warning offset for BSW/LCW-3 and -4 when longer tractor/trailer combinations were evaluated.

The following recommendations were given based on the results of this study.

1. When appropriate, the BSW/LCW test procedures should include two tests. One with the HV turn signal off before the HV or RV starts to pass and a second with the HV turn signal on. These two tests in combination can be used to determine if the V2V system extends the base BSW blind zone for LCW conditions.
2. A base BSW blind zone for CCV needs to be determined. Further literature review should be conducted. The base BSW blind zone should at least cover the length of the tractor/trailer combination.
3. The base BSW blind zone programming in the Freightliner Cascadia WSUs should be reviewed further. The base blind zone needs to be properly extended when trailers are added to the tractor.

### *V.B.3. Safety Impact Methodology – SIM*

A significant challenge in determining the effectiveness of V2V safety systems lies in the ability to estimate potential safety benefits when production systems are not yet available. NHTSA has engaged in an effort under the ACAT program to establish and test SIMs [44]. These SIMs used a common framework (see Figure 70) to use available information in conjunction with limited testing and modeling to generate estimates of expected safety benefits associated with crash avoidance systems that are still in the pre-production stage. The fundamental nature of the benefits estimation is to identify the specific crash populations affected by a particular crash avoidance countermeasure, and calculate the expected crashes with and without the system. The corresponding measures of harm associated with these crash groups can then be used to calculate benefits in terms of fatalities prevented and reduced occurrence and severity of injuries and property damage.

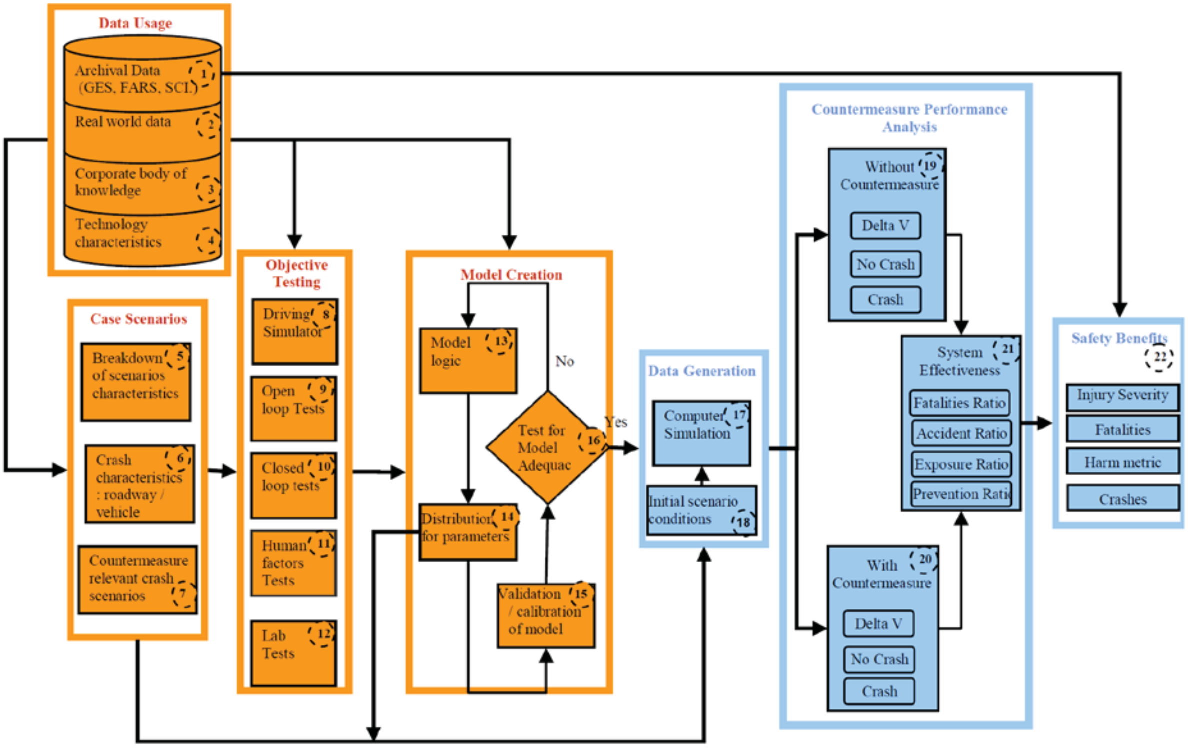

**Figure 70: NHTSA SIM Framework [Fig 2 from 09-0259]**

Source: Figure 2 from [44]

### *V.B.4. Driving Simulator Study – NADS*

In order to better understand driver performance in crash scenarios with heavy vehicle V2V systems, NHTSA engaged the University of Iowa to perform human subject testing using NADS. The goal of the effort, which is currently in progress [44], was to recruit professional commercial vehicle drivers and evaluate the response to several V2V application warnings in a variety of controlled, simulated conditions. By using a simulation-based approach, crash-imminent scenarios could be tested without risking any injuries or vehicle damage, and scenarios could be controlled with precision and repeatability.

The NADS-1 simulator consists of a 24-foot dome, within which a Freightliner tractor cab was mounted. To portray the external roadway environment, the simulator includes three front projectors and five rear projectors. In addition, two displays were mounted inside the cab to interface with the subjects, including facilitating the setup of experimental scenarios, and the provision of V2V warning alerts. The NADS was configured to record details of vehicle state (e.g., lane position) within the simulated environment and driver inputs (e.g., steering wheel position) to enable later analysis. The simulated vehicle configuration included a fully loaded 53-foot box trailer which enabled the vehicle dynamics and visibility to reflect typical operating conditions.

