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Automation in the long haul: Challenges and opportunities of autonomous heavy-duty trucking in the United States

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1. Introduction

Research and development in autonomous vehicle technologies has taken place for more than two decades, with interest and investment proliferating in recent years sparked by breakthroughs in sensing, communications, and computing technologies. The majority of investments and media attention to date have been concentrated in the passenger vehicle space (Slowik & Kamakaté, 2017), yet the technologies and their capabilities carry over to freight trucks and the commercial vehicle sector. An increasing number of stakeholders are actively involved in bringing this technology to on-road commercial vehicles—especially, tractor-trailers. With heavy-duty tractor-trailers accounting for a disproportionately high share of negative impacts—including local air pollutants, greenhouse gas emissions, and fuel consumption (Sharpe, 2017)—the sector is ripe for the application of autonomous technology, perhaps even more so than the passenger vehicle sector.

The implications of autonomous trucking are broad and extend beyond the trucking sector to include infrastructure, urban planning, cyber security, privacy, and insurance. Within the freight trucking sector, many see a future where the technology dramatically alters the truck driver's responsibilities and may eventually eliminate the need for a driver. Several industry groups envision autonomous vehicle technology as an attractive return on investment, with potentially large economic benefits. However, the extent of these benefits is generally unknown to date, and there are also risks and drawbacks to adoption of autonomous trucking. From a typical fleet perspective, the potential impacts of autonomous trucking include

- improved on-road safety (i.e., fewer collisions and fatalities);
- greater fuel efficiency and reduced emissions (i.e., higher miles-per-gallon);
- ease of driving (e.g., automation technologies increasingly control vehicle functions);
- increased operational efficiency (e.g., real-time planning, reduced truck downtime); and
- reduced labor costs (i.e., technology reduces or eliminates the need for human drivers).

This paper explores the state of autonomous trucking technology and the benefits and drawbacks of its adoption from multiple stakeholder perspectives. We are especially interested in how autonomous technology will affect fuel use and emissions in the on-road freight sector This paper is also a first step toward better understanding the existing regulatory landscape and the types of policy measures needed to responsibly bring fuel-saving autonomous trucking technology to market. The data and analysis presented in this study focus on North America. More research is needed to better understand the challenges and opportunities presented by autonomous trucking in other regions around the world.

Table 1 outlines the levels of automation, as defined by SAE International

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(2014) and adopted by the U.S. federal government, and offers examples.

From Level 0 to Level 5, the automated vehicle system progressively handles additional tasks and increasingly monitors the driving environment. Level 0 trucks may still include advanced technologies such as active safety systems (e.g., automatic emergency braking) or warning features (e.g., lane departure warning), but because these features provide momentary intervention and are not sustained, they are considered Level 0 as defined by the J3016 standard published by SAE International (2016). As shown in Table 1, heavy-duty trucks capable of Level 0 and Level 1 automation are commercially available today, and trucks with Level 2 capabilities are rapidly nearing commercialization. A small number of trucking demonstrations considered Level 3 have occurred to date. For autonomous vehicle systems Levels 3+, the technology is responsible for monitoring the driving environment and is in control of vehicle functions and decision making. Autonomous vehicles Level 4+ do not require human intervention, which means these vehicles theoretically could be manufactured without typical hardware such as a steering wheel or brake and accelerator pedals.

The remainder of the paper is organized as follows. In Section 2, we summarize the current state of autonomous trucking technology, highlighting the relevant technologies, costs, and demonstrations, emphasizing those that promise to improve fuel economy. Section 3 introduces several societal acceptance considerations related to autonomous trucking and discusses the potential benefits and drawbacks of technology adoption. Section 4 outlines the current policy landscape in the United States. Section 5 summarizes the findings from 15 interviews with industry experts that explore technical, economic, and societal barriers to higher levels of automation in trucking, as well as the potential ways that policy can effectively address these issues. In Section 6, we conclude by outlining several key reflections from our research and highlight areas for future work.

2. State of autonomous trucking technology

This section provides an overview of the current technology landscape for autonomous heavy-duty trucking and what it might mean for fuel economy. We review and summarize the relevant research literature on automated and connected heavy-duty vehicle technologies, costs, deployment, and the implications of truck platooning and other technologies on fuel economy. Our review includes literature from independent researchers, academia, national laboratories, federal agencies, nongovernmental organizations, and industry stakeholders.

Automated and connected heavy-duty vehicle technologies, costs, and deployment. Table 2 outlines several examples of automated and connected vehicle technologies and technology applications identified in the heavy-duty trucking space. Broadly speaking, a handful of sensor, communication, and processing software technologies are enabling varying degrees of trucking autonomy by commanding actuators such as steering and braking. As shown, vehicle sensor technologies include cameras, radar, LiDAR (which stands for light detection and ranging), and GPS units. Connected vehicle technologies allow for communications across vehicles (vehicle-to-vehicle) and infrastructure (vehicle-to-infrastructure), commonly referred to as *V2V* or *V2I*. The current leading vehicle communications technology is dedicated short-range communications

Table 1. Description of levels of automation

Level	Name	Description	Examples	Technology status
0	No automation	Human performs all driving tasks, even if enhanced by active safety systems.	Navistar LT, Peterbilt 579	Commercially available
1	Driver assistance	Vehicle can perform sustained control of either steering or acceleration/deceleration.	Peloton Platooning System, Volvo VNL	Commercially available
2	Partial automation	Vehicle can perform sustained control of both steering and acceleration/deceleration.	Embark, Starsky Robotics	Pre-commercial
3	Conditional automation	All tasks can be controlled by the system in some situations. Human intervention may be required.	Freightliner Inspiration, Uber ATG / Otto	Prototype retrofit
4	High automation	All tasks can be handled by the system without human intervention, but in limited environments (e.g., dedicated lanes or zones).	Not currently available	Research and development
5	Full automation	Automated system can handle all roadway conditions and environments.	Not currently available	Research and development

(DSRC), but research in 5G mobile network and other technologies could also facilitate vehicle connectivity in the future (National Academies of Science, Engineering, and Medicine, 2017). Software is needed to process information gathered from sensors and communications and control vehicle functions. Autonomous and connected vehicle technologies frequently are discussed together because of the synergies between them, yet the technologies may be deployed and adopted separately. Connectivity allows autonomous vehicles to process the additional sensing information from other nearby vehicles, allowing them to effectively "see" the road ahead beyond the immediate surroundings that are captured by the vehicles' own sensing technologies.

Many of these technologies are available today and are being purchased by several fleets (North American Council for Freight Efficiency [NACFE], 2016). The farthest right column of the table shows examples of companies that are involved in manufacturing one or more autonomous and connected vehicle technologies. Many of these companies are active in both the passenger car and commercial vehicle sectors, as the core sensing, communications, and software technologies are generally applicable to both the light-duty and heavy trucking sectors (National Academies of Sciences, Engineering, and Medicine, 2017). The list of industry players is far from exhaustive; Comet Labs mapped out a chart of more than 250 companies that are pursuing autonomous vehicles (Stewart, 2017). Furthermore, we note that many companies do not disclose information about which technologies they manufacture in-house and which they purchase from parts suppliers.

Table 2. Example automated and connected vehicle technologies in on-road heavy-duty trucking

Technology	Components	Description	Commercially available?	Example technology makers
Sensors	Cameras	Used to identify other objects using visible light. Cameras have limitations compared to other sensor technologies and function poorly in darkness, extremely bright light, and certain weather conditions.	Yes	Continental, Mobileye, Delphi
	Radar	Used to identify the velocity, direction, and distance of other objects by emitting high-frequency radio waves.	Yes	Bosch, Continental, Autoliv, Delphi
	LiDAR	Considered the most reliable and robust sensing technology. LiDAR measures the range and speed of objects using reflected light. Range and speed are measured based on the time that laser light takes to reflect. LiDAR systems can process and record images. (National Highway Traffic and Safety Administration [NHTSA], 2013).	Yes	Velodyne LiDAR, LeddarTech, Quanenergy, Delphi, Strobe, Waymo
	GPS	Used to identify vehicle position and velocity by communicating with satellite signals.	Yes	Linx Technologies
Communications	DSRC	Dedicated short range communications (DSRC) is two-way communications in 5.9 GHz band that allows for high data transmission over a moderate range. DSRC allows for V2V and V2I communications which can send messages and provide alerts to drivers in real time. The U.S. Department of Transportation (DOT, 2017a) considers this technology the basis for intelligent vehicle safety application integration.	Yes	NXP, Qualcomm
	5G	The 5th generation wireless systems currently under development will allow for higher capacity and better coverage with less latency. 5G is expected to support device-to-device communications with increased reliability. 5G is believed to be a promising communications technology with applications for connected and autonomous vehicles within the next decade (National Academies of Sciences, Engineering, and Medicine, 2017).	No	Not currently available
Software	Algorithms, artificial intelligence	Millions of lines of software code enable autonomous and connected trucking. Computing software systems are used to process images captured from sensor technologies, interpret communications messages from other vehicles or infrastructure, and control vehicle functions in real time. Software refinement and validation is considered a much larger challenge than deploying sensor and communication hardware (Tesla, 2016).	Yes, with limitations	Nvidia, Intel, Autoliv, Cisco, Uber ATG, many others

Sensors, communication, and processing software enable a variety of vehicle applications including but not limited to driver alerts and collision avoidance systems, automatic braking, lane keeping assistance, adaptive cruise control, platooning, and eco-driving optimization. Many of these technology applications are described in greater detail in Table 3. A few examples of companies that offer, or seek to offer, automated and connected vehicle technology applications in the trucking sector are shown in the column farthest to the right.

The market demand for autonomous vehicle technologies of low and high levels of automation is quite strong, and numerous industry groups are aggressively developing products. In the future, additional advancements in vehicle sensor quality, bandwidth availability for vehicle communications, and processing software and algorithms are likely to enable more robust technology applications and higher levels of automation.

Return on investment (ROI) is often a key factor influencing the adoption of new technologies on freight applications. Upfront technology costs and per-mile operating costs are core components that influence the value proposition for fleet adoption. Table 4 shows some estimates of the upfront costs for several examples of autonomous heavy-duty vehicle technologies and systems.

Several of the technologies shown in Table 4 cost only a few hundred dollars. These include driver assistance and driver alert systems, which typically are purchased for safety and collision mitigation. While there are some estimates, less information is known about the technology costs for trucking automation for Levels 3 and above, especially the projected cost reductions that would stem from increased production volumes and broader commercialization. This information is needed to better assess the value proposition for fleets to adopt various autonomous trucking technologies. There are several potential direct and indirect economic benefits that autonomous trucking may offer, and a deeper understanding of the costs will better inform the pace and scale of technology adoption.

In addition to what the research literature reveals about autonomous trucking technology costs, rough estimates can be compiled using information from third-party parts suppliers. For example, a review of the parts components for Meritor Wabco's OnGuardActive system, a radar-based active collision mitigation and adaptive cruise control system, on the independent truck parts marketplace finditparts.com website suggests system costs of around $2,500 to $3,500. This is roughly in line with the costs for other similar technology applications documented in Table 4. There also has been some speculation in the media about technology costs. As reported for the American Transportation Research Institute by Short and Murray (2016), additional technology costs for Uber's retrofitted long-haul truck—believed to be Level 3, as identified earlier in this report—as well as Daimler's Freightliner Inspiration, which also is believed to be Level 3, have been estimated at $30,000 per truck (McNabb, 2015; Stewart, 2016). These cost estimates for a Level 3 truck are approximately twice the estimates reported in Roland Berger (2016). One reason for the large discrepancy may be the difference in assessing the cost of a single retrofit prototype versus assuming some level of market adoption and achieving economies of scale.

Several of the technologies and systems shown in Table 4 are available today, and some have had notable commercial adoption. For example, Meritor Wabco's OnGuardActive collision mitigation system is reported to be in 120,000 heavy-duty trucks (Meritor Wabco, 2017). Not exclusive to heavy-duty trucks, Mobileye's Advanced Driver Assistance System is used in nearly 15 million vehicles worldwide (Mobileye, 2017b). A study by Rodríguez, Muncrief, Delgado, and Baldino (2017) estimated the market penetration of several heavy-duty vehicle technologies in the United States and the EU, including automated manual transmissions (AMTs), predictive cruise control (PCC), and adaptive cruise control (ACC). The 2015 U.S. and EU market penetration of these technologies in new tractor-trailers was 28% (U.S.) and 70% (EU) for AMTs, 3% (U.S.) and 20% (EU) for PCC, and 10% (U.S.) and 50% (EU) for ACC. More research is needed to more fully identify the suite of autonomous-vehicle-related technologies that have been adopted to date and the fleets that are adopting them.

Technological barriers remain for commercial deployment of heavy-duty truck platooning and higher levels of automation (Levels 3+). Despite current barriers, researchers and industry stakeholders have made predictions about the commercial availability and uptake of autonomous trucks. A few of these predictions are documented here.

- NACFE (2016) reports that "it is extremely likely that in the near future, Class 8 tractors will be sold as platooning capable 'right out of the box'" (unspecified, assumed Level 2).
- Commercial deployment of platooning applications (unspecified, assumed Level 2) could occur around 2020 on select U.S. roads (National Academies of Sciences, Engineering, and Medicine, 2017).

