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POTENTIAL IMPROVEMENTS IN SAFETY AND EFFICIENCY WITH AUTONOMOUS TRUCKING

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16. Abstract

The primary focus of this white paper was to analyze and compare the relative advantages and disadvantages for autonomous large trucks versus autonomous light-duty vehicles.

The examined topics are as follows:

- Overview of the U.S. trucking fleet
- Current safety status of large trucks in the U.S.
- Overview of autonomous and connected large-truck technologies
- Safety improvements for autonomous large trucks, including sensor placement considerations relative to light-duty vehicles, blind-spot and sensor-coverage improvements, additional sensor considerations, and the effects of autonomous and connected operation on nighttime crash risk
- Financial costs of large-truck crashes and the associated financial incentive to transition to autonomous and connected trucking
- Efficiency improvements for large trucks, including eco-driving and powertrain management, platooning and cost savings (and platooning's potential role in the introduction of alternative-fuel large trucks), changes in driver tasks and efficiency, and motion sickness considerations for large-truck drivers

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Abbreviations used in this report

Abbreviation	Definition
ADAS	advanced driver-assistance system
AV	autonomous vehicle
CAV	connected autonomous vehicle
CV	connected vehicle
DSRC	dedicated short-range communications
FARS	Fatality Analysis Reporting System
FMCSA	Federal Motor Carrier Safety Administration
lidar	light detection and ranging
NHTSA	National Highway Traffic Safety Administration
radar	radio detection and ranging
U.S. DOT	United States Department of Transportation
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything

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Contents

Background

As discussed in our previous reports addressing the safety implications of self-driving vehicles (Sivak and Schoettle, 2015a; 2015b), and as envisioned and supported by NHTSA (2016), fully autonomous vehicles could potentially replace the human driver for most if not all driving situations and scenarios. One major component of the transportation system that is likely to experience a variety of unique benefits with the introduction of fully autonomous vehicles is the medium- and heavy-duty trucking industry (i.e., large trucks). Just as with light-duty vehicles, major improvements in traffic safety are expected as autonomous large trucks are introduced and start to become commonplace on public roads. But an additional benefit of autonomous vehicles that is likely to be more pronounced for large-truck fleets (versus individual or family-owned light-duty vehicles) is the efficiency gains—for both truck and driver—that are expected when fully autonomous trucks hit the road. Ultimately, autonomous trucks that are also fully connected (such as V2V, V2I, V2X; for additional details, see NHTSA, 2017b) are expected to maximize both the safety and efficiency improvements for the trucking industry worldwide.

Extent of the U.S. trucking fleet

In the U.S. alone, NHTSA (2017) reports that 11.2 million large trucks were registered in 2015 (the latest available data), driving approximately 280 billion miles that year. The number of registered large trucks has continually increased for the past 11 years, with approximately 2.4 million registered trucks being added to U.S. roads between 2006 and 2015. As described in Schoettle, Sivak, and Tunnell (2016), in 2015 the U.S. trucking industry hauled 70% of all freight transported in the United States, equating to more than 10 billion tons. Trucking also collected 81.5 cents of every dollar spent on freight transportation in 2015, representing more than $726 billion in gross revenue. Over the next decade, trucking volumes are expected to increase by 17%, while revenues are projected to increase nearly 50% (ATA, 2015).

According to the U.S. Bureau of Labor Statistics (BLS, 2017), the heavy-duty trucking fleet alone employs just over 1.7 million drivers[1] across the country (excluding medium-duty drivers and self-employed heavy-duty drivers), or approximately 12 out of every 1,000 jobs. The top five states for total number of heavy-duty truck drivers employed are Texas (175,780), California (130,640), Pennsylvania (78,320), Florida (77,660), and Ohio (70,740); the top five states with the highest rate of employment (per 1,000 jobs) for heavy-duty truck drivers are North Dakota (28.7), Arkansas (27.9), Nebraska (27.8), Iowa (24.5), and Wyoming (22.5). While truck drivers may hold the most common job in 29 states, a shortage of qualified drivers and high turnover rates (estimated at approximately 80% per year for truckload fleets) are a growing problem for staffing future U.S. large-truck fleets (ATA, 2016; Business Insider, 2017; New York Times, 2017).

One long-term benefit expected from autonomous trucking is the ability to help alleviate some of this driver shortage. However, the general consensus among AV trucking developers is that the human truck driver will still be needed for the foreseeable future, as the first generation of autonomous large trucks will most likely drive autonomously on highways (i.e., "exit to exit"), with the human driver taking control on city and local streets (Trucks.com, 2016; Wired, 2017). It is anticipated that drivers in these initial fleets will likely shift from driving full time to performing a wider array of tasks, many of which will likely be done while the truck is autonomously driving and the driver is free to perform other work. Such tasks include route or cargo logistics, paperwork and other administrative duties, scheduling, resting, training, etc.

[1] BLS (2017) definition of heavy and tractor-trailer truck drivers: "Drive a tractor-trailer combination or a truck with a capacity of at least 26,000 pounds Gross Vehicle Weight (GVW). May be required to unload truck. Requires commercial drivers' license."

Large-truck safety status

FMCSA (2017b) reports that 4,050 large trucks were involved in fatal crashes in 2015, resulting in 4,067 fatalities with an overall rate of 1.45 fatalities per 100 million miles. Additionally, approximately 87,000 large trucks were involved in crashes that injured an estimated 116,000 people, at a rate of 31 injured persons per 100 million miles. For comparison, in 2015, the entire U.S. fleet of 281 million registered vehicles (including large trucks) drove approximately 3 trillion miles, with 35,092 fatalities (1.13 per 100 million miles; 22% lower than large trucks only) and 2.4 million persons injured (79 per 100 million miles; 155% higher than large trucks only). Table 1 summarizes the general fleet characteristics and crash totals for both the large-truck fleet and all vehicles in the U.S. for 2015, and Table 2 summarizes the associated crash rates for both vehicle types (NHTSA, 2017a; FMCSA, 2017b).

