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Feasibility of Vehicle-to-Vehicle Retrofit For Heavy Vehicles

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16. Abstract
Research on the feasibility of vehicle-to-vehicle (V2V) retrofits for heavy trucks in this report includes an estimate of the total number of buses and trucks in the U.S. fleet (class 3 to 8), an engineering analysis of three installation configurations to support retrofits of nearly all of the vehicles in the fleet, cost estimates for the V2V technologies and the installation of each of the three configurations across four volume estimates, and total cost estimates of retrofitting nearly the entire fleet using three scenarios based on different distributions of the three installation configurations. The lowest estimated cost per vehicle for the V2V technology and its installation was approximately $450 to $550, based on volume estimates of 10 million and 1 million, respectively. The total costs of retrofitting nearly the entire fleet of class 3 to 8 vehicles ranged from $5.5 billion to $8.5 billion.

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Glossary

BSM	basic safety message
CAN	controller area network
DSRC	dedicated short range communications
DVI	driver vehicle interface
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
Ghz	gigahertz
GNSS	global navigation satellite system
IEEE	Institute of Electrical and Electronics Engineers
IMA	intersection movement assist
LV	light vehicle
MCMIS	Motor Carrier Management Information System
OBU	on board unit
OEM	original equipment manufacturer
RF	radio frequency
ROI	return on investment
RSD	retrofit safety device
SAE	Society of Automotive Engineers (in 2006 SAE changed its name to SAE International, although the inistialism SAE remains in place)
SPMD	Safety Pilot Model Deployment
UMTRI	University of Michigan Transportation Research Institute
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
VAD	vehicle awareness device
VIUS	Vehicle Inventory and Use Survey
WWAN	wireless wide-area network

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Executive Summary

The strength of vehicle-to-vehicle and vehicle to infrastructure technologies lies in their ability to communicate information to and from vehicles. The applications that support V2V/V2I technologies can provide a variety of safety and efficiency improvements. But contrary to how other vehicles safety technologies function, V2V/V2I requires a "community" of vehicles to take advantage of these technologies by "talking" to each other. From a technological standpoint, use of dedicated short range communications has been tested and found capable of providing the technological support for V2V/V2I vehicle safety communications systems.

It is difficult to retrofit light duty vehicles, but heavy vehicle classes 3 through 8 vehicles, traditionally trucks and buses, show potential for retrofits. The National Highway Traffic Safety Administration contracted with the University of Michigan Transportation Research Institute to estimate the feasibility of retrofitting this class of vehicles. The project includes all class 3 to 8 vehicles classified into four categories: buses, truck tractors, straight trucks, and vocational trucks. It also includes an engineering assessment of possible installation configurations for the various types of class 3 to 8 vehicles, and cost estimates for the onboard DSRC and GPS units, antennas, and installation.

Though some vehicles were designated as too difficult or costly to retrofit, nearly 90 percent of all class 3 to 8 vehicles were included in the analyses. The resulting group of vehicles were distributed over three different technology and installation configurations. Technology providers were surveyed to generate average cost estimates for the onboard units, GPS units, and antennas. One major truck retrofitter was surveyed about the cost of installing the technologies using the three configurations. For both technology and installation costs, estimates were gathered for varying volumes of 10,000, 100,000, 1,000,000, and 10,000,000. For the purposes of results presented in this report, researchers focused on the 1 million and 10 million volumes, where estimates ranged from around $450 to $550 per vehicle for the combined hardware, software, and installation average costs. (These results are presented in Tables 16-27).

Because of the uncertainty of how each of the configurations would apply to the four vehicle categories, three scenarios were developed to estimate the total costs of retrofitting the more than 11 million vehicles included in the analyses. Each scenario adjusted the percentage of all vehicles across each configuration and across the four vehicle categories to test the effects of shifting distributions. Depending on the distribution of the different configurations across the four vehicle categories and volume assumptions, costs will vary from $5.5 billion to $8.5 billion, with increases in volume lowering the total cost by about $1 billion. At the one million volume estimate, retrofit scenarios 1 and 3 both cost $8.5 billion while retrofit scenario 2 costs about $6.3 billion. With a 10 million volume estimate, retrofit scenarios 1 and 3 both cost $7.1 billion while retrofit scenario 2 costs $5.5 billion.

This report provides an engineering and cost support for retrofitting vehicle safety communications technologies on class 3 to 8 vehicles, showing the potential for retrofitting vehicles across a wide variety of vehicles.

1. Introduction

NHTSA sponsored this project that examines the feasibility of retrofitting the United States class 3 to 8 truck and bus fleet with V2V and vehicle to infrastructure (V2I) connectivity using DSRC technology. The heavy-truck industry has a long history of retrofitting. Drivers, in particular, have long added new technologies to their trucks that provide improved efficiency (CB radios, wind fairings, GPS systems), comfort (luxury seating, onboard beds), safety (lighting packages), and entertainment (advanced stereo systems). This customization also occurs at the fleet level, where carriers, focused on the bottom line, continuously look for technologies that provide improved fuel economy, safety, and tracking of their expensive assets. Much of the fleet level customization takes place at the manufacturer level where carriers spec out exactly what they want on their fleets' tractors via a checklist of hundreds of combinations. It is safe to say that the heavy-truck industry is one of the most customized and retrofitted industries.

The heavy-truck and bus industry has a unique opportunity to improve its safety and efficiency through the installation of new technologies onto new vehicles. While comprehensive from one point in time going forward, installation onto new vehicles does not cover the rest of the installed fleet that continue to operate without the technology.[1] But a new technology that can be retrofitted unto the whole fleet has the potential to accelerate the adoption of that technology, whether the technology is regulated or not. Retrofitting a portion of the existing heavy-truck fleet can significantly increase the number of trucks on the road that can communicate messages/signals that increase the safety and efficiency of those trucks. There are costs and commercial vehicle fleet perspectives to consider, however, and these are part of the work of this project. For our purposes, we are viewing a retrofitted safety device consisting of an onboard unit that manages safety, security, and applications, and antennas that support GPS and DSRC messages that enable applications and security.

In this report, we approach feasibility from perspectives by focusing on:

- the breadth of the heavy-truck fleet;
- the restrictions different shapes of trucks impose on installing retrofit devices;
- the costs of the retrofit devices to be installed;
- the costs of the installation of the retrofit devices; and
- and different scenarios for the costs of retrofitting the fleet.

To support our efforts, we enlisted the support of three companies intimately involved in the industry: Navistar, a truck manufacturer; Denso, a DSRC component supplier; and Velociti, a truck retrofit specialist. They provided valuable knowledge of technology development and implementation as it applies to introducing new technologies into the class 3 to 8 bus and truck fleet. They met with the research team regularly, giving insight into the future development of

[1] Our analysis of the introduction of advanced powertrains into the light vehicle fleet found that in the United States it would take over 40 years to turnover all the vehicles with internal combustion engines. Belzowski, B., & McManus, W. (2010, August). *Alternative powertrain strategies and fleet turnover in the 21st century* (Report No. UMTRI 2010-20). Ann Arbor, MI: University of Michigan Transportation Research Institute. Available at https://deepblue.lib.umich.edu/bitstream/handle/2027.42/78001/102673.pdf?sequence=1&isAllowed=y

V2V and V2I technologies as well as the costs of the hardware, software, and installation of the technologies.

V2V and V2I technologies considered in this study are designed around the DSRC device that was used as the base retrofitted device for this study. UMTRI has significant knowledge in working with DSRC devices through its work on the Safety Pilot Model Deployment [2] and its research on the interoperability issues for commercial vehicle safety applications.[3] A unique feature of V2V/V2I technologies that use DSRC is that it provides both safety and efficiency applications, which were highlighted in surveys and interviews with the trucking and bus companies in the study. The team considered the findings of the NHTSA report, *Summary of NHTSA Heavy-Vehicle Vehicle-to-Vehicle Safety Communications Research*,[4] and selected a baseline set of V2V/V2I applications.

V2V Applications

- Forward collision warnings to prevent rear-end crashes
- Warnings about hard braking by vehicles ahead in traffic
- Intersection collision avoidance warnings about vehicles approaching from around corners
- Blind spot indicator warnings
- Logging driver performance metrics for support and training
- Warnings about loss of traction by other vehicles ahead

V2I Applications

- Red light violation warnings
- Work zone warnings
- Curve speed warnings
- Uniform electronic tolling across states
- Traffic light management for fuel efficient driving
- Wireless inspections
- Weigh in motion

Though some of these applications can be provided via cellular long-term evolution technology, or other wireless wide-area network approaches, the combination of all these applications is currently uniquely supported by DSRC.

This report is organized according to the four major goals of the study.

1) Develop estimates of the number of Class 3 to 8 vehicles that can benefit from vehicle safety communications retrofit technology for safety and convenience/efficiency across four main vehicle categories: tractors, straight trucks, buses, and vocational trucks.

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[2] *The Safety Pilot Model Deployment (SPMD)*, Sponsor: U.S. Department of Transportation; Federal Highway Administration; Washington, DC, August 2011 to August 2014. Contract number: DTFH61-11-C-00040

[3] Le Blanc, D., & Belzowski, B. (2012). *Interoperability issues for commercial vehicle safety applications*. Ann Arbor, MI: University of Michigan Transportation Research Institute.

[4] Chang, J. (2016). Summary of NHTSA heavy-vehicle vehicle-to-vehicle safety communications research (Report No. DOT HS 812 300). Washington, DC: National Highway Traffic Highway Safety Administration.

2) Categorize the commercial vehicle fleet into different types of trucks and packages of vehicle safety communications technologies that will be used to generate technology and installation cost estimates.

3) Estimate the cost of each safety communications technology package for each of the categories of trucks and estimate the cost of installation of each of the technology packages for each of the truck categories.

4) Estimate the cost of retrofitting vehicles using three potential scenarios for implementation.

Figure 1 shows the elements of the project.

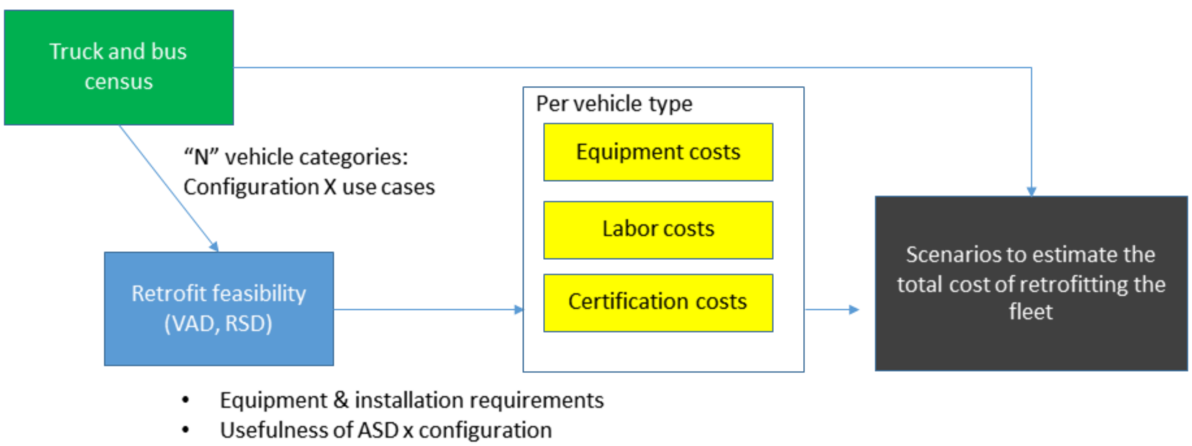

Figure 1: Elements of the project

2. Estimating counts of class 3 to 8 trucks in the United States

The first phase of the study requires the identification of all the heavy trucks and buses (over 10K GVW) that will form the base of the study. Using the IHSMarkit/Polk registration data for April 2017, with some additional information from the Federal Highway Administration's *Highway Statistics* publication, estimates were generated for the four categories of vehicles: buses, truck tractors, straight trucks, and vocational trucks.

