21st Century Truck Partnership
Research Blueprint

21st CENTURY TRUCK PARTNERSHIP

February 2019

Introduction

The 21st Century Truck Partnership (21CTP, or the Partnership) is a long-standing government/industry research collaboration with industrial partners across the commercial truck value chain and government partners with civilian and military missions. The Partnership aims to foster technological innovation in improving the energy efficiency and reducing the costs of the nation's economically vital truck freight transportation system through this strategic public-private partnership. The partners are shown in Figure 1. Partners are involved as a result of their interests in the overall aims of 21CTP as described above.

INDUSTRY MEMBERS

- Allison
- Cummins
- Daimler
- DENSO
- Eaton
- Ford
- Meritor
- Navistar
- Oshkosh
- PACCAR
- Volvo

GOVERNMENT MEMBERS

- US DOD
- US DOE
- US DOT
- US EPA

Figure 1. 21CTP Partners

This blueprint document is meant as a summary of the Partnership's updated collaborative research efforts to make transportation energy more affordable and secure. The Partnership is developing all-new roadmap documents with additional details to provide the technical foundation for research priorities, and the reader is encouraged to review these resources for more information.

Vision

The vision of the 21st Century Truck Partnership is:

> *Our nation's trucks and buses will safely and cost-effectively move larger volumes of freight and greater numbers of passengers with increased energy efficiency, productivity, reliability, and equivalent or lower total cost of ownership (including capital and operating costs), while supporting national energy security and environmental stewardship.*

Guiding Principles

The new guiding principles for realizing the vision for the Partnership are summarized in Figure 2. In general, 21CTP research efforts are intended to address issues of economic growth, energy affordability for businesses and consumers, business competitiveness, and national energy dominance.

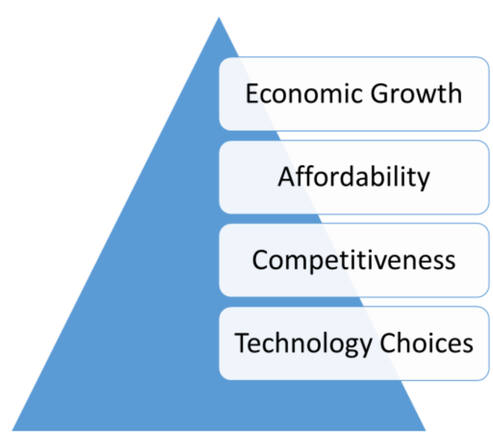

Figure 2. 21CTP Guiding Principles

Economic Growth: Trucking drives the economy

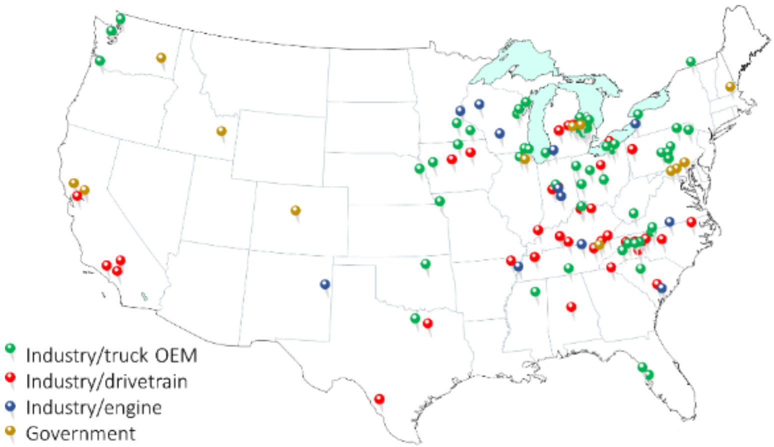

Figure 3. U.S. Locations of 21CTP Partner Operations

Affordable truck freight movement is essential for the nation's economy. Trucks carry over 70% of the nation's freight on a tonnage basis and 73% of freight on a value basis.[1] In 2016, the trucking industry collected around 80 cents of every dollar spent on freight transportation.[2] Virtually all goods consumed in the United States are shipped by truck for at least part of their trip to the consumer. The trucking industry paid over $17 billion in annual federal highway user taxes in 2016.[3]

Trucking is an important source of U.S. employment as well. The trucking sector is a $700 billion industry.[4] About 90% of the regulated carriers in the United States are relatively small businesses, operating fewer than 10 trucks.[5] The truck and engine manufacturing industry represents almost a million U.S. manufacturing jobs.[6]

The industry partners involved in 21CTP have research, development, manufacturing, and distribution facilities providing jobs across the United States as Figure 3 illustrates. These facilities develop, produce, and sell the commercial trucks that drive economic growth and create jobs in the broader freight transportation industry in the United States. Federal research agencies in 21CTP also have facilities across the nation (shown in Figure 3) conducting cutting-edge early stage research in support of broader national goals. Together, these organizations serve as economic drivers in communities across the country.

Affordability: Efficient and safe vehicles and operations reduce costs for businesses and customers

Trucks are a dominant factor in energy independence and energy security, as the fastest growing fuel users in the United States as well as the world. Class 3-8 trucks are only 4% of the total number of U.S. on-road vehicles but represent a quarter of the annual vehicle fuel use.[7] Commercial trucks in classes 3 through 8 used a total of approximately 44 billion gallons of fuel in 2015.[8]

Economic growth and commercial truck transportation energy use are closely aligned. Expansion in the global economy will thus result in a similar growth in truck fuel use unless technology advances in efficiency are made to improve the energy productivity in moving freight. U.S. Energy Information Administration (EIA) projections illustrated in Figure 4 show that the freight truck sector's annual vehicle miles traveled (VMT) is likely to increase by 54% through 2050.[9] Fuel economy of these trucks is expected to rise as well, but the rate of increase slows down over time and does not completely offset the rise in annual miles traveled. This leads to an 11% increase in freight truck energy use by 2050.[10]

Cost-effective ways to improve freight fuel efficiency, potentially maintaining the pace shown in the early years of Figure 4, can represent a clear benefit to businesses and ultimately consumers by improving the affordability of shipping for the goods consumers rely on daily. Improving the energy productivity or reducing the fuel used per ton-mile of freight shipped will represent an economic competitiveness benefit even if overall economic growth increases the total fuel used for freight movement.

