Roadmap and Technical White Papers

February 2013

Table of Contents

List of Figures

Revision History

Final (February 27, 2013)

Minor editorial corrections for final publication

Version 6-1 (December 6, 2012)

Reviewed by 21CTP management and approved for final publication

Version 6 (October 2, 2012)

Chapter	Revision	Page(s)
Introduction	▶ Added section to describe 21CTP organization and structure	25-28
Engine	▶ Incorporated cleaner version of graphic showing trends in diesel engine efficiency	32
Natural Gas	▶ Added an "issue in focus" section describing the results of a 2012 21CTP workshop on natural gas research needs	129-138

Version 5-1 (June 20, 2012)

Chapter	Revision	Page(s)
Table of Contents	▶ Added list of figures	8
Introduction	▶ Added energy balance diagrams for medium-duty trucks ▶ Added text describing the energy balance diagrams for medium-duty trucks	22-24 22-24
Back cover	▶ Added back cover	After page 129

Version 5 (May 22, 2012)

Chapter	Revision	Page(s)
Executive Summary	▶ Added proposed hydraulic hybrid goals from EPA and separated these goals from the electric hybrid goals	12-13
Introduction	▶ Revised energy balance diagrams with updated versions from ORNL ▶ Added text describing the revised energy balance diagrams	21-22 21-22
Engine	▶ No changes	--
Hybrid	▶ Added hydraulic hybrid technology discussion (per EPA) ▶ Recommended change to e-machines cost goal (was $50/kW, Meritor recommended $23/kW to be discussed) ▶ Added hydraulic hybrid technology goals (per EPA)	51 61 64-67
Vehicle Power Demands	▶ Removed references to appendices from first version of roadmap ▶ Inserted missing figure on oil viscosity relation to fuel efficiency	74, 75 74
Safety	▶ No changes	--
Efficient Operations	▶ Revise EISA discussion in Section 6.1 ▶ Revise power diagram and text for over-the-road truck ▶ Revise discussion on ITS technologies ▶ Remove redundant idle reduction section ▶ Add section on weight limit allowance for fuel efficiency technologies	112 113 115-116 118 118

Strategic Vision

Vision

Our nation's trucks and buses will safely and cost-effectively move larger volumes of freight and greater numbers of passengers while emitting little or no pollution and dramatically reducing the dependency on foreign oil.

Message

Accelerate the introduction of advanced truck and bus technologies that use less fuel, have greater fuel diversity, operate more safely, are more reliable, meet future emissions standards and are cost-effective. The ultimate goal is safe, secure, and environmentally friendly trucks and buses, using sustainable and self-sufficient energy sources that enhance America’s global competitiveness.

National Imperatives

- Transportation in America supports the growth of our nation’s economy both nationally and globally.
- Our nation’s transportation system supports the country’s goal of energy security.
- Transportation in our country is clean, safe, secure, and sustainable.
- America’s military has an agile, well-equipped, efficient force capable of rapid deployment and sustainment anywhere in the world.
- Our nation’s transportation system is compatible with a dedicated concern for the environment.

Strategic Approach

- Develop and implement an integrated vehicle systems R&D approach that validates and deploys advanced technology necessary for both commercial and military trucks and buses to meet the aforementioned national imperatives.
  - Conduct research for engine, combustion, exhaust aftertreatment, fuels, and advanced materials to achieve both significantly higher efficiency and lower emissions.
  - Conduct research focused on advanced heavy-duty hybrid propulsion and auxiliary power systems that will reduce energy consumption and pollutant emissions.
  - Conduct research to reduce vehicle power demands to achieve significantly reduced energy consumption.
  - Support research toward the development of technologies to improve truck safety, resulting in the reduction of fatalities and injuries in truck-involved crashes.
  - Support research toward the development and deployment of technologies that substantially reduce energy consumption and exhaust emissions during idling.
  - Conduct the validation, demonstration, and deployment of advanced truck and bus technologies, and grow their reliability sufficient for adoption in the commercial marketplace.

- Research, validate, and deploy technologies and methods that save fuel through more efficient operations of trucks and transportation systems, targeting an overall improved freight efficiency.

This is an "agreement to agree" between Government and Industry - a public-private partnership. Through this initiative the members of this Partnership will conceive, develop and deploy future transportation technologies that will keep America rolling efficiently, safely and securely while respecting our environment.

Executive Summary – Goals

Specific technology goals[1] have been defined in six critical areas that will reduce fuel usage and emissions while increasing heavy vehicle safety. The aim of the Partnership is to support research, development and demonstration that enable achieving these goals with commercially viable products and systems.

Engine Systems

Engine system refers to the combination of fuel, engine, and emissions aftertreatment equipment. Increasing the energy-efficiency of the engine system reduces fuel consumption by a corresponding amount. Specific technology goals are:

- Develop and demonstrate an emissions compliant engine system for Class 7-8 highway trucks that achieves 50% brake thermal efficiency in an over-the-road cruise condition, improving the engine system fuel efficiency by about 20% (from approximately 42% thermal efficiency today). (2015)
- Research and develop technologies which achieve a stretch thermal efficiency goal of 55% in prototype engine systems in the lab. (This efficiency gain would be equivalent to an additional 10% gain in over-the-road fuel economy when prototype concepts are fully developed for the market.) (2015)
- Through experiments and models with FACE fuels and other projects, determine the most essential fuel properties, including renewables, needed to achieve 55% engine brake efficiency. (2014)
- Identify alternatives to fossil petroleum based fuels and technology pathways (vehicle, fuels, and infrastructure) to a sustainable, long-term fuel supply.

Heavy-Duty Hybrids

Hybrid Electric

A heavy-duty hybrid implies a hybrid-electric propulsion system and auxiliary power system and/or any equivalent hybrid technology. The electric propulsion system refers to the combination of the drive unit (a system of electric motor(s), generator(s), mechanical power transmission elements, and inverter(s)), energy storage system(s) and control device(s). Overall challenges include reliability, cost and system integration, with the conventional heavy-duty automatic transmission as the benchmark. Specific technology goals are:

- Ability to attain fuel consumption reductions (compared to today's conventional, non-hybridized heavy-duty vehicles) in a commercially viable manner.
- Develop a hybrid system with a design life of 15 years.
- Achieve cost targets for energy storage ($45 per kW and/or $500/ kW- hour for an energy battery by 2017; $40 per kW and/or $300/ kW- hour for a power battery by 2020; and cost of overall battery pack

[1] Achievement of the goals contained in this document is subject to a number of factors, including availability of funding to perform the research work. This document will be reviewed periodically by the Partnership to ensure that it reflects current goals and funding availability.

should not exceed cost of the cells themselves by more than 20% by 2016) and for e-machines ($23/kilowatt by 2016).

Hybrid Hydraulic

A heavy-duty hydraulic hybrid implies a hybrid-hydraulic propulsion system with auxiliary hydraulic power components. The hydraulic propulsion system refers to the combination of the drive unit (a system of hydraulic pump-motor(s) and mechanical power transmission elements), hydraulic energy storage system(s) and control device(s). In this type of system, deceleration energy is taken from the drivetrain by an inline hydraulic pump/motor unit by pumping hydraulic fluid into high pressure cylinders. The fluid, while not compressible, pushes against a membrane in the cylinder that compresses an inert gas (usually nitrogen) to 5,000 to 7,000 pounds per square inch or more when fully charged. Upon acceleration, the energy stored in the pressurized tank pushes hydraulic fluid back into the drivetrain pump/motor unit, allowing it to motor into the drivetrain and assist the vehicle's engine with the acceleration event. Overall challenges include reliability, system integration and manufacturing costs, with the conventional heavy-duty automatic transmission being the benchmark. A family of similar, but different sized, devices is needed to adequately cover vehicle applications ranging from Class 2b through Class 8. Specific technology goals for hydraulic hybrid technology are:

- *Hydraulic energy conversion devices:* Develop and demonstrate a new generation of hydraulic pumps and motors that meet the on-highway markets demands for performance, cost, durability, and reliability. Higher pressure limits (7000-10000 psi) and the optimization of efficiency, weight, and NVH will also be important areas of development. Axial piston, radial piston, bent-axis, and variants of these types and potentially other types of pumps and motors are being studied to determine their suitability for HD hydraulic hybrid systems.
- *Hydraulic energy storage:* Develop and demonstrate energy storage systems that meet the life targets of the vehicle. Develop storage devices with higher specific energy and energy density (e.g., higher maximum pressure, lower weight, etc.). Develop the manufacturing processes needed for high-volume production and the associated supplier base.
- *Hydraulic controls:* Develop and demonstrate valves capable of higher operating pressures while maintaining low cost, high efficiency, and high reliability. Develop and demonstrate sensing and control solutions to lower cost and improve reliability and safety. Optimize hydraulic circuit design to enhance system performance while maintaining simple system architecture.
- *Hydraulic energy transfer fluids:* Develop and demonstrate cost-effective fluids that meet the performance requirements of the system over the entire operating temperature range of the vehicles. These fluids must also meet the bio-degradability and fire resistance requirements. Many of these requirements are undefined and resources will be focused on both defining the requirements and testing the potential fluids to verify fluid life and component and system durability under anticipated environmental conditions.
- *Technical readiness:* Advance the designs of promising hydraulic hybrid component systems to a technical readiness level that will make them commercially viable (advanced hydraulic pump-motors, valves and high pressure accumulators that are: a) capable of attaining the high fuel efficiency gains shown by series hydraulic hybrid demonstration trucks and buses, b) durable and have long life, and c) easy to manufacture and install for both domestic and international markets).

