21st CENTURY TRUCK PARTNERSHIP℠

Safety Technical Sector Team

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The 21st Century Truck Partnership would like to acknowledge the valuable inputs from all of our partners in creating this technical roadmap. We greatly appreciate the technical expertise of the subject matter experts at the U.S. Department of Energy's national laboratories in helping create the technical roadmap sections. Thanks also to the many industry and government partners who provided input through participation in group discussions about the roadmap.

NOTE: Achievement of the goals contained in this document is subject to a number of factors, including availability of funding to perform the research work. The Partnership will periodically review this document to ensure that it reflects current goals and funding availability.

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Message from The Leadership

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NOTE: Achievement of the goals contained in this document is subject to several factors, including the availability of funding to perform the advanced research work. The Partnership will review and potentially revise this document annually to ensure that it accurately reflects current and emerging goals, funding availability, and any relevant emerging technical or market information. Major new releases are planned at 3 to 5-year intervals.

Skip Yeakel
Industry Co-Chair
(formerly of) Volvo Group North America

Alrik Svenson
Government Co-Chair
U.S. Department of Transportation, National Highway Traffic Safety Administration

Chris Flanigan
Government Co-Chair
U.S. Department of Transportation, Federal Motor Carrier Safety Administration

Michael Laughlin
Federal Manager, 21st Century Truck Partnership
U.S. Department of Energy, Vehicle Technologies Office

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Executive Summary: Proposed Goals and Opportunities for Medium- and Heavy-Duty Vehicle Safety Research and Development

The medium- and heavy-duty vehicle (MHDV) industry is undergoing dramatic change. Regulators, society and, in some cases, end users (and shippers) are demanding the industry develop new technology to reduce our dependance on carbon-based fuel. It is generally accepted that electrified powertrains (battery electric, fuel cell, and/or low-carbon fueled hybrids) will play a dominant role; however, this transition must be met with safe and cost-effective technologies that enable stakeholders to meet their individual mission requirements.

The 21CTP Safety Technical Sector Team aims to **create a safe and efficient freight and passenger transportation network using the unique resources available across the Partnership to discover and implement technologies at the intersection of safety, efficiency, and productivity.** While MHDV electrification is already occurring in limited vocations, the identified goals can form the basis for U.S. Department of Energy and U.S. Department of Transportation sponsored research that will allow for a dramatic increase in safety during the adoption of electrified powertrains.

MHDVs have unique operational characteristics that differ substantially from those of light-duty vehicles (LDVs). For example, MHDVs have more extreme duty cycles. MHDVs also have much higher power requirements for charging than LDVs because of the battery size and charge time requirements. In addition, the MHDV market differs from the LDV market in that MHDV fleets are run as businesses and make their purchasing decisions based on evidence-based data, such as total cost of ownership. These attributes translate into industry-specific challenges that are then reflected in the MHDV technical requirements, including safety provisions. To achieve the full safety potential of MHDV electrification, while simultaneously maximizing efficiency and productivity, a specific set of dedicated safety technologies must be developed.

To this end, the team developed this roadmap to identify research and development strategies specific to MHDVs that can facilitate their widescale transition to electrification while maintaining or improving safety over baseline non-electric powered vehicles.

MHDV Safety – Gaps, Barriers, and Strategies to Overcome

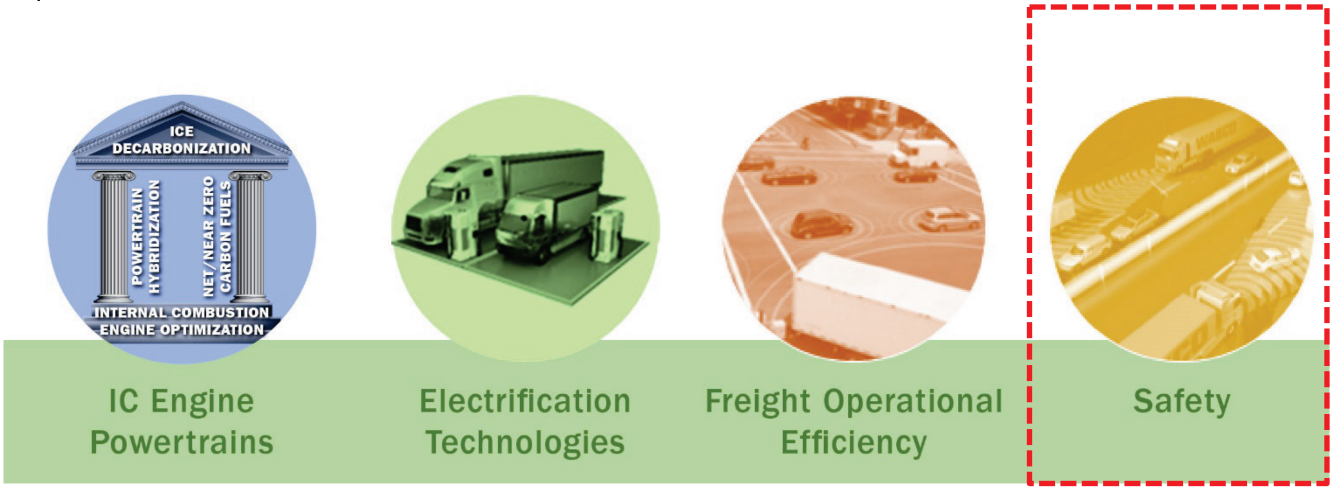
- Foster the widespread use of known safety features to be included on all MHDVs through regulations and other means. Common present-day MHDV safety features include:
  - Disc brakes in all brake locations
  - Tire pressure monitoring systems (TPMS)
  - Automatic emergency braking (AEB) systems
  - Lane departure warning (LDW)
  - Adaptive cruise control (ACC)
  - Electronic controlled braking systems (ECBS)
  - Electronic stability control (ESC)

- Electronic controlled steering systems (ECSS)

- Develop standardized protocols, both wired and wireless, for tractor–trailer communications. This is the first step required to implement many of the safety features discussed in this roadmap.
- Foster the development of industry-consensus safety standards and training for the new electrified fleet. This includes very high-voltage (>600 V) systems that are currently being researched and very high-pressure vessels (>10,000 psi) that are currently being researched for fuel cell electric vehicle (FCEV) MHDVs. Both vehicle (crashworthiness) and infrastructure safety standards will need to be robust and work together. FCEVs are powered by hydrogen fuel, which has unique features requiring specific safety considerations. Additional training may be required for operators and service personnel for any hydrogen-fueled vehicle. Lastly, hydrogen storage tanks may need additional shielding against localized fire (fire that compromises a section of the tank without activating the thermally activated pressure relief device) and correct mounting to avoid abrasive damage over time. Equipment standardization (e.g., charging receptacles and crash protection) is also required for the MHDV fleet.
- Continue research into the safety aspects of FCEV MHDVs traveling in tunnels and enclosed portions of bridges, particularly in urban areas. These efforts address concerns about limited access and egress, ventilation system capacity, and emergency response limitations. The research needs to consider probabilities and consequences of various events, including overpressures, thermal effects on tunnel components from a hydrogen jet fire, and hydrogen release with delayed ignition, to ensure that risks to tunnels imposed by hydrogen do not exceed those imposed by gasoline and/or diesel.
- Research opportunities for increased weight limits and longer combination vehicles, similar to our North American trade partners (Canada and Mexico), that could significantly improve productivity and reduce overall vehicle miles traveled (VMT) in the MHDV long-haul transportation sector. *Reduced VMT would itself lead to improved overall safety of MHDVs.*
- Research the requirements, both vehicle and infrastructure, of “managed lanes.” A comprehensive vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) integration would be required, in addition to Level 2 automation of the vehicles. *This is one of the few strategies that can help improve both safety and efficiency for both LDVs and MHDVs simultaneously*.
- Monitor ongoing and/or upcoming demonstration projects regarding platooning. This would allow us to learn about any concerns early and properly address those concerns. Outside organizations should be engaged to leverage any lessons learned from the demonstrations. These partners could include the Federal Highway Administration and SAE International, as well as universities (e.g., Penn State) and industry.
- Build on the past work of the V2I safety inspection demonstration (ongoing, conducted by the Federal Motor Carrier Safety Administration), automated wireless roadside inspections (ongoing, conducted by the Commercial Vehicle Safety Alliance) and the Trusted Truck® demonstration (complete, conducted by the Volvo Group).
- Conduct new safety data analysis studies, especially those pertaining to MHDVs, with present-day statistics. Many safety studies were completed 10–20 years ago.

Introduction

The 21CTP has divided its initiatives into four technical sectors, with teams of partners supporting each one, respectively, as shown in Figure 1. This roadmap provides technical details in the Safety focus area, describing current technology status, outlining recommended goals and targets, identifying major barriers, and proposing research to overcome these barriers. The *21st Century Truck Partnership Research Blueprint* provides the overall vision and goals for 21CTP (21CTP 2019). The reader is encouraged to refer to that document for additional perspective.



IC=internal combustion

Figure 1. 21CTP Technical Sector Teams

Background

Safety of medium- and heavy-duty vehicles (MHDVs) and mobility systems remains an uncompromised requirement as the Partnership seeks improvements in efficiency, environmental sustainability, and productivity. Safety is an important element in the 21CTP high-level vision, and truck manufacturers have stated on numerous occasions that safety is their number one priority. Current and future technologies have the potential to change the transportation landscape, with important implications—both positive and negative—for safety and efficiency, and these implications must be addressed. The Partnership, with resources across multiple agencies, is uniquely positioned to lead collaborative research at the intersection of safety, efficiency, and productivity, as well as to discover and implement synergistic benefits in these areas.