Fuel costs are still a significant fraction of freight movement costs, but fuel costs can be reduced through efficiency improvements even with low fuel prices. Many truck owners are small organizations whose ability to compete for freight business depends on careful control of costs. Improved efficiency is a very important part of this cost control. Research must address the affordability of efficiency technologies to ensure overall energy productivity and economic benefits are realized.

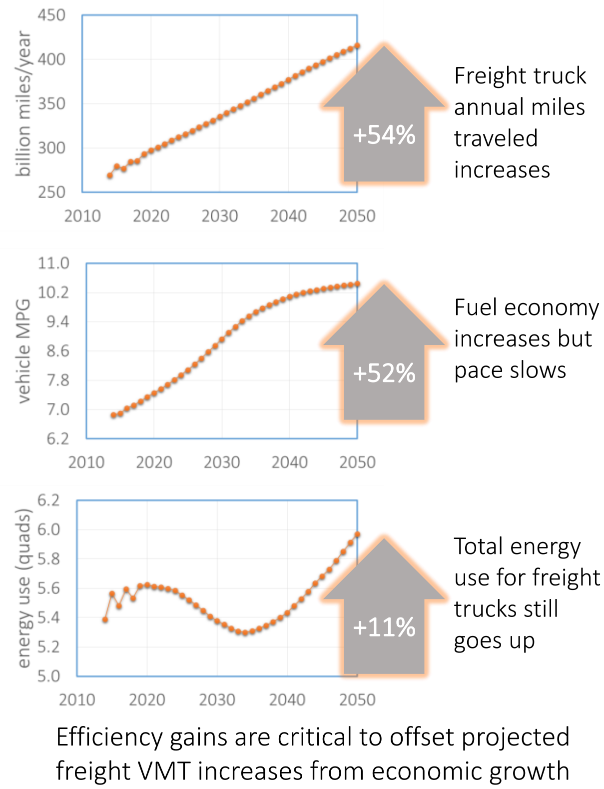

Figure 4. U.S. Freight Transportation Energy Use Projected to Rise (U.S. Energy Information Administration)

Competitiveness: U.S. competitiveness is maintained with technology research

American commercial truck manufacturers and technology suppliers are competitive in the global market and 21CTP research efforts will help sustain this competitiveness with technology improvements. Based on EIA forecasts referenced above, improving energy efficiency will be necessary to meet the need for additional freight transport. Competitive companies will be able to keep jobs for engineering and manufacturing these trucks and developing technologies here in the United States. Advanced research can improve competitiveness by maintaining and expanding this technological advantage for U.S. companies.

Technology Choices: Multiple fuel and vehicle options are key to meeting industry needs

Future freight and passenger transportation solutions will need to be affordable, efficient, clean, and safe to meet customer needs and broader societal demands. Technology and fuel choices will be essential for meeting the varying needs of commercial truck customers. Multiple fuel options, including natural gas, propane, electricity, and diesel, will all play a role in future commercial truck markets. Research work in areas such as high efficiency engines, advanced domestically-sourced fuels, connected and automated vehicle systems, electrified drivetrains, and improved freight and passenger routing will lay the groundwork to create these future transportation solutions.

Partnership Scope

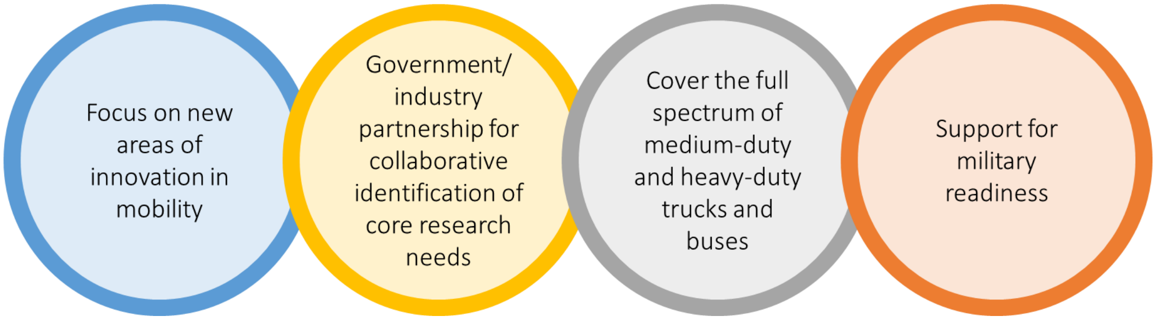

Figure 5. 21CTP Scope

Achieving the vision of 21CTP will require careful and logical actions that involve all the partners and draw in the latest ideas for the transportation system. To guide the development of specific actions, 21CTP has developed a new program scope to drive work toward a new vision as shown in Figure 5.

Focus on new areas of innovation in mobility

Addressing the considerable challenges facing the commercial truck market in the future will require new thinking and new technologies. Shifts in consumer purchasing behavior have already changed the freight shipment landscape, and traditional solutions will no longer be sufficient because of new consumer expectations about delivery speed and cost (free shipping, for example). Connected and automated vehicles, transportation as a service, and novel freight shipment methods will be required to meet future freight needs. Early-stage research will be necessary to find new solutions to create safer, more cost-effective, and more energy-efficient freight movement that keep up with the demands of a growing economy. The Partnership's research is incorporating the latest ideas and mobility trends to facilitate rapid progress in freight efficiency through advancements at both the vehicle and transportation-system level.