Power Demands (Vehicle Technology)

The power demand of a heavy-duty vehicle includes aerodynamic drag resistance, rolling resistance, drivetrain losses, and auxiliary loads. Fuel consumption is reduced in direct proportion to the reduction in power demand. Specific technology goals for 2021 are:

- Develop and demonstrate advanced technology concepts that reduce the aerodynamic drag of a Class 8 highway tractor-trailer combination by 20%. Evaluate a stretch goal of 30% reduction in aerodynamic drag.
- Develop and demonstrate low rolling resistance tires that can reduce vehicle rolling resistance and wheel weight for a Class 8 tractor-trailer. Demonstrate 35% reduction in rolling resistance.
- Develop and demonstrate technologies that reduce essential auxiliary loads by 50% for Class 8 tractor-trailers.
- Develop and demonstrate engine, transmission, and driveline systems that enhance engine cycle operating efficiency and reduce friction losses.
- Develop and demonstrate lightweight material and manufacturing processes that lead to a 10% reduction in tare weight for a tractor/trailer combination. Establish a long-term stretch goal of reducing combined vehicle weight by 20%.
- Increase heat-load rejected by thermal management systems by 20% without increasing radiator size. Develop and demonstrate technologies that reduce powertrain and driveline losses by 50%.

Idle Reduction

Extended idling by commercial trucks costs truck owners about $6 billion annually and wastes over 1% of our petroleum usage. 21CTP goals to address this issue are:

- Promote the incorporation of idle reduction (IR) equipment on new trucks as fuel saving devices as they are identified through the DOE SuperTruck project.
- Establish a nationwide multi-mode IR education program.
- Work with OEM truck manufacturers to obtain data on the number of new trucks being ordered with IR options.
- Conduct a fleet survey to gather data on the amount of in-use idling hours that are accumulated by type of heavy-duty vehicle.
- Analyze data from the EPA SmartWay Transport Partnership to measure fuel savings and emissions reductions associated with the various type of IR equipment available.
- Develop improved IR systems to minimize fuel required, cost, and weight to meet hotel functions in sleeper cabs.

Safety

- The 21CTP will work collaboratively with DOT to enhance safety primarily through a variety of crash avoidance strategies that include on-board vehicle technologies as well as operationally-focused programs designed to reduce crash risk. The overall goals of this collaboration are to 1) ensure that advancements in truck design and technology to improve fuel efficiency do not have any negative impacts on safety; and (2) conversely, to ensure that efforts to improve safety to not reduce efficiency—and, where possible actually contribute to improvements in overall motor carrier industry system efficiency.

Operational Efficiency

Medium- and heavy-duty trucks cover a broad spectrum of vehicle types, and their operations are as diverse as the applications themselves. The fuel efficiency improvements that can be achieved and the technologies that will be most effective depend strongly on operational characteristic that are unique to each application. Improved understanding of heavy-duty truck usage, targeted operational changes (through incentives or elimination of barriers imposed by regulations, legacy industry practices, etc.) and widespread implementation of high-impact technologies can yield significant fuel consumption reductions. Specific goals and recommended projects are listed below:

- Develop and demonstrate technologies that minimize the impact of driver behavior for optimal acceleration efficiency by automatically controlling vehicle accelerations at a level for which the engine operates in its most efficient operational state for the current environment. Driver feedback information devices can also be implemented as a retrofit option for existing vehicles.
- Develop simple tools for the trucking industry that will provide estimates of the fuel savings potential of advanced efficiency technologies and technology combinations depending on specific usage information of a particular fleet (measured drive cycle data). The tools will provide cost and benefit analyses for the selection of technologies on a case-by-case basis when representative drive cycles for an individual fleet or owner-operator are available (and recommendations to the fleet for obtaining the drive cycles can be provided).
- Conduct a study to identify proposed ITS/connected vehicle technologies that offer significant fuel savings and quantify the reduction in fuel consumption for technologies that offer the greatest benefits. Select one technology, evaluate the benefits for fuel consumption as a function of market penetration and identify the infrastructure needs and costs for deployment of the technology to a level at which the benefits of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) networking are realized.
- Establish a real-world test corridor for commercial vehicles focused on improving Commercial Vehicle Operations, including Fuel Efficiency. The test corridor should include DSRC and Wi-Max technologies in the infrastructure, would involve one or more fleets enabled for DSRC/Wi-Max capability and outfitted with various applications designed for improved efficiency of commercial vehicles.
- Explore regulatory changes to permit the replacement of body-mounted mirrors with a camera-based system and quantify the fuel saving benefits associated with such a change.
  - Quantify the fuel consumption penalty imposed by mirror regulations on highway-based commercial vehicle operations. Perform track test evaluations to demonstrate a 3-5% reduction in fuel consumption when mirrors are removed from class 8 tractor trailers.
  - Develop safety and robustness requirements for camera-based systems and conduct human factors research to develop and demonstrate equivalent safety of a camera-based system.
  - Assess procedural requirements for implementing the necessary regulation changes and quantify the efforts required to modify regulations to permit camera-based systems in place of truck mirrors for class 8 long-haul vehicles.

- Demonstrate the fuel savings benefits and develop policy guidelines for extending the use of long combination vehicles (LCVs), particularly triple-trailer units.
    - Complete long-term in-fleet measurements to quantify the fuel savings of triple-trailer combination vehicles in comparison with single- and double-trailer operations in the same fleet (on a load-specific fuel consumption basis). Conduct an analysis to quantify expected fuel savings if triple trailers are permitted on all interstate highways in the United States.
- Promote improved supply chain management strategies in the commercial freight industry with an objective to increase the loads carried per truck and reduce vehicle miles traveled (VMT).
    - Conduct a study to identify fleet best practices for supply chain management, and quantify the fuel savings that are achieved with efficient fleet operations vs. operations of fleets that do not have streamlined supply chains.

Additional Infrastructure Considerations

Our nation's infrastructure has a large impact on the amount of fuel used by medium-duty and heavy-duty commercial vehicles. Additional opportunities to reduce fuel usage may include:

- Harmonization of national and state regulations for the commercial vehicle industry.
    - MD and HD commercial vehicle speed limit
    - MD and HD commercial vehicle weight restrictions
    - MD and HD commercial vehicle length restrictions
- Road congestion
    - Dedicated truck lanes within the National Interstate Highway System

Conclusion

The heavy duty vehicle industry is a small base of companies with a huge impact on petroleum consumption and economic growth. Despite this, there has been minimal public-private partnership activity to address these many opportunities. The commercial vehicle industry comes together with governmental agencies within the 21st Century Truck Partnership, and 21CTP is poised to serve as a focal point to create a longer term vision for the future of commercial vehicle technology.

I. Introduction

I.1. Partnership History

The 21st Century Truck Partnership (21CTP) was formally launched on April 21, 2000, in a press event in Romulus, Michigan. This event gathered together U.S. truck and supporting industries, concerned environmentalists, and federal agency representatives. At that time, the Vice President of the United States said, "The heavy truck manufacturing industry deserves great credit for pledging to work with this Administration to create trucks and buses that are cleaner, safer, and more economical. We have learned that a strong economy and a safe environment go hand in hand."

21st CENTURY TRUCK PARTNERSHIP

One of the first accomplishments of the Partnership was the development of an initial research roadmap outlining the areas of focus for the Partnership and the research barriers to be overcome. That roadmap set aggressive goals for fuel efficiency and safety for specific classes of heavy vehicles. As the Partnership has worked together over the past decade, it became apparent that the participants could best achieve common interests by establishing goals more specific to industry sectors. For that reason, this roadmap document was developed to pursue detailed goals for engine systems, heavy-duty hybrids, parasitic losses, idle reduction, and safety, and should be considered the current roadmap for the Partnership. The specific goals may have changed since 2000, but a common thread is shared among the first roadmap, this current roadmap/white paper document, and all other Partnership discussions: the need for safer, cleaner, and more fuel efficient trucks and buses. The Partnership's focus has not wavered from this vision throughout its history.

I.2. Partnership Benefits

The 21st Century Truck Partnership is structured to coordinate efforts to improve the efficiency, emissions, and safety of class 2b to 8 commercial trucks and buses. Industry members include original equipment manufacturers and, unique to a public-private partnership, also include key suppliers such as heavy-duty diesel engine manufacturers and major component suppliers. Member companies are all multi-national organizations with major U.S.-based research and development activities and domestic manufacturing capabilities. The industry members are joined by relevant federal agencies; the Department of Energy, the Department of Transportation, the Department of Defense, and the Environmental Protection Agency. In addition, fleet customers and small suppliers can gain access to 21CTP programs by working through the partner companies.

The 21st Century Truck Partnership is not merely a means to fund research projects, but also serves as a forum for information exchange across all government and industrial sectors related to heavy truck research. This allows for all partners to clearly understand the breadth of research activities, avoiding duplication of effort and enabling industrial partners to build relationships to more effectively team on research projects. In this way, the entire Partnership can move together to meet the goals as set forth in these white papers. This "one-stop-shop" forum also enables outside agencies to bring issues to the entire heavy-duty industry at once, saving time and hassle.

The forum also enables sub-groups to pursue individual discussions on issues relevant to an industrial sector, and to work effectively toward a conclusion that can be returned to the group to benefit the entire Partnership. A sub-group that resulted from 21CTP discussions was a group of hybrid team members, truck manufacturers, and electrical suppliers that came to agreement on areas in need of standardization relative to electrical truck components and systems. This group came together quickly, and with a single one-day workshop was able to agree on three areas of interest and press forward with outlining standardization needs, working with SAE to incorporate these thoughts into their standards work.