21CTP intends to pursue the development and early adoption of technologies and processes to improve truck safety, resulting in the reduction of truck-involved crashes, fatalities, and injuries, thus enabling ancillary benefits related to congestion mitigation, emissions reduction, reduced fuel consumption, and improved productivity.

First and foremost, safe trucks preserve the lives of truck operators and others with whom they share the road. The public has also placed a high premium on safety, with concerns about driver distraction, driver fatigue, truck aggressivity, and risks associated with exposure to heavy trucks. Crashes involving heavy trucks still account for almost one out of seven motor vehicle fatalities in the United States (U.S. Department of Transportation, 20.

Although secondary in significance to fatalities, there are a variety of costs on society associated with crashes involving trucks. Truck crashes on the nation's highways (even non-fatal ones) come with high costs for reduction in quality-of-life injuries, traffic congestion, lost cargo, insurance expenses, and reduced economic productivity. Based on a study by the Pacific Institute, the estimated average cost of police-reported crashes involving trucks with a gross weight rating of more than 10,000 pounds is $91,112 (in 2005 dollars). Crashes in which truck tractors with two or three trailers were involved were the rarest, but their average cost was the highest—$289,549 per crash. The costs of nonfatal injury crashes averaged $195,258, and fatal crashes—at $3,604,518 per crash—were the most expensive (Zaloshnja and Miller 2006).The 21st century truck must be not only designed to the highest levels of safety and productivity standards but must also be easily, cost-effectively, and comprehensively maintained. This is particularly true as new safety systems and technologies (i.e., advanced driver assistance systems (ADAS) like lane centering and forward collision avoidance) require precise calibration to operate optimally.

Throughout its history, the Partnership has consistently included safety as a focus area in its work. MHDV manufacturers, industry suppliers, and federal agencies that participate in 21CTP are working collectively to ensure that safety goals remain uncompromised as fuel economy improvements are pursued through advanced technologies—and even to improve safety in parallel with efficiency and mobility improvements.

The goal of 21CTP collaborative research in this area is to create a safe, efficient, equitable, and transformative freight and passenger transportation network using the unique resources available across the Partnership to discover and implement technologies to benefit system safety, efficiency, and productivity.

National Highway Fatality Statistics

Between 1966 and 2014, total annual traffic fatalities generally decreased, and the fatality rate per 100 million vehicle miles traveled (VMT) steadily declined, as Figure 2 shows. Vehicle improvements such as air bags and vehicle stability controls, combined with safety programs for increased seat belt use and reduced impaired driving, are credited for this steady decline.

This downward trend in fatalities reversed in 2015 and 2016, however. The total number of fatalities increased by 7.2% in 2015 relative to 2014, the largest percentage increase in nearly 50 years. The fatality rate per 100 million VMT also increased, by 3.7%. In total, traffic crashes resulted in 35,092 fatalities in 2015 (U.S. Department of Transportation 2016). This trend continued in 2016 with a total of 37,806 fatalities (U.S. Department of Transportation 2018). The U.S. Department of Transportation's (DOT's) National Highway Traffic Safety Administration (NHTSA) has suggested several causes for this increase in fatalities, including an increase in driving as a result of job growth and low fuel prices. After the two consecutive yearly increases, the trend reversed somewhat in 2017, with 37,133 motor vehicle crash fatalities, or a rate of 1.16 per 100 million miles (U.S. Department of Transportation 2018). The most recent report shows total fatalities decreasing again back to 36,096 in 2019 (U.S. Department of Transportation 2020).

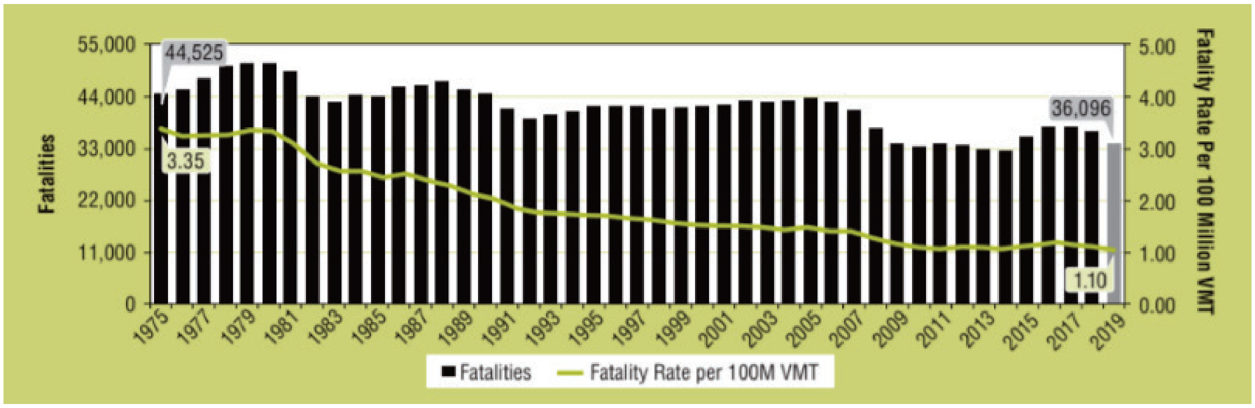


Figure 2. Fatalities and Fatality Rate per 100 Million VMT, 1975–2019

(U.S. Department of Transportation 2020)

Crashes and Fatalities in the Medium- and Heavy-Duty Truck Segment

As Figure 3 shows, the proportion of fatalities in the MHDV area has remained relatively consistent over the last decade, representing around 4% of total fatalities (U.S. Department of Transportation, 2019). Some of the factors that may have driven change to overall fatality statistics (see above) are less applicable to MHDVs (e.g., air bag use is uncommon, and impaired driving is far less prevalent among MHDV drivers). Large truck fatalities, although a relatively small and consistent portion of total fatalities, are still of concern to the industry. Any technology changes to trucks for improved efficiency should avoid making any negative impacts on these rates and should improve them, if possible.

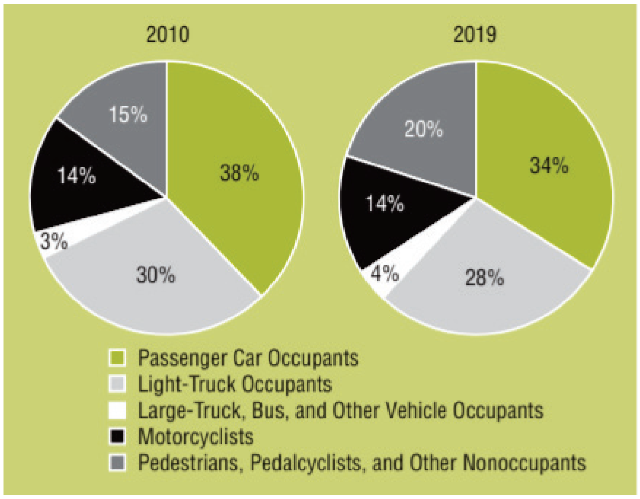


Figure 3. Fatality Composition 2010 and 2019

(U.S. Department of Transportation 2020)

The Road to Zero

The safety-related activities within 21CTP should be viewed within DOT's larger national framework for safety. Partly driven by the large increase in traffic fatalities in 2015 (noted above), DOT launched a Road to Zero Coalition with the goal of ending fatalities on the nation's roads within the next 30 years (U.S. Department of Transportation 2016). This coalition includes DOT organizations—the NHTSA, the Federal Highway Administration, and the Federal Motor Carrier Safety Administration—and is managed by the National Safety Council, a non-profit organization with the goal of eliminating preventable deaths across the nation's daily activities.

Under the Road to Zero Coalition, DOT initially committed a total of $3 million between 2016 and 2018 for grants to organizations working on lifesaving programs. Focuses included increased seat belt use, rumble strip installation, truck safety improvements, behavior change campaigns, and data-driven enforcement.

U.S. DOT is committed to the ambitious long-term goal of reaching zero roadway fatalities and has adopted the Safe System Approach to help address the crisis on the nation's roadways. The Safe System Approach is the guiding paradigm of the National Roadway Safety Strategy (NRSS), and the department is dedicated to implementing the actions outlined in the NRSS to move the U.S. closer to its zero deaths goal.

Over many decades, the United States has experienced reductions in roadway fatalities through successful interventions like the widespread use of seat belts and air bags in motor vehicles, effective State laws such as a 0.08 or lower blood alcohol concentration limit to reduce impaired driving, and consistent improvement of roadway design and traffic operation practices. Roadway fatalities declined consistently for 30 years, but progress stalled over the last decade and is moving in the wrong direction. In 2021, an estimated 42,915 lives were lost on U.S. roads, and early estimates for 2022 show similar numbers of people dying on U.S. roadways.

In response to this crisis, U.S. DOT adopted a Safe System Approach as the guiding paradigm to address roadway safety. The Safe System Approach holistically builds and reinforces multiple layers of protection to both prevent crashes from happening in the first place, and minimize the harm caused to those involved when crashes do occur.

The National Roadway Safety Strategy is arranged around five complementary objectives corresponding to the following Safe System Approach elements:

- Safer People: Encourage safe, responsible driving and behavior by people who use our roads and create conditions that prioritize their ability to reach their destination unharmed.
- Safer Roads: Design roadway environments to mitigate human mistakes and account for injury tolerances, to encourage safer behaviors, and to facilitate safe travel by the most vulnerable users.
- Safer Vehicles: Expand the availability of vehicle systems and features that help to prevent crashes and minimize the impact of crashes on both occupants and non-occupants.
- Safer Speeds: Promote safer speeds in all roadway environments through a combination of thoughtful, equitable, context-appropriate roadway design, appropriate speed-limit setting, targeted education, outreach campaigns, and enforcement.
- Post-Crash Care: Enhance the survivability of crashes through expedient access to emergency medical care, while creating a safe working environment for vital first responders and preventing secondary crashes through robust traffic incident management practices.