Government/industry partnership

The fundamental purpose of the Partnership is to take advantage of the collective experience of the partners to identify the critical technology barriers that can be overcome with early-stage research efforts. Through the Partnership, duplication of effort is prevented, research efforts are focused on the most critical technical barriers, and progress in the development of innovative transportation technologies for increased efficiency, safety, and environmental benefits is accelerated.

The Partnership brings together truck manufacturers, engine manufacturers, key technology suppliers, and federal agencies to address research challenges of joint interest. By including all of the key participants in the commercial truck research community, the Partnership ensures that the critical research barriers are identified and research plans are developed to address them. This comprehensive list of partners (refer back to Figure 1) ensures that no essential research areas are missed.

Cover all truck and bus classes

The economic well-being of the nation requires trucks in many sizes, configurations, and duty cycles. The Partnership's efforts are designed to address research barriers across all truck classes from 2b through 8. This ensures that no application critical to the success of a business or end customer is missed and the entire commercial truck fleet becomes more efficient at accomplishing its varied tasks.

Support for military readiness

Reducing fuel use in the military sector allows the deployed forces to move more quickly as they need to carry less fuel. Reduced fuel convoys mean increased survivability for military missions with fewer opportunities for soldiers to be exposed to enemy threats. The nature of military truck operation means that designs must address vehicle stability and safety across many types of on-road and off-road terrain. The non-tactical vehicle fleet at the Department of Defense numbers more than 180,000 and uses almost 80 million gallons of fuel per year.[11] The research efforts conducted in 21CTP include military considerations as part of the overall set of research priorities so that our nation's military is as effective as possible in protecting our national security.

Research Priorities

The Partnership has already helped the government/industry research effort achieve unprecedented benchmarks in engine efficiency, reduce criteria emissions by more than 95%, and demonstrate the potential to double the overall efficiency of moving freight. Industry partners have already commercialized many innovations. New challenges for freight transportation lie ahead, so the Partnership has developed new priorities to achieve its vision and execute its strategy.

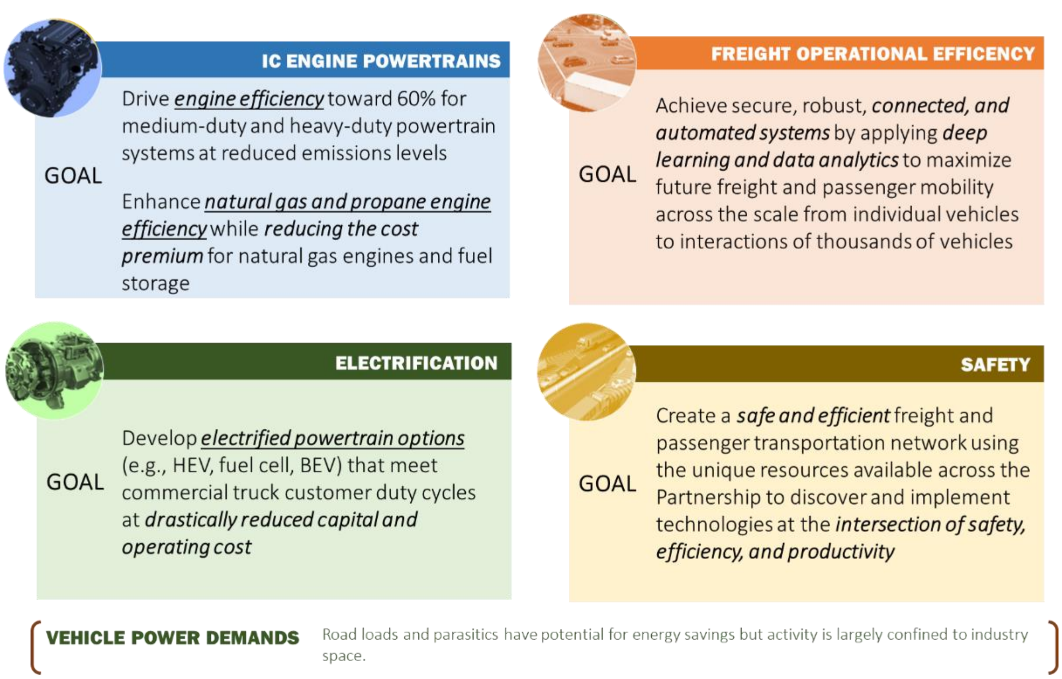

Figure 6. 21CTP Technical Focus Areas and High-Level Goals

A new series of major technology focus areas (as illustrated in Figure 6) will address the key areas for advanced innovative precompetitive research for commercial trucks as well as the broader transportation system in which they operate. The Partnership has chosen to focus on these areas after a deep technology assessment and careful examination of the modern commercial truck and the broader freight system. Figure 7[12] provides an overview of the potential efficiency opportunities for technologies across the spectrum of truck classes which helped drive the Partnership's research priority areas. These focus areas (highlighted with green arrows in the sections that follow) encourage collaboration from technical experts within the Partnership to address efficiency, safety, and environmental technical opportunities across the entire commercial truck sector.