Table 3. Examples of automated and connected vehicle technology applications in on-road heavy-duty trucking

Technology applications	Technologies used	Description	Commercially available?	Example companies
Lane departure warning	Sensors such as cameras, processing software	These systems send an audible or haptic warning to drivers when there is risk of the vehicle unintentionally drifting outside of the lane. This technology is considered Level 0 because it does nothing more than alert a driver. (National Academies of Sciences, Engineering, and Medicine, 2017).	Yes	Mobileye, Meritor Wabco
Blind spot detection	Sensors such as cameras and radar, processing software	Blind spot detection devices can detect if other vehicles are located in the driver's blind spots and notify the driver. The alerts can be audible, haptic, or visual. Like lane departure warnings, blind spot detection alerts are considered Level 0.	Yes	Mobileye, Meritor Wabco, Volvo
Automatic braking	Sensors such as cameras and radar, processing software	Automatic braking systems can detect the speed and distance of vehicles ahead of them and automatically apply the brakes if needed. This technology is considered Level 0 because the feature provides momentary intervention and is not sustained.	Yes	Scania, DAF, Daimler, Meritor Wabco, Volvo, Bendix
Automated manual transmissions (AMT)	Electronic control unit, hydraulics, software	Automated manual transmissions control the operation of the clutch and gear selection automatically, based on information gathered from vehicle sensors. AMTs are an enabling technology and are generally required on all Level 1+ autonomous trucks.	Yes	Eaton, Volvo, Daimler
Eco-driving systems	On-board diagnostics, monitoring and processing software, telematics	A system that monitors human driving and provides real-time advice and feedback for drivers to achieve greater fuel performance, for example by moderating highway speed and by smoothing acceleration and braking.	Yes	TomTom, Ruptela, SmartDrive
Automated lane keeping	Sensors such as cameras or radar, processing software	These systems monitor the vehicle placement within road lane markings. If the vehicle is departing the lane, the system corrects the lateral direction automatically. The technology is considered Level 1.	Yes	Scania, Meritor Wabco
Adaptive cruise control (ACC)	Sensors such as radar, processing software	Adaptive cruise control adjusts vehicle speed, controlling throttle and braking, based on the speed of the vehicle in front of it in order to maintain a set distance. ACC technology is considered Level 1.	Yes	Meritor Wabco, DAF, Volvo, Bendix
Predictive cruise control (PCC)	GPS, topographical mapping data, processing software	Predictive cruise control combines cruise control with GPS and topographical data inputs, altering vehicle speed to optimize performance over various types of terrain. PCC technology provides maximum benefits in conditions with rolling hills. The technology is considered Level 1. PCC and ACC can be active simultaneously or the functions could be offered separately.	Yes	Kenworth, DAF
Platooning	Sensors such as radar, processing software, could also include vehicle communications using DSRC	Platooning is when groups of vehicles travel close together to minimize aerodynamic drag. Truck platooning typically includes sets of two or three trucks paired together using sensor and communication technologies. At basic levels, ACC alone (Level 1) could enable truck platooning. More advanced platooning technology controls for both longitudinal (ACC) and lateral (automated lane keeping) movements and is considered Level 2.	Yes (Level 1), Level 2 systems are pre-commercial	Peloton, Volvo, Uber ATG, Daimler
Highly automated trucking	Will likely include cameras, radar, LiDAR, DSRC, processing software.	Highly automated trucks will be capable of operating autonomously without human intervention in limited environments such as dedicated areas or highway lanes. Highly automated trucks (Level 4+) are not commercially available for on-road applications today, but there are a few examples of their use in mining and farming operations.	No	Daimler, Uber ATG
Telematics	GPS, DSRC, or other wireless communications technology, asset management software	Telematics systems combine telecommunications and informatics, which is the collection, classification, storage, retrieval, and dissemination of information. Telematics equip fleet managers with valuable real-time data such as vehicle location, speed, service needs, weather, road conditions, and driver performance. Telematics are expected to complement connected and autonomous vehicles, for example by enabling the transmission and processing of communications data from nearby vehicles, or by facilitating identifying opportunities to link vehicles to form a platoon.	Yes	Zonar, Geotab, Openmatics

Table 4. Estimated costs for examples of autonomous and connected truck technologies and technology applications

Study or reference	Technology or application	Technology description	Cost	Time frame	Notes
Waymo (2017)	LiDAR	Considered the most robust sensing technology for processing images.	$75,000	"A few years ago" (unspecified)	Cost estimates are per unit. Companies typically install one to four LiDAR units per vehicle. Waymo CEO John Krafcik revealed the company has reduced the cost of $75,000 "top-of-the-range" LiDAR units by 90%.
			$7,500	2017	
Nordrum, A. (2016)	DSRC modules	V2V communications hardware.	$100 to $200	Around 2016	Cost estimates are for DSRC module made by NXP.
Harding et al. (2014)	V2V communications	V2V communications equipment and functions.	$341 to $350	2020	NHTSA estimates the cost of V2V equipment and communications functions for light-duty vehicles. The technologies include DSRC transmitter/receiver, DSRC antenna, electronic control unit, GPS, GPS antenna, wiring, and displays.
U.S. Environmental Protection Agency [EPA] and NHTSA (2016a)	Automated manual transmission	A transmission that facilitates truck shifting by utilizing a computer and eliminating the manual shifter and clutch.	$5,100	2013	EPA and NHTSA estimate the cost of automated manual transmissions for medium- and heavy-duty vehicles and report the values in 2013 dollars.
			$3,750	2018	
National Academies of Sciences, Engineering, and Medicine (2017)	Blind spot detection system	A system of sensors that identifies vehicles in the driver's blind spots and provides a warning.	$250 to $850	Available today	Cost estimates are for aftermarket system cost.
National Academies of Sciences, Engineering, and Medicine (2017), Mobileye (2017a)	Mobileye Advanced Driver Assistance System	Driver assistance through collision avoidance intelligent vision sensor technologies.	$850 with $150 installation	Available today	A driver alert safety package that offers a variety of alerts and driver assistance features including forward collision warning, lane departure warning, headway monitoring and warning, pedestrian and cyclist warning, intelligent high beam control, turn signal reminder, and low visibility indicator.
Meritor Wabco (2017, n.d.)	Meritor Wabco OnGuardActive	Radar-based sensor system identifies potential collisions and sends warning notifications to drivers.	Not disclosed	Available today	The collision mitigation system also includes adaptive cruise control and active braking applications. More than 120,000 OnGuard collision mitigation systems have been sold in North America and are being used by more than 200 fleets.
DOT (2014)	Adaptive cruise control	Vehicle technology to dynamically control longitudinal movement and maintain consistent following distance.	$3,000	Around 2006	Cost estimates not explicit to heavy-duty vehicles. Assumed to include sensing technologies (cameras, radar) and processing software.
			$2,000	Around 2014	
International Council on Clean Transportation (ICCT, 2017)	Predictive cruise control	A technology that alters vehicle speed to optimize performance over various types of terrain based on GPS and topographical data.	$760	2030	The study reports the estimated 2030 vehicle technology costs and reports the values in 2015 dollars.
EPA and NHTSA (2016)	Predictive cruise control	A technology that alters vehicle speed to optimize performance over various types of terrain based on GPS and topographical data.	$953	2018	EPA and NHTSA estimate the cost of predictive cruise control for heavy-duty tractors and reports the values in 2013 dollars.
			$766	2027	
Daimler AG (2015)	Predictive cruise control	A technology that alters vehicle speed to optimize performance over various types of terrain based on GPS and topographical data.	$1,300 with installation (€1,500)	2015	Cost estimate indicates the advertised cost (excluding VAT) in Germany to purchase and install the retrofit technology. Based on typical mileage of 81,000 miles/year, the technology payback period from fuel savings (up to 5%) is advertised as less than 1 year.
American Trucking Associations Technology and Maintenance Council (2015)	Adaptive cruise control and lane keeping assist	Vehicle technologies for longitudinal and lateral controls.	$3,000	Available today (in light-duty vehicles)	Study not specific to heavy-duty vehicles. Together, adaptive cruise control and lane keeping assist are considered Level 2 by enabling the system to control both longitudinally and laterally.
Janssen, Zwijnenberg, Blankes, & Kruijff (2015)	Platooning	Technology that enables vehicles to travel close together to minimize aerodynamic drag.	About $11,900 per truck (€10,000)	2015	Includes V2V communication technology and "necessary additional safety measures" which are unspecified but assumed to include sensor systems such as LiDAR, radar, and/or cameras.
NACFE (2016)	Platooning	Technology that enables vehicles to travel close together to minimize aerodynamic drag.	$1,500 – $2,000 per truck	2016	Estimated cost of required technologies to enable two-truck platooning, based on industry interviews from unnamed fleet manager and technology developer.
Roland Berger (2016)	Level 1	Incremental technology costs (above Level 0) for Level 1 to Level 5 truck automation.	$1,800	Unspecified	Study estimated the incremental costs of adding technology to enable Level 1 through Level 5 automation. Total incremental technology cost to reach Level 5 is estimated at $23,000. Incremental technologies include hardware (sensors, communications) and additional processing software.
	Level 2		$6,900		
	Level 3		$13,100		
	Level 4		$19,000		
	Level 5		$23,400		

- Level 3 automation capabilities are most likely to come within a decade for heavy trucks (American Trucking Associations Technology and Maintenance Council, 2015).
- The International Transport Forum (ITF, 2015) predicts that Level 4 trucking on highways could be available before 2030.
- A study requested by the European Parliament finds that platooning technology will allow truck drivers to legally disengage from the driving task within 10 to 20 years. Fully driverless trucking (Level 5) could emerge after 2035 (Frisoni et al., 2016).
- Early adoption of highly automated trucks (Levels 4+) may occur in the form of a trailing truck in a platoon, following closely behind a driver-assisted (Level 1) truck (NACFE, 2016).

Heavy-duty truck platooning demonstrations and implications for fuel economy. A major focus of the research literature and industry R&D efforts to date has been on truck platooning, driven partially by the potential fuel savings and attractive return on investment that can result. Platooning technology combines safety and collision mitigation technologies with vehicle communications and automated vehicle controls to tether trucks together in formation (NACFE, 2016). As noted in Table 3, basic levels of platooning can be realized by adaptive cruise control alone, while more advanced platooning controls both longitudinal (ACC) and lateral (automated lane keeping) movements and is considered Level 2.

In the most basic form, platooning could be conducted manually, which is to say without automation, simply by driving with short following distances; however, this method poses significant crash risk and safety considerations. Emerging sensor technologies, vehicle communications, and vehicle control technologies are enabling much shorter following distances due to electronic systems that read and react to the driving conditions several times faster than a human driver. Reliability of these technologies is becoming increasingly important as the required reaction times for safe operation reach levels beyond human capabilities (NACFE, 2016). Relatively advanced platooning systems that control both following distance and steering are likely needed to minimize driver error and maximize the fuel savings benefits that platooning promises.

Suppliers, truck manufacturers, and freight operators have interest in platooning technology because of the attractive fuel cost savings and return on investment that the technology promises. However, freight operators are likely to chart their own unique paths to technology adoption. For example, Auburn University (2017) notes that perspectives on fuel savings might differ for large versus small fleets. For large fleets with economies of scale, fuel savings alone can be sufficient motivation. However, for smaller fleets, low upfront costs are crucial and additional benefits may be needed for small fleets to adopt the technology. Key priorities for fleets to adopt *driver assistive truck platooning technology* (Level 1) include affordability, ability to coexist with collision mitigation systems, and availability as a retrofit device. In the near term, platooning technology is more likely to be adopted within fleets, rather than across fleets, until trust, assurance, and interoperability is established among fleet operators (Auburn University, 2017).

Numerous demonstrations and tests have occurred in recent years that quantify the fuel savings from truck platooning; many are outlined in Table 5.

As shown in the table, the realized fuel savings from truck platooning varies from trial to trial, although the general magnitude of team savings—average savings of both the lead and platooned vehicle—is approximately 4% to 15%. Because platooning requires at least two vehicles and relatively fast speeds, there is some limitation to the percentage of fleet-miles that can occur in a platoon and thus the realized fuel benefits. Furthermore, the literature reveals that several variables have an impact on fuel savings, including following distance, travel speeds, and vehicle weight. There does not appear to be a consensus in the literature about how to ideally optimize fuel savings from truck platooning when including each of the factors above. Here are several research findings on the relationships between fuel savings and the various factors:

- A review of several platooning tests found fuel savings generally increase as the gap between vehicles decreases (National Academies of Sciences, Engineering, and Medicine, 2017).
- Auburn University (2017) along with industry partners including Peloton, Peterbilt, Meritor Wabco, and the American Transportation Research Institute (ATRI) (Short & Murray, 2016) conclude that “trucks should be spaced as close as safely feasible” to optimize combined fuel economy.
- Lammert et al. (2014) found 50 feet to be the optimal distance for team savings, with savings decreasing by about one-third with 20-foot following distances.
- Simulations by Auburn University (2017) suggest that 2-foot lateral offsets can increase the coefficient of drag by up to 30%, thereby squandering the aerodynamic gains and fuel savings of platooning.