Nearly all components of the NRSS align with the goals of the Partnership as well.

U.S. Department of Transportation Strategy

In 2022, DOT released its Strategic Plan for 2022 through 2026 (U.S. Department of Transportation 2022). Several strategies in this current plan are of common interest to DOT and the Partnership:

- Research and support initiatives to improve occupant protection and reduce risky operator behaviors, such as speeding, distraction, fatigue, and operating under the influence.
- Implement measures that mitigate or eliminate incidents among rail, transit, aviation, and trucking operations and the traveling public.

- Advance U.S. best practices in road safety and vehicle standards in collaboration with global initiatives.
- Work with research and private institutions to harness technological innovations to reduce and mitigate safety incidents.
- Use data and data analytics to take proactive actions to address emerging safety risks and support compliance.
- Set safety management systems-related standards and guidelines that hold industry and public agencies accountable for safety and establish partnerships with these entities to promote safety.
- Adopt an interdisciplinary approach to reducing speeding-related crashes, fatalities, and injuries.
- Provide technical assistance to critical infrastructure owners and operations to better identify, assess, and address critical physical and cybersecurity vulnerabilities.
- Foster safe innovation and global competitiveness, especially with respect to growing transportation industries such as EVs, advanced transportation technologies, and commercial space.
- Support freight operations safety through engaging with domestic and international stakeholders.
- Develop a decarbonization strategy for the transportation sector and incentivize stakeholders in their efforts to reduce emissions.
- Support innovative programs, policies, and projects to reduce environmental impacts associated with freight movements.
- Capture and disseminate lessons learned from demonstrations or projects.
- Support adoption and implementation of new technologies and innovative practices.
- Provide technical assistance to stakeholders on emerging transportation technologies in ways that better serve their needs and match their values.

The Safety–Efficiency Nexus

Federal and industry partners in 21CTP intend to conduct extensive research to make dramatic improvements in the efficiency of MHDVs in multiple sectors using technologies that affect the entire truck (and indeed, in some cases, the larger freight movement system). Because these technologies are part of a broader freight movement system, changes in the technologies do not happen in isolation. It is very likely that efficiency technologies will have some impact on the safety of the trucks in which the technologies are included, and those effects can be negative or positive. The Partnership will play an important role in providing the broad system-level understanding of future technology plans and in facilitating discussions about the impacts those technologies might have on safety. In this way, the Partnership can encourage the development of safety and efficiency synergies and minimize safety disbenefits associated with efficiency improvements. Ultimately, the Partnership will seek to ensure that future trucks will be highly efficient while still contributing to the overall Safe Systems Approach (SSA) that is working towards a future with zero roadway fatalities and serious injuries. In support of this approach, safety programs are focused on infrastructure, human behavior, responsible oversight of the vehicle and transportation industry, and emergency response.

Current State of Technology

As noted above, one of the Partnership's main interests in safety is in how emerging efficiency technologies, including those developed through other Partnership research activities, intersect with the transportation system's overall safety goals. Many technologies being considered by 21CTP are likely to have some effect on safety. This section will outline a number of technologies and the current thinking within the community on safety effects. DOT and NHTSA conducted an extensive literature search and analysis to explore the safety implications of efficiency technologies across a wide range of equipment types and applications (Brecher, Epstein and Breck 2015). The Partnership will draw on this detailed analysis for many of the initial conclusions contained in this section.

Technologies in this section have been subdivided into four distinct areas: internal combustion engine powertrains, electrified technologies, freight operational efficiency, and safety. These align with the four focus areas of the Partnership shown in Figure 1. This State of Technology section will explore the safety and efficiency intersections of new technologies in these four 21CTP focus areas. Additional mention is made of other technologies with efficiency and safety implications, such as tire rolling resistance and vehicle aerodynamics, that are of interest to 21CTP but are not part of the Partnership's early-stage research objectives.

Internal Combustion Engine Powertrains

Alternative Fuels

Alternative fuels have been of interest to the Partnership as a means of displacing petroleum and potentially reducing both emissions and fuel-related operating costs. In recent years, the low cost of natural gas has produced considerable interest in employing this fuel for operational cost improvements. Advanced combustion regimes may require fuels with properties different from those offered by conventional gasoline and diesel, and alternative fuel blend stocks are one opportunity to achieve these properties. These fuels have characteristics that vary from those of conventional petroleum fuels, and thus, the safety characteristics of vehicles using alternative fuels may also be different.

DOT and NHTSA examined the potential safety implications of several alternative fuels, including natural gas (compressed and liquefied), biodiesel, and propane (Brecher, Epstein and Breck 2015). DOT did not identify any clear safety contraindications for the use of compressed or liquified natural gas but did observe that the potential safety hazards for these vehicles would be different from those of conventional diesel vehicles. Some additional training for natural gas vehicle operators and mechanics can improve safety, as can sound design and manufacture of natural gas storage tanks. DOT did not find any significant issues with safety related to biodiesel as a drop-in diesel fuel replacement. DOT noted that the flashpoint for biodiesel was considerably higher than for petroleum diesel, representing a safety benefit for biodiesel. However, biodiesel does have challenges related to its solvent properties and its low-temperature gelling characteristics, which may result in fuel filter clogging, presenting safety concerns if the vehicle were to be disabled due to this clogging. FMCSA's review of propane safety determined that these vehicles can be as safe as conventional fuel vehicles if care is taken to prevent tank overfills and tank pressure relief valves are properly maintained.

For advanced spark-ignition and compression-ignition engines, the U.S. Department of Energy's (DOE's) Co-Optimization of Fuels & Engines (Co-Optima) initiative is considering safety implications of new fuels and fuel blends. The work to date has considered corrosion, fuel toxicity, biodegradability, and fuel handling safety as part of its set of first-tier screening criteria for spark-ignition fuels. Potential fuels/feedstocks are rejected if they are corrosive, toxic/carcinogenic, less biodegradable than MTBE (a fuel oxygenate that presented groundwater contamination issues), or unstable in ways that are not addressable with antioxidants (Fioroni 2021). In this way, Co-Optima seeks to identify fuels for advanced combustion engines with safety characteristics similar to or better than conventional fuels.

Driver Incentives

There is a potential safety concern related to a method to encourage drivers of current compression-ignition engines to follow environmental recommendations. Specifically, the driver inducement strategies are meant to ensure that selective catalytic reduction systems used to address NOx emissions receive regular maintenance and replenishment of the diesel exhaust fluid (DEF) necessary for proper operations. The U.S. Environmental Protection Agency (EPA) issued revised guidance in late 2009 that covered these strategies, stating that possible approaches include reducing maximum available engine torque enough that an operator would notice the operational difference. If left unaddressed, the engine performance would degrade enough to prevent the truck's operation without DEF (U.S. Environmental Protection Agency 2009). This guidance acknowledged the potential safety implications of severe degradation or disablement of a vehicle's powertrain and recommended that such inducements be initiated at the time of refueling, parking, or engine restart. EPA's guidance provided general approaches but left the specific details to the manufacturers. In practice, engine and vehicle manufacturers have implemented strategies such as limiting vehicle speed to 55 mph when the DEF level is empty, with subsequent limitation to 5 mph if the DEF level remains empty and the warning is ignored for a designated time (Detroit Diesel Corporation 2013). These inducements could be a safety concern if activated in an area far from a service location.

Advanced Technologies

The North American Council for Freight Efficiency (NACFE) conducted a study of electronically controlled transmissions (including automated manual transmissions) and found that these may offer the potential for improved safety (Menig, et al. 2014). The study suggested that an automated shifting process has potential safety benefits. The driver would not be distracted by having to shift gears, allowing for better concentration on the road, and driver fatigue would be reduced.

Variable engine accessories also represent more benefits than drawbacks, as they provide an opportunity for efficiency improvement through reductions in the power required to drive this equipment. Coolant water pumps, cooling fans, alternators, power steering pumps, air compressors, and air conditioning compressors are the major accessories being considered for improvement. The only safety implications for simple efficiency improvements to these accessories are possible reduced reliability and durability that could represent a failure while driving on the road. Electrification of these accessories with a high-voltage electrical system may present electric shock hazards, but these risks can be mitigated in much the same way as the hazards for hybrid electric vehicles (Otto, et al. 2017).

Advanced drivetrain technologies provide more complicated offerings in terms of benefits and drawbacks. Class 8 tractors can be equipped with a 6x2 axle configuration that may offer both improved efficiency and better stability in slippery road conditions. The 6x2 axle configuration is becoming more common in production vehicles; all SuperTruck I teams employed this technology. In this setup, one axle in the tractor tandem is unpowered, resulting in improved fuel efficiency through reduced weight and reduced friction losses in the unpowered axle. The 6x2 configuration may provide enhanced safety if drive axle traction is lost: whereas a 6x4 axle configuration may have all four drive wheels spinning, a 6x2 axle will have only two of the four wheels spinning, allowing the two tag axle wheels to maintain grip for lateral stability. This technology may require higher rated front axles and components, and therefore increased weight and cost, so is best suited for fleets with particular duty cycles (NACFE 2017).