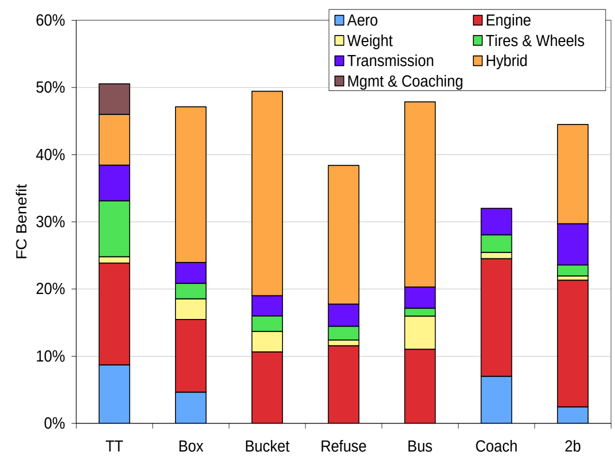

Figure 7. Estimated Technology Improvement Impacts Across Truck Classes (National Academies)

Internal Combustion (IC) Engine Powertrains

Analyses by the National Academies (Figure 7) and assessments by the Partnership point to advanced internal combustion engine (ICE) powertrains and electrified powertrains having the largest potential for reducing fuel consumption at the vehicle level. ICEs encompass all configurations of piston engines, both reciprocating piston and rotary, and even gas-turbine vehicle engines. Four-stroke cycle reciprocating piston engines are the prevailing configuration, fueled by diesel fuel, gasoline, natural gas, and propane.

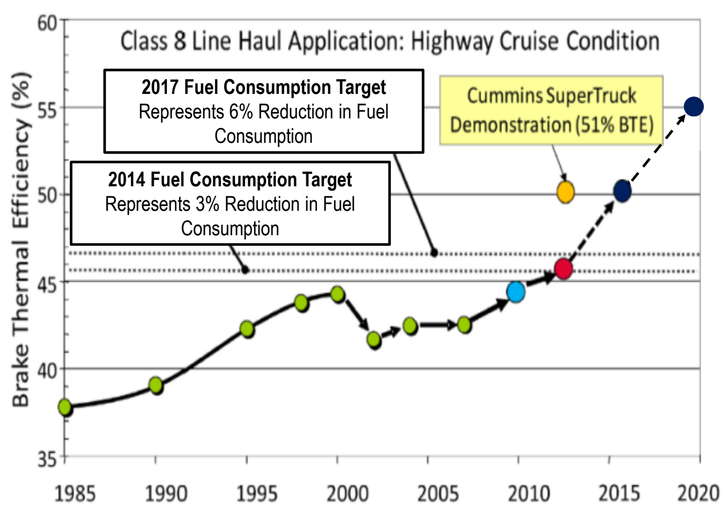

Figure 8. Progression of Engine Efficiency for Class 8 (Cummins)

These engines are used in virtually all current production commercial vehicles, as well as off-highway applications, and are forecasted to play a significant role in powering them well into the 21st century.

Improving efficiency. Research and technology advancements have increased the brake thermal efficiency (BTE) of ICEs[13] for the commercial truck market (Figure 8)[14], apart from a temporary stagnation when more stringent emission standards were enacted. The Partnership prioritizes maintaining and maximizing this upward trend in engine BTE to the maximum extent practical for a range of engine classes while also meeting current and future low emissions requirements. A new emphasis on concurrent design of engines and fuels (including biofuels) for medium duty vehicles will be a particularly strong focus, incorporating such activities as the DOE Co-Optimization of Fuels and Engines.[15]

Natural gas. With the abundant domestic supply of natural gas fuel[16] and the relatively low and stable fuel prices,[17] natural gas-fueled trucks show potential for increasing energy affordability and security. Research opportunities exist in responding to technical challenges related to lower cost and weight for onboard natural gas storage, improved efficiency for a wider range of natural gas engine choices, and innovative fueling infrastructure solutions. Propane engines will generally benefit from similar technical strategies as their efficiency also needs to be increased.

In a recent workshop, natural gas engine requirements were reviewed, and barriers noted included ignition systems, knock mitigation, catalysts for methane emission control, and fuel systems. A lean burn combustion strategy for higher efficiency will require emission control development for oxides of nitrogen.

Barriers and Research Needs. Waste heat recovery systems with improved overall cost effectiveness are needed to achieve efficiency targets, especially for Class 7-8 on-highway trucks. The research would cover the energy conversion efficiencies of WHR, heat transfer, and reducing cost.

Further research to enable combustion modes that lower heat transfer losses and engine out emissions is warranted, in combination with co-optimization of fuel properties (Figure 9).

Increasing compression ratios, as well as more boosting for high brake mean effective pressure (bmep), are effective for efficiency gains but engines have already reached temperature and strength limits of modern materials for pistons, turbochargers, and valves. This fundamental barrier will be addressed by materials research discovery supported by high-performance computing (HPC) methods and hybrid additive manufacturing methods.

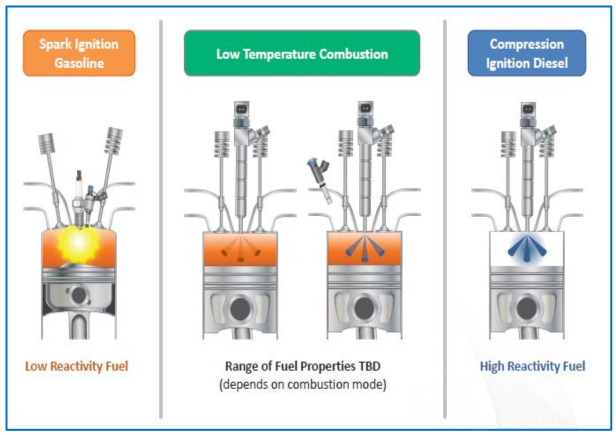

Figure 9. Range of combustion modes and fuels considered for co-optimization. An engine can use more than one mode. (US DOE)

Innovations in catalyst materials and emission control systems, especially effective at low exhaust temperatures, are needed to greatly reduce the cost and ensure energy penalties are negligible.

The goal of 21CTP collaborative research in this area is that engine BTE will approach 60% at reduced emissions levels and at half the current aftertreatment cost for medium-duty and heavy-duty powertrain systems.