Table 5. Fuel savings demonstrated in example truck platooning projects

Source	Lead vehicle	Platooned vehicle(s)	Team	Study method	Technologies used	Description
Auburn University (2017)	0.4% to 5.3%	8.6% to 10.2%	4.5% to 7%	Evaluated using "SAE Type II FE test" at TRC Ohio	Radar, DSRC-based V2V communications, satellite positioning, actuation for vehicle controls, and human-machine interfaces	Testing of one platooned and one lead truck at following distances from 30 to 150 feet at 65 mph. Tests were conducted at the Auburn test track using Peterbilt 579 tractors with 53-foot trailers using Peloton's truck platooning system. Because longitudinal movement is automated, and drivers were responsible for steering, the technology is considered Level 1.
Peloton Technology (2017)	4.5%	10%	7%	Real-world testing	DSRC V2V communications, radar collision mitigation system, front facing camera, GPS	Testing of one platooned and one lead truck at a following distance of 36 feet.
Lammert, Duran, Diez, Burton, & Nicholson (2014)	2.7% to 5.3%	2.8% to 9.7%	3.7% to 6.4%	Evaluated on test track	Radar, DSRC V2V communications, vehicle braking and torque control interface, cameras, driver displays	Testing of one platooned and one lead Peterbilt Class 8 tractor-trailers vehicles at the Continental Tire Proving Ground test track in Texas. Conducted with varying speeds, following distances, and vehicle weights.
Safe Road Trains for the Environment Project (SARTRE, 2014)	2% to 8%	8% to 13%	Not reported	Evaluated on test track	Camera, radar, and laser to support adaptive cruise control, V2V communications	Testing of one platooned and one lead Volvo FH12 rigid truck at the IDIADA test track in Spain at following distances of 16 to 82 feet (5 to 25 meters) at 53 mph (85 km/h).
NACFE (2013)	4.5%	10%	Not reported	Real-world testing on I-80	Radar	Testing of one platooned and one lead Peterbilt 386s model year 2011 tractor trailers in Salt Lake City, Utah. Conducted at 64 mph with 36-foot following distance using Peloton platooning technology. Vehicles were fully loaded.
Tsugawa (2013)	0% to 9%	12% to 22%	9% to 15%	Evaluated on test track	Radar, laser scanner, adaptive cruise control, V2V communications	Testing of two platooned trucks and one lead truck at the AIST test track in Japan traveling 50 mph (80 km/h) at distances from about 15 to 65 feet (4.7 to 20 meters). Vehicles were unloaded.
Browand, McArthur, and Radovich (2004)	5% to 10%	10% to 12%	8% to 11%	Evaluated on test track	Electronic longitudinal control system	Testing of one platooned and one lead Freightliner 2001 Century Class tractor-trailers at the Crows Landing runway in California. Conducted with varying speeds and following distances, and the trucks were empty.
Bonnet and Fritz (2000)	3% to 9%	9% to 21%	Not reported	Evaluated on test track	Electronic tow bar	Testing of one platooned and one lead Mercedes-Benz ACTROS semi-trailer trucks at the Papenburg test track in Germany. Conducted at 37 mph and 50 mph (60 km/h and 80 km/h) with following distances from about 15 to 53 feet (4.5 to 16 meters). Vehicles were partially loaded.
	2% to 6%	13% to 17%	Not reported	Simulation	Simulation	Simulation to extrapolate potential fuel savings at 50 mph (80 km/h) when trucks are fully loaded and weigh up to 40 tons.
NACFE (2016)	3% to 5%	8% to 19%	4%	Compilation of literature review and interviews	Not applicable	Summary findings based on desk research, events, and industry interviews with fleets, manufacturers, and platooning technology developers in North America. Values based on following distance of 40 to 50 feet.

- Ellis, Gargoloff, and Sengupta (2015) found that platooning distances of 16 feet (5 meters) or less can have significant costs by reducing engine cooling air flow and therefore requiring a cooling fan and mitigating the potential fuel savings that platooning promised.
- Lammert et al. (2014) found higher average fuel savings at lower speeds (55 mph versus 65 mph or 75 mph).
- Lammert et al. (2014) found fuel savings from platooning were reduced with higher gross vehicle weight. Similarly, Bonnet and Fritz (2000) found through platooning simulations that greater truck weight reduced fuel savings benefits.
- Increasing the number of trucks in a platoon could accrue more benefits as more vehicles realize the slipstream benefits (National Academies of Sciences, Engineering, and Medicine, 2017).
- For truck platooning systems using trucks with different aerodynamics, it is most favorable for the least aerodynamic truck to be in a following position (Auburn University, 2017).

In addition to these factors, atmospheric conditions like temperature, wind, and humidity can have an impact on aerodynamics and therefore on the ability of tractor-trailers to realize fuel benefits from platooning. Similarly, traffic congestion, terrain, road construction, and other real-world factors can reduce the feasibility and benefits of platooning. NACFE (2016), for example, recommends fleet managers should expect smaller fuel savings than reported in the demonstration projects, which are not representative of road traffic congestion.

More research is needed to identify the ideal combinations of travel speed, gap distance, weight, number of platooning vehicles, and the types of trucks and their aerodynamic profiles to optimize for fuel economy. Beyond optimizing for fuel savings, more research is needed to identify the implications of each of the factors on safety, road infrastructure, public acceptance, and logistics.

Testing of truck platooning typically has been conducted in relatively limited real-world on-road applications. An important industry consideration for technology adoption is the number of freight miles that are suitable for platooning. National Renewable Energy Laboratory (NREL) researchers examined real-world truck usage data in the United States to statistically analyze the percentage of miles suitable for platooning (Muratori et al., 2017). By using recent data on highway vehicle usage and velocity, they found that approximately 65% of truck miles could be driven in a platoon, at 50mph or greater, translating to about 4% reduction in overall trucking fuel consumption in the United States based on a team fuel improvement of 6.4% as found in Lammert et al. (2014). More research is needed to identify the percentage of fleet platoonable miles that can tip the fleet value proposition in favor of adopting platooning technology.

Fuel efficiency benefits of nonplatooning technologies. Platooning has received significant attention in the research literature and industry R&D efforts, but several other autonomous-vehicle-related technology applications are poised to offer some fuel savings benefits as well. In this section, we highlight other autonomous trucking technology applications and discuss their implications on fuel performance. Table 6 summarizes several research and demonstration projects.

As shown, our research identifies several of technology applications in addition to platooning that can improve fuel performance of heavy-duty trucking, including predictive cruise control, adaptive cruise control, automated eco-driving, driver feedback systems to promote eco-driving, and automated manual transmissions. Adaptive and predictive cruise control are considered Level 1. Automated eco-driving was unspecified but assumed to be Level 1 by enhancing vehicle acceleration and deceleration profiles. Automated manual transmissions and driver eco-driving feedback systems do not automate either longitudinal or lateral movement and therefore are considered Level 0. As shown in the table, the fuel benefit of eco-driving feedback systems can be significant, at approximately 10%. However, the materialization of this fuel consumption benefit will depend on the extent to which drivers actually use feedback and react appropriately, and therefore may require monitoring verification and incentives to maximize fuel benefits.

Less information is available on the fuel-savings potential for technology applications such as blind spot detection, lane departure warning, forward collision warning, and other collision mitigation systems. Furthermore, improving trucking fuel performance is not the intent of these types of technology applications. The safety benefit and potential payback period of collision mitigation systems are discussed in Section 3. Nevertheless, collision avoidance systems may have an indirect relationship with fuel economy. For example, Meritor Wabco's OnGuardActive system, which includes collision mitigation as well as adaptive cruise control functions, could help smooth acceleration and deceleration profiles and therefore enable more efficient driving. The extent to which these types of technology applications result in real-world fuel economy gains, however, has yet to be quantified and is largely unknown.

Table 6. Potential fuel savings of nonplatooning trucking applications

Source	Technology application	Fuel efficiency improvement	Notes
EPA & NHTSA (2016a)	Predictive cruise control	2%	The real-world CO_2 emissions and fuel consumption reduction benefit from predictive cruise control as estimated by the U.S. federal agencies in the Phase 2 medium- and heavy-duty vehicle regulatory impact assessment.
Lattemann, Neiss, Terwen, and Connolly (2004)	Predictive cruise control	2.5% to 5.2% over conventional cruise control	Investigated the fuel economy improvement realized through predictive cruise control technology compared to conventional cruise control. Unlike conventional cruise control, predictive cruise control takes road elevation information into account using GPS and 3-D mapping information. Predictive cruise control was found to be more effective with greater vehicle weights and on roads with more rolling hills.
DAF (2017)	Predictive cruise control	1.5% to 4%	Enabled by GPS and mapping technology, predictive cruise control saves fuel by anticipating the road ahead and adjusting vehicle speeds to optimize fuel consumption.
Lutsey, Langer, and Khan (2014)	Predictive cruise control	0% to 5%	Estimates based on industry communication and stakeholder workshop.
Daimler AG (2015)	Predictive cruise control	5%	The press release indicates that 5% fuel savings is the high end of what the predictive cruise control technology can offer. Estimates are based on typical annual mileage of 81,000 miles (130,000 kilometers).
Faber et al. (2012)	Adaptive cruise control, forward collision warning	1.9%	Estimates from the euroFOT project. ACC offers fuel consumption benefits from smoother truck speed profiles.
ITF (2017)	Automated eco-driving (unspecified)	4% to 10%	The authors report estimates of fuel savings for automated eco-driving of 4% to 10%. Automated eco-driving elements are assumed to include smoother acceleration and deceleration profiles which could stem from technologies like adaptive cruise control.
National Center for Sustainable Transportation (2016)	Eco-driving feedback system	11%	Results of a truck driving simulator. Eco-driving feedback technology provides driver feedback in real time, recommending optimal speed and alerting drivers in instances of aggressive acceleration and speed.
NACFE (2014)	Automated manual transmissions	1% to 3% reduction in fuel consumption	Automated manual transmissions offer fuel savings from more efficient shifting. Estimates based on compilation of existing sources on the technology performance and data as well as input from industry.
Lutsey, Langer, & Khan (2014)	Automated manual transmissions	2% to 3%	Estimates based on review of literature, industry communication, and stakeholder workshop.

3. Societal acceptance and the benefits and drawbacks of autonomous trucking

This section introduces several societal acceptance considerations related to autonomous trucking and discusses the potential benefits and drawbacks of technology adoption.

SOCIETAL ACCEPTANCE

Several studies have outlined the societal acceptance considerations of automated trucking, identifying both positive and negative perceptions (Tsugawa, 2013; American Trucking Associations Technology and Maintenance Council, 2015; NACFE, 2016; National Academies of Sciences, Engineering, and Medicine, 2017; ITF, 2017). From the industry perspective, new technologies and the potential for reduced costs from fuel savings and collision avoidance can be appealing. For drivers, platooning and higher levels of automation could ease the tediousness of long shifts and allow drivers to engage in other tasks. Yet the research indicates that there are several major challenges and barriers to widespread acceptance. Table 7 captures many industry, driver, and public acceptance concerns related to autonomous trucking.

As shown in the table, there are several negative perceptions and acceptance considerations related to automated trucking. It is likely that nearly all of these acceptance issues will need to be resolved or minimized before widespread adoption of the technology. A recurring theme among industry, drivers, and the public is the concern over safety and system reliability. Heavy-duty trucks by their very nature could cause significantly more harm and damage compared to a passenger car. Research investigating the potential adoption of platooning technology found that fleets want proof that the technology works and the ability to pilot and test the technology before investing (Auburn University, 2017). There are also uncertainties related to the impact of automation on the operating conditions for drivers. For example, as tasks are increasingly handled by the computer system, there is the risk of drivers becoming complacent, overly disengaged and unable to reengage in a timely and safe manner, and experiencing high stress from close following distances. There is also the possibility of future job loss due to high levels of automation. From industry's perspective, studies suggest that fleet managers are unlikely to make major operational and logistical alterations to their freight schedules to take advantage of platooning.

Many of the considerations in Table 7 are somewhat uncertain and need to be investigated further. More research is needed to more fully understand the impacts of automated trucks—from lower levels of automation to highly automated trucking—on industry, drivers, and the general public. For example, studies could inform how obstructed views from platooning at close following distances affect driver comfort, stress, and vigilance (American Trucking Associations Technology and Maintenance Council, 2015). Safety testing, reporting, and demonstrations of automated heavy trucks are needed and should be available to the public (Short & Murray, 2016).

Table 7. Industry, driver, and public acceptance concerns about autonomous trucking

Industry	Driver	General public
• Some fleet managers are unlikely to make operational and logistical changes or reroute trucks to take advantage of platooning. • Privacy and access to key data and tracking by competitors and governments. • One accident could eliminate the monetary gain from platooning fuel savings. • May need to pay a premium for the driver of the trailing truck in a platoon due to high stress from close following distance. • Costs of driver education, training, and technology maintenance. • Ability for drivers to safely operate with limited situational awareness and restricted views due to platooning at close distances. • System security and reliability. • Truck platooning with other companies could increase liability and insurance pressure.	• Potential boredom and complacency when the system is operating the vehicle. • Monotonous yet high stress when platooning at close following distances. • Risk that drivers get pushed to operate longer hours if disengaging means that drivers are considered off the clock. • Risk of passenger cars breaking into the platoon unsafely. • Fuel savings could be outweighed by negative impacts on drivers and driver health. • Big Brother and constant monitoring. • Long-term employment security and potential job loss. • System security and reliability; drivers must believe the system is safe and appropriate.	• Safety, system security, and reliability. • Risk of hacking and hijacking a long-haul freight truck poses much greater danger than a passenger car. • Lack of awareness and familiarity. • Trust over system reliability when driving next to a computer-controlled tractor-trailer. • Ability to merge on and off highways between a series of trucks in platoon formation. • Long-term employment security and potential job loss.

BENEFITS AND DRAWBACKS OF AUTONOMOUS TRUCKING

Autonomous and connected trucking has the potential to offer several benefits, yet the extent of these benefits is generally unknown to date. Furthermore, there are several risks and drawbacks to adoption of the technology. Multiple research studies (e.g., Short & Murray, 2016; NACFE, 2016; National Academies of Sciences, Engineering, and Medicine, 2017; ITF, 2017) outline the potential impacts of autonomous trucking from the fleet perspective, which include

- improved on-road safety (i.e., fewer collisions and fatalities);
- greater fuel efficiency and reduced emissions (i.e., more miles-per-gallon);
- ease of driving (e.g., technology increasingly performs control of vehicle functions);
- increased operational efficiency (e.g., real-time planning, reduced truck downtime);
- additional road capacity (i.e., less gap between vehicles, better physical road usage);
- reduced labor costs (i.e., technology eliminates or reduces the need for human drivers).

Some of the potential impacts of autonomous trucking are likely to be realized with no or low levels of automation (Levels 0–2), whereas others emerge with high or full automation. For example, driver alert and collision avoidance systems (Level 0) can offer significant safety benefits, and truck platooning (Levels 1 or 2+) can offer considerable fuel savings. At higher levels of automation (Levels 3+), the autonomous system handles multiple elements of driving execution and monitors the driving environment. In theory, this would enable drivers to disengage, opening up the possibility of handling alternative tasks, resting, or not being present in the vehicle at all. In the following subsections, we describe and discuss each of the potential benefits of autonomous trucking in more detail while highlighting relevant risks, limitations, and drawbacks.

Improved on-road safety. The potential for autonomous vehicles to improve on-road safety is attractive to industry groups and government stakeholders and is one of the most frequently cited benefits of the technology. The elimination of driver error could save the trucking industry billions of dollars each year from collision avoidance as the system increasingly handles driving tasks (Short & Murray, 2016). Although there is some early evidence of safety improvements from the technology, government regulators currently lack the data needed to validate safety impacts (National Academies of Sciences, Engineering, and Medicine, 2017).