Advanced drivetrain technologies are also employed in engine downspeeding. This combines changes to the rear axle ratios with changes to transmission gear ratios to reduce steady-state engine cruise speed for improved fuel economy. Downsped trucks tend to be significantly quieter at their typical operating points because of the lower engine speed, which results in less driver fatigue and therefore improved safety. However, depending on the engine horsepower and torque characteristics, a downsped engine may have less horsepower available to accelerate quickly without multiple downshifts, which could present a safety concern. An additional vehicle level system outcome is that downspeeding results in lower output from the compression brake, putting a higher burden on the foundation brakes of the combination especially in down grade driving environments.

Driveline failures can also occur with the stronger and less flexible components used in downsped powertrains, and these failures may represent a safety issue, depending on where they occur (Baxter, Rondini and Roeth 2015). Proper engineering of the components for strength should reduce or eliminate this safety concern.

Electrified Technologies

The Partnership has a great interest in electrification for the MHDV market at all levels, from mild hybrid to full battery electric vehicles (BEVs)—and, in the future, even fuel cell electric vehicles (FCEVs). These drivetrains offer the potential for significant emission and efficiency improvements, as well as ancillary benefits for driver comfort and convenience. These technologies have potential safety upsides (e.g., no missed gear shifts, reduced noise, and the resulting reductions in driver fatigue and distraction) and downsides (high-voltage electrical systems and very high-pressure storage vessels) that must be considered.

DOT examined the safety implications of hybrid (electric and hydraulic) and full electric drivetrains in its literature search (Brecher, Epstein and Breck 2015). For electric drivetrains, the main safety concern is the presence of high-voltage electrical service and high-power energy storage. These require additional training and conspicuity measures to reduce the level of electric shock hazards to operators and service personnel. Some potential exists for battery-related fire hazards that must be mitigated with additional safety measures. Safety concerns might arise if the electric drive system (motor or power electronics) were to fail, resulting in an immobilized vehicle. Weight increase of hybrid systems may result in increased stopping distances or changes in handling (although the additional braking energy recovery for these hybrids may mitigate the stopping distance increase).

FCEVs are powered by hydrogen fuel, which has distinct features requiring specific safety considerations. A number of hydrogen's properties make it safer to handle and use than conventional fuels—for example, it is non-toxic and dissipates rapidly when released. However, because of its wide range of flammable concentrations in air and its ignition energy (which is lower than that of gasoline or natural gas), hydrogen requires additional engineering controls to enable its safe use, both on the vehicle and at the refueling station. Hydrogen can also be a simple asphyxiant in high concentrations or oxygen-depleted environments. Hydrogen is odorless, tasteless, and colorless, so sensors are required to detect hydrogen leaks. Adequate ventilation is necessary to prevent accumulation in enclosed spaces, including garages and maintenance facilities. Because hydrogen's flame is nearly invisible, special flame detectors are needed. Also, appropriate materials must be used to prevent embrittlement of metals when exposed to hydrogen, which can lead to component failure and leaks.

Current FCEVs store gaseous hydrogen fuel in high-pressure (350–700 bar) onboard tanks. As is the case for compressed natural gas vehicles, the high-pressure onboard storage presents different safety concerns from conventional vehicles, requiring specialized training for operators, service personnel, and first responders. Government agencies regulate the design and implementation of the hydrogen pressure vessels and require specific design standards and certifications. Similarly, hydrogen refueling stations must adhere to strict codes and standards to ensure safety of users as well as occupants of nearby buildings.

FCEVs are currently not permitted to travel through certain tunnels and enclosed portions of bridges, particularly in urban areas, because of concerns about limited access and egress, ventilation system capacity, and emergency response limitations. Multiple studies have evaluated failure modes and consequences associated with hydrogen FCEVs in tunnels and probabilities and consequences of various events, including overpressure and jet fire (thermal effects on tunnel components). However, some research gaps remain (LaFleur, et al. 2020).

Freight Operational Efficiency

Driver Behavior

The medium- and heavy-duty truck driver's behavior plays a critical role in both vehicle efficiency and safety performance. The Large Truck Crash Causation Study, commissioned by FMCSA and conducted with the help of NHTSA, investigated a nationally representative sample of fatal and injury crashes between April 2001 and December 2003 at 24 sites in 17 states (Federal Motor Carrier Safety Administration 2007). A key take-away from the study is that driver action or inaction, whether by the driver of the truck or the driver of the other vehicle, was the critical reason for 88% of the crashes—thus highlighting the driver's important role in safety. In a preliminary study conducted for DOE's Vehicle Systems Program, data collected for the Heavy Truck Duty Cycle Project were analyzed for fuel efficiency and driver behavior. Researchers examined trips on identical routes with identical cargo loads but differing driver behavior, finding variations in fuel efficiency of up to 50%.

Preventing driver fatigue and distraction and providing the driver with eco-driving feedback information are critical components of enhancing safety and efficiency through driver behavior.

Technologies

Vehicle speed limiters offer the potential for efficiency and safety improvements through limiting the top speed of vehicle to a preset value. Reduced speeds improve fuel efficiency and decrease the number of crashes attributable to excess speed. DOT literature searches indicated that crash rates for trucks without speed limiters were higher than for those with speed limiters (16.4 versus 11 crashes per 100 trucks per year). There have been questions in the past about whether the possible differential in speed between limiter-equipped trucks and non-limited traffic (probably running at a higher speed) represents a safety problem. "Europe's experience with speed limiters that cap truck speeds at a speed substantially lower than the average speed of passenger vehicles also suggests no degradation in safety." (Brecher, Epstein and Breck 2015). The Federal Motor Carrier Safety Administration (FMCSA) intends to proceed with a motor carrier-based speed limiter rulemaking by preparing a supplemental notice of proposed rulemaking (SNPRM) to follow up on the National Highway Traffic Safety Administration's (NHTSA) and FMCSA's jointly issued September 7, 2016, notice of proposed rulemaking (NPRM) on this subject. The new rulemaking will consider whether additional regulatory actions should be taken concerning MHDV manufacturer requirements. Specifically, motor carriers operating MHDVs in interstate commerce with a gross vehicle weight rating (GVWR) or gross vehicle weight (GVW) of 11,794 kilograms or more (26,001 pounds or more), whichever is greater, that are equipped with an engine electronic control unit (ECU) capable of governing the maximum speed be required to limit the MHDV to a speed to be determined by the rulemaking and to maintain that ECU setting for the service life of the vehicle.

Intelligent speed adaptation or intelligent speed assist (ISA) systems take the concept of speed limiters a step further by alerting the driver when the speed limit is exceeded and automatically reducing the vehicle speed to the legal limit. ISA systems verify the speed limit using cameras with software to interpret speed limit signs or comparing mapped speed limit data with the vehicle location using global positioning satellite (GPS). Driver acceptance has been identified as a possible barrier to widespread acceptance, but field tests have shown ISA use can reduce speeding and risks of serious injury and fatal crashes (Vaa 2014). ISA systems are commercially available in North America. In 2019 the EU mandated ISA to be equipped (but overridable by the driver) on new vehicles effective in 2022 (Official Journal of the European Union 2019). Whether used to alert drivers or actively limit vehicle speeds to the posted speeds, more research is needed to understand potential safety benefits and risks of ISA when used in MHDVs in the United States.

Idling reduction technologies seek to improve efficiency—and may also enhance safety—by eliminating unnecessary idling for cab comfort and hotel loads during rest periods or other daily operations. These technologies range from very simple (engine idle shutdown timers) to very complex (battery auxiliary power units that are potentially integrated into future electrified drivetrains). DOT literature reviews did not locate any safety issues related to idling reduction technologies but did identify the possibility for safety benefits from reduced driver fatigue through better sleep patterns and improved in-cab air quality from these systems (Brecher, Epstein and Breck 2015). The North American Council for Freight Efficiency noted findings from a DOT study that indicated 13% of all large truck crashes were found to involve driver fatigue (Rondini, Schaller and Swim 2014).

Vehicle automation can also provide safety and efficiency improvements. Automation covers the spectrum of vehicle control, from providing useful features for a driver who is completely responsible for vehicle operation to giving the vehicle total control (full automation). DOT has considerable interest in the safety benefits of vehicle automation, particularly at the lower levels of automation (see Figure 4 for an overview of automation levels). For example, advanced driver-assistance systems (ADAS, enable onboard systems to work together to provide assistance to the driver (for example, adaptive cruise control with lane centering). These systems can address collisions and other safety incidents arising from human error, e.g., distracted driving. Some of these systems are available in today's MHDVs, and considerable research effort is being applied to expand the capabilities of these systems. The Bipartisan Infrastructure Law (Infrastructure Investment and Jobs Act of 2021) directs DOT to prescribe a motor vehicle safety standard and accompanying performance requirements for automatic emergency braking systems for heavy-duty vehicles and to require that systems installed in such vehicles be in use during operation no later than 2 years after enactment. DOE is also interested in vehicle