The method of estimation proceeded as follows: The IHSMarkit/Polk data includes a vehicle type classification that identifies tractors, straight trucks, school buses, non-school buses, pickups, and other medium and heavy vehicle types. However, the classification also includes several categories for incomplete vehicles, such as glider kits, cab-chassis, and cutaways, amounting to about 25 percent of the total population of all class 3 to 8 vehicles. These latter are vehicles that are manufactured and sold as incomplete vehicles that will later have the final body installed. Glider kits are typically turned into truck-tractors (i.e., power units with a fifth wheel used to haul semitrailers). Vehicles sold as cab-chassis and cutaways can be turned into either straight trucks or buses by the addition of a cargo-carrying body or a passenger-carrying body.

Thus, it was necessary to allocate the incomplete vehicle types between trucks and buses. Glider kits (35,387 vehicles, 0.3% of the total) were added to the truck-tractor category. The remaining incomplete vehicles were then split between straight trucks and buses. The total number of vehicles in bus categories in the IHSMarkit/Polk data amounted to only about 660,000 vehicles. However, the FHWA's *Highway Statistics* estimates of the number of buses is consistently higher: 872,027 for 2014 and 888,907 for 2015. It is believed that the FHWA has additional information to identify buses, beyond the IHSMarkit/Polk data available for this project, and that the FHWA estimate of the total number of buses is the best available.

FHWA's estimates of the number of buses show fairly consistent annual increases. To match the 2017 IHSMarkit/Polk data (which was extracted in April and thus do not include the full year of growth), we estimate about 900,000 buses. That number is consistent with the general pattern of growth in FHWA's estimates, without claiming too much precision. The difference between the 900,000-bus estimate and the total of defined buses in the Polk data was subtracted from the incomplete vehicle categories and the remainder were assumed to be straight trucks. This procedure produced Table 1.

Vehicle types	N	%
Bus	900,000	6.9
Truck-tractors	2,946,611	22.5
Straight trucks	6,138,972	46.9
Pickups	1,864,909	14.3
SUVs	6,729	0.1
Motor homes	928,419	7.1
Fire trucks	32,857	0.3
Unknown	259,679	2
Total	13,078,176	100

Table 1: Initial Class 3 to 8 Truck Counts from IHSMarkit/Polk

The categories in Table 1 were reduced by eliminating the "Unknown," placing the "Motor Homes" in the bus category, and placing "Pickups," "SUVs," and "Fire Trucks" in the straight truck category. Pickups and SUVs are defined as vehicles over 10,000 pounds GVW. This yielded the distribution in Table 2.

Vehicle types	N	%
Bus and Motor Homes	1,828,419	14%
Truck-tractors	2,946,611	23%
Straight trucks	8,043,467	63%
Total	12,818,497	100

Table 2: Redistribution of IHSMarkit/Polk Class 3 to 8 Truck Counts

Identifying vocational trucks within the straight trucks category was challenging. "Vocational" has no fixed definition. The purpose of identifying so-called vocational trucks within the truck population was to estimate the magnitude of straight truck configurations for which retrofitting might present significant problems. For example, straight trucks with movable booms or cranes might interfere with the location of antennas. Accordingly, here we use available data to estimate the distribution of straight truck body styles in the population.

The only data available on the cargo body type of the population of registered straight trucks is from the Bureau of Census's Vehicle Inventory and Use Survey. The most recent VIUS data is from 2002, so these estimates should be regarded with caution. The distribution of body styles may have evolved over the period but there are no data from which to determine the nature of that evolution with any precision.

The VIUS was a nationally representative sample survey of truck owners, designed to describe the population of registered trucks in the United States. For the 2002 survey, approximately 136,000 truck registrations were sampled and a questionnaire mailed to the owner. The data collected included the physical characteristics of the trucks and how they were operated over the course of a year. For the purposes of this project, owner responses on the body type of class 3-8 trucks were used. Table 3 shows the classes of cargo bodies, proportions in the 2002 VIUS data, and application of those proportions to the estimated number of straight trucks in the current population of trucks. The starred cargo bodies are considered part of the vocational truck category.

Straight Truck Type	N	%
Van/Enclosed Box	2,664,314	33.1%
Pickups	1,864,909	23%
*Flatbed	1,387,408	17.2%
*Utility (service)	632,314	7.9%
*Dump	546,369	6.8%
*Cargo Tank	331,504	4.1%
*Wrecker	178,030	2.2%
*Garbage/Refuse	165,752	2.1%
*Concrete Mixer	141,196	1.8%
*Fire trucks	32,857	0.4%
*Logging	30,695	0.4%
*Crane	30,695	0.4%
*Vacuum	24,556	0.3%
SUVs	6,729	0.1%
*Street sweeper	6,139	0.1%
Sub-Total Straight Trucks	8,043,467	100.0%

* Vehicles considered vocational trucks

Table 3: Redistribution of IHSMarkit/Polk class 3 to 8 truck counts using VIUS Survey data and the list of vocational trucks

The combination of the buses, truck tractors, straight trucks, and vocational trucks in Table 4 yields the final version of the truck population that will be used to estimate the total cost of retrofitting the entire fleet of trucks in the United States.

Vehicle types	N	%
Bus and Motor Homes	1,828,419	14%
Truck-tractors	2,946,611	24%
Straight trucks	4,535,951	35%
Vocational Trucks	3,570,515	27%
Total	12,818,497	100%

Table 4: Final distribution of class 3 to 8 trucks in the United States for 2016-2017

3. Requirements For V2V/V2I Retrofits

Having developed the final list of trucks and buses available for potential retrofits, researchers worked with industry research partners who specialize in retrofits in general and vehicle safety communications retrofits specifically to examine and detail the issues related to equipment, installation, testing and certification, as well as the cost of retrofitting the different vehicle safety communications technology packages for each of the selected vehicle types.

The general process for defining the retrofit configurations for the entire fleet of trucks is shown in Figure 2. This process is addressed in this section, which addresses the left-most three blocks in the figure, and in Section 4, which addresses the right-most blocks in the figure. In this section, the components that are needed to comprise the retrofit vehicle safety communications equipment are developed, and a set of requirements is generated for the installation of those components. This includes data requirements to support the device's need to broadcast (Basic Safety Messages) BSMs and perform the representative applications; hardware requirements to support sensing and computation needs; and installation requirements that reflect practical needs from both the V2X performance perspective, integration processes, and fleet or owner needs.

One outcome of these steps is the recognition that a key consideration is where DSRC and GPS antennas are located on the vehicle, since there are constraints on the necessary "views" of the antennas and the wiring between the antennas and other device components. Therefore, the component sets and the antenna types and locations will vary somewhat depending on the physical configuration of the vehicle. In turn, the number and type of modules are influenced by the antenna locations.

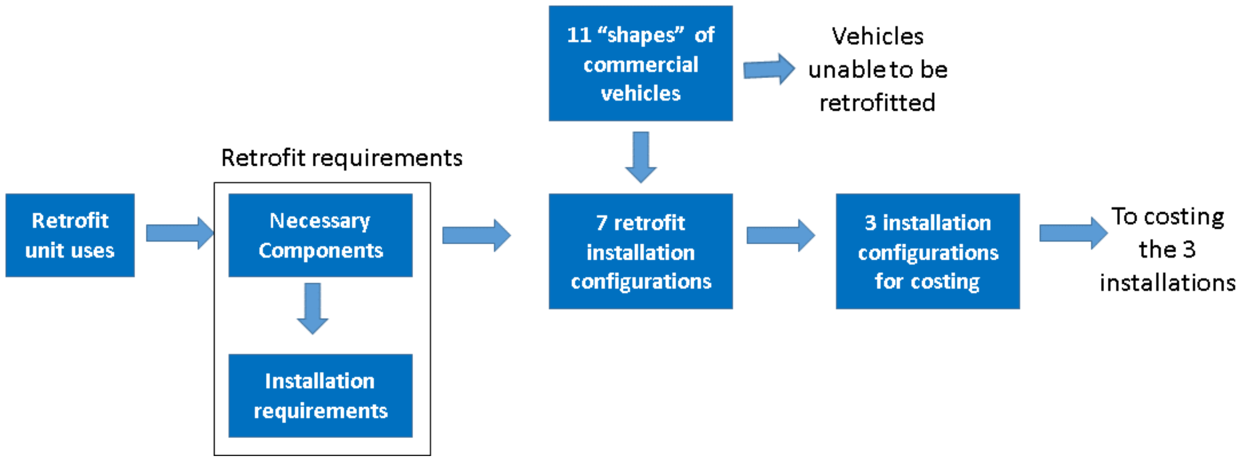

Figure 2: General Process for Defining Retrofit Configurations

3.1 Introduction to the vehicle safety communications onboard components

When considering system designs and capabilities, assumptions and considerations were needed. These include the following items:

- The team decided to consider technology as it is expected to be in the 2020 to 2022 timeframe. This is enough in the future that certain technologies and standards will be in place to support mass product sales, such as low-cost automotive-grade GPS systems that can meet the performance standards for V2X (SAE J2945). On the other hand, the selected time frame is not so distant that wholly new technologies need to be imagined, which would make the task difficult and perhaps leading to inaccurate assumptions.

- The project was tasked to address retrofit systems using vehicle safety communications technology. Other forms of wireless V2V and V2I technology are possible in the timeframe being considered, especially the existing LTE cellular data technology and future cellular or cellular/DSRC hybrid approaches. The work focuses on DSRC technology only, but does consider that many applications, especially V2I applications and possibly interactions with the security certificate management system, could use other technologies. DSRC has capabilities including low latency and security designs which make it unique for certain applications, especially split-second V2V driver alerts or possibly future vehicle control enhancements.

- The project assumed a stand-alone vehicle safety communications system would be retrofitted on the commercial vehicles. In the future, vehicle safety communications systems may be part of a larger telematics and safety module that may include logistics, fleet communications, and other functionalities. This would decrease incremental costs for fleets and owners acquiring the retrofit capability, but it would be difficult for the project team to properly assess costs and therefore to pose questions to fleets regarding these technologies.

- For combination vehicles, the project team addressed the issue of equipment on trailers as follows: NHTSA and others are working to demonstrate the possibility that low-cost equipment could be installed on tractors and/or trailers so that a vehicle safety communications unit on the trailer could know whether one or more trailer was being towed, and know the dimensions and other information needed to broadcast BSM information that is compliant with standards. The means of knowing this information is called a "trailer information system" in this report, and it is assumed that this exists separately from the vehicle safety communications retrofits being considered. Therefore, the trailer information system components are not specified in this report, nor are costs for hardware or installation being considered.

- Another concern that was addressed was whether a large and diverse set of onboard vehicle safety communications systems would be needed to retrofit the US commercial vehicle fleet, or whether just a few variants are needed. One question in particular was whether there would be one system for broadcast-only "vehicle awareness devices" and a different system to be used when BSMs for onboard applications, such as forward collision warning or red-light violation warning. A more general question was whether the wide variety of physical configurations of trucks and buses would lead to a large set of suggested vehicle safety communications system configurations. A disadvantage of having many retrofit system versions could be a loss of the economy of scale. In that case, many variants would need to be manufactured and installed, increasing costs and possibly reducing demand and fleet/owner acceptance. As the development of system requirements and potential configurations continued, it was realized that the difference between systems was significant but probably not enough to warrant more than a handful of system variants in the marketplace. In particular, the project adopted the approach that all units would be assumed to be capable of hosting applications and executing the required security functions. That is, no broadcast-only units (VADs) are being considered.