Several collision mitigation systems are available today and are considered Level 0 or 1. These systems typically alert drivers of potential safety risks through blind spot detection and forward collision warnings, or actively support drivers with automatic emergency braking systems. Forward collision warning systems are estimated to reduce rear-end collisions by 10% (National Academies of Sciences, Engineering, and Medicine, 2017). Meritor Wabco reports that its collision mitigation system has reduced accidents by 87% and accident costs by 89%, paying for itself in approximately 12 months (Meritor Wabco, 2014, 2017). The National Highway Traffic Safety Administration (NHTSA) conducted a field study of heavy-vehicle crash avoidance systems to assess their incident mitigation potential. The agency found that no rear-end collisions occurred in more than 3 million miles of data (NHTSA, 2016a, 2016b).

Slightly more advanced technologies are expected to further improve on-road safety by handling a greater number of driving tasks and mitigating human error. For example, Peloton's platooning system (Level 1) in theory is expected to prevent collisions through more reliable, precise, and instantaneous braking (Peloton, 2016). Yet experts express the need for additional testing to validate the safety potential both of the system itself and more holistically across all highway transportation under all road conditions and environments (National Academies of Sciences, Engineering, and Medicine, 2017).

No real-world data are available on the safety impacts of vehicles with higher levels of automation (Levels 3+). Improved safety frequently is cited as a key benefit to vehicle automation, and more information is needed to validate this claim. Sivak and Schoettle (2015) argue that the assumption that autonomous vehicle technologies will result in zero fatalities is unrealistic. Furthermore, some experts argue that Level 3, which requires human intervention, is unsafe and could even increase traffic collisions (Naughton, 2017). Some industry groups find that humans are too quick to fully trust Level 3 technology, and that they are less likely to successfully reengage with the vehicle. As a result, some companies plan to skip Level 3 automation (Naughton, 2017; Volvo, 2017; Google, 2015). This discussion has been concentrated mostly in the passenger vehicle sector, but the implications extend to heavy trucks. Further study is needed to identify and assess the safety potential of connected and autonomous vehicle technologies at all levels of automation. With higher levels of vehicle autonomy (Level 4+), safety risks posed by hacking and remote hijacking could become a significant issue and deserve further study (U.S. Government Accountability Office, 2016).

Greater fuel efficiency and reduced emissions. In North America and Europe, fuel consumption typically accounts for 25% to 40% of total costs in long-haul trucking (Sharpe, 2017). Freight trucks contribute a disproportionately large share of overall fuel consumption and environmental pollution from on-road vehicles. Improvements in long-haul fuel economy directly lead to economic benefits and emission reductions. In the autonomous trucking space, the most frequently discussed fuel savings technology application is platooning. According to Peloton, a technology company developing Level 1 platooning systems, the fuel savings from truck platooning is significant, estimated at $3,000 to $11,000 per truck annually, ranging from $0.02 to $0.042 per mile per truck (Peloton, 2016). A review of several truck platooning demonstrations finds that platooning can improve average fuel savings by 4% to 15% (see Table 5).

A series of industry interviews conducted by Auburn University (2017) show that the benefits and drawbacks of platooning are likely to differ based on company operations and fleet size. For example, although large fleets realize substantial savings from economies of scale, upfront costs are very important to smaller fleets, and they may require benefits (e.g., safety) beyond fuel savings to invest in the technology. Freight logistics could be another factor, and some companies reported that their trip distances are not long enough for platooning, and that their trucks travel alone. Inducing additional miles traveled by going out of the way to create a truck platoon could undermine the fuel savings and environmental benefits. Key considerations and possible limitations to the adoption of platooning technology include upfront costs, fleet size, logistics, and the number of freight miles suitable for platooning.

As identified in Section 2, other autonomous-vehicle-related technologies including adaptive cruise control, predictive cruise control, eco-driving feedback systems, and automated manual transmissions also may offer fuel efficiency improvements. More data and research are needed to better understand the real-world fuel efficiency improvement potential of these technologies. No data are available regarding the potential fuel efficiency improvement of highly automated trucks (Levels 4+).

Although several autonomous trucking applications offer a fuel consumption benefit, as shown in Table 5 and Table 6, certain outcomes could have a negative effect on fuel efficiency. Research examining the energy impacts of autonomous vehicles suggests that faster travel could increase fuel consumption by up to 30% (Brown, Gonder, & Repac, 2014). If collision mitigation systems and higher levels of truck automation improve safety to the point that policymakers and the public accept faster highway travel, this could pose a risk to long-haul fuel economy. There is also early evidence that autonomous vehicle technology requires significant power to operate and process data from sensors such as radar and LiDAR (Coppola & Dey, 2017), directly affecting overall fuel efficiency.

Ease of driving and increased operational efficiency. Automated driving systems are expected to improve driving conditions and allow for increased operational and logistical efficiency. As the automated driving system becomes capable of handling more driving tasks, there is the potential to reduce driver stress and the monotonous nature of long trips by allowing drivers to temporarily disengage, work on logistics, or rest. These factors open up the possibility of increased human productivity, improved driver health, quality of life, reduction in stress, and decreased fatigue (Short & Murray, 2016; National Academies of Sciences, Engineering, and Medicine, 2017; Lockridge, 2015). Truck driving jobs could then become more attractive, appealing, and gather a larger prospective driver base. Some experts believe that the technology will attract a new generation of drivers including millennials, who may be more likely to value a new emerging technology that facilitates being connected with the outside world (Kilcarr, 2016).

Autonomous vehicle technology might positively alter the roles and responsibilities of drivers, who could engage in real-time route planning through the ability to find real-time data on traffic, collisions, road closures, construction, or other road conditions. Drivers also could engage in other administrative tasks, such as scheduling and engagement with customer groups. Each of these factors could contribute to increased operational and logistical efficiency of fleets, while possibly improving the working conditions and skill sets of drivers.

Regulations exist on the number hours that truck drivers can work or drive in the United States, and these *hours of service* regulations are frequently cited as a top industry issue limiting productivity (Short & Murray, 2016). Many groups envision the need for changes in the hours of service regulations as autonomous trucking technology increases the ease of driving and reduces driver fatigue (Short & Murray, 2016; ITF, 2017; National Academies of Sciences, Engineering, and Medicine, 2017). Extensions of or flexibilities in the current hours of service regulations could significantly increase productivity and operational efficiency by enabling trucks to travel further and for longer hours, possibly requiring fewer trucks and drivers to move similar volumes of freight. In other words, autonomous trucking has the potential to increase freight capacity without requiring additional vehicles or drivers. More research is needed to better understand the risks and rewards that might stem from a modification of the hours of service regulation, perhaps drawing on related vehicle automation experiences in aircraft and locomotives.

While there is early evidence that autonomous trucking technology could improve the daily tasks of truck drivers, certain autonomous driving applications could have negative impacts. In truck platooning for example, it could be more stressful or mundane to be the driver of the following truck. NACFE (2016) reported that some fleet managers worried about the psychological well-being of drivers in the rear platoon truck. Union groups also have voiced concern that because of autonomous driving, truckers "may be pushed to operate on a 24-hour continual basis because the company is claiming he's in the back of a cab" (Marshall, 2017).

Additional road capacity. Technological capabilities from autonomous and connected vehicles offer the potential to increase road capacity. As platooning technology enables safe operation at close following distances, more efficient use of road space could result. The National Academies of Sciences, Engineering, and Medicine (2017) reports that there is a consensus among researchers that the technology will allow for shorter following distances compared to nonautomated trucks. Other researchers have quantified the road capacity benefits from platooning trucks, and found that when the vehicles decrease the gap distance between trucks from 2 seconds to 0.3 seconds, the road distance decreases from 82 meters to 44 meters (Janssen et al., 2015).

At the same time, shorter gap distances between trucks have implications for other vehicles that share the road, making the deployment more complex. Drivers of passenger vehicles may experience fewer opportunities to merge lanes and more frequently cut in between trucks, disrupting platoons and increasing risk of collisions. Passenger vehicle drivers likely have a comfort barrier to overcome before driving next to a computer-controlled freight truck. There is also early evidence that autonomous vehicles operate timidly and extremely cautiously in mixed traffic (Richtel & Dougherty, 2015), leaving even greater space between vehicles than the status quo. More research is needed to understand the effects on road capacity, especially in the interim state when roads are shared by both autonomous and legacy vehicles.

Reduced labor costs from driver elimination. Driver salary is the second largest cost for a fleet owner behind fuel costs (Bergenheim, Shladover, and Coelingh, 2012). Analysis by ATRI estimates that driver wages and benefits make up 35% of the average marginal costs per mile of trucking in the United States (Torrey & Murray, 2015). Therefore, there is a significant and direct economic incentive to limit or reduce trucking labor costs. ITF (2017) finds that autonomous trucks that are fully capable of operating without human intervention (Level 5) can reduce operating costs by 30%. The prospect of driver elimination and the associated labor savings is a primary motivator for fleet interest in autonomous trucking (National Academies of Sciences, Engineering, and Medicine, 2017). Yet this potential remains unproven, and significant technological, political, and public acceptance barriers remain.

In a series of industry interviews on autonomous trucking adoption, Auburn University (2017) identified a mix of opinions related to driver acceptance. Some fleets reported that drivers view the technology as a risk to employment and reject it while others found that drivers are generally accepting of the technology. The researchers found that one strategy to incentivize drivers to adopt the technology, specifically platooning, is to share some of the financial benefits from fuel savings with drivers.

The potential job loss from vehicle automation is a significant public and driver acceptance barrier to technology adoption. With 3.5 million truck drivers in the United States (American Trucking Associations, 2017), the potential job loss from trucking automation is staggering. Yet numerous researchers and industry groups view the technology as an opportunity to solve one of the industry's most pressing challenges: the current and projected shortage of truck drivers (ITF, 2017; NACFE, 2016; National Academies of Sciences, Engineering, and Medicine, 2017; Short & Murray, 2016).

There are many uncertainties surrounding truck driver employment security, but industry groups have an obvious direct incentive to reduce labor costs. There is a clear need to plan for the negative social externalities of job elimination in order to alleviate risks from the transition to fully autonomous trucking. Further studies are needed to identify the range of employment impacts and strategies to smooth the transition.

Summary of potential benefits and drawbacks of autonomous trucking. Return on investment (ROI) is often a key factor influencing the adoption of new technologies on freight applications. The adoption of autonomous trucking technologies partially depends on the direct and indirect economic benefits of the technology. The potential benefits and drawbacks discussed above are summarized in Table 8. Each of the potential benefits has a direct or indirect economic incentive associated with it.

While there are clear economic incentives for technological adoption, the industry-wide business case is currently lacking and there remain several unknowns related to ROI. Early adoption of the technology is anticipated to occur in niche markets with the right operational and logistical settings (National Academies of Sciences, Engineering, and Medicine, 2017). Fleet characteristics such as size and operations can influence the value proposition of adopting some connected and autonomous vehicle technologies: Upfront technology costs are very important to smaller fleets whereas larger fleets may be more driven by aggregated savings

Table 8. Summary of potential benefits and drawbacks of autonomous trucking

Potential benefits	Potential drawbacks
Improved on-road safety, reduced collisions and fatalities.	Little real-world data to validate prospective benefits. Drivers may be too quick to fully trust Level 3 automated driving systems and be unable take back control in a timely manner. Security risks and hacking potential unknown.
Greater fuel economy and reduced emissions.	Driver acceptance of fuel-saving applications (platooning) and limitations related to technological adoption and utilization on a fleet-by-fleet basis. Faster travel could undermine fuel benefits of autonomous trucking technology.
Ease of driving and increased operational efficiency.	May require regulatory changes to hours of service, platooning could induce greater stress and negative health effects for rear truck driver. Could push drivers to work longer hours if industry can claim drivers are not working when in the back of a cab.
Additional road capacity.	Little real-world data to validate actual road capacity impacts. Risk of passenger cars breaking into a truck platoon unsafely.
Reduced labor costs.	Millions of lost jobs.

from economies of scale, and some companies' logistics are unsuitable to make investing in technological capabilities worthwhile (Auburn University, 2017). For example, investing in platooning technology may be more attractive to large fleets that operate consistent and predictable routes compared to smaller fleets that have fewer opportunities.

Freight carriers are likely to chart their own unique paths to autonomous trucking technology adoption, driven largely by economics. The broader environmental and societal costs and benefits of technology adoption are difficult to assess and are generally not estimated. Further study is needed to identify the types of policies and actions that could maximize sector wide benefits from trucking automation.

4. Regulations and regulators

In this section, we introduce the policy landscape related to autonomous and connected technologies for heavy-duty vehicles. We focus primarily on policy at the federal and state level in the United States.

Several government agencies currently have a stake in regulating trucking in the United States. NHTSA regulates vehicle manufacturing and sets safety requirements, the Environmental Protection Agency (EPA) regulates greenhouse gas emissions of heavy-duty vehicles, the Federal Motor Carrier Safety Administration (FMCSA) ensures interstate trucking operations are consistent with federal regulations, and state agencies provide licenses for commercial vehicle drivers, which could vary whether vehicles operate intra- or interstate (National Academies of Sciences, Engineering, and Medicine, 2017). Autonomous vehicle technologies could complicate regulation. For example, with greater levels of vehicle automation, it may be more appropriate to require an autonomous vehicle to obtain a license for operation, as opposed to requiring a human to obtain a driver's license, as is the practice today. Complications could arise as automated vehicles are permitted to drive conditionally, such as on particular roadways with robust infrastructure, thereby blurring lines between vehicle, infrastructure, and operations regulations (National Academies of Sciences, Engineering, and Medicine, 2017).