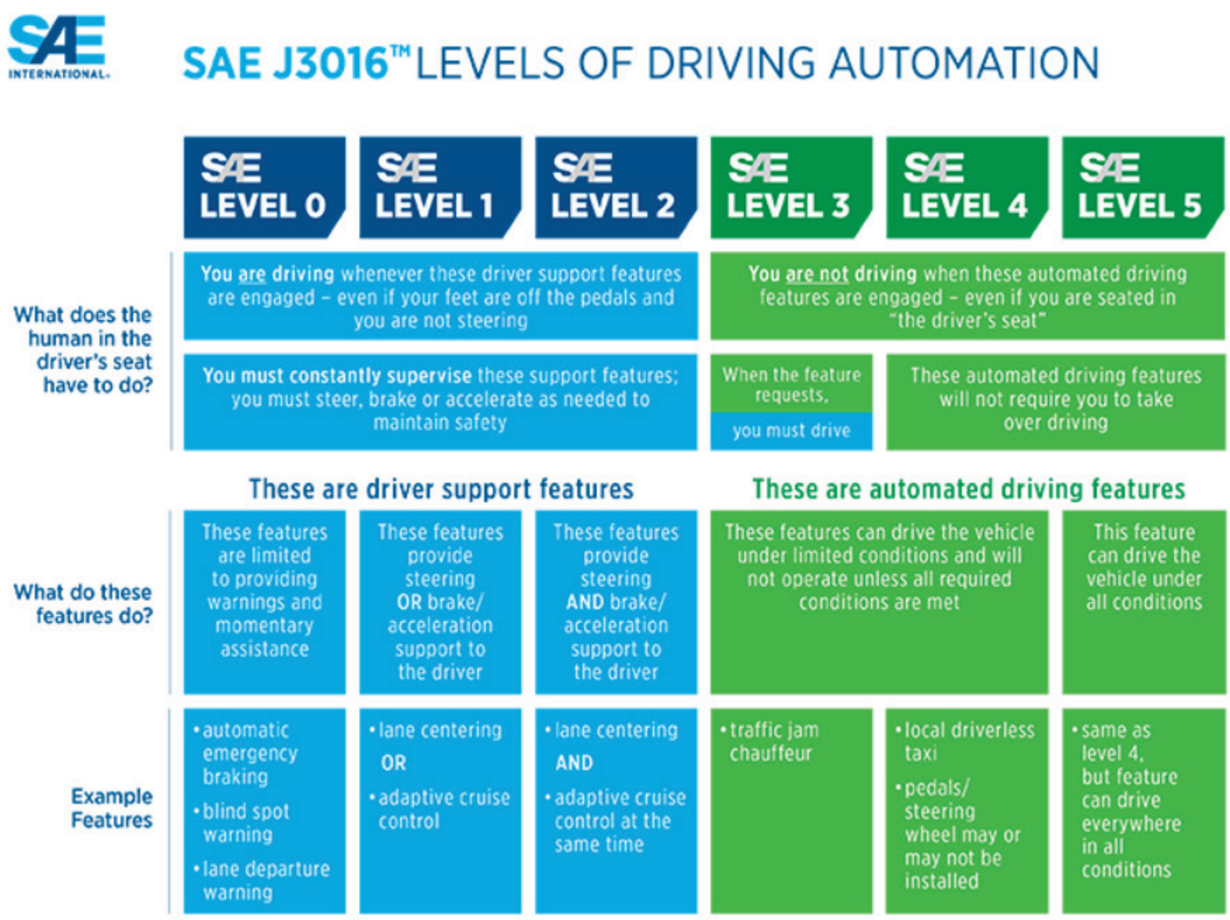


Figure 4. Levels of Driving Automation (SAE International 2021).

automation for its potential positive and negative impacts on transportation system efficiency. In these early stages of vehicle automation technology development, the DOE Vehicle Technologies Office is conducting analysis and technology research through its Energy Efficient Mobility Systems program.

Safety

Development of vehicle safety and efficiency technology can sometimes outpace the regulations in place to govern safe and efficient vehicle operations. Implementation of camera systems as external mirror replacements will require changes to the prevailing Federal motor vehicle safety standards (FMVSS) that include specific requirements for mirror surface area and positioning (U.S. Department of Transportation 2011). Many LDVs already come equipped with both cameras and mirrors. FMCSA, in 2019, granted a limited 5-year exemption from the heavy-duty requirement for rear-vision mirrors in 49 CFR 393.80(a) to certain motor carriers to pilot using camera monitoring systems only (FMCSA 2019). The systems use displays in the cab but no rear vision mirrors. In addition to the improvement in aerodynamics from removing side mirrors, potential safety benefits cited by the petitioners in FMCSA's notice included: greater field of view, fail-safe design, augmented and enhanced vision quality, and trailer panning (to improve blind spots turn visibility). This is an interim step that can generate confidence in future camera-only solutions for rear vision in regulatory requirements. Another area of opportunity for regulations to evolve with technology is the accommodation of electronic braking systems, which have potential benefits but do not fit within the current regulatory language for braking systems.

Other Technical Areas of Interest

Approaches to Tires

One common way to improve truck fuel efficiency is reducing tire rolling resistance, either with single wide tires or conventional dual tire systems with low-rolling-resistance tires. DOT noted several potential safety impacts with single wide tires. For example, two tires on a dual wheel assembly can lead to different tire pressures; these pressure differentials increase the load on the tire with the higher pressure and make a blowout more likely. In addition, there are fewer tire breakdowns, as underinflated tires are more easily discerned with the naked eye and low pressures are addressed more quickly. DOT also noted that single wide tires prevent operators from "limping in" a truck on one tire of a dual wheel setup, but this advantage may become moot, as regulations and fleet practices may prevent this practice in the future (Brecher, Epstein and Breck 2015). Anecdotal evidence from fleets suggests that the outboard mounting of the wide base tire is a safety benefit, as it exposes a portion of the brake drum to airflow for cooling (Park, et al. 2015). Regarding low-rolling-resistance tires, DOT's main identified safety issue is concern about traction in snow or rain. DOT noted that there were no specific data on these safety impacts in the literature (Brecher, Epstein and Breck 2015).

Tire pressure maintenance is very important for both efficiency and safety. Underinflated tires have higher rolling resistance and are at higher risk for tire failure. Underinflated tires may also wear irregularly, resulting in lower tire road grip in adverse weather conditions. Tire pressure monitoring systems help fleets identify incorrect tire pressures and alert operators to take action on this problem. Several studies have shown fuel economy increases of more than 1% when these monitoring systems were implemented (Brecher, Epstein and

Breck 2015). Automatic tire inflation systems (ATIS) take tire pressure monitoring a step further by actively pressurizing any tires that are found to be underinflated. ATIS systems are currently available for trailer tires; the air supply lines are usually routed through the hollow tube axle on the trailer tandems. Implementing ATIS in drive and steer axles is difficult from a technology standpoint, but suppliers are developing systems to overcome these challenges (Heavy Duty Trucking 2015). It does not appear that these automatic systems would have any detrimental effect on vehicle operations (Brecher, Epstein and Breck 2015). However, DOT noted that it was not clear whether automatic tire monitoring or inflating systems would provide better vehicle operations than manual examination of tire pressure.

Aerodynamics

Aerodynamics improvements are an essential tool for improving efficiency of MHDVs, particularly truck tractor and trailer combinations that spend long periods at higher speeds. Tractor aerodynamics technologies are relatively well-developed, and marketplace adoption is increasing because of the ease of procurement (direct factory ordering) and high potential fuel savings. These technologies do have safety implications. On the plus side, aerodynamic tractors often have steeply sloped hoods and fenders that improve visibility. However, some aerodynamic components, such as side skirts and wheel covers, may limit access to safety-critical components, impeding repair technicians and inspection officials (Mihelic, Schaller and Roeth, Confidence Report: Tractor Aerodynamics 2016). In some cases, aerodynamic devices may increase braking distances because of the vehicle's reduced aerodynamic drag and the added weight of the devices.

Trailer aerodynamics have also seen increasing popularity in recent years, with fleet uptake rising to more than 30% of new trailers with aerodynamic devices in 2015 (Mihelic, Schaller and Roeth, Confidence Report: Trailer Aerodynamic Devices 2016). These devices (trailer side skirts, boat tails, and gap closures) can work synergistically with tractor aerodynamics for dramatic fuel efficiency increases. These devices have some safety implications. Drivers have observed that aerodynamic trailers are more stable, requiring less lane correction and reducing driver fatigue. There appear to be benefits for reducing splash and spray around the vehicle by improving the aerodynamic flow, thus enhancing safety by improving visibility around the truck (Mihelic, Schaller and Roeth, Confidence Report: Trailer Aerodynamic Devices 2016). In addition, side skirts could provide both aerodynamic benefits and vehicle underride protection (mitigating vehicle underride crashes from side impacts), although it is unclear at present how much underride protection current U.S. production skirts provide (Brecher, Epstein and Breck 2015). Aerodynamic side skirts can also reduce fatalities in collisions with trucks and vulnerable road users (pedestrians, bicyclists, etc.) if the skirts have sufficient rigidity to achieve this dual function. NHTSA has published an advanced notice of proposed rulemaking and initiated research to better understand potential safety effects of side underride guards (NHTSA 2023). In terms of negative impacts, as with truck tractor devices, some trailer devices may limit the accessibility by drivers or safety inspectors to safety-critical systems. There may also be safety concerns associated with aerodynamic devices getting damaged and subsequently detaching from the vehicle, as well as the possible buildup of ice and snow around these devices in colder climates.

Vehicle Length and Weight

Length and weight are additional considerations for improved efficiency of MHDVs. However, length and weight policies are not uniform across the United States, Mexico, and Canada (USMCA) region.

The U.S. federal and state governments have their own policies that apply to roads under their respective authority, i.e., state roads are governed by individual state policies, while interstate and national network facilities are governed by federal law. The Surface Transportation Assistance Act of 1982 effectively froze size and weight limits on the national network, limiting vehicle weight to 80,000 pounds and limiting so-called longer combination vehicles (LCVs) to twin 28-foot trailers. However, grandfather rights were given to states that allowed higher weights when the Interstate Highway Program was established in 1956. More than a dozen states have gross vehicle weight limits on state roads that exceed the limits on the interstate and other national truck network routes, and many more states have commodity- or industry-specific exemptions that allow even higher truck weights on specific routes.