The system designs developed in this project do not assume that the vehicle safety communications technology needs signals from OEM data buses. The retrofit units are specified so that they can create the minimum necessary data for both broadcasting standards-compliant BSMs as well as generate the data necessary for the applications. GPS data, in particular, can be useful for approximating accelerations and yaw rate. Among the signals that would be convenient to receive from the vehicle are the following.

- Speed (as a backup to GPS speed in GPS-denied environments)
- Driver brake switch
- Turn signal (often not available on data buses)
- Treadle position
- Torque request
- Retarder on/off

An example of how OEM data bus signals can be convenient to applications is the following: A forward crash warning might be delayed slightly if the driver is already on the brake, but not braking significantly, and the warning might be advanced earlier if the treadle position shows the driver is still applying torque and not yet slowing. The data bus signals are also more accurate and have less delay for some signals, such as acceleration and yaw rate; however, some of these secondary signals are often not on SAE J1939 data buses on heavy vehicles, or on the OEM data bus on non-J1939 vehicles. For vehicles without the J1939 protocol, those signals are proprietary, and a retrofit system supplier would need to obtain information on hundreds of different models, model years, and even trim levels. Though CAN bus connectivity is not assumed for this study, the modules quoted for the study allow for CAN connectivity if it is desired. But the cost of de-coding all the CAN bus signals for all the different types of class 3 to 8 vehicles on the road today is not included in the cost estimates.

3.2 Performance and hardware requirements

The SAE J2735 standard and the SAE J2945/x standards address the BSM content and the minimum requirements for the message content itself, respectively. Among these requirements are:

- BSM minimum message content includes several fields, although many of the defined fields can be unpopulated and still be compliant.
- BSM transmission from an installed unit must be receivable 300m away, in all directions, using a receiver that meets specific criteria.
- DRSC units have a minimum signal reception capability.
- GPS absolute positioning must meet a J2945/1 specification, to provide accurate BSM content to nearby vehicles and infrastructure.
- Security functions, which are carefully defined, must be executed on the DSRC unit.

Some of the implications of these and many other requirements in the SAE standards (as well as protocol stack standards, including the IEEE 1609 set), are:

- At least two DSRC radios are recommended. One radio would be responsible for the continuous use of the “channel 172,” which is the highest-priority of the seven current channels within the DSRC band, where BSMs are exchanged. The second radio would be responsible for other channels, which are used for messages with less time criticality, as well as communications related to the receiving of security certificates. This will be called the “channel 174+” radio in this report. This two-radio approach is represented in recent SAE standards and is also used in the New York City Connected Vehicle Pilot project. The team considers the two-radio approach as the likely future configuration.

- The channel 172 radio is responsible for most V2V communications. From earlier projects, it was established that for large trucks, this radio should be supported by two antennas – one on each side of the vehicle. To broadcast and receive messages on these two antennas, the radio should have “full diversity,” which is the capability of handling the receiving of the same incoming signal, which arrives at slightly different times at the two antennas, as well as the broadcasting of signals from each antenna.

- Finally, for the radios, an important requirement for this project is that a simple cable from the DSRC radio to the DSRC antenna should be no longer than 3.0 m (9.8 ft.) and should be of a type suitable to the 5.9 GHz frequency, for example, RF-195 low-loss cable. The restriction of cable length is due to the losses at such high frequencies. Therefore, if the DSRC antenna must be located far from the main module of the V2V/V2I device, two options are available: (1) an in-line amplifier can be installed to extend the allowable cable distance, or (2) the DSRC radio board may be located outside of the main module, nearer to the antenna. Both options are more expensive due to additional hardware costs (e.g., enclosures and power cabling) and extra installation labor. Also note that these cables are thick – up to 0.2 inches – and the bend radius cannot be too tight or damage and loss of signal applies.

Another requirement for the V2V/V2I technology is that the system should support updating of the unit's firmware. This is useful for security patches, software patches, and also allows the unit to be upgraded to new or improved applications or capabilities. Software updates could be supported either through a wired connection (logging on to the unit from a laptop, for instance) or wirelessly (probably Wi-Fi or other communication technologies).

3.3 Driver-vehicle interface hardware

The final component in a complete V2V/V2I configuration is the driver vehicle interface that provides information to the driver from any onboard applications. The DVI may be a standalone unit, as shown in Figure 3, or it may be part of an existing DVI within the vehicle. This project assumes that retrofitting the vehicle includes installation of a simple DVI. Some key requirements include:

- Accepting driver input through the DVI may not be necessary (e.g., the fleet or owner sets options)
- Warnings and important information require two sensory modalities, according to longstanding human factors practice, for instance, using audible tones and visual icons to ensure that drivers can confirm the system that is issuing the tones.
- The DVI needs the ability to tell the driver that a malfunction has occurred.
- A wired connection from the OBU is strongly recommended, as wireless techniques such as Bluetooth or Wi-Fi are not robust enough to power cycling, and daily maintenance on the vehicle.
- Therefore, the DVI needs battery power and an ignition signal (or signals from the OBU for powering up and down), a simple icon to indicate its operational status to the driver or truck technician, and an automatic illumination adjustment for night and day operations. For audio, the DVI unit is assumed to provide audio upon command from the OBU.

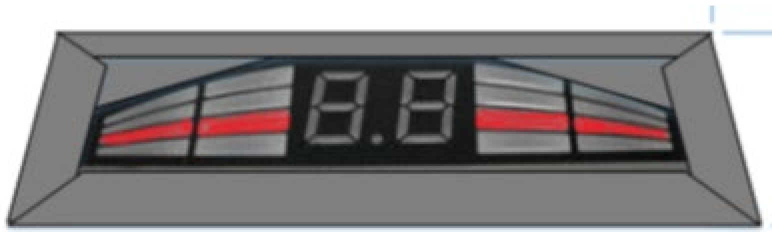

Figure 3: Examples of potential DVIs (image from www.ford.com)

Given this discussion, the basic hardware elements of a V2V/V2I system are shown in Table 5. The hardware elements include the OBU unit, which includes the main processor and memory, GPS receiver, and interfaces. The default location of the radios is also inside the main enclosure, although later there are configurations that are required for certain truck configurations that call for at least one radio to be located remotely, near the DSRC antennas. (Specific configurations of hardware location are described in detail later in this section.) The OBU is assumed to be within a dedicated enclosure and may be installed inside or outside the cab, with the recommended locations in this report to be inside the cab for convenience of running wires and for physical protection of the unit. The channel 172 DSRC radio will require one or two antennas located on the exterior of the vehicle, with details of antenna placement to be described later. The channel 174+ radio to support V2I and security communications is most likely inside the main enclosure. Only one antenna is needed for this radio, almost always located on the cab, sometimes on the exterior and sometimes as a glass-mounted patch antenna. As mentioned earlier, the DVI is located on the dashboard of the cabin. Yaw rate and acceleration sensors are listed in the table as optional – if the supplier can meet SAE 2945 requirements with OEM signals or by processing GPS or other OBU-internal signals, then these sensors are not required.

Regarding wiring harness requirements, a selected set is included in Table 5. A direct connection to the OEM bus is also optional, as described earlier. Other wired connections are listed. The table also shows some other hardware. A Wi-Fi and/or cell modem is listed as optional – such a modem can be useful in configuring the unit and is one method for updating software.

Hardware	Required?
OBU (radio, processor, memory, interface, etc.)	Required (1 or 2)
DSRC Ch 172 antennas	Required
GPS & DSRC Ch174+ antennas, integrated	Required
Driver vehicle interface (DVI)	Required
OBU Yaw rate & accelerometer sensor	Optional
Wiring harnesses	
OBU to GPS/DSRC Ch174+ antenna (or remote radio)	Required
OBU to DSRC Ch172 antenna(s) (or remote radio)	Required
Power, ignition to OBU	Required
OBU to DVI	Required
Power, ignition, headlamp to DVI	Required for dedicated DVI
OBU to OEM data bus	Optional
Wired input from trailer info device	Required, if unit pulls trailers
Other Hardware	
RF amps/filters, external radios	Depends on configuration
Wi-Fi/cell modem	Optional
Power conditioning (if not within OBU)	Required
Software	
Basic codeset, including signing messages	Required
Application Code	Required
Security authentication of received messages	Required
Trailer information communication	Required

Table 5: Hardware elements of a retrofit V2V/V2I unit

Figure 4 shows a diagram of the system that reflects the descriptions presented so far. Note that there will be configurations in which DSRC radios may be located outside the main enclosure.

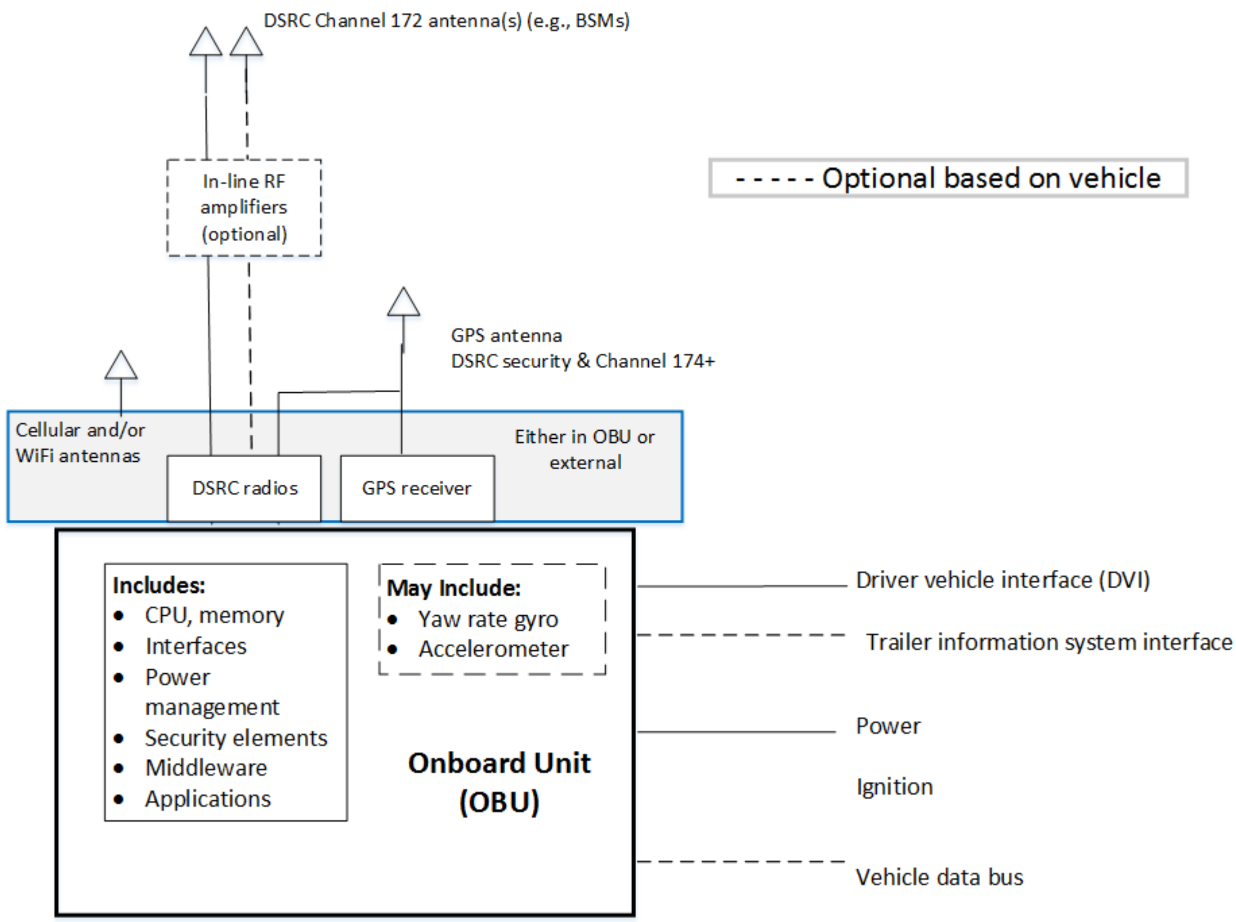

Figure 4: Elements of retrofit safety device

A next step is now to create a set of high-level installation concepts for the retrofit V2V/V2I system hardware. This will be driven by antenna placements, constraints on DSRC cabling lengths, and practical considerations for the placement of retrofit hardware on a commercial vehicle. These high-level concepts will later be reduced to a small set of three representative installations that can support the development of costing estimates. More specific installation requirements are provided for those three configurations.