The Partnership has several specific research priorities to support this broad focus area goal. These include:

- 57% engine BTE (Class 7-8)

- 45% engine BTE (MD SI)
- 48% engine BTE (MD CI)
- Reducing natural gas engine efficiency penalty and incremental cost premium NG engine/storage
- 50% emissions reduction (below current standard) at 50% lower cost for the aftertreatment system

These targets represent improvements of 20-30 % over today's engines, with the largest opportunities for improvement in the medium duty applications. Figure 10 illustrates the state of the cycle-averaged BTE of current engines as found in public certification data.[18] This figure demonstrates the potential opportunity for improving engine efficiency in smaller medium-duty engines, particularly spark-ignited engines smaller than 9 liters.

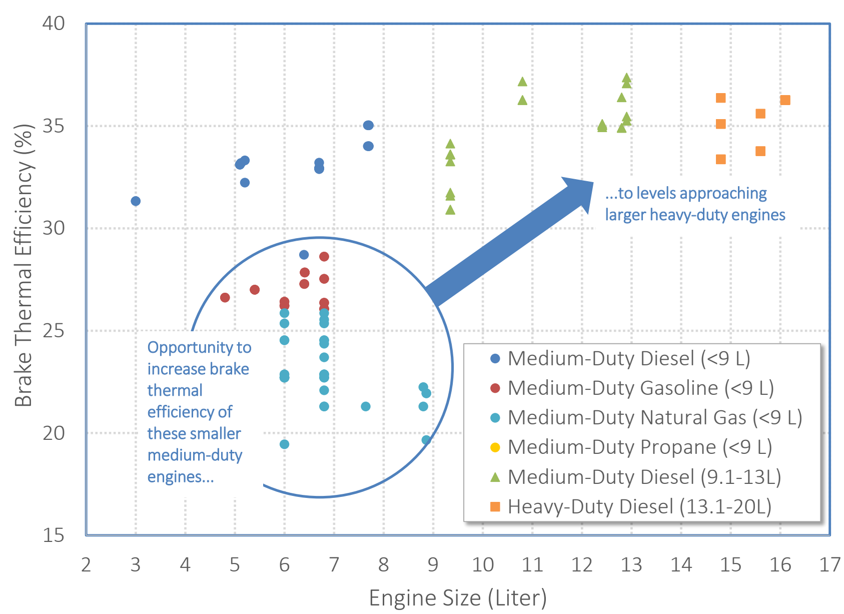

Figure 10. Engine Size versus Brake Thermal Efficiency in Current Engines

The key technical paths to achieving higher engine efficiencies include:

- Waste heat recovery (WHR), or conversion of exhaust energy and heat to useful work rather than lost as waste heat
- Increased cylinder pressure and engine power density through boosting and higher compression ratio. Engine downsizing and downspeeding are part of this strategy.
- Reduction of combustion heat losses
- Combustion system improvements
- Co-optimization of the fuel with engine combustion categories, such advanced compression ignition, and higher octane for advanced spark ignition engines in medium-duty vehicles

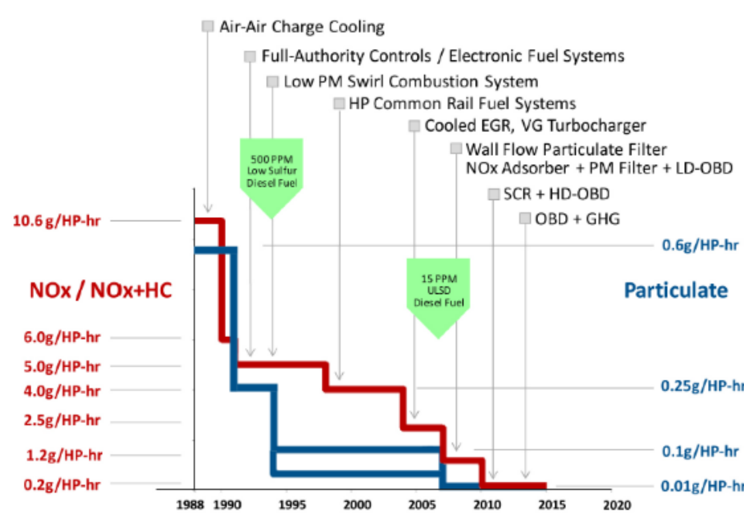

Figure 11. Progression in Criteria Emissions Regulations (Cummins)

Reducing emissions. Criteria emissions (NOx, particulates) from diesel engines have been reduced by about 95% from 2000 levels (Figure 11)[19], and yet another 90% reduction is being discussed. This will challenge all combustion modes and their exhaust aftertreatment systems.

Further reductions in NOx and PM appear feasible with progress in aftertreatment catalysts and systems. In fact, prototype systems have already achieved NOx emissions 90% lower than the prevailing regulation, but with considerable added complexity and cost, and an energy penalty.

Electrification

Whereas hybrid-electric vehicles (HEVs) show improvements in fuel economy of 30-50%,[20,21] even greater impacts are achievable with plug-in hybrid vehicles (PHEV) or battery-electric vehicles (BEV) if they can be introduced into the market successfully. BEV or PHEV trucks and buses could have even greater impact on reducing petroleum use and emissions, but market success for all forms of electrification in the United States has been limited in part due to the high cost of batteries. Tremendous progress has been made in improving battery performance and reducing cost in the last decade (Figure 12)[22]. Battery costs have been reduced by 75% since 2008, compelling a new examination of the opportunities and remaining barriers for high degrees of electrification in medium-duty and heavy-duty vehicles. ICCT[23] recently reported nearly 40 worldwide operations and demonstrations of BEV and PHEV freight trucks (not including all-electric buses). Transit bus manufacturers report increasing market success due to reduced battery cost, and that applying the electric powertrains to freight trucks is on the horizon.[24] Fuel cell electric vehicles (FCEVs) are also making significant progress, with the cost of a fuel cell system dropping by around 60% in the last decade[25] resulting in increased interest in the potential of these systems for medium-duty and heavy-duty vehicles.