Neighboring countries go beyond even these limits. For instance, Canada now allows gross vehicle weights up to 102,500 pounds. In addition, the requirements for these higher weight vehicles with 4 or 5 axle trailers include dual air circuits on the trailer to assure at least partial function in single point failures (similar to tractor set up of today). Other countries' increase of length and weight limits may be seen as a move to balance infrastructure consumption (and substantial associated improvements in transportation efficiency) with vehicle productivity and safety. For example, LCV efficiency can be improved by increasing the cargo hauled by each combination vehicle. Examples of potential higher-volume LCVs are twin 33-foot trailers, twin 53-foot trailers, and triple trailers.

This patchwork of truck size and weight limits presents challenges for interstate and cross-border trucking operations, as well as for public regulation of the trucking industry. This increases the cost of operations for truck fleets and contributes to suboptimal transport efficiency. More closely aligning U.S. regulations with those of USMCA partners would significantly reduce VMT. There is considerable evidence that the safety benefits of reduced VMT would outweigh any reduction in safety to passenger car drivers and vulnerable road users that might result from longer and heavier vehicles. Lastly, safety technologies such as stability control, forward collision warning and mitigation systems, and lane departure warning systems would likely improve the safety performance of LCVs even further and increase the acceptability of such vehicles.

Technical Goals and Opportunities

Many technologies are being considered across the MHDV market for improving the efficiency of these vehicles. These technologies have safety implications, both positive and negative, that will be important for the Partnership to consider in its research. The technical goals outlined in this section will address these implications.

The overarching goal of the Partnership in the area of safety is to communicate and collaborate to further the following objectives:

- Ensure that trucks, drivers, and roads are ready and suitably equipped for platooning and for broader applications such as multimode convoys envisioned via "managed lanes" of travel.
- Develop and apply virtual tools that can study and test the safety systems of automated trucks in faster-than-real time.
- Develop and test wireless safety inspection systems to enhance and streamline safety monitoring and reduce fuel waste and congestion.
- Detect cybersecurity threats, distinguish them from benign misbehaviors, and develop corrective solutions (shared efforts with the Freight Operational Efficiency focus area).
- Seek synergies and resolve conflicts between vehicle features for safety and efficiency, e.g., trailer skirts for aerodynamic benefits and vulnerable road user protection, tire traction and rolling resistance, and following distances.
- Ensure that electrification features of medium- and heavy-duty vehicles do not compromise safety, including crashworthiness and risks to first responders.
- Continue NHTSA efforts to expand collision avoidance technologies (while still considering the role of collision mitigation).

The Partnership proposes these activities over the next five years (2023–2028) to enhance and facilitate this collaboration with the goal of improved safety. This list is subject to change as industry needs, technologies, and markets evolve.

Automation

Automation can take many forms and provide many functions. SAE International (SAE) has classified the levels of automation (as noted above in Figure 4) and worked with the traffic safety community to define some of the common terms used below for advanced driver assistance systems (SAE International 2020). The Partnership will consider some of the most likely driver assistance or automation features that are in, or soon to be in, production with major MHDV original equipment manufacturers, as follows.

- **Forward collision warning** (FCW) detects a potential collision with a vehicle ahead and alerts the driver. Some systems also provide alerts for pedestrians or other objects.
- **Lane departure warning** (LDW) monitors vehicle's position within the driving lane and alerts driver as the vehicle approaches or crosses lane markers.
- **Adaptive cruise control** (ACC) is now standard on many MHDVs. This cruise control feature assists with acceleration and/or braking to maintain a driver-selected gap to the vehicle in front. Some systems can come to a stop and continue while others cannot.
- **Automatic emergency braking** (AEB) detects potential collisions with a vehicle ahead, provides forward collision warning, and automatically brakes to avoid a collision or lessen the severity of impact. Some systems also detect pedestrians or other objects.
- **Cooperative adaptive cruise control** (CACC) is similar to ACC, but this system is also connected to the surrounding traffic through V2V communication and can respond to inputs from the surrounding traffic.

This feature can respond more quickly to changes in traffic conditions because of the information provided by the surrounding vehicles.

- **Lane keeping assist** (LKA) provides steering support to assist the driver in preventing the vehicle from departing the lane. Some systems also assist to keep the vehicle centered within the lane.
- **Lane change assist** (LCA) steers the vehicle with no input from the driver. This feature can change lanes as required using input from cameras and/or radar.
- **Auto-coupling** of the tractor–trailer is now available in Europe. Using cameras and automation of both the tractor and trailer, this automation feature performs the coupling function faster and safer than doing this manually.
- **Electronic steering** (ES) can be either electronic power steering (EPS) or torque overlay steering (TOS). ES integrates electronic technology with steering hardware. When combined with a comprehensive suite of vehicle sensors and hardware, this feature can also keep a truck centered in the lane. This would support a **Level 2** system. ES can also be used as part of an autonomous driving stack to control steering when designed with fully redundant power and control hardware, which is critical for the safe deployment of autonomous trucks.
- **Improved platooning** is possible for future use but would require Level 4 automation. Both CACC and LCA are required, with a high-speed (likely a hard-wired controller area network [CAN]) data link to the trailer.

Platooning and Managed Lanes

Platooning and Managed Lane technologies and/or improved braking systems via V2V, V2I, or vehicle-to-everything (V2X) communication have the potential to improve truck efficiency for long- and regional-haul trucking. Platooning could improve truck efficiency by reducing the following distance between vehicles. This close following distance reduces the total aerodynamic drag of the convoy of trucks and thus improves efficiency of the entire group. The Managed Lane concept is one by which mixed modes (cars, trucks, buses) of traffic would use the same lane in which speed would be controlled in its simplest form by ACC or CACC in a V2V protocol. As such research progresses, the use of V2I and V2X are foreseen to make such constant speed travel even better at reducing fuel consumption (particularly with heavy trucks) while improving both safety and efficiency vs. current congested stop-and-go practices that result in wasting time and fuel. The platooning and managed lane systems maintain wireless communication among the vehicles in the line to speed up or slow down based on the road conditions.

Present-day technologies present a number of challenges and limitations. The future of Platooning and Managed Lanes will be dependent upon resolving the following challenges – and thus maintaining or improving the safety of these systems – while also improving the overall efficiency of the convoy.

- Platooning systems tested to date control only lateral acceleration and deceleration and do not provide steering input. The driver must still be behind the wheel to keep the truck in line.
- There are significant safety considerations with allowing trucks to operate with these narrow following distances, which at highway speeds may be 50 feet or less (the typical following distance for a Class 8 tractor–trailer is around 300 feet at 65 mph).

- Law enforcement may perceive a platoon of trucks to be simply a set of trucks following too closely, resulting in an enforcement action, so a technological solution is needed to notify law enforcement officers about platoons moving through the area.
- Platooning systems have been designed to prioritize safety and will place trucks in a convoy according to their capabilities (for example, strongest-braking trucks are positioned at the trailing end to prevent rear-end crashes). However, platooning systems are not yet capable of making reliable predictions of stopping distance under all conditions, so the performance of the truck's brakes is the ultimate limiting factor in the following distance. Therefore, the platoon system must simply assume a maximum stopping distance based on the current speed.
- Driver distraction may increase if drivers in the following trucks take advantage of the reduced workload to multitask, so drivers may not be alert enough to take over control of the vehicle quickly in the event of an emergency.
- The security of the wireless communication system is a critical factor, as a malicious actor could hack the system and take over the vehicle(s). A convoy of trucks operating at highway speeds among other traffic poses considerable risk.
- The reliability of each component within the system could have a major impact on the overall safety of the entire platoon system (Roberts, Mihelic and Roeth 2016).

Connectivity

Advantages

This is one of the most important areas of improvement. We as a government and industry need to resolve the communication needs between the towing and towed units to allow the available technology to work properly. Tractor to trailer communication covered in the braking section is the most basic and important area of improvement and lay the foundation for the needed future communication technologies such as V2X.

Connected vehicle technology has the potential to significantly reduce the impacts of MHDV crashes. The technology will provide alerts to the driver—or even proactively apply the brakes when potentially dangerous situations are developing (U.S. Department of Transportation n.d.).

With V2V and V2I technology, a vehicle will transmit, receive, and continually monitor signals that will provide it with a 360-degree view of other vehicles nearby. The system will operate in the background and alert, or take other action, only if an unsafe situation is developing. In many situations, the system can provide warnings of dangers that cannot be seen with the human eye. For example, a driver can see the truck ahead but not the car ahead of that truck, so the third driver in line will not know if the car slams on its brakes; a connected system gives the third driver enough warning to avoid crashing into the rear end of the truck ahead. If a driver begins to pass a tractor–trailer, the system provides a warning if a fast-moving (still unseen) car is coming in the other direction. A driver is also notified, when changing lanes, if a vehicle is traveling in their blind spot. Other safety applications can warn of poor spot-weather road conditions or of dangerous curves ahead (U.S. Department of Transportation n.d.).

In the past, DOT has engaged in a multimodal initiative that aims to enable safe, interoperable wireless communications among vehicles (i.e., V2V communications) and between vehicles and the infrastructure (i.e., V2I communications). This research was originally conducted to leverage the potentially transformative capabilities of dedicated short-range communication (DSRC) technology to make surface transportation safer, smarter, and greener.