Table 1
General fleet characteristics and crash totals for all vehicles and for large trucks only in the U.S. in 2015 (NHTSA, 2017a; FMCSA, 2017b).

Vehicle type	Registered vehicles	Miles traveled (million)	Crashes	Injured persons (nonfatal)	Fatalities
All vehicles	281,312,446	3,095,373	6,296,000	2,443,000	35,092
Large trucks	11,203,184	279,844	415,000	116,000	4,067

Table 2
Crash rates for all vehicles and for large trucks only in the U.S. in 2015 (NHTSA, 2017a; FMCSA, 2017b; and based on the values in Table 1).

Vehicle type	Rates per 100,000 registered vehicles			Rates per 100 million vehicle-miles of travel		
	Crashes	Injuries (nonfatal)	Fatalities	Crashes	Injured persons (nonfatal)	Fatalities
All vehicles	2,238	868	12.5	203	79	1.13
Large trucks	3,865	1,035	36.3	155	41	1.45

As shown in Tables 1 and 2, some of the most important differences in fleet characteristics and safety between light-duty vehicles and large trucks on U.S. roads include the following:

- Large trucks make up around 4% of all registered vehicles, yet annually they account for approximately 9% of all miles driven on U.S. roads.
- The crash, injury, and fatality rates per registered vehicle are all higher for large trucks than the average for all vehicles, particularly the fatality rate, at 2.9 times the rate of all vehicles (36.3 vs. 12.5, respectively).[2]
- However, the rates per distance driven for all crashes and injuries are notably lower for large trucks versus all vehicles (24% lower for all crashes and 48% lower for injuries).
- Nevertheless, fatality rates per distance driven still tend to be about 28% higher than for all vehicles.

In addition to the higher crash, injury, and fatality rates per vehicle, and the higher fatality rate per distance driven, crashes involving large trucks tend to be financially costly, particularly when a fatality results. A detailed study of the financial costs (in 2000 dollars) of large-truck and bus crashes (FMCSA, 2002) estimated that the average cost per victim in fatal crashes involving large trucks was approximately \$2.7 million, and the average total cost per fatal crash was approximately \$3.3 million. Annually, fatal-crash costs for all large trucks were estimated at around \$19.6 billion. Consequently, large-truck insurance-policy premiums are two to three times higher than for typical light-duty vehicles. (The ratio of insurance losses per policy for large trucks vs. light-duty vehicles is similarly high.) Thus, a large financial incentive exists for the operators of large-truck fleets to reduce fatal crashes and overall crash severity, both from a per-crash cost perspective and an insurance-premium cost-reduction perspective.

[2] Several factors contribute to the higher fatal-crash rates for large trucks, including different overall exposure (e.g., frequent operation in inclement weather, more extensive nighttime driving) and unique operating characteristics (e.g., more limited maneuverability, large mass requiring long stopping distance, large blind spots).

Autonomous and connected large-truck technologies

With 94% of crashes associated with "a human choice or error" (NHTSA, 2016), implementation of safe, successful, automated-vehicle technology stands to significantly improve safety on U.S. roads when implemented across all major forms of road transportation. Figure 1 presents a summary of the current definitions of vehicle automation levels, including the corresponding levels of required driver engagement, available driver support, and overall responsibility for monitoring the driving task and controlling the vehicle. (Connected-vehicle technology, discussed later in this section, is not shown in Figure 1 as it does not require automation of the vehicle, and as such can be applied to vehicles operating at any automation level.) For the purposes of discussion in this report, autonomous trucking refers to fully automated medium- and heavy-duty trucks operating at automation level 3 or higher. However, the concept of large trucks with no one in the driver's seat (either with a driver in the back area or a driverless truck that is part of a platoon; see Platooning section below, page 16) are only possible with automation levels 4 and 5. (For a detailed discussion of the relative strengths of human drivers and automated vehicle sensor systems, see Schoettle [2017].)

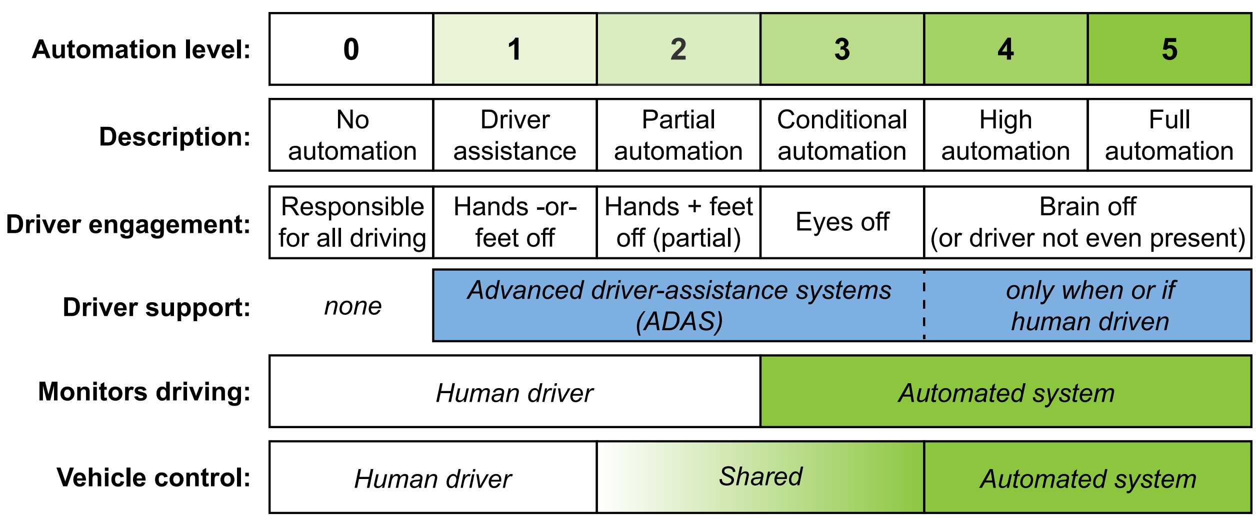

Figure 1. Summary of the current levels of vehicle automation, including the corresponding levels of required driver engagement, available driver support, and overall responsibility for monitoring the driving task and controlling the vehicle. (From Schoettle, 2017; adapted, in part, from NHTSA, 2016.)