The existing trucking safety and operational regulatory structure at the federal level could act as a barrier to the deployment and potential operational benefits of automated trucking. For example, the Federal Motor Vehicle Safety Standards (FMVSS) regulation assumes a human driver is present and mandates vehicle design with respect to humans, therefore posing as a barrier to innovative vehicle designs for Level 4+ automated trucks that could exclude floor pedals, a steering wheel, or control interfaces. The FMCSA regulates truck drivers operating hours of service, limiting daily and weekly driving hours and requiring rest breaks. Some groups note that if autonomous trucking technologies reduce driver fatigue or allow drivers to disengage during autonomous driving mode, the hours of service regulation should be more flexible or extended, thereby increasing productivity and the attractiveness of investing in autonomous trucking technology (National Academies of Sciences, Engineering, and Medicine, 2017).

The EPA regulates greenhouse gas emissions of heavy-duty vehicles under its Phase 2 rule (U.S. EPA & NHTSA, 2016b). Two of the autonomous vehicle-related technologies considered in this report, shown in Table 3 and Table 6, are included in the Phase 2 regulation: advanced manual transmissions and predictive cruise control. It is the agency's inherent jurisdiction to regulate the greenhouse gas emissions of autonomous trucks; future regulations may factor in additional autonomous vehicle technology applications such as platooning.

Laws and rules explicitly governing autonomous and connected vehicles are in their infancy, and the regulatory landscape is fragmented. As of 2016, 10 states and the District of Columbia had enacted some form of legislation. States are charting different regulatory paths that typically include topics like addressing legality and liability, establishing definitions, permitting testing on public roads, directing motor vehicle departments to adopt rules, and calling for further study (Slowik & Kamakaté, 2017). Generally speaking, the state legislation enacted to date has broadly included the phrase *autonomous vehicles* in its purview, rather than focusing on a particular vehicle segment such as passenger cars or heavy-duty trucks. However, two states have passed legislation that is explicitly related to heavy-duty trucks: Nevada and Texas have passed legislation that permits limited testing and use of autonomous and truck platooning technology on public roadways (NACFE, 2016). In contrast, the governor of Missouri vetoed a bill that would have legalized platooning in the state, noting that the technology is unproven. States also have unique requirements related to truck following distances and licensing for vehicle operation (National Academies of Sciences, Engineering, and Medicine, 2017), which could be a barrier to the adoption of platooning.

At the federal level, the U.S. Department of Transportation (DOT) released an autonomous vehicle preliminary policy statement in 2013 (DOT, 2013) that established definitions for autonomous driving and issued guidance to states. In 2016, DOT released the first Federal Automated Vehicles Policy to serve as agency and industry guidance. The policy requests that industry voluntarily report on how the guidance has been followed; it is not enforceable. The policy guidance is intended for automated vehicles that use public roadways and includes light-, medium-, and heavy-duty vehicles (DOT, 2016a). The document suggests that DOT will work with industry to ensure safety, and outlines an approach to accelerate autonomous vehicle adoption. More recently, DOT replaced the policy with new voluntary guidance, "Automated Driving Systems 2.0: A Vision for Safety" (DOT, 2017b). The document outlines 12 priority safety design elements and offers a flexible framework for industry to address each. The guidance encourages groups that are testing automated driving systems applicable to all motor vehicles under NHTSA's jurisdiction to publish a self-assessment to publicly demonstrate safety approaches and build public trust and acceptance. The document also suggests the optimal federal and state regulatory roles and offers best practices for states to consider, such as allowing NHTSA alone to regulate automated vehicle safety and performance. Like the 2016 Automated Vehicles Policy, the new voluntary guidance is not enforceable and there are no requirements for compliance.

NHTSA also has advanced rules that would mandate V2V communications technology on all new light-duty vehicles. The primary motivation of the Notice of Proposed Rulemaking is to improve automobile safety; the agency estimates that the full adoption of V2V would annually prevent between 439,000 to 615,000 crashes and save 987 to 1,366 lives (DOT, 2016b). NHTSA expects that V2V technology will be more effective at mitigating collisions than camera and other sensor-based technologies. The proposed rule would establish communications requirements using DSRC to send and receive safety messages related to vehicle speed, direction, braking status, and other information. Although the proposed rulemaking is for light-duty vehicles, a similar approach could be used to require V2V technologies in heavy-duty trucks.

Looking internationally, the EU mandates lane departure warning systems and automatic emergency braking on new commercial vehicles since late 2015. In contrast, these technologies are recommended by NHTSA in the United States (NHTSA, 2016b). Stemming from the international European truck platooning challenge, the 28 EU member states signed a Declaration of Amsterdam to create a common policy framework for deployment of truck platooning and other connected automated technologies (National Academies of Sciences, Engineering, and Medicine, 2017).

Broadly speaking, the U.S. federal government currently is working to develop a framework to advance the deployment of connected and autonomous vehicle technologies. In 2017, the U.S. House of Representatives and Senate released draft legislation that would support the development of autonomous vehicle safety technologies and establish federal pre-emption (Self Drive Act H.R.3388, AV Start Act S.1885). Notably, trucks are excluded from both bills. Clearly there are unique policy and political considerations in the automated trucking space, and these will have to be addressed by policymakers.

The energy and environmental impacts of autonomous vehicle technology have largely been omitted from the nascent laws and rules governing them. These impacts are not a priority of any existing or proposed federal guidance or legislation. More work is needed to identify policy approaches to responsibly bring fuel-savings autonomous trucking technology to market and achieve real, surplus, and quantifiable environmental benefits.

5. Industry survey

Given the complexities associated with autonomous trucking from both technical and societal perspectives, we wanted to reach out to experts in relevant fields to learn about their experiences and expectations in this quickly emerging sector. We designed a questionnaire survey template (provided in the annex) with the overall objective of better understanding issues related to autonomous trucking in four broad areas:

1. the value of increased levels of automation in the trucking industry;
2. key technical barriers;
3. timeline expectations for the commercial emergence of Level 3, 4, and 5 trucks; and
4. the role of policy.

The structured interviews were conducted over the telephone from September to November 2017, lasted roughly 30 minutes each, and consisted of a mix of quantitative and qualitative questions. Participants were not required to answer all questions in order to participate. As summarized in Table 9, we spoke to different stakeholders across the autonomous trucking ecosystem. Our interviewees from the 10 telephone surveys fall roughly into the following categories: telematics providers; trucking industry research consultants; and companies

Table 9. Number of interviews in each stakeholder group

Stakeholder group	Number of interviews
Telematics providers	3
Trucking industry research or consultants	5
Communications, radar or LiDAR suppliers	2
Truck drivers and fleet representatives	5 (informal interviews during Run on Less event on September 24, 2017)

that supply telecommunications, radar, or LiDAR systems.

In addition to the 10 formal telephone interviews, we had the opportunity to engage with various trucking fleets and industry experts as part of the Run on Less roadshow. Run on Less was a first-of-its-kind event in which several trucking fleets showcased highly efficient tractor-trailers in real-world operations. Seven fleets partnered with the North American Council on Freight Efficiency, and each fleet contributed one driver and tractor-trailer to be tracked over a 3-week period during normal operations running across the United States and Canada in certain instances. The vehicles were outfitted with telematics measurement software to log fuel usage and other operational data, which were shared with the public every day on the Run on Less website (Run on Less, 2017). Run on Less had its culminating event on September 24, 2017, in Atlanta, Georgia, as part of the inaugural North America Commercial Vehicle show. At the event, we were able to speak with five of the seven fleet teams and ask them questions on a range of different topics, including their thoughts on the various technologies and issues related to increased automation in the trucking industry. We did not go through the formal questionnaire survey with these five fleets and drivers, but we were able to collect valuable information from these conversations that is relevant to this study.

The remainder of this section summarizes the information that was gleaned from the formal interviews and the conversations with the Run on Less trucking fleet teams.

Findings. The 10 telephone interviewees were asked the same set of questions, with minor wording changes to reflect the nature of the company or organization that each survey participant represents. In addition to some background questions about each participant's company or organization with respect to their role in truck automation, we touched on issues in four areas, which are summarized in following four subsections:

Value of increasing automation in the trucking industry. After learning some background information about each of the survey participants' products or services, we explored the various motivations for engaging in the autonomous trucking space. As discussed in Section 3, there are several potential benefits around increased automation in trucking. We asked the interviewees to rank each of the following factors for why their company or organization engages in the autonomous trucking sector: fuel savings, safety, ease of driving, operational efficiency improvements, and reduced labor costs.

The participants were asked to rank each these five potential benefits of autonomous trucking from 1 to 5, with a 1 ranking for the most important factor, and a 5 for the least important factor. The results from this question are show in Figure 1. In the figure, each of the lighter-shaded points represents how that factor ranked for each of the respondents, and the darker point with the yellow outlining is the average of all of the rankings. Overall, the figure shows that there was diversity of opinion as to what are the biggest benefits for pursuing increased automation in trucking. Improvements in operations or logistics ranked as a 1 or 2 with a large majority of the interviewees, and safety also ranked fairly high, with nearly half of people ranking this as the most important benefit of autonomous trucking. Next, fuel savings and reduced labor costs both had rankings ranging from 1 to 5, with averages just over 3. Ease of driving ranked the worst, on average, out of the five factors.

The relatively large spread in rankings for all five factors reflects the large diversity of perspective in what people see as being the primary benefits of increased automation in trucking. This wide range in opinion likely can be explained by the different motivations and business strategies represented across the various companies and organizations.

Contrasting the results from the 10 telephone interviews from the conversations with the five Run on Less trucking fleets, we found somewhat of a divergence in opinion as to the value of truck automation technologies in

Figure 1. Survey responses: Motivations for developing or researching autonomous trucking technologies.

easing the driving burden. Across the five Run on Less fleets that we spoke with in Atlanta, all five drivers cited the automated manual transmission (AMT) as one of their favorite technologies. With an AMT, the transmission is controlled and operated with sophisticated software algorithms, and the driver does not need to manually shift the transmission gears, which can be stressful on the body after hours of driving—particularly in stop-and-go driving, which requires frequent shifting. Clearly, ease of driving is going to be more important to truck drivers than it is to people who don't drive trucks for a living. Thus, hearing this sentiment from truck drivers about the high value of technologies such as AMTs and lane departure systems makes sense, as these technologies directly make their job easier. However, positives such as fuel savings and operational improvements are benefits typically enjoyed by fleet owners and shippers rather than by drivers.

Another key topic area of both the telephone interviews and conversations with Run on Less fleets was the value of increased truck automation from a fuel savings perspective. Higher levels of truck automation can lead to reduced fuel consumption in several ways, including platooning (see Sections 2 and 3 for more details), reduction in driver-to-driver variability, and route optimization. In the telephone interviews, we asked the participants to give scores of 1 through 5 for 10 fuel-saving technology areas, with 1 being a very high value technology and 5 implying little or no value for that technology. We asked them to take the perspective of a typical long-haul tractor-trailer fleet operating in North America.

The results are shown in Figure 2. As with Figure 1, the lighter shaded points represent the scores from each respondent, and the darker points with the yellow outline are the average scores across all respondents. The five technology areas on the left side of figure are the technologies that are most associated with automation and include platooning, predictive and adaptive cruise, AMTs, and telematics. Of these technology areas, the AMT scored highest, with all but one of the respondents giving it a 1 (i.e., high value) rating, whereas platooning scored the lowest. Technology maturity and market penetration may have some influence on the technology's perceived value in terms of fuel savings. For example, there may be greater consensus in terms of the impact AMTs have on fuel use, as the technology has been tested and adopted by thousands of fleets, compared to platooning, which is largely under development and nearing commercialization. For the other four automation-related technologies, the scoring generally ranged between 1 and 3, with the average scores between 2 and 2.5. The remaining five technology areas included low rolling resistance (LRR) tires, tire inflation systems, 6x2 axles, engine efficiency improvements, and aerodynamics. Of these technologies, aerodynamic and engine improvements scored as relatively high-value fuel-saving technologies, while the two tire technologies and 6x2 axles had more modest average scores, ranging between roughly 2.5 and 3.5. These results are primarily valuable in providing insights into how various technologies are perceived by a variety of industry stakeholders. Technologies with lower average scores, which is to say toward the top of Figure 2, should not be interpreted to necessarily be more cost-effective than technologies with higher average scores, because fuel savings are often heavily dependent on drive cycle and operating conditions.

Overall, from the discussions with industry experts, in thinking about the various benefits of increased automation in the trucking sector, there does not seem to be one or more factors or

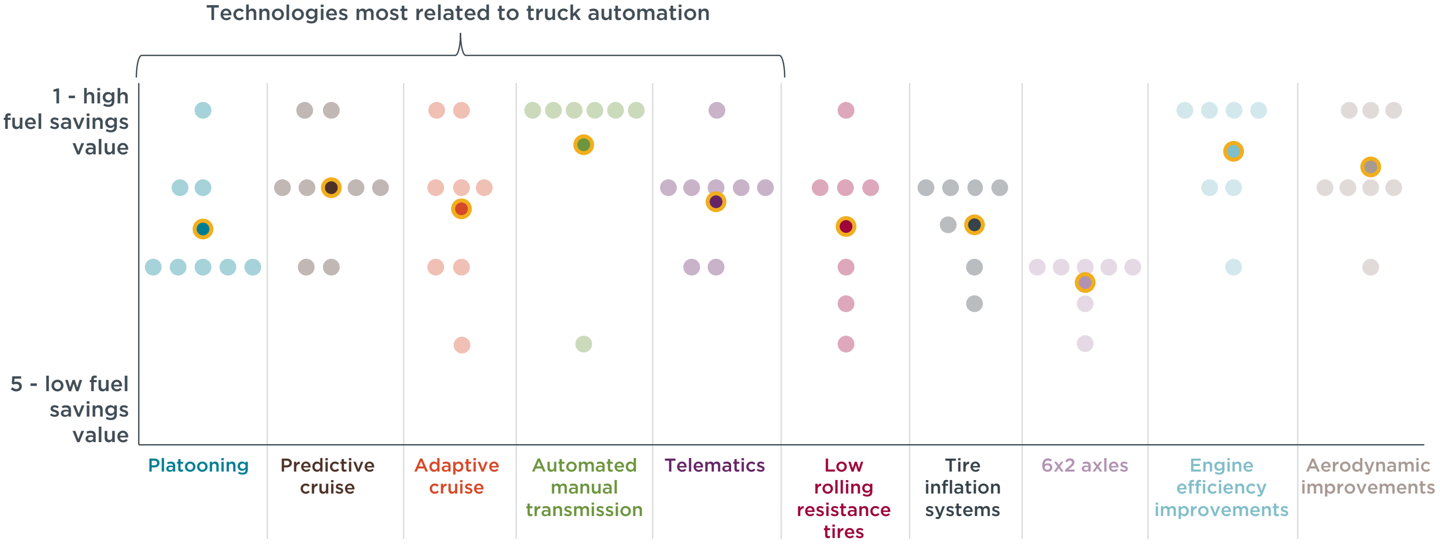

Figure 2. Survey responses: Value of various fuel-saving technologies.

technologies that clearly rise above the rest in terms of importance or value. This finding is reflected by the averages displayed across Figure 1 and Figure 2. Diverse perspectives within and across the stakeholder groups is one likely reason for the wide range of viewpoints. In addition, the five factors—fuel savings, safety, ease of driving, operational efficiency improvements, and reduced labor costs—are all highly interrelated, which makes ranking these benefits somewhat difficult.