It now appears that DSRC will be replaced with 5G wireless cellular technology to provide vehicle and infrastructure connectivity, as well as communications with light-duty vehicles (LDVs). Potential benefits include communication over longer distances, higher data capacity, and improved non-line-of-sight performance relative to DSRC technology (Nigro 2018). Indeed, In November 2020 the Federal Communications Commission issued a ruling that DSRC technology envisioned for vehicle and infrastructure connectivity (V2X and V2V via DSRC) will be transitioned to cellular vehicle to everything (C-V2X) based technology. Whichever the communication technology, such standardized communications would ultimately enhance the safety, mobility, and quality of life of all U.S. citizens, while helping to reduce the environmental impact of surface transportation.

The vision for DOT's Connected Vehicle Program is that every vehicle operating on the nation's highways will broadcast so-called "heartbeat" messages at a rate of about ten times per second. Each "heartbeat" will include information about the vehicle's location (GPS coordinates), speed, acceleration, heading, and other kinematic and vehicle descriptive information. The standardized vehicular-based wireless communication will provide "situational awareness" among vehicles to enhance crash warning and prevention systems such as FCW, LDW, and intersection collision avoidance. These wireless communications among vehicles can also provide efficiency benefits in the form of reduced traffic congestion through the prevention of collisions as well as enabling technologies such as platooning, as described above.

Connective technologies could also enable "managed lanes," a concept that continues to be researched. A managed lane would be a dedicated lane on an interstate highway that would facilitate a smooth flow of traffic for both LDVs and MHDVs. A minimum list of equipment (i.e., AEBS, CACC, V2V, and V2I) would be required to enter this lane. This technology would then be used to reduce accordion effects of traffic flow that produce slow-down events, resulting in a faster trip overall. Another DOT report indicates that connected vehicle mobility applications may be able to cut travel time delays caused by congestion by more than a third. Ultimately, such technologies will form the basis for implementing connected and automated vehicles with the safety and efficiency benefits these systems are projected to provide. Continued collaboration with the U.S. DRIVE Partnership will serve to coordinate efforts between connected LDVs and MHDVs.

> A 2012 study shows that Americans spent 5.5 billion hours in 2011 stuck in traffic on U.S. highways (Texas A&M Transportation Institute 2012). That amounts to almost one full work week (or vacation week) for every traveler. During the 3rd Annual TMC/SAE Symposium, Michael Berube noted that eliminating such wasted time would eliminate the entire driver shortage long noted by the American Trucking Associations.

Another example of V2V connectivity would be the communication between the tractor and the trailer. There is a plethora of information that could be shared: weight, brake pad wear status, tire pressures, stop light status, running lights status, reefer status, etc. V2V connectivity between the tractor and trailer will provide both freight efficiency and safety benefits to the Class 7/8 truck market.

Once V2I connectivity is commonplace, there is great potential to improve safety and freight efficiency. Re-routing for traffic congestion would be helpful in avoiding lost time as well as improved safety through better traffic flow. Early braking can also be applied if the infrastructure or vehicle ahead provide communications (via V2X) of a braking event.

Another potential application for wireless communication for both safety and efficiency would be in inspection systems to enhance and streamline safety monitoring. More than 3.5 million such inspections are conducted each year and are estimated to save hundreds of lives annually (U.S. Department of Transportation 2016). As these trucks can be stopped for an hour or more, these inspections have an impact on the efficient movement of freight and can potentially cause traffic congestion in the areas where inspections are taking place. Wireless communication has the potential for sending vehicle status information to the inspecting entity while the vehicle is in motion to enhance roadside truck inspection processes.

Lastly, V2X communications can ultimately be used to improve pedestrian safety. For example, communications could be added to a wheelchair or even a personal cell phone to alert LDVs or MHDVs of someone's approach, which would help drivers to avoid pedestrian accidents.

Challenges

Connected driving has the potential to make trucks, buses and trailers safer and more efficient. But the [connected] revolution also brings along risks that the MHDV industry hasn't faced before. (ZF 2022)

Connected vehicles present not only many benefits but also some significant challenges, particularly a need for sophisticated cybersecurity. Basic automotive technologies have evolved from on-board, standalone systems to complex, interconnected and intraconnected (e.g., tractor–trailer) systems. Not only do they now communicate directly to the internet and the cloud, they also rely on increasingly complex software. The move toward these complex systems is accelerating: Frost & Sullivan, a global market research and analysis firm, forecasts that 43% of medium- and heavy-duty trucks in Europe and 55% in North America will be connected by 2025 (2021). With more vehicles connected to the cloud via telematic systems—and more to become connected to each other via V2X mesh networks—the complexity of the network creates new nodes and potential entry points for cybersecurity breaches.

The MHDV industry has a longstanding tradition of focusing on the functional safety of the trucks and their components. Based on years' worth of captured data related to vehicle dynamics controls, the industry has successfully mitigated safety hazards originating from the road. However, in the connected environment, functional safety also needs to mitigate risks that come from "off the road," which is what cybersecurity is needed to address. Fleet owners and operators must consider the growing impact of cybersecurity, along with the financial and safety implications, and the industry and its stakeholders need to understand how to solve the growing exposure to cyberattacks (ZF 2022).

For example, cyber attackers could take advantage of the internet and cloud connectivity to send malicious commands to a vehicle and disable the brakes or manipulate steering. This threat was demonstrated in a passenger vehicle when security researchers were able to slam the brakes and turn the steering wheel on a Jeep

Cherokee by sending messages via the CAN. Doing the same in a MHDV could have devastating results, not just for the driver but also for other road occupants and the environment.

Addressing the off-the-road risks is a bigger challenge than on-the-road risks. Cyberattacks are more difficult to predict and model than road hazards.

Regulatory bodies and industry groups are leading efforts to standardize cybersecurity requirements. In October 2016, the International Organization for Standardization (ISO) and SAE launched a joint project to standardize automotive cybersecurity engineering. The main principles of ISO/SAE 21434 focus on a risk-oriented approach, as well as cybersecurity processes for all phases of vehicle lifecycle: design and engineering, production, operation, maintenance and service, and decommissioning. This standard was released for publication in August 2021. Furthermore, NHTSA recently published an update to its *Cybersecurity Best Practices for the Safety of Modern Vehicles* (NHTSA 2022). In the long term, it is expected that providing a framework for the industry to follow will improve the cybersecurity environment.

Electrification

Battery electric MHDVs face safety concerns similar to those of LDVs. The primary difference is the absolute high voltage level (up to 800 volts) and the amount of on-board energy within the energy storage system (up to 900 kWh).

Battery Safety

The lithium-ion battery chemistries currently on the market are susceptible to self-ignition. Additional product cost is needed to ensure safe operation and to meet energy and power demands of MHDVs. Special precautions must be taken because of pack size; a particular challenge is preventing thermal propagation, which might involve the use of non-flammable electrolytes. Safety determinations are warranted and should be based on failure testing below a certain European Council for Automotive R&D (EUCAR) rating.

As with LDVs, specific training for technicians and first responders will be required as BEV MHDVs become more common.

Charging Safety

There is a need for BEV charging safety in three distinct areas:

- The electrical power from the utility, which runs through the property electrical meter and is delivered to the charging station. MHDV BEVs have high power requirements.
- The charging station and its cable or wireless connection to the vehicle. This safety area includes any power conversions necessary, safety systems to detect and notify of defects, communication hardware and software to both track the power and status, cooling systems and sensors for station hardware and cables, and the software to manage the handshake to the vehicle.

- The systems on board the vehicle itself to safely deliver the power from the charging connector to the batteries. This safety area includes the other half of the handshake system with the charging station, temperature monitors, battery cooling systems, battery pack monitors, and safety monitoring systems.

Government agencies regulate the design, implementation and certification of electric charging stations and support equipment. In addition, industry organizations (e.g., EPRI, IEEE, and SAE) develop standards for charging equipment and the charging system within the vehicle. Both the electric charging stations and the BEVs need to adhere to these strict codes and standards to ensure user safety.

Diagnostics

Diagnostic systems of both the electric vehicle supply equipment and the BEV will need to have strategies for fault detection/notification to the proper people, as well as accommodation strategies to prevent damage to components. These strategies could be shutting down the operation or managing it (i.e., reduced power) in such a way that all safety concerns are kept within acceptable limits.

Crash Safety

Crash safety for MHDVs has been a consistent subject in the industry for many years—and will continue to be a high priority going forward. Continued work by MHDV manufacturers, Industry organizations (e.g., SAE and TMC) and government agencies (e.g., DOT, including FMCSA and NHTSA) are required to further improve the crash safety around MHDV BEVs and FCEVs. Although gasoline- and/or diesel-powered vehicles generally seem to have a much higher rate of crash-related fires than BEVs, the fires that do result from BEV accidents tend to be much more severe and harder to extinguish.

Models can be used to design safe and reliable battery packs in the event of a vehicle crash, and some relevant models have already been developed. In 2018, Oak Ridge National Laboratory published a report that modeled the critical deformation necessary to trigger an electrical short in a lithium-ion battery, which could result in thermal runaway and lead to catastrophic failure (Kalnaus, et al. 2018).

MHDV crash safety can also leverage findings from a National Transportation Safety Board (NTSB) report, published in 2020, that reflects the findings from three separate LDV BEV crashes. The NTSB identified two main safety issues: (1) inadequacy of vehicle manufacturers' emergency response guides for minimizing the risks to first and second responders (firefighters and tow operators) posed by high-voltage lithium-ion battery fires in electric vehicles, and (2) gaps in safety standards and research related to high-voltage lithium-ion batteries involved in high-speed, high-severity crashes. On the basis of its findings, the NTSB makes safety recommendations to the NHTSA, the manufacturers of electric vehicles equipped with high-voltage lithium-ion batteries, and six professional organizations that represent or operate training programs for first and second responders. The findings and recommendations from these reports would certainly also apply to MHDVs.