I.3. Strategic Importance of the Partnership

A productive, innovative U.S. trucking and supporting industry is essential for the economic prosperity of every American business. Innovation is also needed to ensure that truck and bus manufacturers and suppliers located in the United States remain competitive in world markets and continue to provide rewarding employment opportunities for large numbers of Americans. U.S. manufacturing facilities face stiff worldwide competition. New truck and bus technologies will help truck and bus owners and operators and their customers cut fuel and operating costs and increase safety. The Department of Defense, a major owner and operator of trucks, would share these gains and also benefit from reduced logistics costs associated with transporting fuel during operations. The truck and bus manufacturing and supporting industries face a range of new challenges: increasingly stringent emissions standards, new concerns about the threat of global warming, concerns about U.S. fuel supplies, increased expectations about safety, and more. The truck and bus industry's future depends on its ability to produce affordable, high-quality, safe, environmentally sensitive products. The new challenges can be met best if government, industry, and universities work together to develop technologies for an improved generation of commercial trucks and buses for our nation's commercial and military truck fleet.

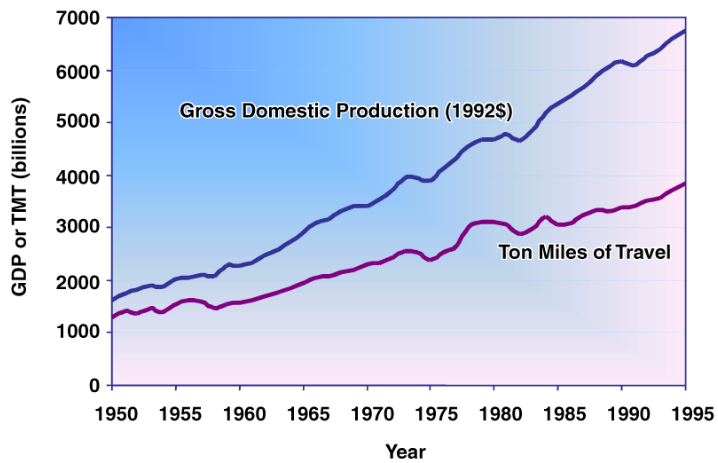

Figure 1. The Nation's Economy is Linked to Truck Transport.
Source: Argonne National Laboratory.

Trucks are the mainstay for trade, commerce, and economic growth in the United States. The gross domestic product (GDP) of the United States, and hence the country's economic activity, is strongly related to freight transport (Figure 1). It is estimated that currently as much as 80% of the total quantity of goods is transported by trucks; therefore, meeting truck transport energy demands for movement of goods and for services is critical to the economy.

Within the U.S. transportation sector, truck energy use has been increasing at a faster rate than that of automobiles. Since the 1973 oil embargo, all of the increase in highway transportation fuel use has been due to trucks, mainly because of their extensive use in trade and commerce and in providing essential services. In recent years, another contributor to the increasing highway transportation energy use has been the popularity for personal use of low-fuel-economy pickup trucks, vans, and sport utility vehicles (SUVs). The demand for freight movement in this sector is directly tied to economic growth, which is expected to grow at 2% or more for the next twenty years. Recent DOE projections estimate that total heavy-duty fuel use could exceed light-duty fuel use by 2040, if all the targets for light duty fuel efficiency are met (see Figure 2).

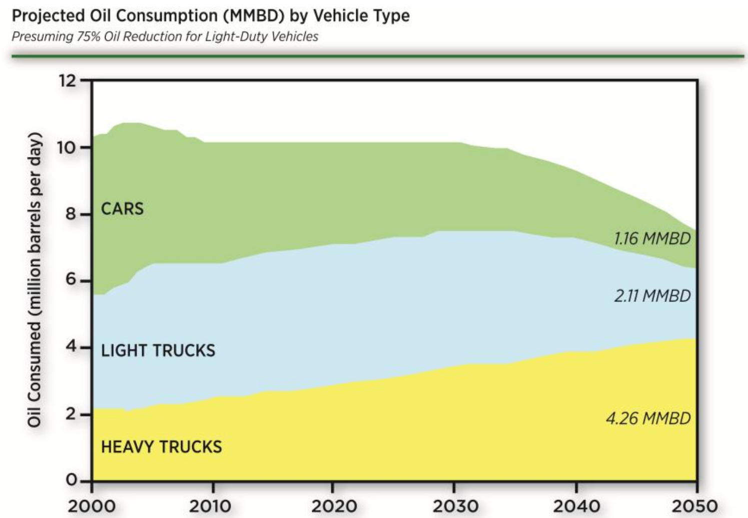

Figure 2. Projection of Transportation Fuel Use to 2050 Source: Internal DOE analysis, August 2008, comparing heavy truck oil consumption at AEO 2008 reference case levels with a 75% reduction in light-duty oil consumption relative to EIA's AEO 2008 reference case due to significant light-duty fuel economy gains and fuel switching.

The 2002 Vehicle Inventory and Use Survey (Department of Commerce, 2005) reports that there were 79 million light trucks [Class 1 and 2 trucks up to 10,000 pounds (4,535 kg) in GVW], 2.8 million medium trucks [Class 3–6 trucks between 10,001 and 26,000 pounds (11,791 kg) GVW], and about 2.3 million heavy trucks [Class 7–8 trucks between 26,001 and 130,000 pounds (56,550 kg) GVW] registered in the United States. In total, heavy single-unit trucks (trucks without trailers that are larger than personal use vehicles) use about 10.6 billion gallons of fuel per year, according to the Federal Highway Administration: combination trucks (trucks with one or more trailers) use about 26.8 billion gallons of fuel per year. As the graph in Figure 3 shows, fuel use for heavy trucks is projected to increase significantly in the next several decades if no significant changes are made to current truck efficiency measures. Figure 4 illustrates the relationship between vehicle class and gross vehicle weight rating, along with a general illustration of the types of vehicles used in each class.

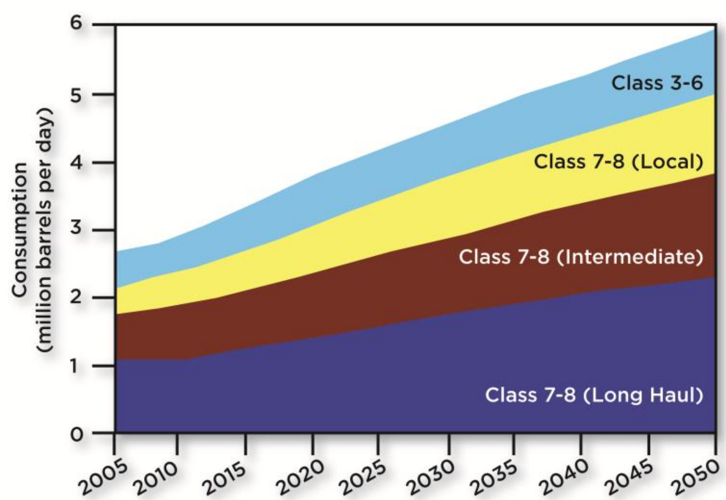

Figure 3. Projected Fuel Use for Heavy Trucks through 2050. Source: GPRA 06 FCVT Heavy Vehicle Benefits, Preliminary Results, TA Engineering

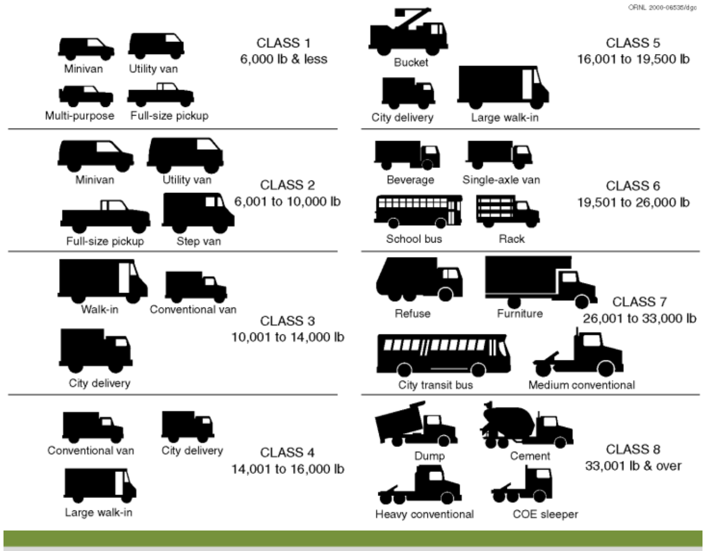

Figure 4. Truck Types by Gross Vehicle Weight (GVW). Source: Commercial Carrier Journal (http:\\www.ccjmagazine.com).

Wartime operation typically increases military truck energy demands to sustain a military force on the battlefield. It is estimated that military operation at the same level experienced during World War II could potentially contribute as much as 6% to total commercial and military truck energy use. The 21st Century Truck Partnership will strengthen our national security by dramatically reducing operational support costs and increasing combat effectiveness through a lighter, more mobile military force resulting from rapid integration of advanced, commercially viable technologies into military trucks.

Government and industry will coordinate R&D efforts and will share costs. The federal agencies will build on existing research and will assign high priority to major new research identified in this technology roadmap. DOE has been assigned to lead the federal R&D component of this program because of the close alignment of the stated 21st Century Truck Program goals and research objectives with DOE's mission "to foster a secure and reliable energy system that is environmentally and economically sustainable...." Since early 1996, DOE's Vehicle Technologies Office (and its predecessor offices), in collaboration with trucking industry partners and their suppliers, has been funding and conducting a customer-focused program to research and develop technologies that will enable trucks and other heavy vehicles to be more energy-efficient and able to use alternative fuels while simultaneously reducing emissions. DOT brings its mission-oriented intelligent transportation systems and highway transportation safety programs to this program. DOD, as a major owner and operator of trucks, will define the military mission performance requirements and will fund appropriate dual-use and military-specific technologies so that national security will benefit by innovations resulting from this Program. R&D will be closely coordinated with EPA so that critical vehicle emissions control breakthroughs can cost-effectively address the increasingly stringent future EPA standards needed to improve the nation's air quality.