In addition to autonomous functions, large trucks that are part of the connected vehicle (CV) network employing dedicated short-range communications (DSRC) to coordinate traffic and roadway data between vehicles and infrastructure are expected to experience significant improvements in both safety and efficiency. A summary of the benefits of CVs for all vehicle types employing DSRC is listed below:

- Applicable to vehicles operating at any automation level
- No line-of-sight requirement (omnidirectional antenna)
- Robust in weather conditions
- Able to both receive and send detailed information
- Range: Long range (~ 500 m) that can be effectively extended by communicating with transportation infrastructure in addition to other vehicles; however, the signal strength of transmissions decreases based on the inverse-square law (i.e., signal strength is inversely proportional to the square of the distance from the transmitter)
- Can communicate future actions or planned maneuvers (especially for AVs) to other traffic, alleviating need for other traffic to sense and/or predict what the connected vehicle will do
- Can communicate information about recently encountered roadway conditions, traffic conditions, etc., to other roadway users
- Able to communicate with other road users or transportation modes within the interconnected DSRC system (e.g., pedestrians, trains, etc.)
- DSRC communication paired with AV technology enables safe and effective truck platooning, maximizing safety benefits and fuel economy (because of aerodynamics) for all trucks linked in the platoon

Table 3 summarizes the key operating characteristics of each sensor for human-driven vehicles, autonomous vehicles (AV), connected vehicles (CV), and a connected autonomous vehicle (CAV). The sensors summarized in Table 3 have the same operating characteristics and typical performance regardless of vehicle type (e.g., light duty vs. heavy duty).

Table 3
Summary of the key operating characteristics of each sensor as they apply to autonomous vehicles. (From Schoettle, 2017.)

Performance aspect	Human (eyes)	AV			CV	CAV
		Radar	*Lidar*	*Camera*	*DSRC*	*CV+AV*
Object detection	Good	Good	Good	Fair	n/a	Good
Object classification	Good	Poor	Fair	Good	n/a	Good
Distance estimation	Fair	Good	Good	Fair	Good	Good
Edge detection	Good	Poor	Good	Good	n/a	Good
Lane tracking	Good	Poor	Poor	Good	n/a	Good
Visibility range	Good	Good	Fair	Fair	Good	Good
Poor weather performance	Fair	Good	Fair	Poor	Good	Good
Dark or low illumination performance	Poor	Good	Good	Fair	n/a	Good
Ability to communicate with other traffic and infrastructure	Poor	n/a	n/a	n/a	Good	Good

Safety improvements for large trucks

According to NHTSA (2017a), for the largest of large trucks on the road—heavy-duty tractor-trailers (classes 7 and 8)—the majority (approximately 60%) of fatal crashes involve impacts with the front-end of the large truck, which includes initial impact points for the large truck at either 11 o'clock (front, left), 12 o'clock (front, center), or 1 o'clock (front, right). The area immediately surrounding the cab of the truck, while sometimes difficult for the truck driver to see due to various blind spots in front or to the sides (FMCSA, 2017a), is likely to be well covered by typical AV sensors (radar, lidar, cameras, ultrasonic). Furthermore, crashes developing from a longer distance than in the area immediately surrounding the cab (for example, as can occur when a distracted driver fails to notice slowing or stopped traffic ahead) should also be able to be sensed well in advance by these same AV sensor systems. However, due to the larger physical area surrounding a large truck versus a light-duty vehicle, it is likely that a larger number of sensors will be required to effectively cover the immediate vicinity of the large trucks, including any trailers. (For a detailed description of the truck driver's field of view, related blind spots, and effects on large-truck crash causation, see Blower [2007].)

Blind spots, sensor coverage, and connected autonomous vehicles

Sensor blind spots can occur because of (1) gaps or limits in sensor coverage, or (2) obscured line of sight. Gaps or limits in sensor coverage include situations with no sensor coverage due to general range limitations of the system, and situations when certain areas or objects are visible to only one sensor, either temporarily (e.g., only within range of one sensor type) or permanently (e.g., only one sensor is capable of detecting a particular object or condition, such as fog).

For line-of-sight obstructions, Figure 2 illustrates the ability of a small number of vehicles—just two additional vehicles are shown in the figure, one ahead and one adjacent—to block the line of sight needed for conventional AV sensors to operate, creating large blind spots in sensor coverage. This problem is most pronounced when AV sensors are installed at or below the height of normal light-duty traffic. (However, certain sensors, such as ultrasonic, function best when installed below the height of normal traffic, as their intended purpose is to detect objects and vehicles relatively close by.) Figure 3 illustrates the ability of a connected autonomous vehicle (CAV) to overcome this problem with omnidirectional DSRC, which does not require line of sight to communicate.