Key technical barriers. Much of the interview time was devoted to discussing the current state of technology and the technical barriers to developing and deploying trucks with higher levels of automation. We asked participants to give their thoughts on what they perceive to be the most significant barriers facing autonomous trucking technologies. As expected, the answers varied across the respondents. Some stated that the necessary advances in sensor technologies (e.g., cameras, radar, LiDAR) will be the greatest challenge to industry, while others held that the difficulties associated with the extensive data processing needs of a highly automated truck will prove most technically burdensome. Despite the range of answers around what will be the most challenging technical issues, there was certainly consensus that designing a robust framework for human-machine interactions will be an incredibly complex technical problem.

Several of the survey respondents discussed the substantial challenges facing Level 3 and 4 trucks in two key areas: (a) how the driver engages with the vehicle, and (b) how the vehicle engages with the environment, more specifically other vehicles, pedestrians, cyclists, objects on or near the roadway, and so on. For situations when the driver needs to take over controls, a common theme from the surveys was that it will be very challenging to manage the instances when rapid human takeover is required for safety reasons. Many interviewees said that it will be problematic in trying to keep drivers' full attention when the system is performing driving tasks during normal operation but relies on the human user for fallback. In addition to the arduous technical hurdle of the driver-vehicle interface, most of the respondents also emphasized that designing autonomous systems that can properly recognize and interpret all environmental stimuli will be a very complicated engineering problem. Many of the survey participants remarked that autonomous vehicle systems will likely be able to manage 99% or more of driving conditions with relative ease, but it is exceedingly difficult to try to design for all possible situations, including rare circumstances and emergencies. One survey participant said that because of the immense demands imposed on the system by both driver-vehicle and vehicle-environment interactions, for at least the next 10 years it will be necessary for trucks to be operated by drivers that are fully alert at all times—even when the system is in control of the vehicle.

Timeline expectations for automation in trucking. The final quantitative question of the survey asked about expectations for the commercial availability of Level 3, 4, and 5 trucks. For the sake of simplicity, we asked the participants to ignore political and societal barriers—which could be formidable—and provide their best estimate as to when Level 3, 4, and 5 trucks will be technically viable and ready for commercialization.

Figure 3 summarizes the responses. The x-axis is the lead time in years for technical readiness, and the data points represent the unique responses from each interview. As in Figures 1 and 2, the points with yellow shading are the average values. As shown, there was a fairly sizeable range in the expectations for when Level 3, 4, and 5 trucks will be ready for commercialization. For Level 3, responses ranged from 1 to 10 years, with an average of just over 4 years. As with Level 3, the longest expectation for Level 4 was 10 years, although the earliest anyone expects to see Level 4 systems is around 2020, which is to say in roughly three years. The average of the values given for Level 4 was about 6 years. As expected, responses for Level 5 readiness had the longest expected timeline, with values ranging from 7.5 to 20 years and an average of roughly 12 years.

Role for policy. The final set of survey questions was centered on the role of policy. The majority of the interviewees

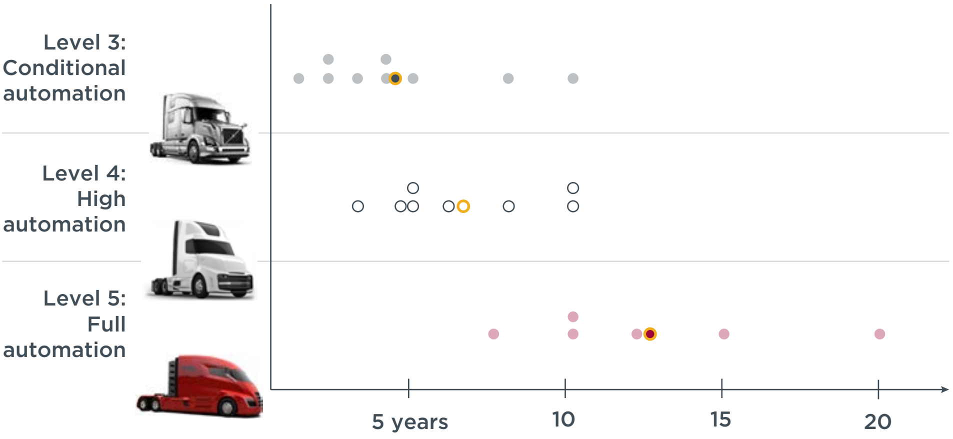

Figure 3. Survey responses: Timeline expectations for the technical readiness of Levels 3, 4, and 5 freight trucks, based on fall 2017 industry survey.

are in product development, research, or sales-focused positions and were not very familiar with the details of how their company or organization participates in policy development. Only one of the survey respondents was in a position that required active engagement in regulatory affairs. Nevertheless, all but one of the interviewees were willing to answer the policy-related questions, and several people gave thoughtful responses about how policies and programs can be designed to maximize the safety, economic, and environmental benefits of autonomous trucking while minimizing drawbacks and unintended consequences. Some common themes emerged regarding the need for (a) federal regulations, (b) public education campaigns, and (c) demonstration projects in real-world settings.

Federal regulations. Focusing on the United States,[1] policies explicitly targeting autonomous vehicles including both passenger cars and commercial vehicles are in their infancy. There is currently a patchwork of 11 states and jurisdictions that have different regulations that affect autonomous operations including, in some instances, platooning. Nearly all of the interviewees discussed the urgent need for a strong regulatory program at the federal level that provides a robust framework for vehicle certification, safety requirements, and operating protocols. Moreover, in the case of platooning systems, which are in the early stages of commercial deployment, several participants stated that a federal standard for minimum following distance that supersedes the various state regulations would be a boon to both manufacturers and fleets in accelerating the uptake of this technology application.

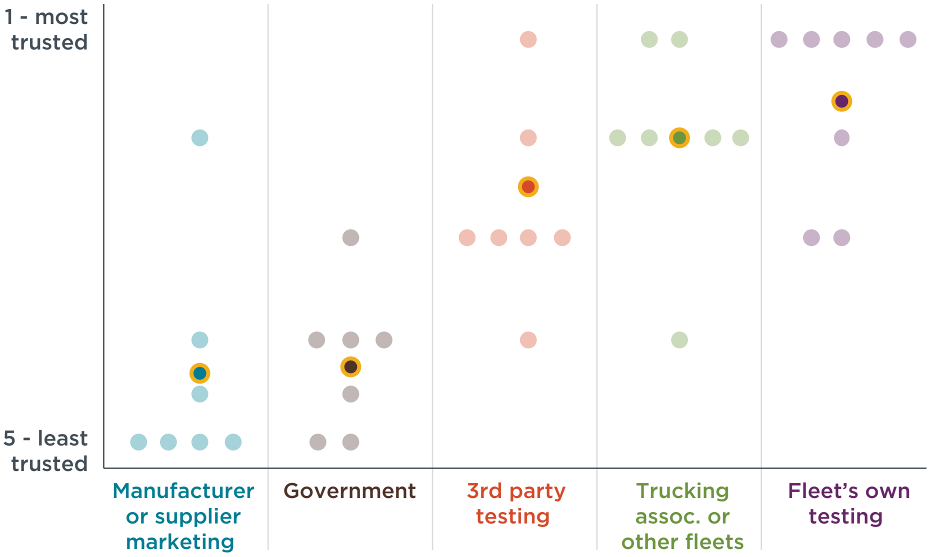

Figure 4. Survey responses: Level of trust of various sources of information when acquiring information about new technologies.

Public education campaigns. All respondents acknowledged that the transition to vehicles with increasing levels of automation will be a seismic societal shift. As such, a number of the interviewees spoke about the need for a fairly massive public education campaign, supported by both government and industry. One respondent in particular suggested that the same federal agency that takes the lead in developing and implementing regulations for autonomous vehicles, presumably the Department of Transportation, also should take on a leadership role in this area. By providing information that is easy to understand and being a clearinghouse for the collection and dissemination of real-world data and best practices, the federal government can help in creating conditions for accelerating the deployment of autonomous trucks and passenger cars in a safe and socially responsible manner.

Funding real-world demonstration projects. One survey question explored the level of trust that trucking fleets have in various sources of information in terms of acquiring information about new technologies. As with the question regarding the value of various tractor-trailer fuel-saving technologies, we asked the interviewees to answer the questions from the perspective of a typical long-haul trucking company in the United States. The results from this question are shown in Figure 4. Similar to the previous three figures, the lighter points represent the individual answers from each participant, and the darker points with yellow outlining are the average for that particular item.

The figure reflects a fairly high level of trust in self-generated testing data as well as information from other fleets or trucking associations. Conversely, most of the interviewees assumed that most fleets put a low level of trust in information presented by manufacturers and government. These findings are similar to results from a previous ICCT survey project in which we found that the majority of the fleets are highly skeptical of manufacturer claims and information disseminated by the government (Sharpe, 2017). Given the trucking industry's relatively low level of trust in these sources of information, multiple interviewees suggested that

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[1] All of the survey participants live and work in the United States and answered the question from a U.S.-centric point of view.

a good use of public funds could be to provide funding for autonomous trucking demonstration projects—particularly in real-world situations. Monetary support from the government could be combined with in-kind contributions from technology providers to help get trucks with higher levels of automation into the hands of fleets that will need to implement these new systems and vehicles. This would greatly help to mitigate the financial risks involved with testing autonomous trucking systems and resolving early technical and operational challenges that are inherent to early generation technologies.

6. Summary and areas for future work

There has been a groundswell of interest and activity in developing freight trucks with increasing levels of automation in recent years. With heavy-duty tractor-trailers accounting for a disproportionately high share of negative impacts—including local air pollutants, greenhouse gas emissions, and fuel consumption—the on-road freight sector is ripe for the application of autonomous driving. In this paper, we investigate the state of autonomous trucking technology and the benefits and drawbacks of its adoption. Special emphasis was given to understanding how autonomous technology will affect fuel use and emissions in the on-road freight sector. This paper is a first step toward better understanding the types of policy measures needed to responsibly bring fuel-saving autonomous trucking technology to market. To complement our literature review, we interviewed 10 representatives from a diverse group of companies and organizations in the United States that are active in the trucking industry and autonomous driving in particular. We also held informal interviews with five of the truck drivers that participated in the Run on Less fuel efficiency roadshow in September 2017.

State of autonomous trucking technology. The core sensing, communications, and software technologies for autonomous trucking are available today, yet technological advancements in sensor technologies and data processing are likely needed to safely deploy trucks with higher automation (Levels 3+). A small number of Level 0 and Level 1 autonomous trucking technologies and applications are commercially available today and cost approximately $1,000 to $2,000. Examples include collision avoidance and driver warning systems, lane keeping assist, predictive cruise control, and adaptive cruise control. Level 2 trucks and platooning systems in particular are rapidly approaching commercialization. Retrofitted Level 3 prototype trucks have been demonstrated on U.S. roads since 2015. Our research reveals that industry expectations for technological readiness of Level 4 and Level 5 trucks varies significantly: 4–10 years for Level 4, and 7–20 years for Level 5. Little information is currently available regarding technology costs for Levels 2–5 autonomous trucks and how costs might fall with increased production volume and commercialization.

Benefits. The potential benefits of autonomous trucking to the goods movement industry and society at large are substantial. Major improvements in on-road safety and reductions in fuel consumption and emissions are anticipated. Many fleets see an inherent value and attractive new business case in adopting autonomous trucking technology, which also holds the promise of facilitating driving tasks, improving operational efficiency through real-time planning, and reduced vehicle downtime. Also, in the long term, there is the potential for minimizing labor costs in the trucking industry by eliminating the need for human drivers. Before commercialization of fully autonomous trucks (Level 5), many envision autonomous trucking technology will have a positive impact on driving conditions by allowing drivers to temporarily disengage, work on logistics, or rest.

Drawbacks. Significant drawbacks and uncertainties remain across each of these elements. A win for long-haul fleet owners may not be a win for society at large. For example, fully autonomous trucks could significantly reduce the cost of labor by eliminating the jobs of millions of truck drivers. This seismic disruption in the labor market could have significant negative macroeconomic impacts if there are not sufficient policies and programs in place to support the drivers displaced from trucking jobs. In addition, little real-world data exists to validate the prospective safety and fuel consumption benefits that would result from autonomous trucking adoption. Significant unknowns remain regarding the deployment of autonomous trucks, their interactions with the public at large, and how the technology impacts driving conditions in a real-world setting.