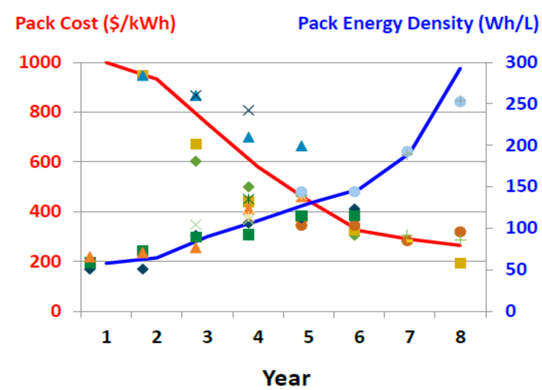

Figure 12. Reduction in battery costs enhances opportunity for electrified MHDVs (U.S. DOE)

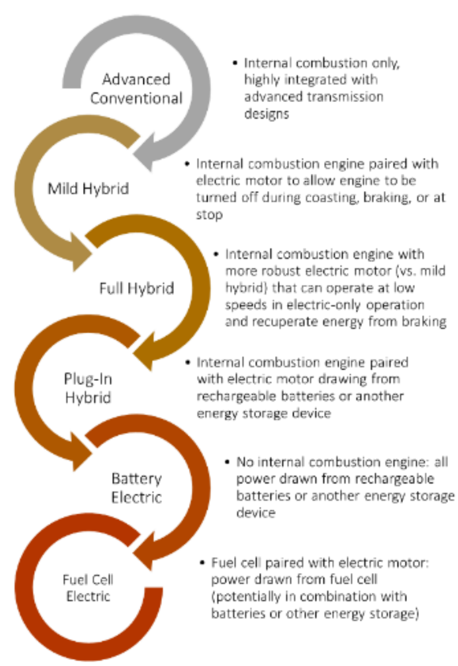

Figure 13. Spectrum of Electrified Drivetrains

The suite of current vehicle drivetrain options includes, in order of increasing electrification: advanced conventional, mild hybrid, full hybrid, plug-in hybrid, and battery electric/fuel cell electric (Figure 13). This range of drivetrain electrification presents great opportunity because of the potential to optimize powertrain configurations, calibrations, and charging strategies for specific duty cycles and applications, thus ensuring market success. Because battery costs are improving and trucks can benefit from a wide range of electrification options, 21CTP is focusing considerable new research on these drivetrain technologies.

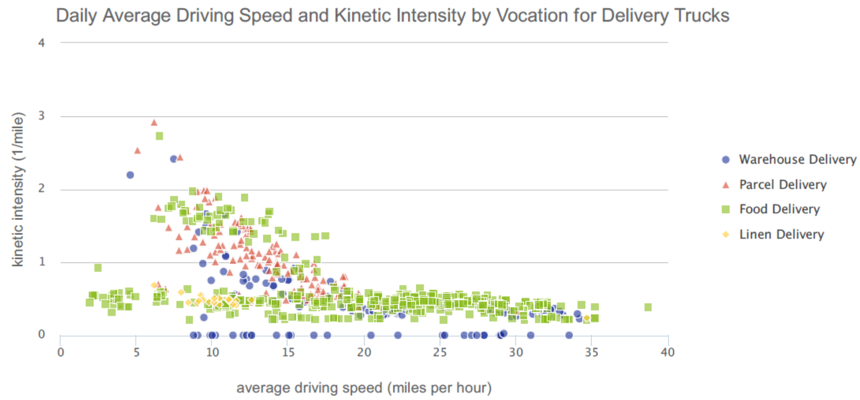

Figure 14. Diversity of Duty Cycles Compounds the Powertrain Optimization Challenge (NREL FleetDNA)

The goal of 21CTP collaborative research in this area is that electrified powertrain options will be developed that meet commercial truck customer duty cycles at drastically reduced capital and operating cost, harnessing high-performance computing to analyze and design scalable, modular systems (motors, power electronics, and energy storage) for high-volume production. Achieving this outcome will require emerging capabilities in vehicle data capture and analytics, development of electric drive technology (including batteries) *specific to medium- and heavy-duty vehicle requirements,* HPC-based methods for determining technology requirements and optimizing component integration and calibrations, and newly developed powertrain laboratory capabilities. Advanced charging technology including stationary and dynamic wireless charging will be investigated to stretch the applications of electrified freight movement. Common electrical architecture will also be of interest to enable "plug-and-play" compatibility as appropriate (an area of particular interest for military applications whose vehicle length of service can be 20 to 30 years).

The Partnership has several research priorities to support this broad focus area goal. These include:

- Reduce operating costs per mile of electrified Class 7-8 vehicles by 50%.
- Development of detailed powertrain requirements based on robust data capture and data analytics. This must address the diversity of duty cycles illustrated in Figure 14.
- Research to ensure energy storage and electric drive components exhibit the necessary performance, costs, and longevity required for commercial vehicles. Determining specific technical requirements for medium- and heavy-duty vehicles (for motors as example) will be a necessary outcome of analysis at the powertrain level. Significant improvements have been made in motors and power electronics, although there are large gains still to be pursued for MHDV applications. In the National Academies reviews of the 21st Century Truck Partnership,[26] the NAS Committee emphasized that technologies for electrifying medium- and heavy-duty vehicles were not a simple application of technology from light-duty vehicles due to the substantially more demanding requirements for longevity, power levels, duty cycles, and ruggedness. Technology for ultrafast charging and/or wireless charging may be a pivotal capability for some freight movements.