The first step, however, is to consider the placement of GPS and DSRC antennas.

3.4 Antenna placements

Perhaps the most important consideration when deciding how to retrofit different types of trucks is the antenna placements for GNSS and DSRC. For GPS/GNSS, the issue is to ensure a good view of the sky, in order that there is a line of sight to the GNSS satellites. Figure 5 below shows a vehicle with a GNSS antenna on the top of a cargo box, on the left of the figure, which allows a wide sky view (assuming no blockage due to nearby objects, foliage, buildings, or landscape features), and with a GNSS antenna on the cab roof, with the cargo box creating sky blockage. A sky view that has major blockages means that the accuracy of a GNSS fix is likely to be compromised.

There is no formula to compute the positioning error due to a particular partial masking of the sky, especially in this case, when the accuracy desired is rather high. Error grows as the sky view decreases, but the magnitude of the error depends on the particular arrangement of satellites in the sky (which is always changing), errors associated with those satellites' onboard clocks and knowledge of their actual orbital parameters ("ephemeris" errors), and the type of receiver and its own clock errors and receiver characteristics. Another type of error is multipath error, which is caused by GNSS signals bouncing off nearby surfaces and creating interference at the antenna.

The approach taken in this report is to seek a wide sky view for the GNSS antenna and avoid nearby sky blockages from cargo or the truck itself. Note that receivers that can handle signals from two GNSS antennas are not considered feasible in the 2020-too-2022 timeframe, so all configurations in this report consider only one GNSS antenna. Also, GNSS antennas are best mounted outside the cabin to reliably obtain the accuracy required by standards.

A quantitative analysis is not used, but rather configurations that lead to a wide sky view angle are developed. Eventually, the supplier of a retrofit V2V/V2I system is likely to be accountable for the GNSS localization to meet SAE J2945 or other applicable standards, and the suppliers will presumably quantify acceptable mounting locations.

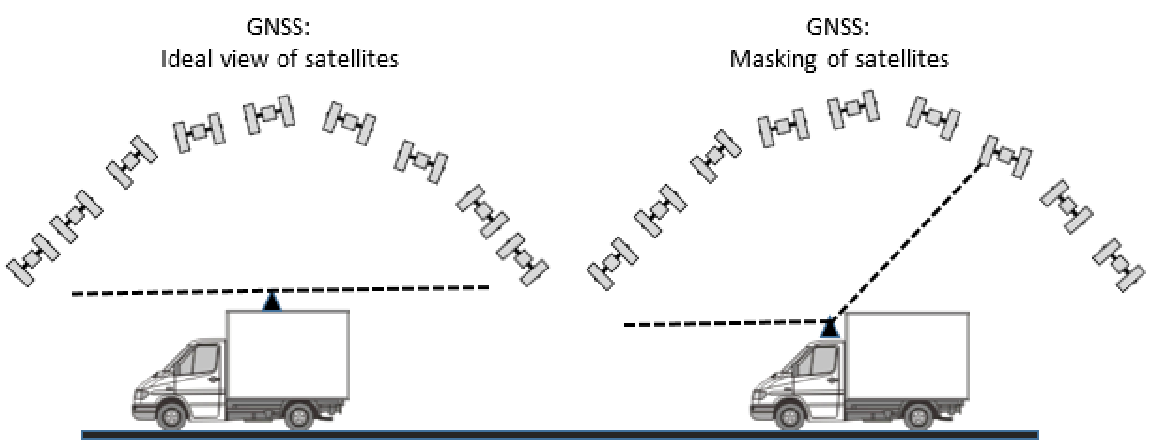

Figure 5: GNSS with good sky view and partial sky view

For the channel 172 DSRC antennas, the goal is to maximize the line of sight to nearby vehicles, and when this is not possible in all directions, to maximize the likelihood that diffraction of the DSRC signal will allow adequate communication with other DSRC devices. A single full-diversity DSRC radio can support broadcast and reception from two antennas.
The best case is a clean line of sight between the host vehicle's DSRC antennas and the nearby target device (which could be associated with a vehicle, road infrastructure, or any other DSRC device). If this is not possible, the communication can still be effective if there are surfaces for the signals to bounce off, toward the receiving unit (multipath), or via diffraction, which is the

"bending" of radio waves around corners. Since there is no guarantee of effective multipath-assisting surfaces nearby, this report focuses on the diffraction effect.

Figure 6 illustrates the concept of diffraction. As the radio waveform propagates past a corner, the waveform expands to fill the space. In the figure, the truck has antennas at each of its two side mirrors, and broadcasts in all directions, including backwards. The rearward waves diffract at the rear corner of the vehicle, and some weaker radio signals propagate into the space behind the truck. The figure shows a sedan following the truck. The signal at that vehicle will be significantly weaker than if the vehicle was in an adjacent lane, within line of sight of the truck side mirrors, but the experience within our team is that the vehicle behind the truck will likely receive the signal.

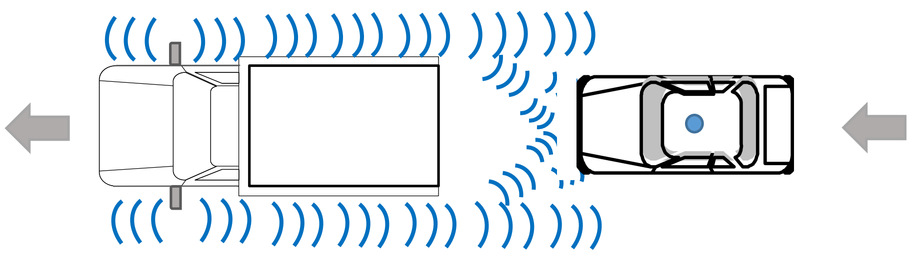

Figure 6: Diffraction of DSRC at corners of the vehicle

Diffraction, however, results in a reduction in the wave signal strength for the diffracted waves. Therefore, for the purposes of this project, the installation concepts for the retrofit V2V/V2I technology include these antenna placement rules:

- Channel 172 DSRC antenna placement cannot depend on diffraction around two corners of the host vehicle to reach nearby vehicles (an example of a disallowed two-corner configuration is in Figure 7, where the two corners are indicated by the numbers "1" and "2" at the corners).

- The distance from the channel 172 DSRC antenna to a corner around which diffraction is required should not be too far, or the diffracted wave strength may not be adequate. In this case, "too far" is selected to be approximately 8 meters (25 feet). Therefore, a single roof-mounted channel 172 DSRC is sufficient on a class 3 or 4 delivery van, but two such antennas are required if the channel 172 antennas are to be on top of a school bus. The height threshold here is based on engineering judgment and not on measurements of signal strength.

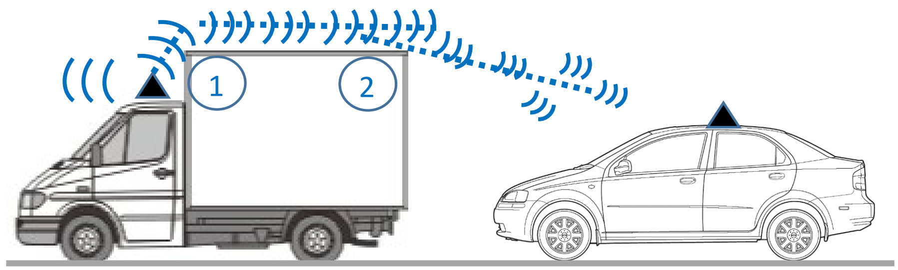

Figure 7: Diffraction around two corners reduces signal greatly and is avoided

For the channel 174+ DSRC antenna, the key factor is whether the antenna has a relatively clear path to the infrastructure DSRC antennas to communicate effectively. While the channel 172 radio needs to continuously communicate in all directions, to detect risks in front of the vehicle, to the rear, and at the sides, and react very quickly, the channel 174+ radio primarily needs to look forward to exchange data as it approaches traffic signals or new roadway features. Thus the configurations that are developed employ a single channel 174+ DSRC antenna, and the approach is to require a plus-or-minus 45-degree angle of line of sight in the forward direction. Finally, to avoid interference, no two DSRC radios should be within approximately a meter of each other, so that the channel 172 and channel 174+ antennas cannot be collocated.

3.5 Other installation considerations

Beyond antenna and radio placement, there are other practical considerations that will eventually need to be considered in designing an installation. These include:

- The placement of hardware should minimize the chance of hardware interfering with vehicle operations and/or impeding the driver or creating tripping hazards. The placement should also minimize the chance of the hardware being damaged by being bumped while the vehicle is in service or is parked.
- Harness simplicity should be maximized, for robustness and to reduce installation labor.
- Integration appearance should be acceptable to the vehicle owner.
- Ease and cost of integration are considerations.
- Ease of maintenance, upgrades, service, and replacement of components are to be considered in the detailed selection of location.

4. Vehicle Configurations for Costing

Given the insights and requirements developed in Section 3, this section continues with the process illustrated back in Figure 6. This process involves examining hundreds of images of trucks, buses, and motor coaches which used to identify a set of 11 “shapes” that are representative of a large majority of commercial vehicles. As Table 6 shows, the shapes are combined with the work in Section 3 to develop seven installation concepts for where to locate the hardware associated with the retrofit V2V/V2I system, for the purpose of maximum function and minimum cost and maintenance. At the end of this section, those seven installations are reduced to a set of three configurations that are used in later sections to generate costs for the hardware and retrofit installation.

4.1 Eleven vehicle shapes and seven installation configurations

Hundreds of images of commercial vehicles were examined to identify representative “shapes” of the vehicles that are important to the problem of locating the retrofit V2V/V2I equipment on the vehicles. These images were gleaned from image searches on the internet, using targeted searches (e.g., “delivery van,” “tractor-trailer,” “garbage truck”) as well as browsing through used vehicle sites, trailer manufacturer sites, vocational truck-related sites, and many more. This search started with smaller delivery vans, initially considered the simplest vehicle shape. A few examples of this vehicle type are shown in Figure 8.