Industry will move research achievements into production vehicles rapidly when their commercial viability has been demonstrated. The partnership will work closely with fuel producers to accelerate the development and production of new fuels required by new engine designs to meet the program goals.

A successful 21st Century Truck Partnership will enable the truck and bus industry and its supporting industries to face new challenges, specifically, increasingly stringent emissions standards, concerns about the threat of global climate change, concerns about U.S. fuel supplies, and increased expectations regarding highway safety. These new challenges will be addressed as government and industry R&D teams work together to develop improved technology for our nation's commercial and military truck fleet. Major advances and breakthroughs are expected toward achievement of the goals set to achieve cleaner, safer, and more efficient trucks and buses.

In recent years, typically about 10 to 12% of the total fatalities from vehicle crashes have involved medium and heavy trucks. In 1998, truck-related crashes resulted in 5,374 fatalities and 127,000 injuries. The majority of those killed were occupants of other motor vehicles. Most fatal crashes occurred on rural roads and involved tractor-trailers, the most common large truck configuration. DOT seeks to enhance safety primarily through a variety of crash avoidance strategies that include on-board vehicle technologies as well as operationally-focused programs designed to reduce crash risk. It is expected that the technology developed through the 21st Century Truck Program will assist in meeting this objective.

The Partnership will also strengthen U.S. national security by dramatically reducing operational support costs and increasing the combat effectiveness of military vehicles. Fuel cost for the Army, as a major owner and operator of military trucks, is more than 20% of the cost of operating and maintaining its truck fleet. In addition, more than 70% of the bulk tonnage needed to sustain the Army during a conflict is fuel. As the Army transforms itself into a lighter, more mobile force, the rapid introduction of advanced, commercially viable technologies into military trucks is vital in reducing the logistics cost associated with transporting fuels during wartime operation.

The Partnership's work also supports recent regulatory initiatives for truck fuel efficiency. In 2011, the Department of Transportation and the Environmental Protection Agency released final fuel efficiency and greenhouse gas regulations for medium-duty and heavy-duty trucks[2]. These regulations take effect with the 2014 model year, and establish these standards:

- Certain combination tractors will be required to achieve up to approximately 20 percent reduction in fuel consumption and greenhouse gas emissions by model year 2018.
- For heavy-duty pickup trucks and vans, separate standards are required for gasoline-powered and diesel trucks. These vehicles will be required to achieve up to about 15 percent reduction in fuel consumption and greenhouse gas emissions by model year 2018.
- Vocational vehicles – including delivery trucks, buses, and garbage trucks – will be required to reduce fuel consumption and greenhouse gas emissions by approximately 10 percent by model year 2018.

The standards are designed to account for the different types of work done by these categories of vehicle. Heavy pickups and vans will meet targets for fuel consumption in gallons per mile, while combination tractors and vocational vehicles have targets for fuel consumption expressed in gallons per thousand ton-miles.

The Partnership's work to increase the efficiency of medium-duty and heavy-duty trucks complements these regulations. The new regulations will help stretch current technologies, while Partnership activities will develop new technologies for the pipeline that push efficiency even farther. The SuperTruck project has set a goal for combination tractor fuel efficiency improvements of 50% on a ton mile per gallon basis (which translates to a 33% reduction in fuel consumption on a gallon per ton mile basis). In this way, the

[2] National Highway Traffic Safety Administration, August 2011, http://www.nhtsa.gov/fuel-economy.

Partnership is setting the technology stage for the future, and ensuring that new ideas are being explored to further improve fuel efficiency of these critical transportation vehicles.

I.4. Vehicle Energy Balance – Class 8 Tractor-Trailer

Although it is not the only focus for the Partnership, energy efficiency is a significant component of the work being done. Heavy truck fuel efficiency is influenced by several factors, including basic vehicle design, zone of operation, driver technique, and weather factors. Extending the definition of fuel efficiency to include the productivity measure of "ton-mile of payload transported" presents a more meaningful measure. Some of the new technologies being developed, such as aerodynamic treatments and idle reduction equipment, will require flexibility in the application of size and weight regulations, as will some of the operational strategies that benefit fuel efficiency.

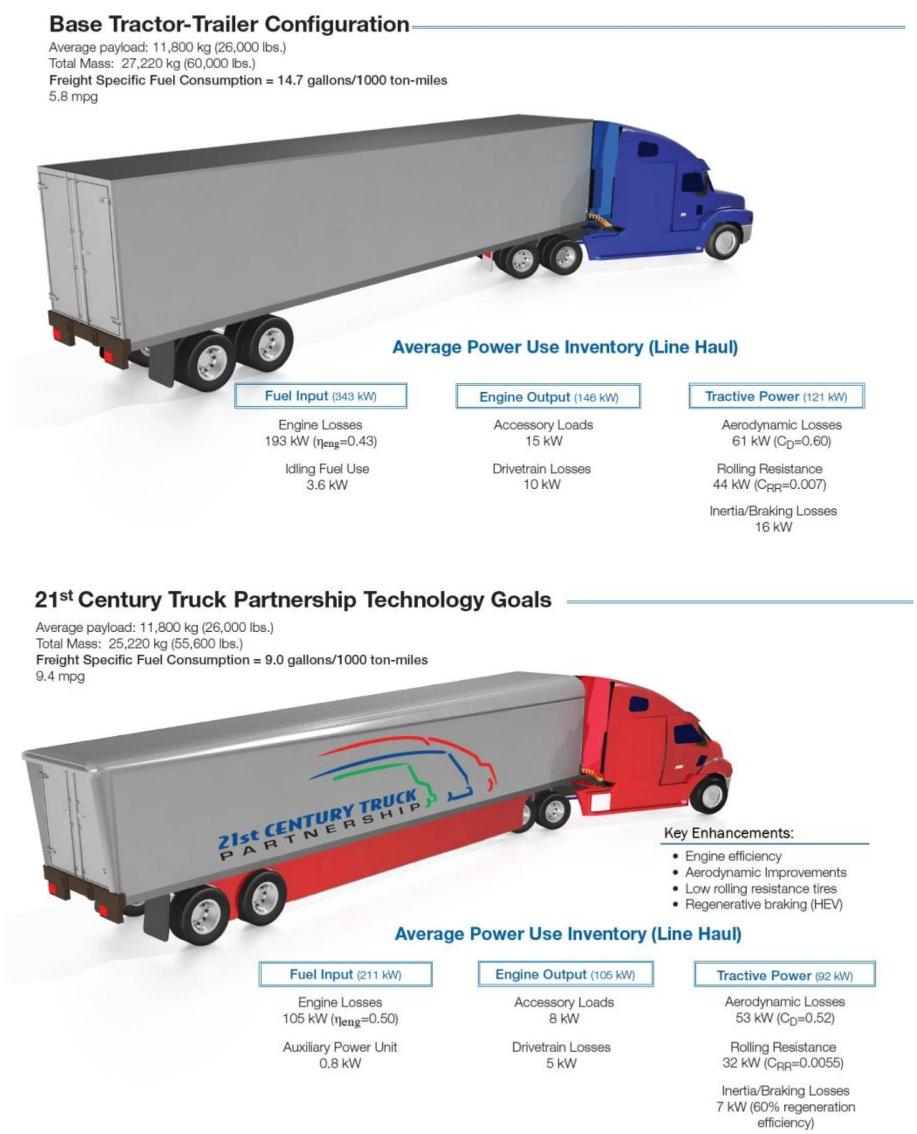

Figure 5. Power Use Inventory for Class 8 Heavy Truck (Base, and with 21CTP Technology Goals)

The nature of heavy truck energy use can be better appreciated if it is summarized in a power use inventory. Figure 5 shows an inventory for a typical Class 8 tractor-semitrailer combination carrying a payload of 26,000 pounds, assuming an over-the-road drive cycle. An inventory is shown for both the base case (current technology) and a 21CTP case (including technologies achieving the goals outlined in this document). The base case achieves a freight specific fuel consumption of 14.7 gallons per thousand ton miles, [3] and the

[3] These freight efficiency figures are based on "long tons" (2,200 pounds per long ton), for payload only.

21CTP case achieves a 40% reduction in freight specific fuel consumption (9.0 gallons per thousand ton miles).

For the base case, engine losses dominate the power use inventory, representing 56% of the total fuel energy input. Drivetrain and accessory load losses take about 17% of the engine output power, resulting in tractive power output that is about 35% of the total fuel energy input. Aerodynamic losses take 50% of the tractive power, rolling resistance takes 36%, and inertia/braking losses represent the remaining 13%. This analysis illustrates the areas in which 21CTP investments could be most useful from an energy basis – engine efficiency, aerodynamics, and other power demands on the engine. Hybrid technology can address inertia/braking losses to improve overall efficiency. All of these energy efficiency improvements are dependent on vehicle speed, terrain, traffic conditions, and other factors, so expected real-world freight efficiency impacts would be highly influenced by the vehicle duty cycle.