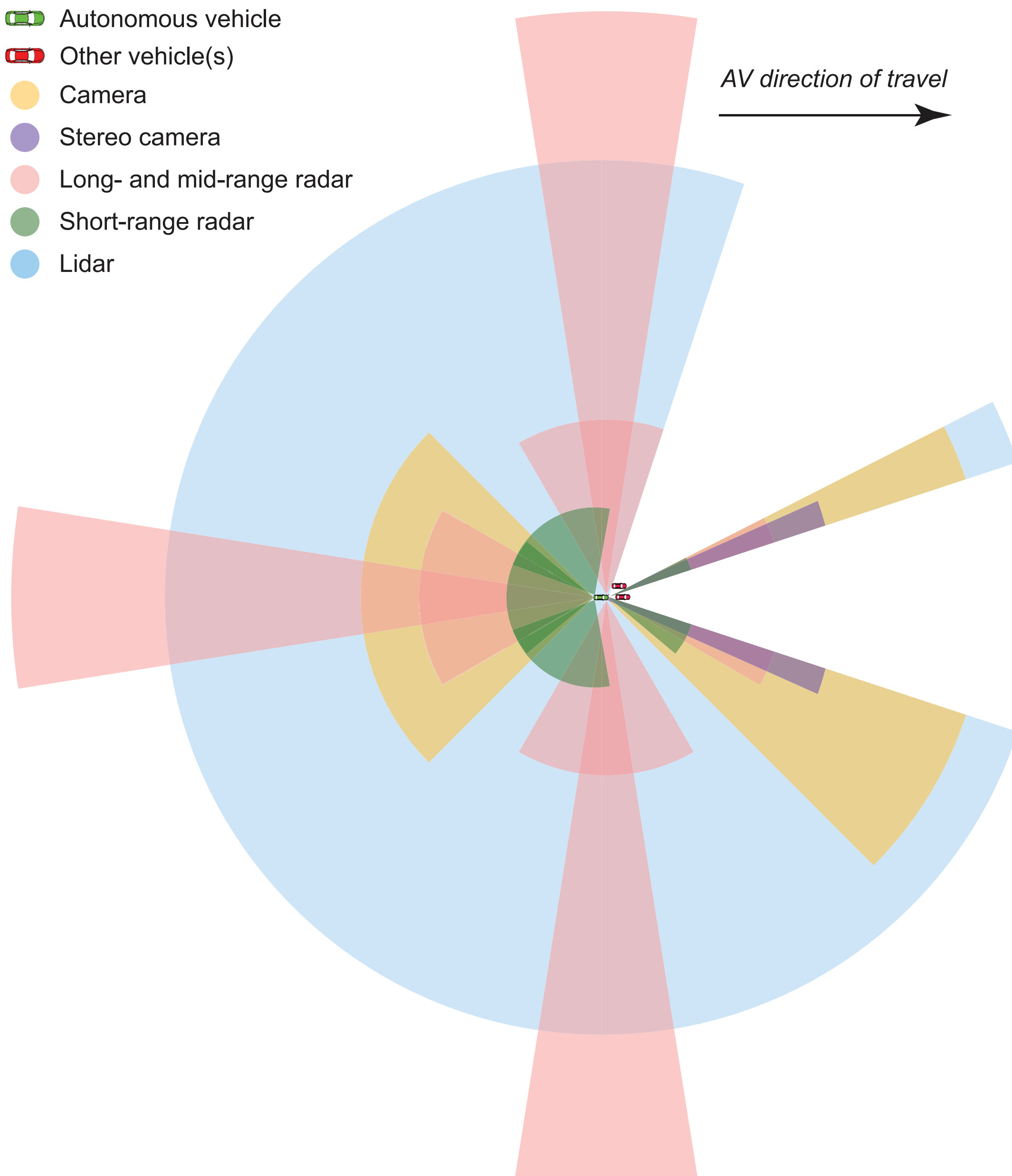

Figure 2. Example illustration of the line-of-sight obstructions (unshaded regions) for the AV sensors that are created by adjacent vehicles in traffic. (From Schoettle, 2017.)