Figure 8: Examples of class 3-4 delivery vans

Based on the discussion in Section 3, the following installation is recommended for this vehicle type, and is called the “Roof-1” installation:

- A single channel 172 DSRC antenna on the roof, preferably centered, but possibly somewhat fore or aft of center, depending on where the main module is located,
- An integrated antenna containing both the channel 174+ and the GNSS antenna, also located on the roof, but displaced at least a meter from the channel 172 antenna to reduce the chances of interference.
- The main module that contains the radios and GNSS receiver, and other elements identified in Table 6 is to be mounted so that the cabling run to each DSRC antenna is no more than 3 meters of length, as discussed in Section 3.
- The DVI – like the DVIs in all installation designs – is located on the dashboard.

Section 3 remarked about the wiring needed to power the unit, to drive the DVI, and connect the retrofit unit’s components. For the small delivery units, it may be impractical to connect to the vehicle data buses unless there is OEM-provided information about data signals. Note that although recent vehicles use CAN buses that can easily be located and tapped into, vehicles in the near future will have more cybersecurity protections in place, and access to OEM data signals will become harder and eventually impossible without OEM cooperation.

Consider another representative "shape" that is not much different than the delivery van shape. The full-size school bus is another two-axle vehicle with a convex, box-like shape, however school buses can be quite a bit longer than delivery vans. In Section 3, it was stated that for vehicle roofs longer than about 8 m (25 feet), a rooftop antenna approach would require two channel 172 DSRC antennas – one near the front and one near the rear of the vehicle.

Another approach for such long vehicles are side-mounted channel 172 antennas, for instance, using side mirror mounting hardware. Side-mounted antennas were used in the Safety Pilot Model Deployment for heavy vehicles. For this project, a recommendation for school buses is to avoid side-mounted antennas due to minimal maintenance budgets associated with most school bus operations, and the tendency for these vehicles to be parked daily in close proximity to other vehicles by part-time drivers. Side-mounted antennas are vulnerable to being bumped and broken. Thus, school buses lead to a second installation option, which is characterized by having two channel 172 antennas on the roof -- one near the front and one near the back.

The main enclosure with the OBU is likely to be near the front of the vehicle where power and access to the DVI are convenient. Given the constraint of DSRC cabling lengths, either in-line amplifiers are needed to get DSRC signals to the far rear DSRC antenna, or a remote radio needs to be located near the rear antenna. The latter is selected since both approaches are similar in installation complexity and the latter avoids extra hardware costs. The channel 174+ and GNSS antennas can be located near the front of the vehicle. This is called the "Roof-2" installation approach.

This exercise of identifying vehicles and variants that might affect the installations was conducted over the period of a few months, with team review and briefings to NHTSA. Table 6 shows a summary of the 11 vehicles shapes (which appear as the rows of the table), and the resulting seven installation configurations (the columns of the table). At the top of the seven columns, the "FINAL SET" label indicates the three selected configurations used for costing and survey purposes.

			FINAL SET			FINAL SET		FINAL SET	
			Roof-1	**Roof-2**	**Roof-3**	**Sides-1**	**Sides-2**	**Sides-3**	**Sides-4**
Shape	Vehicle type	Examples	Two antennas on highest roof of single-unit with OBU in cab	Three antennas on roof (fore/aft), OBU in cab	Two antennas on working body roof with OBU also at working body	One antenna on cab roof plus two on antlers or protrusions on each side	One antenna on cab roof plus a mirror mounted antenna on each side	One antenna on cab roof plus a mirror mounted antenna & radio on each side	Mirror mounted antennas & radios, plus separate GPS and Ch174+ antennas
1	Box shape / shorter length	Delivery van	ALL VARIANTS (PREFERRED)						
2	Box shape/ longer length, mirror mounts not	School bus		ALL VARIANTS (PREFERRED)					
3	Box, long, mirror mounts and DSRC cabling to those antennas feasible	Motorcoach, transit bus		MOST VARIANTS		ALL VARIANTS (PREFERRED)	MOST VARIANTS		
4	Cab and taller working body (single unit, nothing overhanging cab)	Delivery single unit truck			MOST VARIANTS (PREFERRED)	MOST VARIANTS	MOST VARIANTS	ALL VARIANTS	
5	Tractor without fairing pulling trailer	Day cab, beverage tractor & semitrailer				MOST VARIANTS (PREFERRED)	MOST VARIANTS	ALL VARIANTS	
6	Tractor with fairing & trailer	Tractor/semitrailer, other combination vehicles				MOST VARIANTS (PREFERRED)	MOST VARIANTS	ALL VARIANTS	
7	Single unit vehicle without ability to install on working body	Garbage truck					MOST VARIANTS (PREFERRED)	ALL VARIANTS	
8	Single unit vehicle with overhang over cab - with ability to install on working body	Paratransit, delivery truck	ALL VARIANTS (PREFERRED)						
9	Single unit vehicle with overhang over cab - without ability to install on working body	Dump truck, double-decker tour bus, tree hauler							MOST VARIANTS
10	Cab and irregular body	Cement mixer, Flatbed, Stake truck				MOST VARIANTS (PREFERRED)	MOST VARIANTS	ALL VARIANTS	
11	Bucket truck	Bucket truck	MOST VARIANTS (PREFERRED)						MOST VARIANTS

Table 6: Eleven commercial vehicle shapes and seven retrofit unit installation approaches

Already the Roof-1 and Roof-2 shapes have been introduced. Highlights are now provided for the remaining five shapes. The Roof-3 installation is also for single unit vehicles, but this shape addresses trucks with working bodies that are much higher than the cab, which does not have a fairing. (This is vehicle shape 4 in Table 6). Class 6 specialty grocery trucks are an example of this. In this case, if the specifics of the working body layout and use are appropriate, antennas for both DSRC channel sets can be mounted on the roof of the working body, with the main module also on the working body, perhaps mounted inside the cargo space, near the top front. The GNSS antenna can also go on the top.

There are of course cases where mounting antennas as described for the Roof-3 design cannot be done. In this case, Table 6 shows that other options include Sides-1, Sides-2, and Sides-3. These three options put the channel 172 antennas on the side of the vehicle. In Sides-1, two channel 172 antennas are mounted to the body of the truck, one on each side, with mast antennas mounted vertically, at least 10 cm outboard of the outer envelope of the vehicle (including any trailer or working body). A variation on Sides-1 is if the antennas are similar to shark fin antennas but are installed to protrude at least the 10 cm outside the outer vehicle envelope. In Sides-1, the channel 174+ DSRC antenna is usually on the roof of the cab or glass-mounted on the interior of windscreen. (Windscreen-mounted equipment must comply with regulations.) The GNSS antenna can be placed in a location with good sky view. (Examples of trucks that do not allow good sky view are discussed later.)

The Sides-2 installation option is similar to Sides-1, except it applies to vehicles where mounting antennas to the sides of the vehicle is difficult or impossible because of a lack of space. Day cab tractors, especially ones with side fairings or vertical exhaust stacks along the rear corner of the cab, are examples where Sides-2 may need to be used. The Sides-2 design puts the channel 172 DSRC antennas onto the side mirror assembly, but this configuration requires that the side mirrors are affixed to the truck body and not to the doors. When these conditions are satisfied, it is often possible to mount the main retrofit unit module within the cab and still reach the side mirrors with the limited DSRC cable lengths. For the Sides-2 design, the radio that drives the channel 172 antennas is within the main module.

For cases in which (a) the channel 172 antennas cannot go on top of the vehicle, (b) there is not a way to mount these antennas to the side of the truck or cab body, and (c) the side mirrors are mounted to the doors, a more complicated installation is required: the Sides-3 design. The DSRC cable cannot be run through the front door hinges due to its thick size and limits on bend radius. Thus, the Sides-3 approach puts the channel 172 antennas on the side mirrors, and now the radios to drive those antennas are mounted remotely to the main module, specifically, on the door or on the mirror bracing. This requires that only power and data wiring is passing from the body, through the door hinging, and to the side mirror area. Putting radios remotely increases hardware cost and makes the installation more difficult. Custom brackets may need to be designed when retrofitting a fleet with these vehicle shape qualities. Table 6 shows, however, that for all its complexity and installation work, Sides-3 appears to represent a robust “fallback” approach, when the specifics of vehicles do not allow other installation methods.

Finally, the last installation type in Table 6 is called Sides-4. The unique problem that Sides-4 addresses, relative to Side-3, is that infrequently there are trucks where it is difficult, but possible, to find a good view of the sky for the GNSS antennas. Figure 9 shows some examples of these trucks. In these two examples, as with almost all vehicles, the channel 174+ DSRC antenna can be mounted on the windscreen or front portion of the cab roof or front surface.

Figure 9: Vehicles with challenging, but existing, locations for the GNSS antenna

Figure 10 shows examples where it is very difficult to find a location for the GNSS antenna. These are trucks where the area with acceptable sky view is occupied by cargo or working equipment that does not include a flat surface safe for mounting an antenna. (It is assumed that antennas should not go on the hood of vehicles due to issues of heat and potential damage to wiring, e.g., when scraping the windscreen for ice. Understanding what percentage these types of vehicles represents in the overall truck population will be addressed using the market study discussed later in this report.

Figure 10: Difficult or expensive vehicles to retrofit due to an absence of a viable location for the GNSS antenna

Table 7 shows which hardware items would most commonly be part of the seven candidate installations. The final sets that are selected for costing purposes are again identified by the “Final set” label at the top of the columns. The table identifies the location of the OBU and the number and location of DSRC radios and antennas (both channel 172 equipment and channel 174+ equipment). The total number of radios and antennas and the number of locations at which those items are to be mounted are shown in the bottom rows. The bottom rows are used in Section 4.2 to reduce the set of configurations to a smaller number for the purposes of costing.

	FINAL SET			FINAL SET		FINAL SET	
	Roof-1	**Roof-2**	**Roof-3**	**Sides-1**	**Sides-2**	**Sides-3**	**Sides-4**
Equipment	Two antennas on highest roof of single-unit with OBU in cab	Three antennas on roof (fore/aft), OBU in cab	Two antennas on working body roof with OBU also at working body	One antenna on cab roof plus two on antlers or protrusions on	One antenna on cab roof plus a mirror mounted antenna on each side	One antenna on cab roof plus a mirror mounted antenna & radio on each side	Mirror mounted antennas & radios, plus separate GPS and Ch174+ antennas
Main module	2-radio OBU in or on cab	1-radio OBU near front of roof	2-radio OBU - inside working body	2-radio OBU - in or on cab	2-radio OBU - near front	1-radio OBU in cab	1-radio OBU in cab
DSRC Ch174+ radio	In OBU	In OBU	In OBU	In OBU	In OBU	In OBU	In OBU
GPS/Ch174+ units, locations	Sharkfin, forward roof	Sharkfin, forward roof	Sharkfin, forward roof	Sharkfin, forward roof	Sharkfin, forward roof	Sharkfin, forward roof	GPS: horizontal surface with sky view. Ch 174+ on inside of window
DSRC Ch172 radios	In OBU	Remote radio, on roof	In OBU	In OBU	In OBU	Remote radios at mirrors	Remote radios at mirrors
DSRC Ch172 antenna location	Sharkfin, center	2 sharkfins, fore and aft roof	Sharkfin on working	Mast antennas, one on each mirror arm	Mast or protruding sharkfin, one on each mirror	Mast antennas, one on each mirror arm	Mast antennas, one on each mirror arm
Number of radios and antennas	4	5	5	5	5	6	7
Number of locations of radios and antennas	3	5	4	4	4	6	7

Table 7: Details of equipment and mounting locations for the seven installations

Based on the review of the placement and performance requirements of the OBUs and antennas, researchers and our industry partners coalesced on two types of OBUs and two sets of antennas. The characteristics of the two types of OBUs include:

OBU Type 1:

- Two (2) DSRC radios (one for high-priority messages on channel 172 (e.g., BSM (Basic Safety Messages)) and one for other channels supporting security and other messages),
  - DSRC radio #1 is intended for operation on channels other than the Safety Channel ("channel 174+") and must support at least one external RF antenna.
  - DSRC radio #2 is to be used for BSM transmission and reception on the Safety Channel (channel 172) and must support two external RF antennas and support full transmit and receive diversity.
- GNSS receiver, not including antenna
- Middleware for interpreting received BSMs as well as broadcasting BSMs
- Yaw rate and longitudinal acceleration sensors
- Application software for about six applications
- Ability to update software through either physical interface or wirelessly
- Ability to both drive a supplied interface (external speaker and 4-LED set) for driver alerts, or drive existing speaker or LED set (e.g., through serial bus .wav files and commands for an existing simple LED set)
- CAN transceiver for J1939 or other OEM CAN bus
- Truck environment design
- Self-contained module for the above, plus power moding

OBU Type 2 is similar to OBU Type 1, except

- DSRC radio #2 is replaced with two external radios, each supporting Safety Channel 172
- Each of the two external radios would be mounted several meters from the OBU, close to an RF antenna (not to be quoted), to avoid running DSRC wires through the door of the vehicle
    - The radios need to be quite small, perhaps fitting within a volume of 65 cubic centimeters
    - The radios each need to interface with an RF antenna and the OBU and would be powered by the OBU
    - The radios will provide synchronized communications to the OBU

For the two antenna sets, all the vehicles will receive one shark fin antenna for both GNSS and DSRC security (and certain other messages not on channel 172). Researchers estimate that because of the challenges of mounting effective DSRC communication antennas on many different styles of trucks, one group will have one shark fin antenna for the Basic Safety Message (BSM) ("channel 172"), and the other group will have two mast antennas for the Basic Safety Message (BSM).

4.2 Three installation configurations to support subsequent project tasks

The reduction from seven to three configurations is based on the need to have a manageable number of configurations that OBU, antenna, and installation companies can use to estimate costs for these components and services. The three configurations were selected to span the space of hardware costs and installation complexity. For this purpose of reducing the number of configurations – but not for the costing itself, which is addressed in following sections – the number of radios and antennas, shown near the bottom of Table 7, were used as a surrogate for hardware cost, and the number of different locations at which radios and antennas are to be mounted was used as a surrogate of installation complexity and cost. The three configurations selected are Roof-1, Sides-1, and Sides-3 (as indicated in Tables 6 and 7). The details of the three configurations were presented earlier in Tables 6 and 7. These configurations, as shown in Figure 14, can cover nearly all different types of trucks in service.

The three major configurations of trucks for V2V/V2I retrofits cover unique designs for these types of trucks. Final Configuration 1 (Roof-1), shown in Figure 16, uses a rooftop mounted unit for both GNSS and DSRC antennas. This configuration applies to all buses, motor homes, and straight trucks that provide an adequate view of the sky, as well as truck tractors that do not use fairings.

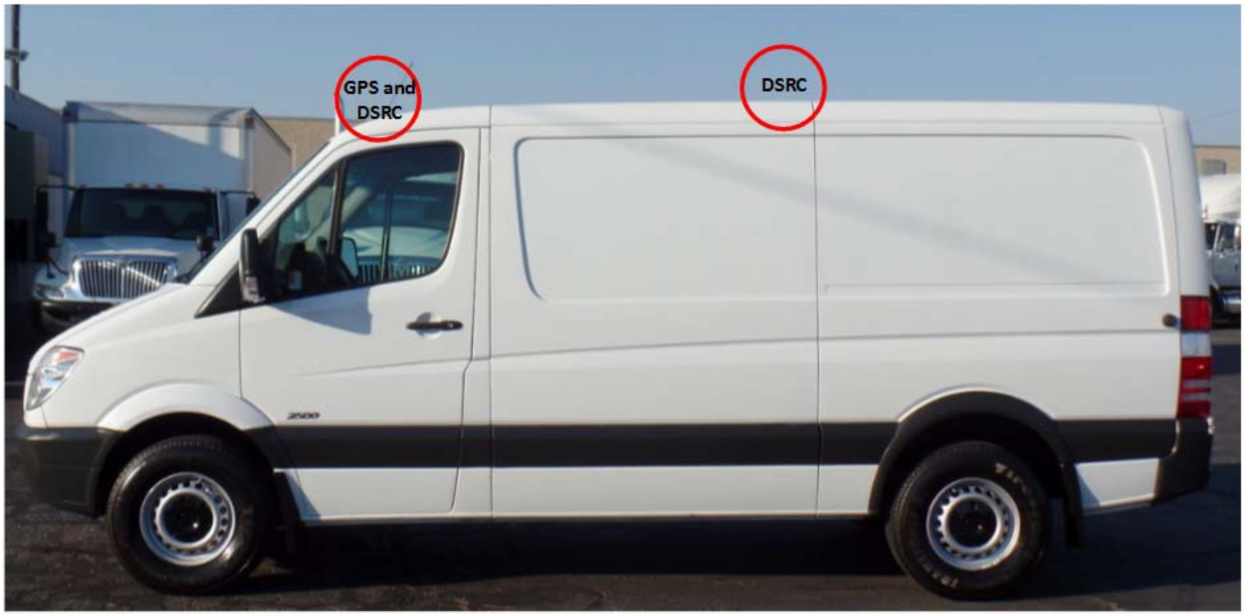

Figure 11: Retrofit Configuration 1 for buses, motor homes, and most straight trucks

Configuration 2, shown in Figure 12, is a fairing mounted design that applies to nearly all truck tractors with articulated trailers that use fairings.

Figure 12: Retrofit Configuration 2 for nearly all truck tractors with articulating trailers

The retrofit configuration 3, shown in Figure 13, uses mirror-mounted “smart” DSRC radios that receive information from vehicles surrounding the truck and links to the main DSRC unit. This configuration is used for trucks where it is difficult for the DSRC unit to receive and send signals because parts of the vehicle block the line of sight.

Figure 13: Retrofit Configuration 3 for use with specific truck tractors, straight trucks, buses, and vocational trucks

5. Configuration Costing for OBUs and Antenna Packages

To estimate the cost of retrofitting the entire fleet of class 3 to 8 trucks and buses in the United States, the project needed an estimate of the cost of the technologies to be installed. To generate these estimates, a survey of OBU and antenna suppliers was performed. Four OBU suppliers were asked to estimate the cost of the two sets of OBUs described in Section 3. Because of the effects of volume on costs, estimates were asked for the two OBU Types described for orders of 10,000, 100,000, 1,000,000, and 10,000,000. Table 8 shows the average technology costs for the two types of OBUs across the four volumes.

The two types of OBUs were chosen to represent different penetrations in the truck population (OBU Type 1: 80 percent, OBU Type 2: 20%). OBU Type 1 will be used for most buses, truck tractors, and many straight trucks and vocational trucks, while OBU Type 2 will be used specifically for some truck tractors, straight trucks, and vocational trucks that do not have a clear line-of-sight for some of the vehicles behind them.

Type of DSRC OBU	Volume: 10,000	Volume: 100,000	Volume: 1,000,000	Volume: 10,000,000
OBU Type 1: Price per Unit Average	Volume: 8,000 $513	Volume: 80,000 $309	Volume: 800,000 $243	Volume: 8,000,000 $189
OBU Type 2: Price per Unit Average	Volume: 2,000 $1,094	Volume: 20,000 $605	Volume: 200,000 $379	Volume: 2,000,000 $302
Weighted Average	$629	$368	$270	$212

Table 8: Weighted cost estimates for two types of OBUs

The weighted cost estimates across the four increasing volumes shows about a 20 percent reduction with each order of magnitude, with a significant reduction of more than $400 from a volume of 10,000 to a volume of 10,000,000.

There are also two antenna technology packages chosen for retrofitting. All vehicles will have one shark fin antenna for both GPS and DSRC security (and certain other messages not on channel 172). The challenges of mounting effective DSRC communication antennas on many different styles of trucks will require that one half of the vehicle population will need one shark fin antenna for the basic safety message ("channel 172"), while the other half will have two mast antennas for the BSM. Three antenna suppliers were surveyed, asking them to estimate the cost of these three types of antennas across the four volume assumptions used for the OBUs. Table 9 shows the survey results across the four volume assumptions.

Type of DSRC Antenna	Volume: 10,000	Volume: 100,000	Volume: 1,000,000	Volume: 10,000,000
A) GPS/Security (Shark Fin): Price per Antenna	Volume: 10,000 $40.39	Volume: 100,000 $36.74	Volume: 1,000,000 $30.19	Volume: 10,000,000 $28.47
A) Basic Safety Message (BSM) (Shark Fin): Price per Antenna	Volume: 5,000 $25.65	Volume: 50,000 $23.16	Volume: 500,000 $15.80	Volume: 5,000,000 $14.49
A) C) Basic Safety Message (BSM) (2 Mast antennas) Price for Two antennas	Volume: 5,000 $66.13	Volume: 50,000 $57.91	Volume: 500,000 $26.60	Volume: 5,000,000 $24.99

Table 9: Cost estimates for three types of antennas

The cost estimates across the four increasing volumes shows an average percent reduction of about 17 percent with each order of magnitude, with the biggest decrease taking place when volumes move from 100,000 to 1,000,000. The biggest percentage price reduction from volumes of 5,000 to 5,000,000 was in the two mast antennas where prices were reduced by 62 percent.

6. Configuration Costing for Installing OBUs and Antenna Packages

For costing the installation of OBUs and antennas, researchers took advantage of the expertise of one of our industry partners, Velociti, that specializes in retrofitting new technologies on trucks across the country. Velociti is expert in large scale retrofitting projects where they work with the suppliers of the technology as well as the fleet to create a detailed installation plan of all the different types of trucks in a fleet. Based on our discussions with them about the three configurations described in Section 4, Velociti provided estimates for each of the three configurations (installations) shown in Table 10.

Similar to the costs of the OBUs and antennas, Velociti provided estimates across four volumes: 10,000, 100,000, 1,000,000, and 10,000,000. A weighted average of all estimates for each volume was generated because of the different distributions associated with each installation: Installation 1: 50 percent of installs, Installation 2: 40 percent of installs, and Installation 3: 10 percent of installs. The biggest percentage decrease occurred when moving from 10,000 to 100,000 installs, 20 percent. The percentage decrease in installation costs from 10,000 to 10,000,000 was 41 percent.

Type of DSRC Installation	Volume: 10,000	Volume: 100,000	Volume: 1,000,000	Volume: 10,000,000
Installation 1 (50 percent of installs) Price per Install	Volume: 5,000 $270	Volume: 50,000 $200	Volume: 500,000 $180	Volume: 5,000,000 $162
Installation 2 (40 percent of installs) Price per Install	Volume: 4,000 $330	Volume: 40,000 $300	Volume: 400,000 $270	Volume: 4,000,000 $243
Installation 3 (10 percent of installs) Price per Install	Volume: 1,000 $270	Volume: 10,000 $200	Volume: 100,000 $180	Volume: 1,000,000 $162
Weighted Average	$294	$240	$216	$194

Table 10: Cost estimates for three types of installations

7. Configuration Costing for Equipment and Installation

Combining the cost of the OBUs and the antennas, as well as the installation of the technology allows for an estimate of the total cost of implementing a complete V2V/V2I system using vehicle safety communications across four different volume assumptions. Table 11 displays costs across the different volumes for the equipment and installation, adjusting for differences in vehicles that use a shark fin or a mast antenna. The shark fin antenna applies to configurations 1 and 2, while the mast antenna applies to configuration 3.