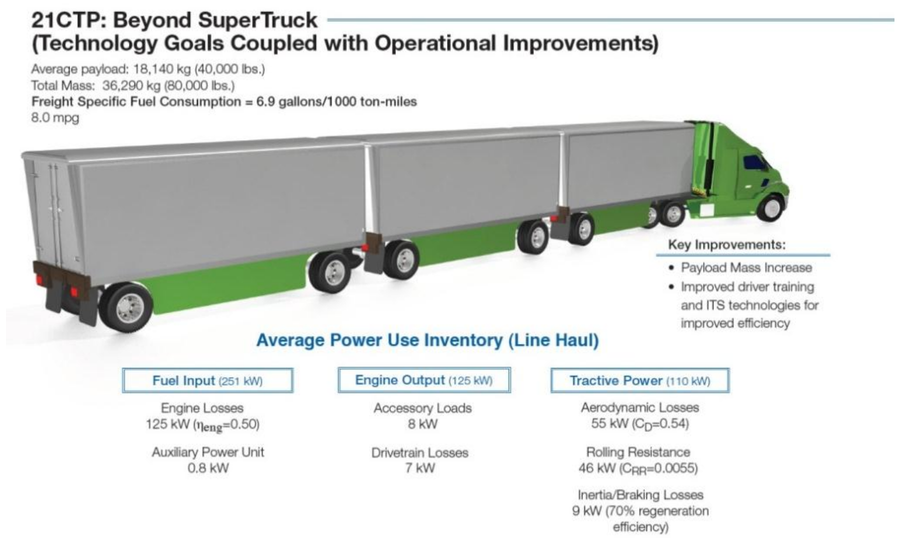

Figure 6. Power Use Inventory for Class 8 Heavy Truck (Beyond 21CTP Technology Goals)

The truck configurations in Figure 5 conform to current regulations for truck size and weight, and assume current levels of driver training and current availability of external driver aids for fuel efficiency. If regulatory changes are made to truck size and weight standards, and ITS technologies are available and can be used with driver training to improve fuel efficiency, a future truck configuration such as that shown in Figure 6 can be envisioned. The truck configuration shown here assumes the use of triple trailers, along with a payload mass increase. The payload increase in this case is offset by reductions in the weight of the tractor and trailers to keep the total mass at 80,000 pounds. This case represents an additional 23% improvement in freight specific fuel consumption from the truck achieving 21CTP technology goals in Figure 5.

I.5. Vehicle Energy Balance – Medium-Duty Truck

The 21st Century Truck Partnership is not solely focused on Class 8 over-the-road trucks: Partnership members are also producers of a variety of medium-duty trucks for a number of vocations. Duty cycles for these medium-duty trucks vary depending on the application (urban pickup and delivery, utility bucket trucks for line maintenance, etc.), and thus fuel use will also vary by application. Because of the differing duty cycles and applications, many of the technologies used to reduce fuel use in the medium-duty truck sector are different than those of the Class 8 tractor-trailer application. To help quantify the opportunity for fuel consumption reductions in the medium truck sector, a representative medium-duty truck (a local delivery truck) on a typical duty cycle (urban delivery) has been chosen for this roadmap.

The power use inventories for the medium-duty delivery truck applications are shown in Figure 7 and Figure 8. The base case vehicle achieves a freight-specific fuel consumption of 34.3 gallons per thousand ton miles, and the 21CTP case achieves a 34% reduction in freight-specific fuel consumption (22.7 gallons per thousand ton miles).

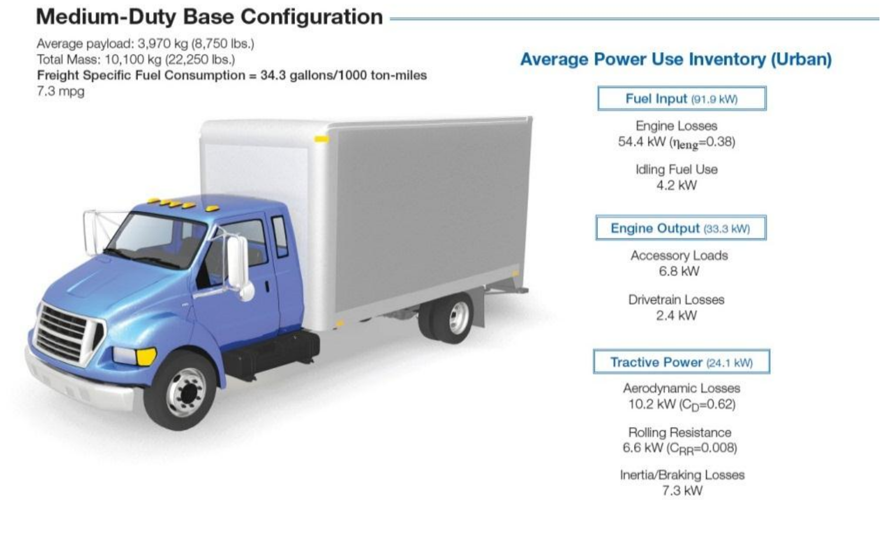

Figure 7. Power Use Inventory for Medium-Duty Truck (Base Case)

Figure 8. Power Use Inventory for Medium-Duty Truck (Improved Efficiency)

As shown in Figure 7, the base case truck carries a payload of around 9,000 pounds at a total vehicle weight of 22,250 pounds. As with the Class 8 tractor-trailers, the engine losses are the most significant portion of the power use, representing 59% of the total fuel energy input. Idling losses represent another 5% of the fuel energy input, resulting in engine output power that is 36% of the fuel energy inputs. Drivetrain and accessory load losses take about 27% of the engine output power, resulting in tractive power output that is about 26% of the total fuel energy input. Aerodynamic losses take 42% of the tractive power, rolling resistance takes 27%, and inertia/braking losses represent the remaining 30%. Note that, relative to the higher-speed duty cycle of the Class 8 tractor that involves a considerable amount of steady-state driving, the slower stop-and-go duty cycle of the delivery vehicle results in lower aerodynamic losses and rolling resistance losses (both typically a function of speed), and higher braking/inertia losses (because of the stop-and-go drive cycle). From an engine standpoint, the engine losses are similar to Class 8 trucks, but idling losses are a bit higher, driven again by duty cycle.

The truck in Figure 8 achieves improved fuel efficiency chiefly through engine efficiency improvements, along with regenerative braking recovery and engine stop-start through a hybrid system. Slight improvements in aerodynamic drag and rolling resistance are also included. The improved engine efficiency and hybrid system allow for a reduced fuel energy input to meet the duty cycle. The hybrid system enables a significant drop in idle fuel use, and significant reductions in the losses from inertia and braking.

I.6. Partnership Organization and Structure

The Partnership brings together the major federal agencies involved in medium-duty and heavy-duty truck research and development with the major industry players across the broad spectrum of truck manufacturers and truck suppliers. Industry partners include the major North American truck manufacturers, engine manufacturers, hybrid system manufacturers, and Tier 1 suppliers to the industry. The full list of partners appears in Figure 9. Dotted boxes indicate groupings of companies within the same parent organization. Prior to the inception of this Partnership, no mechanism existed to bring these key industry and government stakeholders together. The Partnership was established to form that mechanism and forge new partnerships among a diverse group of companies and federal agencies.

Figure 9. 21CTP Government and Industry Partners

I.6.1. Purpose of 21CTP

The commercial vehicle market is complex, and many factors affect the success of the participating companies, as shown in Figure 10. As noted earlier in this section, commercial truck fuel use is projected to continue its increase, so efficiency improvements are needed to mitigate this. Truck sales trends are cyclical, so corporate research funding availability can be constrained and the levels available can be unpredictable. Commercial vehicle manufacturers invest roughly the same percentage of gross revenue in research as light-duty vehicle manufacturers do, but the overall gross revenues are lower resulting in lower total funding for research. Finally, the

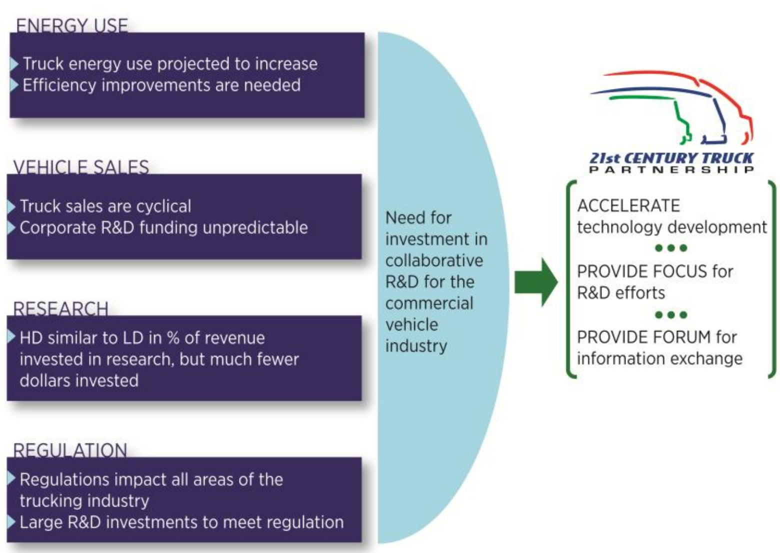

Figure 10. Drivers for 21st Century Truck Partnership

regulatory environment affects all areas of the commercial vehicle industry, and considerable research investment is made to address these mandatory constraints. All of these factors drive the need for collaborative research investments to benefit the entire commercial vehicle industry.

The Partnership has several main purposes, outlined below, to support its overarching aim to accelerate introduction of truck and bus efficiency and safety technologies and address the driving factors for the industry. These include:

- Acceleration of technology development through collaborative, pre-competitive, and pre-regulatory research projects at the system and component levels. Partners have access to research resources and expertise from the federal agencies and their national laboratories.
- Focus of R&D efforts on topics of interest to the partners through a forum for discussion of areas of common interest and consensus building tools such as this roadmap. Partners have a number of collaborative discussion opportunities to identify research needs on a near real-time basis, and have access to Partnership reference materials to assist partners in discussing these research needs.
- Information exchange and dissemination forum through regular conference calls and meetings and information distribution tools. Partners have access to current information about industry and government activities and opportunities.