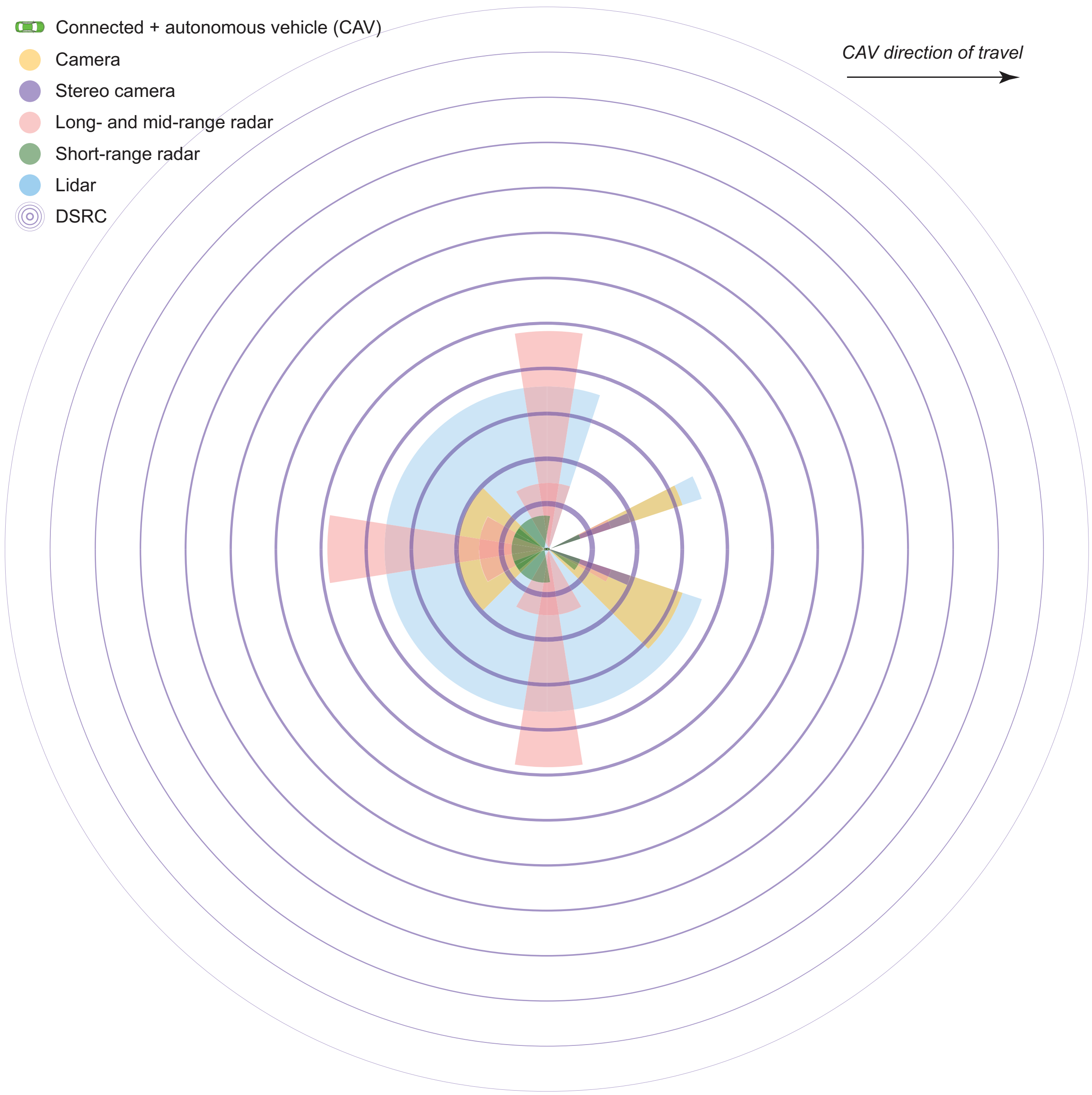

Figure 3. Example illustration of the ability of a connected autonomous vehicle (CAV) to overcome the line-of-sight obstruction problem with omnidirectional DSRC, which does not require line of sight to communicate. (From Schoettle, 2017.)

Blind-spot and sensor-coverage advantages of connected autonomous large trucks

With autonomous medium- and heavy-duty vehicles, some of the line-of-sight problem is likely to be alleviated by the higher placement of sensors that can look over or down onto surrounding traffic, taking advantage of the additional height afforded by such vehicles. Figure 4 illustrates this point (drawn to scale), showing examples of two heavy-duty vehicles and a bus (examples A through C), a medium-duty vehicle (example D), and a light-duty vehicle (examples E and F), and the corresponding vehicle geometries and lines of sight for direct driver vision and AV sensor coverage. The AV sensor locations shown in the illustration correspond to the highest reasonably available space on each vehicle where AV sensors are likely to be installed.

In Figure 4, an example of a very tall preceding light-duty vehicle (a high-roof cargo van) is used to illustrate the ability of high-mounted AV sensors installed on medium- and heavy-duty vehicles to see over relatively dense traffic when the direct view of drivers, even in elevated positions (such as for a tractor-trailer driver), is obstructed. To further illustrate the clear detection advantage such vehicles with high-mounted AV equipment would have, a very small traffic obstruction (i.e., a two-seater, subcompact vehicle) is shown to still be visible (direct line of sight) to the AV-equipped large trucks in the figure (examples A through D), while the direct vision of both the large-truck drivers and light-duty vehicle drivers are all obscured (all examples). Furthermore, the AV sensors on the light-duty vehicle are only able to see over other light-duty vehicles of similar height (such as an AV-equipped SUV seeing over a pickup truck), but are unable to see over the tallest light-duty vehicles (examples E and F).