Hydrogen and Fuel Cells

New hydrogen and FCEV technologies continue to be developed, each with its own set of safety considerations. For example, adsorbents, metal–organic frameworks, metal hydrides, chemical hydrides, and liquid hydrogen carriers are being developed to store hydrogen onboard FCEVs at lower or even ambient pressure. In addition, many configurations are possible for hydrogen production, delivery, and dispensing infrastructure. Hydrogen may be produced onsite at fueling stations via electrolyzers. Hydrogen may also be delivered by pipeline or over the road as a gas by tube trailer or as a cryogenic liquid by tanker truck. Each component and each configuration of the infrastructure requires careful evaluation of safety requirements.

Further research is needed on thermal effects of jet fires on tunnel structures, what types of critical tunnel infrastructure might be affected by overpressures in tunnels, how likely hydrogen is to ignite in different release configurations, and the probability of hydrogen release with delayed ignition. Since most studies to date have focused on LDVs, more modeling and experiments on larger-capacity vehicles is needed to ensure that the risks to tunnels imposed by hydrogen do not exceed those imposed by gasoline and diesel (LaFleur, et al. 2020).

Safety

Cameras

External mirrors on the tractor are an area of focus for improving aerodynamic drag. Several SuperTruck teams have explored the potential of replacing these external mirrors with cameras and displays inside the cab. The camera system is designed to reduce the frontal area of the mirror housing while providing an equivalent field of vision for the driver.

The camera system may present safety challenges, however. Camera failure is a significant safety concern. A camera system has more points of failure than a simple mirror, and a camera failure can mean the vehicle can no longer be operated safely (Brecher, Epstein and Breck 2015). Of lesser (but still real) concern is the adjustment period, as the displays are likely to be in a slightly different location than the external mirror, requiring operators to accustom drivers to the location of rear vision displays and learn how to use the system effectively. As mentioned earlier, FMCSA has given select motor carriers exemptions from the side mirror requirement to pilot camera-only systems, with the expectation that those carriers will provide feedback about their experience with the technology.

Braking

Several “braking” subsystems that can improve safety are already in production or are under development. This section presents a few promising examples.

Disc brakes are becoming more common but are not required as standard equipment. Disc brakes can improve braking performance, and often service life, over S-cam drum brakes in many MHDV applications (as they provide minimal brake fade and braking consistency), which adds to the overall safety of most MHDVs.

Disc brakes can be combined with **pad wear sensors**, which provide operators with real-time access to the health of the wheel end.

Brake systems would be greatly enhanced through **a dedicated CAN data link** between the tractor and the trailer, establishing a robust communication protocol and maximizing combination safety as a tractor–trailer system. Today, tractors and trailers do not communicate electronically beyond the use of an indicator lamp (wired or wireless) to communicate the status of the anti-lock braking system. Therefore, even though tractors may be equipped with the latest safety features (e.g., electronically controlled braking systems [ECBSs]), this brake demand information is not shared with the trailers, and the tractor has no information from the trailer (e.g., to understand actual brake retardation). It must be assumed that the trailer does not to have anti-lock brakes, so brake interventions in critical situations are minimized (pulsed from the tractor to ensure combination stability, sometimes known as "the poor man's anti-lock braking system").

Having a dedicated wired link to provide two-way information would help optimize the braking balance between the towed and towing units of the tractor–trailer combination. A wireless communication protocol would not be fast enough or reliable enough for a robust braking system; a CAN data link with braking information could be hard-wired for real-time control. This communication link would improve performance of both braking systems and stability control. Trailer diagnostics/prognostics could also be communicated into the tractor, alerting the driver to any possible safety issue with the trailer. These capabilities are crucial for vehicle health and performance in future automated driver or autonomous Level 4 combinations.

Advanced communications technology has also enabled development of **ECBSs**, systems that communicate the brake signal electronically back to the trailer (deceleration control). This signal is then used to control the pneumatic brake pressure, modulating the pneumatic pressure in line with the electric signal from the brake treadle (ensuring each part of the combination has the same requested deceleration level). ECBSs have improved performance over conventional pneumatic braking systems, primarily because of the speed of the brake signal. An electronic brake signal moves at the speed of light, whereas a pneumatic brake signal moves at the speed of sound. It is estimated that a full tractor–trailer ECBS can reduce braking distance from one to three car lengths in a maximum braking event. The longer the tractor–trailer is, the more the performance is improved (i.e., doubles and triples would benefit most from these braking systems).

ECBSs are now common in Europe and will be available soon on many tractors and straight trucks in North America. The faster response time of the ECBS braking will improve the overall safety of any single unit truck or bus. However, ECBSs for tractor–trailer combinations are possible only where CAN data interfaces between the tractor and the trailer are installed, and the United States does not have a standard calling for these tractor–trailer interfaces. For the near future, ECBSs for U.S. tractor–trailers will most likely be found only on married pairs. For the longer term, ECBS braking architecture will be necessary to support BEVs, Level 4 automation, and functions such as platooning.

However, these advanced technologies to operate in a L4 environment require redundancies. Vehicles must have redundant power to feed the steering and braking systems, and the systems themselves need redundancy. These technologies ensure that, in the event of a system failure, full function is still available to finish the mission (steering and braking) defined by the use case. This holds true also for the trailer systems.

Diagnostic Tools for Data Sharing

An approach in which the fleet or driver openly shares vehicle safety data would improve both safety and freight efficiency. Diagnostic tools should be developed that can electronically test for safety and emission systems.

With a connected truck (V2I), these diagnostic tools could broadcast safety data each time the vehicle passes a weigh/inspection station.

Aerodynamics

Aerodynamics can significantly improve efficiency, but aerodynamic devices have safety implications (see Aerodynamics in the Current State of Technology section). Additional research is needed to develop aerodynamic devices that do not impact safety.

Major Barriers and Challenges

The following are the major barriers to achieving the safety goal within the 21CTP roadmap framework:

- Continued communication among the members to facilitate the safety/efficiency discussion. The Partnership discusses many issues over the course of a given year, and finding an opportunity to include safety/efficiency in the discussions can be challenging.
- Willingness of efficiency project performers to engage in discussions and possible activity regarding safety. Project partners in federal agency-funded work may be reluctant to engage the Partnership's members in a discussion of the safety implications of their technologies, either because of a concern about potential negative impacts on safety or because of concerns about future regulations.
- Availability of resources to pursue any opportunities in the safety/efficiency space. Project partners conducting efficiency-related research may not include a discussion of safety implications in their research plans and may thus not have funding available to address safety explicitly.

Approach to Resolving Barriers and Attaining Goals

Communication

Safety considerations should be discussed and addressed wherever possible in efficiency research projects such as SuperTruck. To address the communication issue regarding safety and efficiency, the Partnership will maintain its regular communication activities among the partners and will ensure that the safety discussion is kept as a high priority.

Engagement

To address the project partner engagement issue, technical representatives from DOT should be engaged to review ongoing efficiency improvement projects such as SuperTruck and provide feedback on safety-related issues. Federal agencies will work with 21CTP to identify which energy projects may have the highest impact (positive or negative) on safety and focus attention on those projects. The federal agencies and the Partnership will establish the boundaries and ground rules for engaging project partners in these discussions to address any concerns the partners may have. The Partnership will consider areas where additional data needs, tests, or analysis would eliminate any apparent conflict between efficiency and safety features.

Resources

To address the resource issue, federal agencies will discuss the costs and benefits of including specific requirements within projects for safety–efficiency intersection analysis and allocate resources appropriately to meet the missions of the specific agency and the broader needs of 21CTP. Agencies can provide periodic reports to 21CTP members on the current state of the art in the safety–efficiency nexus, as well as suggestions as to how future projects might take advantage of possible synergies in this area.

Appendix A: Documents to be updated as new papers are published

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Acronyms

Acronym	Definition
21CTP	21st Century Truck Partnership
ACC	Adaptive Cruise Control
ADAS	Advanced Driver-Assisted System
AEBS	Automated Emergency Braking System
ATIS	Automatic Tire Inflation System
BEV	Battery Electric Vehicle
C-V2X	Cellular Vehicle to Everything
CACC	Cooperative Adaptive Cruise Control
CAN	Controller Area Network
Co-Optima	Co Optimization of Fuels & Engines (initiative)
DEF	Diesel Exhaust Fluid
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DRSC	Dedicated Short-Range Communication
ECBS	Electronically Controlled Braking System
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
EPS	Electronic Power Steering
ES	Electronic Steering
EUCAR	European Council for Automotive R&D
FCEV	Fuel Cell Electric Vehicle
FCW	Forward Collision Warning
GPS	Global Positioning System
IC	Internal Combustion
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
LC	Lane Centering
LCA	Lane Change Assist

Acronym	Definition
LCV	Longer Combination Vehicle
LDV	Light-Duty Vehicle
LDW	Lane Departure Warning
MHDV	Medium- and Heavy-Duty Vehicle
mph	Miles per Hour
MTBE	Methyl Tert-Butyl Ether
NHTSA	National Highway Traffic Safety Administration
NOx	Nitrogen Oxide
NTSB	National Transportation Safety Board
SAE	SAE International (formerly the Society of Automotive Engineers)
TOS	Torque Overlay Steering
USMCA	United States, Mexico, and Canada
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VMT	Vehicle Miles Traveled