I.6.2. Partnership Structure and Regular Activities

The Partnership maintains a flexible and informal structure to respond quickly to changing conditions in the dynamic commercial transportation market. The general structure of the Partnership is shown in Figure 11. The partners are divided into federal and industry sectors, as noted in the figure. Within the industry sector, the partners are further organized into three main industry groups: the engine team, the hybrid team, and the truck OEM team, with members noted in the figure. For organizations such as Volvo and PACCAR whose activities overlap these industry groups, the Partnership allows for membership in multiple teams.

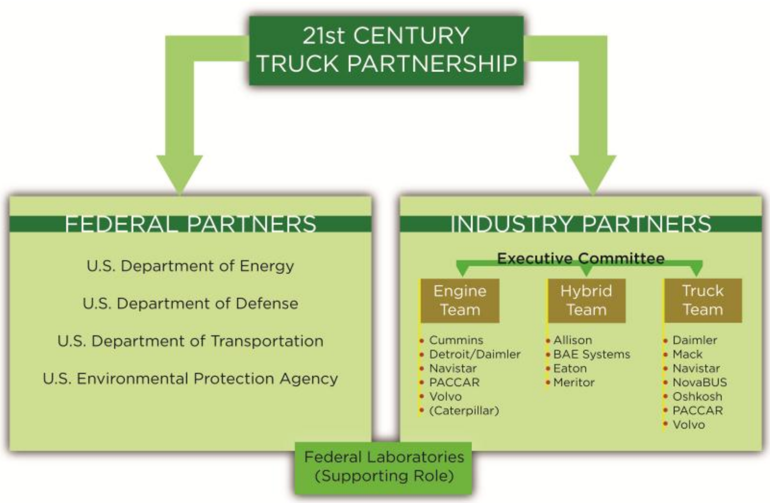

Figure 11. 21CTP Structure

The three industry teams are represented by an Executive Committee. The Executive Committee consists of one nominated industry member from each of the three industry sectors. The Executive Committee meets as a group once per month to discuss high-level partnership issues and to identify any topics that need to be addressed by the full Partnership. Executive Committee members also have the responsibility of gathering specific consensus on 21CTP topics (such as the content of the roadmap) from their industry sectors.

The federal partners include four major Cabinet-level agencies with a role in the commercial vehicle market. Within these agencies, the Partnership engages the offices most involved with commercial vehicle activities: for the Department of Energy, the Office of Energy Efficiency (specifically the Vehicle Technologies Office) is involved; for the Department of Defense, the U.S. Army's National Automotive Center is the partner; for the Department of Transportation, the National Highway Traffic Safety Administration and the Federal Motor Carrier Safety Administration are involved; and for the Environmental Protection Agency, the Office of Transportation and Air Quality is the partner. Each of these agencies addresses a portion of the commercial transportation landscape relative to safety, efficiency, or emissions.

The federal laboratories have a supporting role in assisting both federal and industry partners in achieving the research objectives of the Partnership. As members of both industry and federal research activities, their expertise is used to support the work efforts throughout the research spectrum from basic to applied research.

The full Partnership conducts monthly business meetings (usually via teleconference) to discuss issues of broad relevance to all members and share information about available funding opportunities, industry news, and technical information. Materials for these monthly discussions are made available to all partners via collaborative web tools. Where appropriate, the Partnership will arrange for technical presentations on topics of interest as part of these regular meetings to provide additional perspective for partners.

In addition to regular business meetings, the Partnership conducts periodic site visits to inform the partners about capabilities and facilities within 21CTP and external to the Partnership. These site visits are conducted on an as-needed basis, and 21CTP averages one to three of these meetings per year. Past meetings have explored the capabilities of DOE national laboratories and industrial partners, to encourage the development of pre-competitive research partnerships among 21CTP members.

Partnership goals and objectives (as outlined in this roadmap and white paper document) are discussed regularly, and adjustments are made as needed to accommodate changing market conditions and research needs. New research directions are brought up for consideration and discussion within the group, and concepts are refined for incorporation into future research plans.

Partnership activities are reviewed frequently. The National Academy of Sciences conducts regular reviews of the Partnership through a formal committee process. This process involves a careful and thorough review of Partnership research directions, goals, and past accomplishments: review committee members are drawn from a wide range of backgrounds and research disciplines. Each review ends with the publication of an extensive report summarizing the committee's findings and recommendations on improving the Partnership.

I.7. Technical White Papers/Roadmap Details

The achievement of the technical goals outlined by the 21st Century Truck Partnership will certainly require the participation of a wide range of organizations within government and industry. Success within the Partnership to achieve safer, cleaner, and more efficient trucks and buses will be a team effort. To this end, the 21st Century Truck Partnership has created this roadmap with a series of six chapters to outline their collaborative research efforts. These chapters represent a cooperative effort by the 21st Century Truck Partnership industry working group members and their federal agency partners. They are designed to identify the key challenges facing the heavy-duty truck industry and outline key areas of research, development, and deployment that the Partnership will concentrate on in the coming years. The roadmap[4] provides guidance to policy makers on the direction and focus of this systems approach to RD&D programs. Below is a discussion of the general roles and responsibilities for achieving the goals of the Partnership.

I.7.1. Engine Systems

Within the Engine Systems area, the main industry partners will be the engine manufacturers (Caterpillar, Cummins, Detroit, Navistar, PACCAR, and Volvo/Mack Powertrain) and their suppliers, which will be working to achieve the efficiency and emissions goals of the Partnership. They will be assisted in this effort chiefly by the U.S. Department of Energy's Vehicle Technologies Office, through the work in combustion and emission controls, materials, and combustion modeling that is ongoing within that office. DOE is also working with industry on advanced fuel formulations for future vehicles to enable these more efficient and cleaner engines. The U.S. Department of Defense has an interest in this work to achieve its goals of more fuel efficient tactical and utility vehicles. The Environmental Protection Agency has played a role in this area through establishment of emission standards and through studies of the fuel efficiency and cost impacts associated with meeting the established standards.

I.7.2. Heavy-Duty Hybrids

In heavy-duty hybrid research, the industry role will be represented by the heavy-hybrid team members (chiefly Allison Transmission, Meritor Inc., BAE Systems, and Eaton Corporation, although Oshkosh Truck is also playing a role in hybrid research). The Department of Energy is pursuing hybrid research through the Vehicle Technologies Office. The DOE Fuel Cell Technologies Program is also interested in hybrid technologies as a bridge to the hydrogen fuel cell vehicle. The Department of Transportation (Federal Transit Administration) is playing a role in demonstration of these vehicles for the transit bus market. The Department of Defense will be working with heavy hybrid equipment suppliers to develop and demonstrate hybrid vehicles for military applications, and has already made significant investments in hybrid technology to reduce fuel consumption and improve their ability to travel silently in combat situations. The Environmental Protection Agency has participated in the heavy hybrid arena through its work on mechanical hybrids for certain applications.

---

[4] Achievement of the goals contained in this document is subject to a number of factors, including availability of funding to perform the research work. This document will be reviewed periodically by the Partnership to ensure that it reflects current goals and funding availability.

I.7.3. Vehicle Power Demands

The industry participation in vehicle power demands reduction research will be through the truck original equipment manufacturers (Daimler Trucks, Navistar, Mack Trucks, Oshkosh Truck, PACCAR, and Volvo Trucks North America), who will be working with their suppliers to develop the product and manufacturing technologies for aerodynamic drag reduction, accessory load reduction, and weight reduction. The truck manufacturers will be working with their suppliers on research to improve performance in these areas. The Department of Energy will be working with truck and engine manufacturers through the Vehicle Technologies Office on several projects, including aerodynamic drag research and electrification of engine accessories. The Department of Defense will also be working in this area to reduce fuel consumption of tactical and utility vehicles.

I.7.4. Idle Reduction

Interest in idle reduction among industry partners will be shared by both the engine manufacturers and the truck manufacturers. Engine manufacturers will work on engine subsystems to enable electrification of many truck accessories, while truck manufacturers will focus on integration of the idle reduction components into the truck. The Department of Transportation and the Environmental Protection Agency have been tasked in the National Energy Plan to lead federal efforts for idle reduction research to reduce emissions and fuel consumption from idling trucks. The DOT and EPA programs are focused on working with fleets and manufacturers to install and use these technologies. The Department of Energy is also participating in the idle reduction initiative through research in idle reduction technologies and truck accessory electrification. DOE is leveraging its resources through development of idle reduction technologies including fuel cell auxiliary power units (being created at the Fuel Cell Technologies Program at DOE). The Department of Defense is researching idle reduction technologies to ensure reliable power sources and silent operation when needed in combat situations.

I.7.5. Efficient Operations

Several fuel efficiency technologies and other approaches have the potential to significantly reduce fuel consumption in truck transportation, and joint involvement with the industry and federal agencies can have particular benefits in these areas. Truck manufacturers have a critical role to play in operational efficiency questions, as do DOE, DOT, and EPA.

I.7.6. Safety

The truck manufacturers are the main industry stakeholders in the safety arena, as they are responsible for producing the vehicles that keep their occupants safe, can operate safely on the highway, and meet the safety standards. The Department of Transportation, through the National Highway Traffic Safety Administration and the Federal Motor Carrier Administration, is the key player in achieving the safety goals outlined in the Partnership's vision. The DOT provides the leadership role by collecting, investigating, and interpreting accident data and fostering R&D that will reduce injuries and fatalities.

1. Engine Systems

Promote research for engine, combustion, exhaust aftertreatment, fuels, and advanced materials to achieve both significantly higher efficiency and emissions-compliance with cost effectiveness. Identify sustainable fuel alternatives for commercial vehicles along with technology and infrastructure requirements for implementation.