DSRC Technology Components and Installation	Volume: 10,000	Volume: 100,000	Volume: 1,000,000	Volume: 10,000,000
A) OBU	$629	$368	$270	$212
B) GPS Antenna	$40	$37	$30	$28
C) BSM Antenna: Sharkfin	$26	$23	$16	$14
D) BSM Antenna: Mast	$66	$58	$27	$25
E) Installation	$294	$240	$216	$194
A+B+C+E	$989	$668	$532	$449
A+B+D+E	$1,029	$702	$543	$459

Table 11: Cost estimates for different volumes and different combinations of technology

With estimates for the number of vehicles in each of the four groups: buses, truck tractors, straight trucks, and vocational trucks; estimates for the cost of different OBUs and antennas based on the type of installation; and estimates for the cost of installing the technology on each of the three configurations, researchers were able to estimate the cost of retrofitting the entire class 3 to 8 trucks, as shown in Section 9.

8. Applying V2V/V2I technology and installation costs to the entire class 3 to 8 vehicles

Using the most recent counts of all the class 3 to 8 trucks in the United States, researchers are able to categorize them according to their potential retrofit penetration based on technical considerations, and multiply the final counts by the costs of retrofit equipment and installation to provide an estimate of the cost of retrofitting the vast majority of class 3 to 8 trucks in the United States.

There are two challenging aspects of generating estimates the costs of retrofitting the entire class 3 to 8 vehicles in the United States. The first is estimating what percentage of trucks requires which equipment and installation configurations. This is called the Configuration challenge. The second is estimating what percentage of vehicles fit into the category of very difficult and too expensive to retrofit, which is called the No-Retrofit challenge.

In the Configuration challenge, three configurations were designed to cover the vast number of vehicles in the U.S. class 3 to 8 universe, these configurations may apply to vehicles in some or all four types of vehicles: straight trucks, truck tractors, buses, and vocational trucks. For example, some of the buses in the bus category will use configuration 1, as will some of the vans in the straight truck category. Configuration 2 will be used for all tractors with fairings, but also on some straight trucks and vocational vehicles that can have "antlers" installed. Configuration 3 will be used for some of the buses, vocational vehicles, and truck tractors.

In the No Retrofit challenge, for estimating the percentage of vehicles that are very difficult and too expensive to retrofit, it is possible to use as a base the percentage of one of a certain type of trucks in the U.S fleet based on the VIUS analysis used to create the vocational truck category. For example, the VIUS estimated that there are 165,752 garbage trucks in the United States. Some percentage of these trucks fall into the very difficult and too expensive to retrofit category, but not all of them. This is also true for car carriers, dump trucks, and many other vocational trucks.

To estimate the effects of these two challenges, three separate estimates are generated that represent potential scenarios for the Configuration challenge and one estimate will be generated for the No Retrofit challenge using estimates from the VIUS as well as from the MCMIS file from FMCSA that was used to generate the sample for the survey. Neither of these two sources provide a census of the population of class 3 to 8 vehicles, but they are good sources from which to generate broad estimates.

8.1 No retrofit calculation

The percentage of No Retrofit vehicles varies by the four types of vehicles: straight trucks, truck tractors, buses, and vocational trucks. The main type of trucks most affected by No Retrofits are vocational trucks, most of which are a subset of straight trucks. The VIUS percentages are a percentage of all straight trucks, while the MCMIS percentages are a percentage of all trucks, not including buses. The most common vocational trucks that fit into the No Retrofits category include the following.

- Auto carriers (MCMIS: 1.4%)
- Garbage trucks (MCMIS: 2.2%, VIUS: 2.1%)
- Dump trucks (VIUS: 6.8%)
- Flatbeds for large objects (MCMIS: 1.1%)
- Concrete mixers: (VIUS: 1.8%)
- Bucket trucks: (VIUS: .4%)
- Utility trucks: (VIUS: 1.2%)
- Construction trucks: (VIUS: 7.9%)

Because not all of these vehicles are considered very expensive and too difficult to retrofit, an estimate for each of the vehicle types will be generated and used for all the cost analyses. The small number of vehicles that fit into the No Retrofit category does not require separate scenarios. Table 12 displays the estimates used for the No Retrofit challenge. Each of these estimates will be subtracted from the total number of vehicles for that vehicle type.

Vehicle types	% of All Vehicles	# of All Vehicles	% of Vehicles: No Retrofits	# of Vehicles: No Retrofits
Auto Carriers	1.40%	179,459	75%	134,594
Garbage Trucks	2.10%	269,188	50%	134,594
Dump Trucks	6.80%	871,658	60%	522,995
Flatbed Trucks for Large Objects	1.10%	141,003	25%	35,251
Concrete Mixers	1.80%	230,733	50%	115,366
Bucket Trucks	0.40%	51,274	75%	38,455
Utility Trucks	1.20%	153,822	50%	76,911
Construction Trucks	7.90%	1,012,661	50%	506,331

Table 12: Estimates for the number of trucks with no retrofits

8.2 Configuration Calculation

The three configurations discussed in Section 4 can be effective in more than one vehicle type. Which configuration works best for a vehicle depends primarily on how the antennas are placed for optimal connectivity. Because of this variance, different vehicles within the same vehicle type may use different configurations. Some buses can use configuration 1 or configuration 3; some truck tractors, straight trucks, and vocational trucks can use configuration 1 or configuration 2 or configuration 3. To see the effects of different distributions of the configurations across the four vehicle types, three separate scenarios were designed. In each of these scenarios, the No Retrofit vehicles were deleted from the vocational truck counts.

Retrofit scenario 1, shown in Table 13, examines high concentrations of configuration 1 for buses and straight trucks, configuration 2 for truck tractors and vocational trucks, and configuration 3 for truck tractors. This distribution is based on the original distribution of 50 percent of all vehicles using configuration 1, 40 percent using configuration 2, and 10 percent using configuration 3. To generate this 50/40/10 distribution, researchers allocated the distributions among the four categories of vehicles. For example, in configuration 1 the distribution of 85 percent for buses, 85 percent for straight trucks, and 10 percent for vocational trucks represents the estimated distribution of this configuration across the four types of vehicles. And the combination of all these vehicles, 5,610,324, represents 50 percent of all vehicles across all three configurations. For configuration 2, the distribution of 80 truck tractors, 15 percent straight trucks, and 75 percent vocational trucks represents a distribution where configuration 2, 4,542,254, represents 40 percent of all vehicles across all three configurations. Finally, in configuration 3, the distribution of 15 percent buses, 20 percent truck tractors, and 15 percent vocational trucks represents a distribution where configuration 3, 1,164,500, represents 10 percent of all vehicles across all three configurations.

Retrofit scenarios 2 and 3 also distribute the three configurations across the four vehicle categories using different distributions based on how the three configurations could be used. Scenario 2 focuses more on equal distributions of the three configurations across the four vehicle categories, and scenario 3 focuses more distributions on configurations two and three compared to configuration one to see how using these different distributions will affect the costs of retrofitting the fleet.

Vehicle types	Total Number of Vehicles	% of Configuration 1	# Vehicles in Configuration 1	% of Configuration 2	# Vehicles in Configuration 2	% of Configuration 3	# Vehicles in Configuration 3
Bus and Motor Homes	1,828,419	85%	1,554,156	0%	0	15%	274,263
Truck-tractors	2,946,611	0%	0	80%	2,357,289	20%	589,322
Straight trucks	4,535,951	85%	3,855,558	15%	680,393	0%	-
Vocational Trucks	2,006,097	10%	200,610	75%	1,504,573	15%	300,915
Total	11,317,078		5,610,324		4,542,254		1,164,500

Table 13: Retrofit scenario 1

Retrofit scenario 2, shown in Table 14, examines equal distributions of configurations 1 and 3 for buses, equal distributions of configurations 2 and 3 for truck tractors, a higher distribution of configuration 2 for straight trucks, and configuration 3 for vocational trucks. In terms of the weighted average across all vehicles, this configuration is weighted more heavily towards configuration 3 (40%) and configuration 2 (37%) than configuration 1 (23%).

Vehicle types	Total Number of Vehicles	% of Configuration 1	# Vehicles in Configuration 1	% of Configuration 2	# Vehicles in Configuration 2	% of Configuration 3	# Vehicles in Configuration 3
Bus and Motor Homes	1,828,419	50%	914,210	0%	0	50%	914,210
Truck-tractors	2,946,611	0%	0	50%	1,473,306	50%	1,473,306
Straight trucks	4,535,951	25%	1,133,988	50%	2,267,976	25%	1,133,988
Vocational Trucks	2,006,097	25%	501,524	25%	501,524	50%	1,003,049
Total	11,317,078		2,549,722		4,242,805		4,524,551

Table 14: Retrofit scenario 2

Retrofit scenario 3, shown in Table 15, looks at higher distributions of configuration 3 for buses, and configuration 2 for truck tractors, and configuration 1 for straight trucks and vocational trucks. The weighted average across all vehicles in this scenario shows configuration 1 with a higher percentage of vehicles (39%) followed by configuration 3 (33%) and configuration 2 (27%).

Vehicle types	Total Number of Vehicles	% of Configuration 1	# Vehicles in Configuration 1	% of Configuration 2	# Vehicles in Configuration 2	% of Configuration 3	# Vehicles in Configuration 3
Bus and Motor Homes	1,828,419	25%	457,105	0%	0	75%	1,371,314
Truck-tractors	2,946,611	25%	736,653	50%	1,473,306	25%	736,653
Straight trucks	4,535,951	50%	2,267,976	25%	1,133,988	25%	1,133,988
Vocational Trucks	2,006,097	50%	1,003,049	25%	501,524	25%	501,524
Total	11,317,078		4,464,782		3,108,818		3,743,479

Table 15: Retrofit scenario 3

8.3 Cost Calculation

Each of the three retrofit scenarios allows for an estimate to be generated for the cost of retrofitting all the vehicles in the U.S. fleet that can be retrofitted. The costs include separate estimates for equipment and installation with separate estimates for volumes of 1 million and 10 million.

In retrofit scenario 1, the distribution across the three configurations is based on the distribution of 50 percent of all vehicles using configuration 1, 40 percent using configuration 2, and 10 percent using configuration 3. Tables 16-18 shows the total costs of using retrofit scenario 1 for configurations 1-3. Table 19 shows the total costs for all three configurations for retrofit scenario 1.