The roadway environments available in the NADS-1 simulator include urban, industrial, and rural conditions that can be set up to suit the experimental scenario. In this project, an urban area with multi-lane roads and intersections was used to help subjects to become familiar with the simulator's driving environment. To test the performance of the BSW/LCW V2V application, a 4-lane rural roadway was used. A rural 2-lane roadway with intersections controlled by traffic signals and traffic control devices (e.g., stop signs) was used for testing FCW and IMA V2V applications. In order to facilitate testing of these warnings, the subject was directed to periodically read messages that were presented on a display in the vehicle, similar to content that might be received from a dispatcher. The timing of these messages was used to assist in establishing a scenario in which the crash-imminent scenarios for V2V applications could be tested.

This project used two between-subjects independent variables as part of the experimental design.

- V2V Warning Condition
    - Baseline – No V2V warnings presented to driver
    - V2V Warning – V2V alert presented to driver when conditions warranted
- Main Driving Scenario Tested
    - Forward Crash Event – 3-4 minutes after a lane change event, forward crash (FCW) scenario presented
    - Intersection Movement Event – 3-4 minutes after a lane change event, intersection (IMA) scenario presented

**Scenario Summary:**

Lane Change

The lane change was selected as a preceding event in order to balance the need for efficient exposure of enough subjects with the objective of not unduly influencing the driver's reaction to more significant events (i.e., FCW or IMA scenarios). Two lane change scenarios were included, with both operating on a 4-lane roadway with a speed limit of 55 mph:

- Lane Change to Left – The subject's truck was in the right lane, with traffic passing it on the left. The truck approaches a slower vehicle traveling 40 mph. In the adjacent (left) lane, a passenger vehicle was present adjacent to the trailer in the blind spot.
- Lane Change to Right – The subject's truck was in the left lane, with slower moving traffic in the right lane. A car was following closely behind the subject's truck, and after clearing the slower moving traffic, the car changed lanes and moved into the blind spot adjacent to the truck trailer.

Forward Crash

The forward crash scenario was designed on a 2-lane roadway with a speed limit of 45 mph. The subject's truck was following a lead vehicle traveling at the speed limit. The subject was then engaged with a secondary task, whereupon the lead vehicle changed lanes to reveal another vehicle stopped ahead.

Intersection

The intersection scenarios included a signalized intersection and a stop-controlled cross intersection, with a 40 mph speed limit on all approaches:

- Signalized Intersection / other vehicle running red light – The subject's truck was approaching a green light, traveling at the speed limit, while another vehicle on the cross

street was also traveling at the same speed, approaching the red light from the left. As the vehicles approached the intersection, the subject was distracted by a secondary task.
- Stop controlled intersection – The subject’s truck was stopped at an intersection where the cross traffic (mainline road) does not stop. Another vehicle approaches on the mainline road from the right in a manner where the subject’s view is obscured.

**Analysis**

Upon completion of the scenarios, the subjects completed a realism survey and two warning system surveys, which depended on the specific scenarios experienced by the subject. Performance measures gathered from the simulation log included variables such as (from Table 3 in [44]).

- Steering wheel position
- Accelerator pedal position
- Vehicle speed
- Tractor orientation and rotational velocities
- Trailer orientation and rotational velocities
- Brake pedal force
- Tractor velocity and accelerations (3-axis)
- Trailer velocity and accelerations (3-axis)
- Trailer articulation angle
- Lane deviation

By using a window of time around the event being tested, an average or maximum of variables of interest could be generated. The key measures being studied are depicted in Table 35, and will serve as the basis for determining the results from the experiments.

**Table 35: Measures of Interest in Study**

| Variable Type | Variable | Description | Event Type | | |
|---|---|---|---|---|---|
| | | | FCW | IMA | BSW/LCW |
| Outcome | Crash | Contact between any part of the truck and the vehicle threat. | X | X | X |
| | Minimum TTC | Minimum Time-to-Collision with the vehicle threat. | X | X | X |
| Response | Brake Reaction Time | The time from the first opportunity to be aware of the threat and first application of the brake. | X | X | |
| | Steering Reaction Time | The time from the first opportunity to be aware of the threat and first sustained steering input away from the threat. | | | X |

Source: Table 4 from [44]

## V.C. Conclusion

NHTSA’s heavy-vehicle V2V research has progressed to a point where safety benefit estimates associated with selected applications have been quantified in initial analyses. As part of the Safety Impact Methodology, assessment results from some prototype applications in both trucks and transit buses have been conducted, yielding both quantitative information from Safety Pilot as well as lessons for further research and implementation. Subsequent developments have addressed specific issues such as formulation of message components for articulated vehicles. Heavy-vehicle V2V systems will still require completion of some additional research to address remaining implementation issues. Some of these areas are specific to heavy vehicles, such as provision of trailer attribute information for the BSM being broadcast by the tractor. In other cases, research continues for topics such as security-related elements for V2V systems, which affect both light and heavy vehicles. However, the significant body of NHTSA’s research results, as summarized in this report, has been supportive of potential future implementation of V2V systems in heavy vehicles.

# VI. References

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