1.1. Introduction

The truck engine is central to all aspects of the 21CTP vision; reduced oil dependency, low air pollution, cost, and even safety. Although diesel engines used in most freight trucks are the most efficient transportation powerplants available today, only about 40% of the fuel energy is converted to mechanical work, resulting in about 60% loss of the energy input via the fuel. Substantial improvements in efficiency can yet be made in combustion engines, and including diesel engines they also can be powered by non-petroleum fuels from a number of feedstocks. The engine, together with the fuel characteristics and exhaust emission control devices, govern the level of exhaust emissions so critical for compliance, environmental impact, and public perception. The engine is critical to the safety of the heavy vehicle by providing braking power, as well as adequate power to blend with traffic. Already a key safety ingredient, importance of the engine brake will increase as aerodynamic and drivetrain enhancements reduce the parasitic drag in future vehicles. Finally the diesel engine is a continuously improving, state-of-the-art transportation technology, offering the lowest life cycle costs of the available technologies.

1.2. Technology Goals

A highly integrated approach involving fuel formulations, engine technology, combustion, emissions controls, and materials is essential in meeting the 21CTP vision for this strategic element. “Engine system” in the goals below refers to the combination of fuel, engine, and emissions aftertreatment equipment. Unlike the other major areas of the truck system, increasing the energy-efficiency of the engine system reduces fuel consumption by a corresponding amount. Specific technology goals are:

- Develop and demonstrate an emissions compliant engine system for Class 7-8 highway trucks that achieves 50% brake thermal efficiency in an over-the-road cruise condition, improving the engine system fuel efficiency by about 20% (from approximately 42% thermal efficiency today). (2015)
- Research and develop technologies which achieve a stretch thermal efficiency goal of 55% in prototype engine systems in the lab. (This efficiency gain would be equivalent to an additional 10% gain in over-the-road fuel economy when prototype concepts are fully developed for the market.) (2015)
- Through experiments and models with FACE fuels and other projects, determine the most essential fuel properties, including renewables, needed to achieve 55% engine brake efficiency. (2014)

1.3. State of Technology

1.3.1. Efficiency

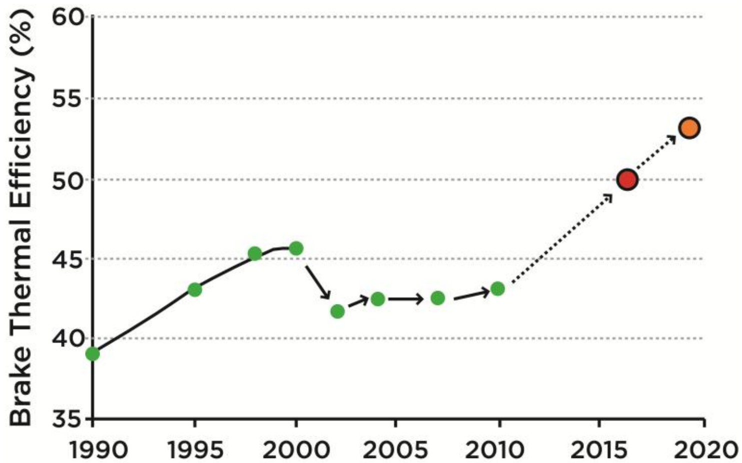

Figure 12. Trend in Highway Diesel Engine Efficiency Source: Cummins Inc.

Diesel engines derive their high efficiency by both utilizing high-efficiency thermodynamic cycles and minimizing mechanical losses. These engines achieve high efficiency via a high compression (expansion) ratio, high rates of combustion under overall lean conditions, and use of air-fuel ratio (instead of throttling) for load control, thus avoiding part-load pumping losses. Turbocharging increases engine power density and recovers some of the exhaust heat. Diesel engines operate at relatively low speeds, which reduce mechanical friction losses, and high power density is achieved primarily through high brake mean effective pressure (bmep). Other design features, such as strategic cooling, serve to minimize thermal energy losses and also augment overall powerplant power density. Due to its fuel economy, reliability and low life cycle cost, the diesel engine has continued to be the preferred power source for commercial vehicles, buses, and military vehicles in the United States and worldwide. The cost of emissions compliance for traditional diesel combustion has given rise to re-consideration of alternative powerplants such as heavy-duty spark-ignition engines in some technical venues, and gasoline engines have regained market share even in Class 6 trucks. High worldwide demand for diesel fuels has driven their price to well above gasoline in the United States, furthering this trend.

Modern highway truck diesel thermal efficiency peaks at about 42%, compared to 30-32% for production gasoline (spark-ignition) engines. This is approximately a 40% improvement relative to the late 1970's diesel engines. Thermal efficiency of 50% is expected to be obtained within the next few years in research designs and demonstrations. As shown in **Error! Reference source not found.** and Figure 13, efficiency gains have been reversed in recent years as criteria emissions have been reduced by an order of magnitude. The expected outcome of a well-supported government industry program is continued advancement in engine efficiency within emissions constraints. Most of the further advances in thermal efficiency will be achieved through continued improvements in

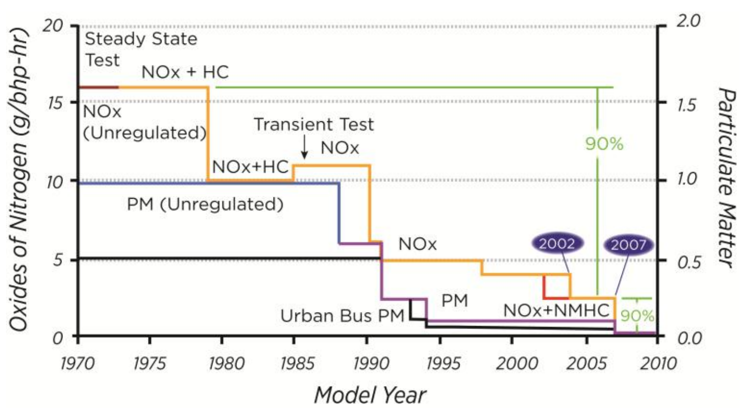

Figure 13. Historical Trend in Emissions from New Diesel Engines

combustion, air handling, other subsystems, and operating characteristics of engines similar in overall architecture to those in use today. In addition, an effective exhaust heat recovery system may be necessary for achieving 50% efficiency, yet must be balanced with the temperature requirements of exhaust emission control devices and must fit within increasingly aerodynamic vehicles without increasing losses for cooling requirements. The longer range potential of engine efficiency, targeting 55%, is supported by the overall technical approach described later in this section. Combustion strategies with highly optimized heat release rates, still at reduced temperatures for low NOx, have been recently demonstrated as having high efficiency potential in single cylinder experiments.

1.3.2. Exhaust Emissions

Over the past 20 years, diesel-engine manufacturers have achieved remarkable reductions in NOx (~90%) and PM (95%) emissions by modifying their engines. Through 2006 heavy-duty diesel engines were certified at 2.5 g/bhp-h of NOx+HC and 0.10 g/bhp-h of PM (<0.05 g/bhp-h for transit buses). In 2007 the regulations allowed a phase-in sales-averaged NOx at approximately 1.2 g/bhp-h and PM at 0.01 g/bhp-h. Until 2007, exhaust aftertreatment had not been required nor utilized to meet emissions standards for heavy-duty diesels, except for limited use of simple oxidation catalysts on buses and medium sized trucks. The 2007-2010 regulations were intended by EPA to be “aftertreatment-forcing.” Aftertreatment technologies for PM were necessary in 2007, and all new truck heavy duty diesel engines were equipped with diesel particle filters (DPF). Catalyst-based DPFs used with ultra-low-sulfur diesel fuel (<15 ppm) achieve PM reductions well in excess of 90%. In October 2006, ultra-low sulfur diesel fuel became mandatory for on-highway fuel, thus enabling DPFs and other types of exhaust aftertreatment. Indeed, when very-low-sulfur diesel fuel is used, the level of particulate emissions is almost undetectable. However, there are several shortcomings with the DPF technology, including initial cost, operating cost, fuel economy penalty due to backpressure, thermal management, and regeneration requirements. Further improvement can be addressed through further research in the areas of substrate materials, coating formulations and reaction modeling. Advancements in in-cylinder emission control allowed most manufacturers to avoid the need for NOx aftertreatment for 2007 engines.

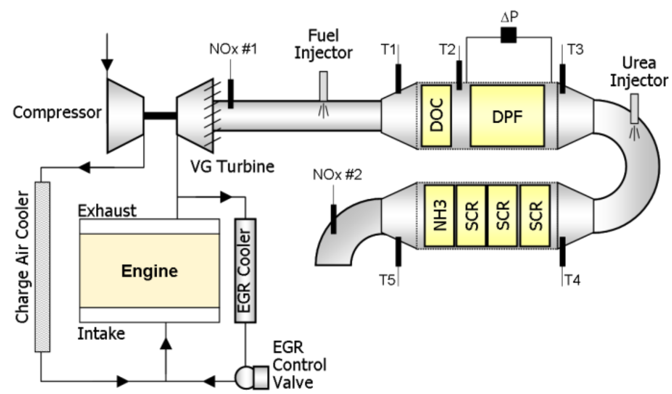

Figure 14. Typical 2010 Compliant Emission Control System

For 2010, NOx emissions had to be lowered another 83% to 0.20 g/hp-h NOx+HC, along with 0.01 g/hp-h PM. These have been met by most engine OEMs by a combination of cooled EGR and SCR for NOx control and an actively regenerated DPF for particulate control. Achieving engine emissions requires significant in-cylinder control, high performing aftertreatment for NOx and PM systems, and engine thermal management which includes a degree of control over exhaust mass flow rate, exhaust temperature and exhaust oxygen. Thermal management is an essential element in the integration of engine and aftertreatment, and allows both the DPF and the SCR to operate at peak efficiency over a wide range of duty-cycles. The typical system architecture chosen to meet U.S. EPA 2010 emissions is shown in Figure 14.