Fuel use and emissions. Several autonomous trucking technologies and functions ranging from Level 0 to Level 2 are expected to improve fuel efficiency, including automatic manual transmissions, eco-driving feedback systems, adaptive cruise control, predictive cruise control, and platooning. The fuel benefits of platooning in particular have been a major focus of the research literature and industry R&D efforts to date. Our review of the literature reveals that the magnitude of *team savings,* which is to say the average savings of both the lead and platooned vehicle, ranges from 4% to 15%. The fuel savings potential of autonomous trucks with higher levels of automation (Levels 3+) beyond platooning is largely unknown and not fully explored in the available research literature. How to optimize truck automation at all levels to yield environmental benefits is a key question that warrants further study.

Role for policy. Laws and rules governing autonomous vehicles are in their infancy, and current rules could be barriers to technology adoption and operations. Our interviews indicate there is an urgent need for a strong federal regulatory program that provides a robust framework for vehicle certification, safety requirements, and operating protocols. Many issues will need to be addressed by policymakers. For example, in the case of platooning systems, a federal standard for minimum following distance that supersedes the various state regulations would be a boon to both manufacturers and fleets in accelerating the uptake of this technology application. A strong but flexible regulatory approach that encourages innovation and deployment while protecting the public is needed. Our research also reveals the need for a public-private education campaign as well as government funding for real-world demonstration projects. Such initiatives could help accelerate autonomous trucking technology adoption in a safe, socially sound manner, while also generating the real-world data needed to validate the prospective benefits of autonomous trucking.

Autonomous trucks are just merging onto the on-ramp of their long-haul journey to transform the freight industry, and much additional research and outreach is needed in this space. Table 10 organizes some of the research questions that have emerged from this study and groups these questions into four topic areas: technology, costs and benefits, maintenance and operations, and policy. The research questions and issues raised in the table are by no means an exhaustive list. Rather, this table primary aims to show the substantial diversity of unknowns facing autonomous trucking and identify some of the most pertinent issues that need to be investigated.

In addition to the questions posed in Table 10, one particularly critical area for future research is exploring how increasing levels of truck automation will impact the emergence of zero emission freight trucks, and vice versa. At present, battery electric, hydrogen fuel cell, and catenary systems are emerging in certain niche, short-haul applications such as drayage operations near ports. Several companies—from startups to more well-established truck manufacturers—are investing in and demonstrating prototypes for the long-haul tractor-trailer market (Moultak, Lutsey, & Hall, 2017), and early commercialization could occur in the next two years (Tesla, 2017). Over the next two decades, we expect advances in both autonomous driving and electrification to revolutionize the trucking industry. Identifying opportunities to link automation with electrification can maximize environmental benefits. However, there is evidence that autonomous vehicle technology is independent of vehicle powertrain. For example, diesel and electric trucks alike can platoon. More research is needed to understand the interactions between these equally seismic transformations in the way goods are moved.

And while it is the technology that grabs the large majority of headlines, there is also a critical need for strong policies that set an appropriate institutional framework so that autonomous trucks are deployed responsibly for trucking fleets and society. Our study indicates that while industry is accelerating toward autonomous trucking commercialization, there is little policy assurance that the outcome will lead to societal benefits. This study was largely centered around North America, but there are important autonomous vehicle developments happening in several countries and regions around the world, and more work is needed to assess the various emerging trends across global markets.

Table 10. Research questions emerging from this study

Technology	Costs and benefits	Maintenance and operations	Policy
• What are the evolutionary advances expected in sensor technologies and telematics systems? • As trucks and trailers become increasingly aerodynamic, how will this impact the fuel savings potential of platooning? • How do drivers respond to various types of system alerts and other stimuli in the cabin? • What is the range of driver response times when the system alerts the need for human control?	• At present, how do costs compare to benefits for automated trucks of various levels? How are these costs and benefits expected to change over the next 5 to 10 years? • How will increasing levels of automation impact the total cost of ownership for various types of trucking operations? • What are the potential impacts on labor costs? Particularly for fleets that deploy non-fully automated trucks where a driver is needed (i.e., Levels 1 – 4), how will labor costs change? • How will risk profiles and insurance costs differ for highly automated trucks? To what extent will the physical and mental burdens of driving be mitigated with automation? • Will truck automation (Levels 1-4) be a tool for driver retention and recruitment? • Safety and fuel savings seem to be the most significant benefits of autonomous trucking from a societal perspective. For various levels of truck automation, how do the monetized benefits of improved safety compare to that of fuel savings? What are the policy implications of the relative benefits of safety versus fuel savings? • What are the ideal combinations of travel speed, gap distance, weight, number of platooning vehicles, and the types of trucks and their aerodynamic profiles to optimize for fuel efficiency?	• Moving from Level 1 to 5, what are the quantifiable changes in safety benefits (e.g., in terms of avoided premature deaths)? • How will truck maintenance intervals and overall useful life be affected with increasing levels of automation? • At the macro level, how will increasing shares of automated trucks on the road affect overall VMT, fuel use, and emissions? • Are there niche trucking applications that are prime for early deployment? • How will the role of the driver change over the next 10 years? 20 years?	• What policy approaches can bring fuel-saving autonomous trucking technology to market and achieve real, surplus, and quantifiable environmental benefits? • What types of incentive programs would be most impactful for fleets? OEMs? Suppliers? • How should governments prioritize incentive funds among the various industry stakeholder groups (i.e., fleets, manufacturers, autonomous technology providers)? • How can private-public partnerships best be structured to support early proof-of-concept vehicles and demonstration projects? • How can hours-of-service regulations be modified to account for the fact that highly automated trucks may allow the driver to partially or fully disengage from driving? • In the longer term, what will be the social externalities of job elimination from the transition to fully automated trucking? What is the role for policy to alleviate the negative consequences of thousands or even millions of lost trucking jobs? • What are the most effective means for educating the public about autonomous trucking technology and best practices for interacting with autonomous trucks as a motorist or a pedestrian? • What policy approaches can lead to greater adoption of eco-driving systems to maximize fuel benefits of autonomous trucks, especially those with lower levels of automation (i.e., Levels 0-3)?

References

American Trucking Associations Technology and Maintenance Council (2015). White paper: automated driving and platooning issues and opportunities. Retrieved from http://orfe.princeton.edu/~alaink/SmartDrivingCars/ITFVHA15/ITFVHA15_USA_FutureTruck_ADP_TF_WhitePaper_Draft_Final_TF_Approved_Sept_2015.pdf

American Trucking Associations. (2017). Professional truck drivers and the trucking industry. Retrieved from http://www.trucking.org/ata%20docs/what%20we%20do/image%20and%20outreach%20programs/misc%20documents/pro%20Truck%20Drivers_final.pdf

Auburn University. (2017). *Heavy truck cooperative adaptive cruise control: Evaluation, testing, and stakeholder engagement for near term deployment: Phase two final report*. Retrieved from http://eng.auburn.edu/~dmbevly/FHWA_AU_TRUCK_EAR/FHWA_AuburnDATP_Phase2FinalReport

AV Start Act of 2017, S.1885. 115th Congress (2017). Retrieved from https://www.congress.gov/bill/115th-congress/senate-bill/1885/text

Bergenheim, C., Shladover, S., and Coelingh, E. (2012). Overview of platooning systems. Proceedings of the 19th ITS World Congerss, Oct 22-26, Vienna, Austria. Retrieved from http://publications.lib.chalmers.se/records/fulltext/174621/local_174621.pdf

Bonnet, C., & Fritz, H. (2000). *Fuel consumption reduction in a platoon: Experimental results with two electronically coupled trucks at close spacing* (SAE technical paper 2000-01-3056). https://doi.org/10.4271/2000-01-3056

Browand, F., McArthur, J., & Radovich, C. (2004). *Fuel saving achieved in the field test of two tandem trucks* (California PATH Research Report UCB-ITS-PRR-2004-20). Retrieved from http://www.escholarship.org/uc/item/29v570mm.pdf;origin=repeccitec

Brown, A., Gonder, J., & Repac, B. (2014). An analysis of possible energy impacts of automated vehicles. In G. Meyer & S. Beiker (Eds.), *Road vehicle automation. Lecture notes in mobility*. (pp. 137–153). doi:10.1007/978-3-319-05990-7_13

Coppola, G., & Dey, E. (2017, October 11). Driverless cars are giving engineers a fuel economy headache. *Bloomberg Technology*. Retrieved from https://www.bloomberg.com/news/articles/2017-10-11/driverless-cars-are-giving-engineers-a-fuel-economy-headache

DAF. (2017). DAF—Predictive cruise control. Retrieved from https://www.daf.com/~/media/files/daf%20trucks/trucks/euro%206/general/safety/pcc/daf-predictive-cruise-control-66431-en.pdf

Daimler AG. (2015). Efficiently improving efficiency: Predictive powertrain control can now be retrofitted for Mercedes-Benz trucks. Retrieved from http://media.daimler.com/marsMediaSite/en/instance/ko.xhtml?oid=9918730

Ellis, M., Gargoloff, J., & Sengupta, R. (2015). Aerodynamic drag and engine cooling effects on class 8 trucks in platooning configurations. *SAE International Journal of Commercial Vehicles,* 8(2), 732-729. doi:10.4271/2015-01-2896

Faber, F., Jonkers, E., van Noort, M., Benmimoun, M., Pütz, A., Metz, B., … & Malta, L. (2012). *SP6 D6.5 D6.6 Final results: Impacts on traffic efficiency and environment*. Retrieved from http://www.eurofot-ip.eu/download/library/deliverables/eurofotsp620121121v11dld65d66_final_results_impacts_on_traffic_efficiency_and_environment.pdf

Frisoni, R., Dall'Oglio, A., Nelson, C., Long, J., Vollath, C., Ranghetti, D., & McMinimy, S. (2016). *Self-piloted cars: The future of road transport?* (Report for the European Parliament's Committee on Transport and Tourism). Retrieved from http://www.europarl.europa.eu/RegData/etudes/STUD/2016/573434/IPOL_STU(2016)573434_EN.pdf

Google. (2015). Google self-driving car project monthly report October 2015. Retrieved from https://static.googleusercontent.com/media/www.google.com/en//selfdrivingcar/files/reports/report-1015.pdf

Harding, J., Powell, G., Yoon, R., Fikentscher, J., Doyle, C., Sade, D., Lukuc, M., Simons, J., & Wang, J. (2014). *Vehicle-to-vehicle communications: readiness of V2V technology for application* (Report No. DOT HS 812 014). Retrieved from https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/readiness-of-v2v-technology-for-application-812014.pdf

International Council on Clean Transportation. (2017). *Heavy duty vehicles technology potential and cost study*. Retrieved from https://www.theicct.org/sites/default/files/publications/HDV-Technology-Potential-and-Cost-Study_Ricardo_Consultant-Report_26052017_vF.pdf

International Transport Forum. (2015). *Automated and autonomous driving: Regulation under uncertainty* (ITF Policy Paper No. 7). http://dx.doi.org/10.1787/5jlwvzdfk640-en

International Transport Forum. (2017). *Managing the transition to driverless road freight transport*. Retrieved from https://www.itf-oecd.org/sites/default/files/docs/managing-transition-driverless-road-freight-transport.pdf

Janssen, R., Zwijnenberg, H., Blankers, I., & Kruijff, J. (2015). *Truck platooning driving the future of transportation*. Retrieved from https://www.eutruckplatooning.com/Support/Trends+and+research+reports/handler-downloadfiles.ashx?idnv=437630

Kilcarr, S. (2016, November 17). Autonomous trucks: They won't be driverless. *FleetOwner*. Retrieved from http://www.fleetowner.com/blog/autonomous-trucks-they-won-t-be-driverless

Lammert, M., Duran, A., Diez, J., Burton, K., & Nicholson, A. (2014). Effect of platooning on fuel consumption of class 8 vehicles over a range of speeds, following distances, and mass. *SAE International Journal of Commercial Vehicles,* 7(2). doi:10.4271/2014-01-2438

Lattemann, F., Neiss, K., Terwen, S., & Connolly, T. (2004). *The predictive cruise control—A system to reduce fuel consumption of heavy duty trucks* (SAE Technical Paper 2004-01-2616). https://doi.org/10.4271/2004-01-2616

Lockridge, D. (2015, July). Can autonomous trucks solve the driver shortage? *Truckinginfo*. Retrieved from http://www.truckinginfo.com/article/story/2015/07/can-autonomous-trucks-solve-the-driver-shortage.aspx

Lutsey, N., Langer, T., & Khan, S. (2014). *Stakeholder workshop report on tractor-trailer efficiency technology in the 2015–2030 timeframe*. Retrieved from the International Council on Clean Transportation, https://www.theicct.org/sites/default/files/publications/HDV_workshop_July2014_report.pdf

Marshall, A. (2017, September 29). The human-robocar war for jobs is finally on. *Wired*. Retrieved from https://www.wired.com/story/trucks-robocar-senate-war/

McNabb, Mark. (2015). 2015 Freightliner Inspiration truck. *Top Speed Trucks*. Retrieved from https://www.topspeed.com/trucks/truck-reviews/daimler/2015-freightliner-inspiration-truck-ar169226.html#main

Meritor Wabco (2014). OnGuard Collision Mitigation System. Retrieved from http://www.meritorwabco.com/MeritorWABCO_document/SP0853.pdf

Meritor Wabco. (2017). Form 10-K 2016. Retrieved from http://ir.wabco-auto.com/secfiling.cfm?filingid=1390844-17-4&cik

Meritor Wabco. (n.d.). OnGuardACTIVE Collision mitigation system. Retrieved from http://www.meritorwabco.com/Product,2,15,2,OnGuard%E2%84%A2-Collision-Safety-Systems-.aspx

Mobileye. (2017a). Heavy duty. Retrieved from http://www.mobileye.com/en-us/solutions/general-fleet/heavy-duty/

Mobileye. (2017b). About. Retrieved from http://www.mobileye.com/en-us/about-mobileye/

Moultak, M., Lutsey, N., & Hall, D. (2017). *Transitioning to zero-emission heavy-duty freight vehicles*. Retrieved from the International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/Zero-emission-freight-trucks_ICCT-white-paper_26092017_vF.pdf

Muratori, M., Holden, J., Lammert, M., Duran, A., Young, S., & Gonder, J. (2017). *Potentials for platooning in U.S. highway freight transport* (Conference paper NREL/CP-5400-67618). Retrieved from https://www.nrel.gov/docs/fy17osti/67618.pdf