- Develop and apply HPC-based methods accelerate discovery of the most effective deeply integrated powertrains and controls in the vast parameter space of electrified powertrain components and controls (Figure 16)[27]. The options of electric components, engines, vehicles, and duty cycles presents a capacious optimization space for limited numbers of vehicles in each application.

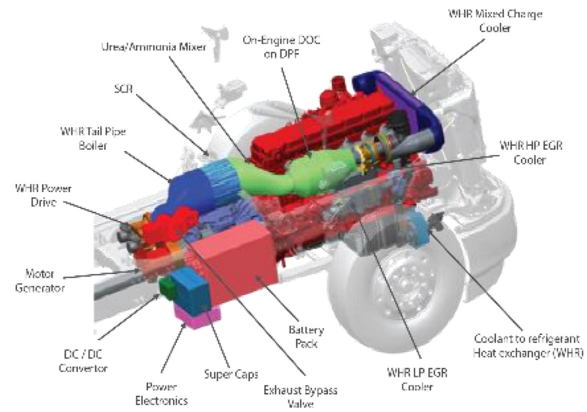

Figure 16. Large Parameter Space in Electrified Powertrains (Cummins)

Given the game-changing progress in batteries, medium duty vehicles with diverse drive cycles (lots of start/stop and speed variation) but often relatively low annual miles travelled, can more likely be equipped with an *affordable* electrified powertrain for reduced fuel cost. For many applications, the critical barriers to expanded availability and deployment of affordable electrified drivetrains are now (1) incomplete duty cycle data from the thousands of applications and drive cycles (refer back to Figure 14) in the medium duty space, (2) incomplete development for electric drive technology with specific capabilities for medium- and heavy-duty vehicles, and (3) robust and fast computational methods for optimizing highly integrated powertrains with their increased complexity, supported by experiments in hybrid/electric-capable heavy-duty powertrain laboratories (Figure 15).

Figure 15. Powertrain laboratories highly effective for discovery and development of complex electrified systems (ORNL)

Freight Operational Efficiency

Highly-efficient individual commercial trucks cannot achieve their full potential if they are part of an inefficient transportation system. Trucks, buses, and personal use vehicles must share the nation's roadways to ensure everyone's transportation needs are met safely and efficiently. In this focus area, the Partnership intends to improve freight efficiency and affordability by optimizing how vehicles move goods throughout the nation's mobility system.

The goal of 21CTP collaborative research in this area is to achieve secure, robust, connected, and automated systems by applying deep learning and data analytics to maximize future freight and passenger mobility across the scale from individual vehicles to interactions of thousands of vehicles. These solutions may involve traffic flow optimization based on vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communications, or changes to freight logistics that shift the role of trucking in goods movement.

The Partnership recommends several research priorities to support this broad focus area goal. These include:

- Exploit connected vehicle technologies to reduce the $60 billion cost of congestion to freight (by connectivity-enabled traffic- and signal-control methods, optimal routing, and mitigating incident congestion).
- Establish a suite of cyber security measures to ensure medium- and heavy-duty vehicles can safely utilize the advantages of connectivity and automation. The efforts here will be blended and shared with those in the Safety focus area.
- Complete the understanding of the potential, limitations, and remaining barriers to truck platooning based on cooperative adaptive cruise control (CACC).
- Analyze and assess the extent to which advances in automation and connectivity could enable greater operational efficiency and cost reduction, defining the most effective roles of driving automation systems[28], and explore the feasibility of enhancing the productivity of vehicle configurations through additional data collection, research, and analysis that will also consider impacts to safety, bridges and pavements, compliance, and modal shift.

Figure 17. Traffic Control on Major Highway

The Partnership seeks to collaborate with the strongest technical resources to accelerate the application of deep learning principles where data from hundreds of vehicles in a private or OEM fleet (or thousands of probe vehicles or sensors in a road network) are analyzed using advanced data analytics methods to discover previously unknown ways to achieve overall economic optimization of commercial vehicle operations. Exemplified via neural network controls with many more layers than typical control systems, deep learning is enabled by rapidly advancing computational power coupled with an explosion of transportation and vehicle data. Data provided by fleets and manufacturers and smaller-scale simulation results can be inputs to a virtual testbed for conducting national-scale simulations, applying machine learning algorithms that can enable/define connected and automated vehicle deployment and operation, optimal traffic controls, and incident mitigation measures to reduce congestion.

Automation. Increasing levels of driving automation systems may enable both increased freight efficiency and roadway safety. For example, truck platooning based on SAE Level 1 ("Driver Assistance")[29] CACC technology has been shown to reduce vehicle-level fuel consumption through both aerodynamic drag reduction and drive cycle smoothing[30] and has the potential to improve safety through automatic braking for the vehicles in the platoon. These systems may lead to significant national-level benefits: if platooning could be applied to 65% of the total miles driven by Class 8 trucks, it could lead to a 4% reduction in total truck fuel consumption.[31] In the future, freight vehicles with SAE Level 4 ("High Driving Automation")[32] may provide even greater improvements in freight productivity and highway safety; however, proper operation of these systems is critical as discussed in the next section.

Connectivity. Though distinct from automation, connectivity enables information that can be used for real-time powertrain recalibration and optimization, which is being studied by teams working on DOE ARPA-E activities and other projects. Connectivity is of importance for military operations as well, not only related to national connectivity standards (DSRC, 5G LTE, etc.) but also communication among and between commercial and military vehicles on public roadways and with infrastructure providing weather, traffic, and accident information.