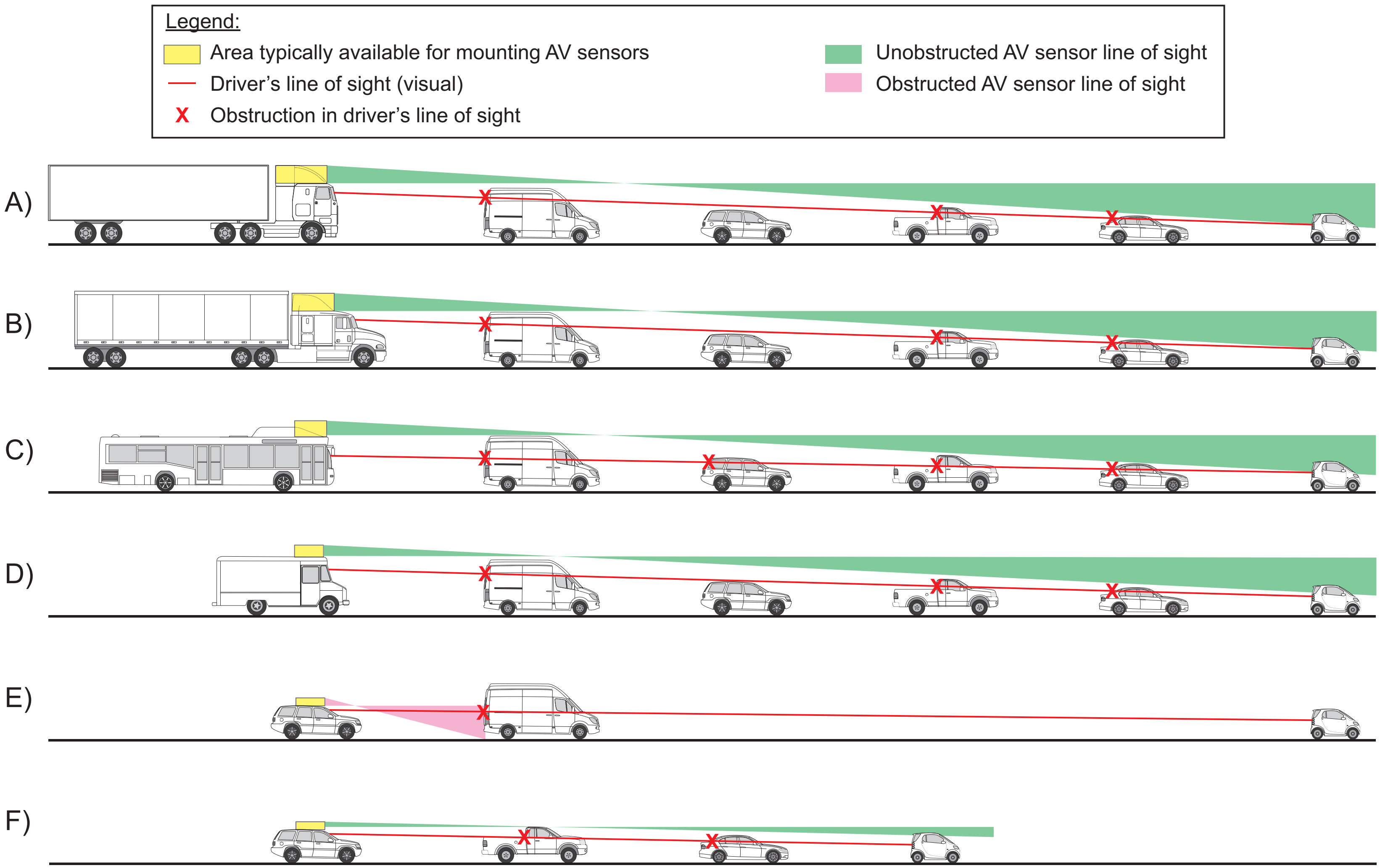

Figure 4. Example illustration (drawn to scale) of two heavy-duty vehicles and a bus (examples A through C), a medium-duty vehicle (example D), and a light-duty vehicle (examples E and F), and the corresponding vehicle geometries and lines of sight for direct driver vision and AV sensor coverage. (Distance from AV sensors to front vehicle: 50 m. Distance between vehicles: approximately 5 m [one car length]. The unobstructed AV sensor lines of sight shown in green do not correspond to the entire viewable area for the AV sensors but rather the applicable, *unobstructed* line of sight to traffic further ahead. This figure illustrates the ability of large trucks to see over light-duty vehicles, which constitute the majority of traffic on U.S. roads; it is unlikely that the AV sensors on a large truck would be able to see over another similarly large truck.)

AV-equipped large trucks, with a better overall view of the road, may ultimately prove to be more effective at sensing roadway objects than most light-duty vehicles,[3] which is especially critical when encountering roadway users[4] or obstacles that are not part of the interconnected DSRC system (including pedestrians, wild animals, dropped cargo, downed trees, etc.). (The possibility of a superior view of the roadway by large-truck AV sensors does not negate any of the need for or benefits of complementary CV technology.)

Additional large-truck sensor considerations

Protective height advantage

The additional height afforded by large trucks not only allows for a better view of the traffic and roadway ahead by the AV sensor systems, it also provides an added layer of protection for those sensors. As is evident in Figure 4, the roof-top mounting locations shown for the medium- and heavy-duty vehicles are located well above the roofline of even the tallest light-duty vehicles and several meters above typical vehicle bumper heights, placing the sensors out of harm's way for nearly all potential collisions with other vehicles (except, perhaps, with other large trucks). In addition to the added protection from physical damage, higher mounting locations will also help reduce the sensors' exposure to roadway dirt and debris.

Furthermore, a high mounting position generally allows for unobstructed views of bridges and other structures by the sensor system, enabling faster and more accurate judgement of overheight situations or other scenarios where a large truck may exceed height or other dimensional restrictions. (Similar functionality can also be provided by connected vehicle technology [HDR, 2017].)

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[3] Though only included in the illustration as a target/obstructing vehicle, the tallest of light-duty vehicles like the high-roof cargo van are also likely to have a distinct advantage over most other light-duty vehicles due to the possible higher mounted location of AV sensing equipment.

[4] It should be noted that there are likely to be many years of overlapping, mixed technologies on the roads, requiring the coordination of traffic at all technology levels: non-CV/non-AV, CV/non-AV, non-CV/AV, and CV/AV (also called CAV). For a more detailed discussion of the challenges associated with road sharing among these differing vehicle technologies, see Sivak and Schoettle (2015b).

Off-highway and severe-duty operating environments

On the other hand, the operating environment for some large trucks is much more harsh or severe than for the vast majority of light-duty vehicles.[5] Correspondingly, sensor systems for such trucks may require extra physical protection or a more robust design to accommodate their specific operating environment, preventing damage and/or the accumulation of excessive dirt and debris on critical sensors. Large trucks that may face such additional requirements include those used for construction-related trucking (e.g., cement trucks, dump trucks, utility trucks, etc.), agricultural trucking, logging trucks, mining trucks, refuse/recycling collection trucks, other specialized vocational trucks, and some emergency vehicles (e.g., fire trucks, ambulances, etc.). For several examples of current off-highway or severe-duty autonomous research vehicles, see Volvo (2017) (refuse collection trucks), and Caterpillar (2017) (mining trucks).

Nighttime crash risk

One element of the additional risk exposure large trucks and their drivers face is the additional time and miles spent driving at night versus the average light-duty vehicle and driver. In fact, an examination of fatal large-truck crashes broken down by daytime and nighttime (NHTSA, 2015) shows that a large proportion of these crashes occur at night (6 p.m. to 6 a.m.). Overall, 35% of fatal large-truck crashes occur at nighttime, with 27% of fatal weekday crashes and a remarkable 62% of fatal weekend crashes happening at night. As summarized earlier in Table 3, autonomous and connected vehicles are generally immune to the effects of darkness, whereas a human driver has comparatively limited nighttime-driving vision due to limitations of the human eye and the relatively short range illuminated by the vehicle headlamps. While human drivers at night are often limited to around 75 m of good visibility in front of their vehicle (mainly illuminated by their low-beam headlamps), common AV sensors typically have a range of 250 m, and CV communications are reliable to at least 500 m (Schoettle, 2017), regardless of ambient illumination levels.

[5] It is assumed that a minimum level of AV sensor robustness will be required and will be standardized for automotive applications to allow autonomous vehicles to continue operating in all reasonable weather and environmental conditions in which a human driver could reasonably perform, including outside temperatures ranging from well below freezing to well above 100 degrees Fahrenheit.