National Academies of Sciences, Engineering, and Medicine. (2017). *Challenges to CV and AV applications in truck freight operations* (NCHRP web-only document 231). https://doi.org/10.17226/24771

National Center for Sustainable Transportation. (2016). *Environmentally friendly driving feedback systems research and development for heavy duty trucks*. Retrieved from https://ncst.ucdavis.edu/wp-content/uploads/2014/08/06-08-2016-NCST-UC-Riverside-Eco-Driving-Trucks-Final-June-2016.pdf

National Highway Traffic Safety Administration. (2013). *LIDAR speed-measuring device performance specifications* (Report No. DOT HS 809 811). Retrieved from https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/809811-lidarspeedmeasuringdevice.pdf

National Highway Traffic Safety Administration. (2016a). Traffic safety facts: Large trucks (Report No. DOT HS 812 279). Retrieved from https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812279

National Highway Traffic Safety Administration. (2016b). *Field study of heavy-vehicle crash avoidance systems final report* (Report No. DOT HS 812 280). Retrieved from https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/812280_fieldstudyheavy-vehiclecas.pdf

Naughton, K. (2017, February 17). Ford's dozing engineers side with Google in full autonomy push. *Automotive News*. Retrieved from http://www.autonews.com/article/20170217/MOBILITY/170219851/fords-dozing-engineers-side-with-google-in-full-autonomy-push

Nordrum, A. (2016, May 3). Autonomous driving experts weigh 5G cellular network against dedicated short range communications. *IEEE Spectrum*. Retrieved from https://spectrum.ieee.org/cars-that-think/transportation/self-driving/autonomous-driving-experts-weigh-5g-cellular-network-against-shortrange-communications-to-connect-cars

North American Council for Freight Efficiency. (2013). Peloton Technology Platooning Test Nov 2013. Retrieved from http://nacfe.org/wp-content/uploads/2018/02/Peloton-NACFE-Fuel-Test-Report-120213.pdf

North American Council for Freight Efficiency. (2014). Confidence report: electronically controlled transmissions. Retrieved from https://nacfe.org/wp-content/uploads/2018/01/Trucking_Efficiency_Transmissions_Confidence_Report.pdf

North American Council for Freight Efficiency. (2016). *Trucking efficiency confidence report: Two-truck platooning*. Retrieved from https://nacfe.org/wp-content/uploads/2018/02/TE-Platooning-CR-FINAL-_0.pdf

Peloton. (2016). Connected and automated trucks. Retrieved from University of Michigan, http://www.umtri.umich.edu/sites/default/files/Michael.Palmer.Peloton.IT_.2016D_0.pdf

Peloton Technology. (2017). The platooning experience. Retrieved from https://peloton-tech.com/how-it-works/

Richtel, M., & Dougherty, C. (2015, September 1). Google's driverless cars run into problem: Cars with drivers. *The New York Times.* Retrieved from https://www.nytimes.com/2015/09/02/technology/personaltech/google-says-its-not-the-driverless-cars-fault-its-other-drivers.html

Rodríguez, F., Muncrief, R., Delgado, O., & Baldino, C. (2017). *Market penetration of fuel-efficiency technologies for heavy-duty vehicles in the European Union, the United States, and China*. Retrieved from the International Council on Clean Transportation, https://www.theicct.org/sites/default/files/publications/HDV-market-penetration_ICCT_White-Paper_050917_vF_corrected.pdf

Roland Berger. (2016). *Automated trucks—the next big disrupter in the automotive industry?* Retrieved from https://www.rolandberger.com/en/press/Automated-Trucks-%E2%80%93-The-next-big-disrupter-in-the-automotive-industry.html

Run on Less. (2017). A first-of-its-kind cross-country roadshow to showcase advancements in freight efficiency. Retrieved from https://runonless.com/

Safe Road Trains for the Environment Project (SARTRE). (2014). *Report on fuel consumption* (Section D.4.3). Retrieved from https://www.sp.se/sv/index/research/dependable_systems/Documents/The%20SARTRE%20project.pdf#%5B%7B%22num%22%3A1174%2C%22gen%22%3A0%7D%2C%7B%22name%22%3A%22XYZ%22%7D%2C0%2C842%2Cnull%5D

SAE International. (2014, June 18). Automated driving: Levels of driving automation are defined in new SAE International standard J3016. *OEM OffHighway*. Retrieved from https://www.oemoffhighway.com/electronics/smart-systems/automated-systems/document/12183694/automated-driving-levels-of-driving-automation-are-defined-in-new-sae-international-standard-j3016

SAE International. (2016). *Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles* (Standard J3016_201609). Retrieved from https://saemobilus.sae.org/content/j3016_201609

Self Drive Act of 2017, H.R.3388. 115th Congress, September 7, 2017. Retrieved from https://www.congress.gov/bill/115th-congress/house-bill/3388/text#toc-H372946DCCC4D44E-883A30401B26CD951

Sharpe, B. (2017). *Barriers to the adoption of fuel-saving technologies in the trucking sector.* Retrieved from the International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/HDV-fuel-saving-tech-barriers_ICCT-briefing_07072017_vF_0.pdf

Short, J., & Murray, D. (2016). *Identifying autonomous vehicle technology impacts on the trucking industry*. Retrieved from http://atri-online.org/wp-content/uploads/2016/11/ATRI-Autonomous-Vehicle-Impacts-11-2016.pdf

Sivak, M., & Schoettle, B. (2015). *Road safety with self-driving vehicles: General limitations and road sharing with conventional vehicles* (Report No. UMTRI-2015-2). Retrieved from https://deepblue.lib.umich.edu/handle/2027.42/111735

Slowik, P., & Kamakaté, F. (2017). *New mobility: today's technology and policy landscape*. Retrieved from the International Council on Clean Transportation, http://www.theicct.org/new-mobility-tech-and-policy-landscape-2017

Stewart, J. (2016, May 17). $30k retrofit turns dumb semis into self-driving robots. *Wired*. Retrieved from https://www.wired.com/2016/05/otto-retrofit-autonomous-self-driving-trucks/

Stewart, J. (2017, May 10). Mapped: The top 263 companies racing toward autonomous cars. *Wired*. Retrieved from https://www.wired.com/2017/05/mapped-top-263-companies-racing-toward-autonomous-cars/

Tesla (2017). Tesla semi. Retrieved from https://www.tesla.com/semi

Tesla. (2016). Master plan, part deux. Retrieved from https://www.tesla.com/blog/master-plan-part-deux

Torrey, W., & Murray, D. (2015). *An analysis of the operational costs of trucking: 2015 update*. Retrieved from http://atri-online.org/wp-content/uploads/2015/09/ATRI-Operational-Costs-of-Trucking-2015-FINAL-09-2015.pdf

Tsugawa, S. (2013). An overview on an automated truck platoon within the Energy ITS project. *7th IFAC Symposium on Advances in Automotive Control,* 46(21), 41-46. https://doi.org/10.3182/20130904-4-JP-2042.00110

U.S. Department of Transportation. (2013). U.S. Department of Transportation releases policy on automated vehicle development. Retrieved from https://www.transportation.gov/briefing-room/us-department-transportation-releases-policy-automated-vehicle-development

U.S. Department of Transportation. (2014). *Driver assistance: Connected eco driving, intelligent speed control, adaptive cruise control, platooning*. Retrieved from http://www.itsknowledgeresources.its.dot.gov/its/bcllupdate/pdf/BCLL_DriverAssistACC_ISC_Eco_Platoon_2014_FINAL.pdf

U.S. Department of Transportation. (2016a). *Federal automated vehicles policy September 2016*. Retrieved from https://www.transportation.gov/AV/federal-automated-vehicles-policy-september-2016

U.S. Department of Transportation. (2016b). *Federal motor vehicle safety standards; V2V communications.* 49 CFR Part 571 [Docket No. NHTSA-2016-0126]. Retrieved from https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/v2v_nprm_web_version.pdf

U.S. Department of Transportation. (2017a). DSRC: The future of safer driving. Retrieved from https://www.its.dot.gov/factsheets/dsrc_factsheet.htm

U.S. Department of Transportation. (2017b). *Automated driving systems 2.0: A vision for safety*. Retrieved from https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/13069a-ads2.0_090617_v9a_tag.pdf

U.S. Environmental Protection Agency and National Highway Traffic Safety Administration (2016a). *Greenhouse gas emissions and fuel efficiency standards for medium- and heavy-duty engines and vehicles—Phase 2—Regulatory impact analysis* (EPA-420-R-16-900). Retrieved from https://nepis.epa.gov/Exe/ZyPDF.cgi/P100P7NS.PDF?Dockey=P100P7NS.PDF

U.S. Environmental Protection Agency and National Highway Traffic Safety Administration (2016b). *Final rule for greenhouse gas emissions and fuel efficiency standards for medium- and heavy-duty engines and vehicles—Phase 2*. Retrieved from https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-greenhouse-gas-emissions-and-fuel-efficiency

U.S. Government Accountability Office. (2016). *Vehicle cybersecurity: DOT and industry have efforts under way, but DOT needs to define its role in responding to a real-world attack* (Report GAO-16-350). Retrieved from https://www.gao.gov/products/GAO-16-350

Volvo. (2017). Volvo cars CEO urges governments and car industry to share safety-related traffic data. Retrieved from https://www.media.volvocars.com/global/en-gb/media/pressreleases/207164/volvo-cars-ceo-urges-governments-and-car-industry-to-share-safety-related-traffic-data

Waymo. (2017). Introducing Waymo's suite of custom-built, self-driving hardware. *Medium*. Retrieved from https://medium.com/waymo/introducing-waymos-suite-of-custom-built-self-driving-hardware-c47d1714563

Annex

Questionnaire survey template used in industry interviews.

This survey has 10 questions and is designed to take roughly **30 minutes** to complete.

Interview Date:	
Interview Conducted:	In person _________ Phone call _________
Interviewer:	

1. Company Information

Name of Company; Headquarters	
Contact Person **Contact Details**	
Technology products	**Notes on technology products**
1	[e.g., type of products; market share; locations]
2	
3	
4	
5	
6	

AUTONOMOUS TRUCKING TECHNOLOGIES

Several rapidly developing and evolving technologies and processes are enabling semi-autonomous trucking such as platooning, including sensors, radar, lidar, cameras, software, electronic control units, vehicle connectivity, data management, and security. This section includes questions related to the current status and expected progress in these aforementioned technologies related to autonomous trucking.

1. Please describe any technologies related to autonomous trucking or automated driving (e.g., platooning, predictive cruise control, collision mitigation systems, telematics systems, etc.) that your company/organization develops, manufactures, or researches. How do you expect this technology(ies) to evolve in the next 5-10 years, or what new technology(ies) do you expect to see in that timeframe?

2. From a technical perspective, what do see as the most significant barriers and opportunities for technologies related to autonomous trucking?

3. Describe the history of your engagement (i.e., development, manufacturing, research) with this technology(ies) and the markets you work in.

3a. Please rank the motivations for developing or researching this technology(ies)?

[1 – most important factor; 5 – least important factor]

Fuel savings ______
Safety ______
Ease of driving ______
Operations / logistics efficiency ______
Labor costs ______
Other (please specify) ______________________________ ______

3b. Do you expect the relative importance of these rankings to change in the next 5-10 years, and if so, how?

4. Describe how you market your products or how products are marketed to you.

4a. From a fleet's perspective, please rank the relative importance of the following:

[1 – most important factor; 6 – least important factor]

Manufacturer/supplier marketing ______
Government verification ______
3rd party testing ______
Trucking association information ______
Fleet's own research or testing ______
Other (please specify) ______________________________ ______

5. From a fleet's perspective, please rate the following items in terms of their impact on fuel-savings:
[1 – critical importance; 5 – would not consider)

______ Low rolling resistance tires
______ Tire inflation system
______ 6x2 axle configuration
______ Automated manual transmission
______ Engine efficiency improvements
______ Telematics
______ Single wide LRR tires
______ Tire pressure monitoring
______ Platooning
______ Predictive cruise control
______ Adaptive cruise control
______ Aerodynamics

6. What do you consider to be an acceptable length of time for a fuel-saving technology to pay for itself, that is, the payback time?

Less than 1 year _____ Not over 2 years ______ 3 – 4 years _____ Other (please specify) _________

7. The following table describes the various levels of automated driving. For those levels that have not been commercialized in the trucking sector (i.e., Levels 2 – 5), please fill in the number of years after which you expect to see these products offered.

Level	Description	Commercial available? If not, after how many years?
0	No automation - Human performs all driving tasks, even if enhanced by active safety systems.	Yes
1	Driver assistance – Vehicle can perform sustained control of either steering or acceleration/deceleration.	Yes
2	Partial automation – Vehicle can perform sustained control of both steering and acceleration/deceleration.	Yes (limited) E.g., Predictive cruise control, adaptive cruise control
3	Condition automation – All tasks can be controlled by the system in some situations.	[Insert number of years]
4	High automation – All tasks can be handled by the system without human intervention, but in limited environments (e.g., college campus or dedicated zones).	[Insert number of years]
5	Full automation – Automated system can handle all roadway conditions and environments.	[Insert number of years]

AUTONOMOUS TRUCKING POLICY

While autonomous-vehicle technology continues to advance and reach the trucking market, policymakers have a unique and significant window of opportunity for shaping its development and deployment toward a low-carbon and socially equitable transportation system. This section includes questions related to the current status and expected development in policies related to autonomous trucking.

8. What policies at the federal, state, or local level are influencing the development and deployment of trucks with higher levels of automation? What policies do you want or expect to see in the next 5-10 years?

9. How can policies related to autonomous trucking be designed to maximize benefits (e.g., safety, fuel savings) and minimize negative impacts (e.g., labor issues)?

10. In what way(s) does your company/organization try to engage with policymaking?

11. What are the critical research and/or outreach gaps that need to be addressed in order to design effective policies related to autonomous trucking?