Vehicle types	Total Number of Vehicles in Configuration 1	Cost of Equipment for Configuration 1: 1 million	Cost of Installation of Configuration 1: 1 million	Cost of Equipment for Configuration 1: 10 million	Cost of Installation of Configuration 1: 10 million	Total Cost Configuration 1: 1 million	Total Cost Configuration 1: 10 million
Bus and Motor Homes	1,554,156	$532.00	$180.00	$449.00	$162.00	$1,106,559,179	$949,589,408
Truck-tractors	0	$532.00	$180.00	$449.00	$162.00	$0	$0
Straight trucks	3,855,558	$532.00	$180.00	$449.00	$162.00	$2,745,157,545	$2,355,746,152
Vocational Trucks	200,610	$532.00	$180.00	$449.00	$162.00	$142,834,106	$122,572,527
Total	5,610,324					$3,994,550,830	$3,427,908,086

Table 16: Retrofit scenario 1 total costs for configuration 1

Vehicle types	Total Number of Vehicles in Configuration 2	Cost of Equipment for Configuration 2: 1 million	Cost of Installation for Configuration 2: 1 million	Cost of Equipment for Configuration 2: 10 million	Cost of Installation for Configuration 2: 10 million	Total Cost Configuration 2: 1 million	Total Cost Configuration 2: 10 million
Bus and Motor Homes	0	$532.00	$270.00	$449.00	$243.00	$0	$0
Truck-tractors	2,357,289	$532.00	$270.00	$449.00	$243.00	$1,890,545,618	$1,631,243,850
Straight trucks	680,393	$532.00	$270.00	$449.00	$243.00	$545,674,905	$470,831,714
Vocational Trucks	1,504,573	$532.00	$270.00	$449.00	$243.00	$1,206,667,346	$1,041,164,343
Total	4,542,254					$3,642,887,868	$3,143,239,906

Table 17: Retrofit scenario 1 total costs for configuration 2

Vehicle types	Total Number of Vehicles in Configuration 3	Cost of Equipment for Configuration 3: 1 million	Cost of Installation for Configuration 3: 1 million	Cost of Equipment for Configuration 3: 10 million	Cost of Installation for Configuration 3: 10 million	Total Cost Configuration 3: 1 million	Total Cost Configuration 3: 10 million
Bus and Motor Homes	274,263	$543.00	$216.00	$459.00	$194.00	$208,165,503	$179,093,641
Truck-tractors	589,322	$543.00	$216.00	$459.00	$194.00	$447,295,550	$384,827,397
Straight trucks	0	$543.00	$216.00	$459.00	$194.00	$0	$0
Vocational Trucks	300,915	$543.00	$216.00	$459.00	$194.00	$228,394,143	$196,497,201
Total	1,164,500					$883,855,196	$760,418,239

Table 18: Retrofit scenario 1 total costs for configuration 3

Vehicle types	Total Cost All Configurations: 1 million	Total Cost All Configurations: 10 million
Bus and Motor Homes	$1,314,724,682	$1,128,683,049
Truck-tractors	$2,337,841,167	$2,016,071,246
Straight trucks	$3,290,832,451	$2,826,577,866
Vocational Trucks	$1,577,895,595	$1,360,234,071
Total	$8,521,293,895	$7,331,566,231

Table 19: Retrofit scenario 1 total costs for all three configurations

In retrofit scenario 2, the distribution across the three configurations is based on the distribution of 23 percent of all vehicles using configuration 1, 37 percent using configuration 2, and 40 percent using configuration 3. Tables 20-22 shows the total costs of using retrofit scenario 2 for configurations 1-3. Table 23 shows the total costs for all three configurations for retrofit scenario 2.

Vehicle types	Total Number of Vehicles in Configuration 1	Cost of Equipment for Configuration 1: 1 million	Cost of Installation of Configuration 1: 1 million	Cost of Equipment for Configuration 1: 10 million	Cost of Installation of Configuration 1: 10 million	Total Cost Configuration 1: 1 million	Total Cost Configuration 1: 10 million
Bus and Motor Homes	914,210	$532.00	$180.00	$449.00	$162.00	$650,917,164	$558,582,005
Truck-tractors	0	$532.00	$180.00	$449.00	$162.00	$0	$0
Straight trucks	1,133,988	$532.00	$180.00	$449.00	$162.00	$807,399,278	$692,866,515
Vocational Trucks	501,524	$532.00	$180.00	$449.00	$162.00	$357,085,266	$306,431,317
Total	2,549,722					$1,815,401,708	$1,557,879,837

Table 20: Retrofit scenario 2 total costs for configuration 1

Vehicle types	Total Number of Vehicles in Configuration 2	Cost of Equipment for Configuration 2: 1 million	Cost of Installation for Configuration 2: 1 million	Cost of Equipment for Configuration 2: 10 million	Cost of Installation for Configuration 2: 10 million	Total Cost Configuration 2: 1 million	Total Cost Configuration 2: 10 million
Bus and Motor Homes	0	$532.00	$270.00	$449.00	$243.00	$0	$0
Truck-tractors	2,357,289	$532.00	$270.00	$449.00	$243.00	$1,890,545,618	$1,631,243,850
Straight trucks	680,393	$532.00	$270.00	$449.00	$243.00	$545,674,905	$470,831,714
Vocational Trucks	1,504,573	$532.00	$270.00	$449.00	$243.00	$1,206,667,346	$1,041,164,343
Total	4,542,254					$3,642,887,868	$3,143,239,906

Table 21: Retrofit scenario 2 total costs for configuration 2

Vehicle types	Total Number of Vehicles in Configuration 3	Cost of Equipment for Configuration 3: 1 million	Cost of Installation for Configuration 3: 1 million	Cost of Equipment for Configuration 3: 10 million	Cost of Installation for Configuration 3: 10 million	Total Cost Configuration 3: 1 million	Total Cost Configuration 3: 10 million
Bus and Motor Homes	274,263	$543.00	$216.00	$459.00	$194.00	$208,165,503	$179,093,641
Truck-tractors	589,322	$543.00	$216.00	$459.00	$194.00	$447,295,550	$384,827,397
Straight trucks	0	$543.00	$216.00	$459.00	$194.00	$0	$0
Vocational Trucks	300,915	$543.00	$216.00	$459.00	$194.00	$228,394,143	$196,497,201
Total	1,164,500					$883,855,196	$760,418,239

Table 22: Retrofit scenario 2 total costs for configuration 3

Vehicle types	Total Cost All Configurations: 1 million	Total Cost All Configurations: 10 million
Bus and Motor Homes	$859,082,667	$737,675,646
Truck-tractors	$2,337,841,167	$2,016,071,246
Straight trucks	$1,353,074,183	$1,163,698,229
Vocational Trucks	$1,792,146,755	$1,544,092,861
Total	$6,342,144,773	$5,461,537,982

Table 23: Retrofit scenario 2 total costs for all three configurations

In retrofit scenario 3, the distribution across the three configurations is based on the distribution of 39 percent of all vehicles using configuration 1, 27 percent using configuration 2, and 33 percent using configuration 3. Tables 24-26 shows the total costs of using retrofit scenario 3 for configurations 1-3. Table 27 shows the total costs for all three configurations for retrofit scenario 2.

Vehicle types	Total Number of Vehicles in Configuration 1	Cost of Equipment for Configuration 1: 1 million	Cost of Installation of Configuration 1: 1 million	Cost of Equipment for Configuration 1: 10 million	Cost of Installation of Configuration 1: 10 million	Total Cost Configuration 1: 1 million	Total Cost Configuration 1: 10 million
Bus and Motor Homes	457,105	$532.00	$180.00	$449.00	$162.00	$325,458,582	$279,291,002
Truck-tractors	736,653	$532.00	$180.00	$449.00	$162.00	$524,496,758	$450,094,830
Straight trucks	2,267,976	$532.00	$180.00	$449.00	$162.00	$1,614,798,556	$1,385,733,031
Vocational Trucks	1,003,049	$532.00	$180.00	$449.00	$162.00	$714,170,532	$612,862,634
Total	4,464,782					$3,178,924,428	$2,727,981,497

Table 24: Retrofit scenario 3 total costs for configuration 1

Vehicle types	Total Number of Vehicles in Configuration 2	Cost of Equipment for Configuration 2: 1 million	Cost of Installation for Configuration 2: 1 million	Cost of Equipment for Configuration 2: 10 million	Cost of Installation for Configuration 2: 10 million	Total Cost Configuration 2: 1 million	Total Cost Configuration 2: 10 million
Bus and Motor Homes	0	$532.00	$270.00	$449.00	$243.00	$0	$0
Truck-tractors	1,473,306	$532.00	$270.00	$449.00	$243.00	$1,181,591,011	$1,019,527,406
Straight trucks	1,133,988	$532.00	$270.00	$449.00	$243.00	$909,458,176	$784,719,523
Vocational Trucks	501,524	$532.00	$270.00	$449.00	$243.00	$402,222,449	$347,054,781
Total	3,108,818					$2,493,271,635	$2,151,301,710

Table 25: Retrofit scenario 3 total costs for configuration 2

Vehicle types	Total Number of Vehicles in Configuration 3	Cost of Equipment for Configuration 3: 1 million	Cost of Installation for Configuration 3: 1 million	Cost of Equipment for Configuration 3: 10 million	Cost of Installation for Configuration 3: 10 million	Total Cost Configuration 3: 1 million	Total Cost Configuration 3: 10 million
Bus and Motor Homes	1,371,314	$543.00	$216.00	$459.00	$194.00	$1,040,827,516	$895,468,205
Truck-tractors	736,653	$543.00	$216.00	$459.00	$194.00	$559,119,437	$481,034,246
Straight trucks	1,133,988	$543.00	$216.00	$459.00	$194.00	$860,696,702	$740,494,001
Vocational Trucks	501,524	$543.00	$216.00	$459.00	$194.00	$380,656,906	$327,495,335
Total	3,743,479					$2,841,300,561	$2,444,491,787

Table 26: Retrofit scenario 3 total costs for configuration 3

Vehicle types	Total Cost All Configurations: 1 million	Total Cost All Configurations: 10 million
Bus and Motor Homes	$1,366,286,098	$1,174,759,208
Truck-tractors	$2,265,207,206	$1,950,656,482
Straight trucks	$3,384,953,434	$2,910,946,554
Vocational Trucks	$1,497,049,886	$1,287,412,750
Total	$8,513,496,624	$7,323,774,994

Table 27: Retrofit scenario 3 total costs for all three configurations

The three retrofit scenarios are designed to provide a range of costs based not only on the uncertainty around all the different types of class 3 to 8 vehicles on the road but also around the potential costs of retrofitting these vehicles. As the previous tables show, depending on the distribution of the different configurations across the four vehicle categories and volume assumptions, costs will vary from $5.5 billion to $8.5 billion, with increases in volume lowering the total cost by about $1 billion. At the one million volume estimate, retrofit scenarios 1 and 3 both cost $8.5 billion while retrofit scenario 2 costs about $6.3 billion. With a 10 million volume estimate, retrofit scenarios 1 and 3 both cost $7.1 billion while retrofit scenario 2 costs $5.5 billion.

9. Conclusion

This report provides the analysis of how vehicle safety communications V2V/V2I technologies can be retrofitted unto nearly all the class 3 to 8 vehicles on the road today, including buses, truck tractors, straight trucks, and vocational trucks. Technology suppliers were surveyed to develop estimates for the cost of the equipment and a retrofit expert generated estimates for the cost of installation of the technology that, when estimated at high volumes, allowed for an introductory cost of about $450 to $550 per vehicle. Estimates for the total number of class 3 to 8 vehicles on the road in 2017 in four major categories were developed: buses, truck-tractors, straight trucks, and vocational trucks. Three configurations used to install the technologies onto nearly all class 3 to 8 trucks in operation were presented. Which configuration works best for a vehicle depends primarily on how the antennas are placed for optimal connectivity. Because of this variance, different vehicles within the same vehicle type may use different configurations and this accounts for the range in total costs presented.

The analyses also provided estimates of the total costs of retrofitting the V2V/V2I technologies onto nearly the entire fleet, using three different scenarios for implementing the three installation configurations. Depending on the distribution of the different configurations across the four vehicle categories and volume assumptions, costs will vary from $5.5 billion to $8.5 billion, with increases in volume lowering the total cost by about $1 billion. At the one million volume estimate, retrofit scenarios 1 and 3 both cost $8.5 billion while retrofit scenario 2 costs about $6.3 billion. With a 10 million volume estimate, retrofit scenarios 1 and 3 both cost $7.1 billion while retrofit scenario 2 costs $5.5 billion.

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