Efficiency improvements for large trucks

Unique efficiency requirements and opportunities

Unlike most light-duty vehicles on the road, medium- and heavy-duty vehicles have additional, unique requirements and opportunities related to on-road efficiency, including the following:

- Financially driven need for effective eco-driving practices and powertrain management to reduce fuel costs
- Ability to coordinate with other large trucks and truck fleets to enable cooperative driving functions for improved efficiency and safety, such as platooning
- Challenges related to the introduction of large trucks (especially heavy-duty and long-haul) that operate on alternative fuels (e.g., battery electric, hydrogen fuel cells, etc.)
- Both the need and opportunity for drivers to safely and comfortably perform other related work while the truck is autonomously driven (or linked into a platoon)
- Legal requirements for drivers to rest periodically due to long hours on the road

Eco-driving and powertrain management

Effective eco-driving plays an important role in improving the fuel economy of all vehicles (Sivak and Schoettle, 2011). In that report, eco-driving was defined as "those strategic decisions (e.g., vehicle selection and maintenance), tactical decisions (e.g., route selection), and operational decisions (e.g., driver behavior) that improve vehicle fuel economy." The tactical and operational aspects of eco-driving when on the road (i.e., how and sometimes where or when the vehicle is driven) are typically under the control of the truck driver, while the fleet owner or manager generally controls the strategic aspects (i.e., what is driven).

Attempts to optimize "how" the truck is driven relative to the local driving conditions (e.g., traffic, weather, road grade, roadway type, etc.) is important for ensuring maximum on-road efficiency, with modern large-truck powertrains already attempting to compensate for such external factors in real time with advanced powertrain-management systems (for examples, see Detroit Diesel, 2017; Eaton, 2013; Volvo, 2017). Connected, autonomous systems (ideally with simultaneous access to all of a vehicle's sensor data) should be considerably more effective than a human driver in the monitoring and controlling of advanced powertrains and other vehicle-system management.

Platooning

An eco-driving concept that relies upon connected and eventually autonomous functionality to ensure complete safety is large-truck platooning. The concept of truck platooning involves two or more trucks being connected electronically (via DSRC or similar means), while also possibly being controlled autonomously, driving in very close proximity to one another (1 second or less separating vehicles). The wireless connection between vehicles allows all following vehicles to take control commands from the lead vehicle, playing "follow the leader" so to speak, driving and responding in precisely the same way as the lead vehicle. Under this system, each truck takes turns being the platoon leader or a follower, enabling drivers in the following truck(s) to rest. For the entire chain of linked trucks driving within a platoon, there are aerodynamic advantages leading to fuel-economy savings, and driver rest and workload improvements that result in safety improvements.

Fuel savings

Several studies (e.g., NREL, 2017; TNO, 2015) have estimated fuel savings of up to 10% for each vehicle within a platoon. U.S. DOT estimates that tractor-trailer trucks consumed approximately 28.8 billion gallons of fuel on U.S. roads in 2015 (U.S. DOT, 2017a), for an average of 10,515 gallons per truck operating at 5.9 mpg. A 10% savings from platooning could save about 1,000 gallons per truck on average each year[6] and boost average fuel economy to 6.6 mpg per truck (with platooning used 100% of the time). As a practical estimate that assumes the use of platooning for 50% of a large truck's annual miles, this would still save an average of around 500 gallons per truck and improve fuel economy to 6.2 mpg per truck. At that rate, with an estimated technology cost of around $2,000 per truck (TNO, 2015), additional costs for platooning would have a payback period of less than two years.[7] TNO also estimates around 8% savings in rest time per day when drivers take turns in a platoon, and as much as 20% savings in

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[6] For comparison, and to further illustrate the greater financial incentive to increase efficiency for large-truck fleets relative to light-duty vehicles, U.S. DOT (2017b) estimates that the total average annual fuel consumption for all vehicles (light-duty vehicles, buses, trucks, and motorcycles) on U.S. roads was 656 gallons per vehicle in 2015, similar to the estimated annual *savings* per large truck when using platooning.

[7] Assumes an on-highway diesel price per gallon of $2.92 (EIA, 2017).

man-hours[8] when one driver controls two trucks (i.e., the following truck is completely driverless).

Alternative fuels and platooning

Large-truck platooning may be especially desirable when attempting to introduce trucks operating on alternative fuels, particularly for long-haul routes. When faced with challenges including reduced range and/or long charge times for battery electric trucks, or limited infrastructure requiring long range between refueling for hydrogen fuel-cell trucks, the aerodynamic advantages afforded by platooning may allow such alternative-fuel large trucks to effectively extend their ranges by increasing their on-road fuel efficiency.

Motion sickness caveat

A frequently overlooked problem with all types of autonomous or self-driving vehicles relates to the increased likelihood of experiencing motion sickness when riding as a passenger in such vehicles, especially when attempting to perform visually intensive tasks with a restricted view of the outside world. This phenomenon is likely to be exaggerated in the rear or sleeper area of large trucks, a space that is often envisioned as being used as a work/office space for the truck driver. Job requirements may make participating in such tasks more of a requirement and less optional for large-truck drivers, which is not the case for a typical light-duty passenger. These requirements could eliminate or interfere with the default option of simply not performing a task if motion sickness is experienced.

As discussed in Sivak and Schoettle (2015), the likelihood of experiencing motion sickness is directly related to the nature of the nondriving activity the driver is attempting to perform. For example, sleeping and watching the roadway ahead are both activities that are unlikely to contribute to motion sickness. However, other activities that are likely to increase the occurrence of motion sickness, especially those related to nondriving work, include reading, watching or performing work on a screen, and work or other activities that require a continuous downward gaze away from the roadway and the outside scene. Table 4 summarizes the contributing aspects that influence the impact of the critical factors for motion sickness, and

[8] The man-hour savings are less than 50% because two trucks being controlled by a single driver will normally need to disconnect eventually from the platoon, continuing on to separate final destinations with one active driver per truck.