Progress is not without barriers and challenges. The speed and volume of transportation data, being made available by new sensing and connected technologies, is challenging to collect, synthesize, store, manage, analyze, and use for transportation planning and control. DOT aims to promote and assist data exchange to aid the safe deployment of automated vehicles and has prepared a set of guidelines for this purpose.[33]

New understanding of barriers to operational efficiency has come from research and analysis in the SMART (System and Modelling for Accelerated Research in Transportation) Consortium. This collaboration of five DOE Laboratories is part of the Energy Efficient Mobility Systems (EEMS) program in VTO. The EEMS program is also supporting the development of the data analytics and computational framework required to build scalable mobility system models that consider future passenger and freight operations, which does not yet exist.

Figure 18. Cybersecurity is a Critical Issue

Cybersecurity. In order to mitigate the risks of connectivity and automation, as well as to realize the benefits (whether V2V control for platooned vehicles or V2I for managing traffic signals and vehicle charging) the communication must be secure from cyber-attack (Figure 18). Unlike light-duty vehicles which may use some proprietary vehicle area network protocols, most heavy-duty vehicles use common controller area network (CAN) protocols conforming to SAE J1939 which must be strengthened to prevent cybersecurity issues. The third-party telematics used by many fleets introduce an additional vulnerability to not only the vehicle but also the third-party aggregator and fleet operator back office systems. In fact, any third-party product that interfaces with the vehicle data bus can be a cybersecurity concern. There are many fewer trucks on the road than light-duty passenger vehicles, but trucks can be more physically damaging if commandeered. Furthermore, as vehicles move toward greater powertrain electrification, particularly grid-connected vehicles, the need to secure vehicle charging becomes critical. Vulnerabilities in vehicle charging could impact the electric grid, reaching beyond trucking as a business and transportation as a service. Such “side-door” vulnerabilities are an area of concern. The Partnership sees a path forward through collaboration across DOE, DOT, industry, and national defense/security agencies.

Truck weights must continue to comply with federal bridge formula weight requirements to reduce the impacts of truck travel on the roadway infrastructure. New technologies need to consider the impact to gross vehicle weight and axle loading and strive to achieve weight savings relative to existing technologies if possible to maintain or improve the percentage of weight that can be dedicated to the load.

Safety

Safety of medium- and heavy-duty vehicles and mobility systems remains an uncompromised requirement as the Partnership seeks improvements in efficiency, emissions, 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. The Partnership, with resources across multiple agencies, is uniquely positioned to lead collaborative research at the intersection of safety, efficiency, and productivity, and 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 fatalities and injuries in truck-involved crashes, thus enabling benefits related to congestion mitigation, emission reduction, reduced fuel consumption, and improved productivity. First and foremost, safe trucks preserve the lives of the truck operators and others with which they share the road. Furthermore, truck crashes on the nation's highways (even non-fatal ones) come with high costs for traffic congestion, lost cargo, insurance expenses, and reduced economic productivity. 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 understood.

The public has also placed a high premium on safety with concern about driver distraction, driver fatigue, truck aggressivity, and risks associated with exposure to heavy trucks. Crashes involving heavy trucks still account for about 8% of the motor vehicle fatalities in the United States.[34]

The goal of 21CTP collaborative research in this area is to create a safer and more efficient 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.

The Partnership has several research priorities to support this broad focus area goal. These include:

- Ensure that trucks, drivers, **and** roads are ready and suitably equipped for platooning (Figure 19).
- 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
- In a shared effort with the Operational Efficiency focus area, cyber security threats must be detected, distinguished from benign misbehaviors, and corrective solutions must be developed.

Figure 19. Platooning Trucks in Operation (Daimler)

- Seek synergies and resolve conflicts between vehicle features for safety and efficiency. Examples of trailer skirts for aerodynamic benefits and vulnerable road user protection, tire traction and rolling resistance, following distances.
- Ensure that electrification features of medium- and heavy-duty vehicles do not compromise safety, including crashworthiness and risks to first-responders.

Additional data are needed to ensure the robustness of platooning systems for ensuring safety, and effectiveness when compared to real-world practices (trucks already follow closely) and in real-world application with road imperfections and harsh ambient conditions (Figure 19).

Beyond platooning there is great potential for increasing freight productivity with level 4-5 driving automation systems. The safety systems used in these types of vehicles operating without driver intervention must be reasonably safe with sufficient redundancy. Physically testing all failure modes and operational scenarios is not feasible, but virtual methods can accelerate the discovery of issues. The Partnership proposes to participate in development and application of virtual tools to facilitate the study and evaluation of electronics reliability in automated trucks (Figure 20).

Figure 20. Virtual Electronic CAV Reliability Simulation (eeNews Europe)

To enhance roadside truck inspections, there is a need to develop and especially validate data for wireless sensing and communications for truck safety systems and weight (Figure 21).

Figure 21. Truck Weigh Stations Are an Opportunity

Data and analysis are needed to ensure truck side guards can have dual purpose aero benefit.

Other Areas of Interest

The Partnership has been involved in other research focus areas in its past collaborative work. Chief among these is the area of vehicle power demands which encompasses both road loads such as aerodynamics and tire rolling resistance and vehicle parasitic losses such as pumps and friction loads. Addressing these losses is still of great interest to the industrial partners in reducing fuel consumption of their truck products. The research advances in the collaborative government/industry space have moved the technology state-of-the-art in this area to a point beyond the early-stage research environment. Therefore, further technology research and development in this space will be largely confined to industry work. The Partnership will continue to acknowledge the importance of these areas to overall truck efficiency and will remain open to potential new early-stage research opportunities here if they arise.

Conclusion

The freight and passenger transportation sectors are undergoing fundamental disruptions because of technology and innovation. Ensuring these critical links in the economic value chain remain competitive requires aggressive technology research work. This 21st Century Truck Partnership Research Blueprint represents the beginning of a significant new effort to develop innovations and technologies that support greater energy affordability and security in a freight and passenger movement system. The Partnership will use this research blueprint to develop more detailed technology roadmap documents that will outline the key barriers and opportunities for addressing this future research.

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