Table 5 summarizes the main effects of alternative activities on the three critical factors that influence the frequency and severity of motion sickness.

While the majority of adults are not expected to experience frequent or severe motion sickness as a passenger in a vehicle,[9] it is estimated that motion sickness will *frequently* be experienced by 15% when viewing video, and 26% when reading (Sivak and Schoettle, 2015). Furthermore, similar numbers of adults are expected to experience *severe* motion sickness when viewing video (15%) or reading (32%). This potential interference with improvements in efficiency and/or additional driver tasks will need to be addressed with effective countermeasures to avoid motion sickness in a substantial proportion of large-truck drivers attempting to perform nondriving activities in the vehicle.

Table 4
Contributing aspects that influence the impact of the critical factors for motion sickness. A negative effect **(-)** indicates a worsening of motion sickness, while a positive effect **(+)** indicates an improvement. (From Sivak and Schoettle, 2015.)

Contributing aspect	Critical factor		
	Conflict between vestibular and visual inputs	Ability to anticipate the direction of movement	Control over the direction of movement
Extent of visual input	• narrow or small windows (-) • opaque or reduced-visibility windows (-) • no conflict when having the eyes closed or sleeping (+)	• narrow or small windows (-) • opaque or reduced-visibility windows (-)	Not relevant for passengers
Direction of gaze	• non-forward gaze (-)	• non-forward gaze (-)	Not relevant for passengers
Posture	• side or rear facing (-) • supine (+)	• side or rear facing (-)	Not relevant for passengers

[9] Frequency and severity are independent factors when experiencing motion sickness. For example, one individual may experience *mild* motion sickness *frequently*, while another individual may experience *severe* motion sickness *occasionally*.

Table 5
Effects of alternative activities on critical functions that influence the frequency and severity of motion sickness. A negative effect (-) indicates a worsening of motion sickness, while a positive effect (+) indicates an improvement. (From Sivak and Schoettle, 2015.)

Alternative activity while riding in a self-driving vehicle	Critical factor		
	Conflict between vestibular and visual input	Ability to anticipate vehicle movement	Control over the direction of movement
Watching the road	+	+	-
Reading	-	-	-
Sleeping	+	-	-
Texting	-	-	-
Talking on the phone	depends on the direction of gaze	depends on the direction of gaze	-
Watching movies/TV	- especially for downward gaze	- especially for downward gaze	-
Working	- especially for downward gaze	- especially for downward gaze	-
Playing games	- especially for downward gaze	- especially for downward gaze	-

Based on the specific combination of alternative activities and critical factors, the contributions of different efficiency-improving activities to motion sickness as a passenger in a vehicle for large-truck drivers are likely to be either less problematic or more problematic (and thus requiring an effective countermeasure) as outlined below:

Less problematic activities:

- *Resting*
    - Sleeping or resting with eyes closed
    - Watching the roadway and/or traffic
    - Talking on the phone or radio (if the driver is able to look outside of the vehicle)
- *Working*
    - Talking on the phone or radio (if the driver is able to look outside of the vehicle)

More problematic activities:

- *Resting*
    - Reading
    - Texting or emailing
    - Watching movies or TV
    - Playing video games
    - Talking on the phone or radio (if the driver is *not* able to look outside of the vehicle)
- *Working*
    - Reading
    - Working on a laptop or other screen
    - Texting or emailing
    - Studying or training (with either book or computer)
    - Paper work and similar administrative tasks
    - Talking on the phone or radio (if the driver is *not* able to look outside of the vehicle)

Key findings

This white paper analyzed and compared the relative advantages and disadvantages of autonomous and connected large trucks relative to light-duty vehicles. The key findings from this study are as follows:

Advantages relative to light-duty vehicles

- Large trucks generally have a height advantage for placement of forward looking AV sensors (radar, lidar, cameras) to more effectively see over traffic that may be too high for even a tractor-trailer driver to see.
- High-mounted sensors are also less exposed to roadway dirt and debris, and are also less likely to be damaged by contact with other, shorter vehicles.
- Sensors “see” much better than drivers at night, when significant amounts of large truck driving and fatal crashes involving large trucks both occur.
- Connected-vehicle (V2V, V2I, V2X) based warnings can improve safety when large trucks approach traffic jams, construction, or inclement weather, and offer the ability to strategically plan for or avoid those problem areas.
- Large trucks have the ability to electronically connect and platoon, affording safety and efficiency improvements; potential annual fuel *savings* per truck are similar to an entire year of fuel consumption for a typical light-duty vehicle.
- Platooning can be well planned or scheduled for trucks with similar routes or destinations, especially for vehicles within the same fleet or with a platooning service provider.
- Platooning or solo autonomous driving time can be effectively used by drivers for rest time, reducing the amount of nondriving time spent resting; these functions may eventually help reduce the number of drivers needed to manage/drive multiple trucks.
- Connected autonomous trucks should be more effective at managing powertrains and other advanced vehicle systems.

Disadvantages relative to light-duty vehicles

- Even with highly effective, computer-controlled driving, large trucks will remain inherently more difficult to control (limited maneuverability and longer stopping distances).
- More frequent cleaning and maintenance of sensors may be required due to the additional time and miles such systems will be in use.
- Sensors may need to be more robust or protected depending on the severity of the truck's specific operating environment.
- To effectively "see" the immediate vicinity of the truck itself, more sensors (such as radar, lidar, cameras) will likely be needed in additional locations.
- Safety and financial consequences are possibly more severe (per crash or per vehicle) when equipment failure occurs, as large-truck crashes tend to have higher fatality rates and to be relatively expensive (both in total crash costs and insurance losses).
- Greater susceptibility to motion sickness for drivers who are either relaxing/resting or attempting to work in the rear or sleeper area of a large truck while it is operating in autonomous mode; an effective motion-sickness countermeasure will be needed, or else increases in driver efficiency and changes to require additional driver tasks may fall short of expectations.

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