Substantial effort across industry went in to the design of the systems for storing and metering urea on the vehicle. Considerations of freeze protection, contamination, anti-tampering, labeling and stability had to be accounted for. In addition, the infrastructure for distributing and dispensing urea at refueling outlets had to be developed. The industry adopted the name of "Diesel Exhaust Fluid" (DEF) for the aqueous urea solution. It was found that there is an optimum balance between in-cylinder control of NOx and PM and aftertreatment control of NOx and PM. The primary parameter determining this optimum balance is the operating cost – driven by both fuel consumption and DEF consumption. The optimum engine-out NOx level depends on the relative price of DEF and diesel fuel. Research to improve urea SCR systems is still warranted, such as to increase the low-temperature effectiveness and mitigate poisoning from hydrocarbons. The successful emission control systems for 2010 have in some cases doubled the cost of an emission-compliant engine, representing another target for further development.

Other key enabling subsystem technologies included high pressure common rail fuel systems (with high pressure capabilities exceeding 2400 bar) and variable geometry turbochargers. The turbomachinery serves several purposes in engine performance and emissions control, including air flow for torque and performance, EGR delivery /control, enhanced engine braking and exhaust thermal management. On-board diagnostics (OBD) were also fully implemented for heavy duty 2010 engines. Engine controls deserve special mention here. Historically, controls requirements for diesel engines have lagged the SI passenger car. For the truck diesel engine, controls were primarily limited to one or two degrees of freedom (e.g., fuel injection delivery and timing) prior to 2004. The beachhead for future controls requirements in the heavy duty diesel engine environment was realized with the introduction of EGR and the ongoing implementation of more sophisticated multi-pulse fuel injection systems and strategies. With the introduction of single and multi-stage exhaust aftertreatment systems in 2007 and 2010, continuing progress of multi-mode combustion toward production feasibility, coupled with legislated or customer-demanded expansion of on-board sensing and diagnostic features, the required capability of heavy-duty control system hardware and software will continue to increase. Advanced control system technologies must be developed and implemented to address these massively complex control system integration and calibration challenges.

At present there is no expectation that new regulations will be promulgated to further reduce criteria emissions from new engines beyond the 2010 levels. Regulations for PM on a particle number basis have been introduced for vehicles and engines in Europe, and California has studies underway on this matter. The EPA and DOT/NHTSA have introduced standards for fuel efficiency and GHG emissions from medium and heavy duty vehicles.

1.3.3. Fuels and Lubricants

Fuels are pivotal in attaining the vision of the 21CTP in two aspects: first, fuel formulation plays a critical role in reaching efficiency and emissions goals, and second, non-petroleum fuels are a direct route to breaking the nation's dependence on oil imports, with biofuels offering the potential for reducing CO_2. In December 2000, regulations were finalized that required much lower sulfur content in diesel fuel (a maximum of 15 ppm) to be available in 2006. Ultra-low sulfur diesel (ULSD), as it is generally called now, was deemed necessary to enable the use of a broader range of effective catalytic NOx aftertreatment devices as well as aiding PM control. ULSD was introduced on schedule with few issues. In addition, other fuel components have been shown to impact engine-out emissions, and oxygen-containing fuels and additives, for example, have been found to reduce PM emissions. However, the understanding of fuel property effects on emissions is highly empirical. Similarly, understanding the relation between fuel properties and low-temperature combustion modes is far from well-understood, although considerable data have been developed in last few years. Modified fuel specifications and new fuel formulation may hold the key to expanding the operating range of new combustion regimes like homogeneous charge compression ignition (HCCI).

Non-petroleum diesel fuels can be produced from renewable resources such as seed oils and animal fat, as well as synthesized from natural gas, oil sands, coal, etc. The production of diesel fuel from these sources is being expanded, and the production of biodiesel is growing, as is the use of oil sands syncrudes from Canada. Much progress has been made in the uniformity of biodiesel properties with new ASTM specifications. Fischer-Tropsch (F-T) diesel fuels, synthesized from natural gas, have been studied in numerous engine tests to determine their impact on emissions. Reduced PM is the primary effect.

In addition to fuel effects, lubricant properties can have a profound effect on emissions by impacting the durability of exhaust aftertreatment devices. The sulfur and "ash" content of lubricants are sufficiently high to be factors in the degradation of performance of NOx adsorber catalysts and to influence the cleaning intervals and regeneration phenomena in DPFs, for example. Research on the fuel savings potential of low-friction lubricants and lubrication systems continues.

1.3.4. Materials

Current heavy duty diesel engines are extremely durable, in most cases performing reliably for more than a million miles. However modern diesel engines have pushed the performance of materials to the limit. As the 21CT partners develop the next generation of clean and efficient engines, new higher-performance and cost-effective materials will be needed, as well as manufacturing and inspection methods and appropriate standards. An example of this need for materials is that the efficiency of the diesel engine is enhanced with the ability to run the engine at higher peak cylinder pressures. Higher cylinder pressures and temperatures will challenge the current mechanical property limitations of many engine components, so new materials will be needed to achieve the engines' efficiency potential. A second example is in the potential to increase fuel economy through the use of fuel injection systems with higher injection pressure, finer spray control, and multiple injection events. To utilize these new fuel injection systems, new materials with higher strength, dimensional stability, and erosion resistance are needed for system components. Lowering the rotating mass in air handling systems has the potential to improve engine response, thermal efficiency, and lower emissions. To capitalize on these potential performance improvements, cost-effective lightweight materials with superior mechanical properties are needed for air handling components. Exhaust aftertreatment systems need compact, lightweight, low back-pressure materials with improved catalytic performance, resistance to poisoning, and reduced PGM loading to reduce cost.

1.4. Research Progress in the 21st Century Truck Partnership

As described in the previous section, compliance with the 2010 Federal emissions standards is perhaps the strongest example of progress by diesel engine manufacturers since the previous 21CTP Roadmap release in 2006. In most cases this has been accomplished with minimal penalty in fuel consumption.

DOE and heavy duty engine industry have been working in public- private partnerships to develop and demonstrate advanced diesel engine technologies and concepts that improve engine thermal efficiency while meeting U.S. EPA 2010 emissions. These projects include; high efficiency clean combustion, waste heat recovery and the "NZ50" (Near-Zero Emissions, 50% efficiency) project.

- High Efficiency Clean Combustion (HECC) – A key objective of the program has been to design and develop advanced engine architectures which improve brake thermal efficiency by 10 % compared to 2006 products. The essence of the work was the development of clean combustion in the form of low temperature, highly premixed combustion and combined with lifted flame diffusion controlled combustion. Engine technologies have demonstrated the above engine efficiency improvement targets using no NOx after treatment, but have not yet been able to develop control systems that will support operation under all operating conditions. When integrating HECC developed technologies with SCR NOx aftertreatment system, further engine efficiency enhancements were demonstrated.
- Waste Heat Recovery (WHR) - The objective of this program was to improve fuel economy improvements by capturing and converting wasted heat energy to useful work. An Organic Rankine Cycle (ORC) captures heat from engine exhaust gas recirculation (EGR), charge air and exhaust streams. WHR systems were designed and developed such that an ORC turbine-expander could be coupled to the engine either mechanically or electrically through a high-speed generator. Fuel economy benefits greater than 7.4 percent were demonstrated when coupled with EPA 2010 engine system under ideal conditions.
- NZ50: The heavy-duty diesel engine has seen a wave of new technology added to help reduce engine out emissions and/or improve engine fuel efficiency. Many of these features that are currently on production engines trace their roots back to public-private partnership with DOE programs: methodologies for understanding and controlling the physical and chemical processes that occur in the diesel particulate filter (DPF) during soot loading and regeneration have been developed. This understanding has influenced all levels of development, from early simulation modeling to understanding how the soot is loaded to the physics of passive and active regeneration.

1.4.1. SuperTruck Project Awards

DOE announced several SuperTruck project awards to demonstrate engine and truck efficiency enhancements for Class 8 vehicles in real world conditions. The aim of these developments is to foster quicker introduction of new technologies into the marketplace, thereby achieving energy savings in later part of next decade. Key technology demonstrations under these initiatives include: increasing Class 8 engine efficiency by 20 percent, from 42% to 50 % brake thermal efficiency; 50 percent increase in truck freight efficiency (ton-miles/gallon) including the higher efficiency engine; and developing engine technology pathways to 55 percent efficiency in a laboratory system.

Research on advanced combustion strategies, including those employing advanced diesel fuel injection approaches (e.g., high-pressure and multi-pulse injection) and Low-Temperature Combustion (LTC) strategies (e.g. homogeneous charge compression ignition (HCCI) and diesel LTC approaches) continue to be conducted under the Advanced Engine Combustion Memorandum of Understanding (AEC MOU) between industry and national labs. This MOU was initiated in 2003. In addition, research coordinated with and complementary to the MOU continues to be conducted in two university consortia involving the major universities in the United States in the engine combustion field. The research on advanced engine combustion strategies offers the potential for enabling dramatic reductions of NOx and PM emissions, as well as higher-efficiency engine operation as indicated in the lab by recent research. The partners involved in the AEC MOU include ten engine producers (Caterpillar, Cummins, Detroit, International, John Deere, Mack/Volvo, General Electric, General Motors, Ford, and Chrysler), five energy companies (Chevron, ConocoPhillips, Shell, ExxonMobil and BP), and six national laboratories (Argonne National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratories, and the National Renewable Energy Laboratory). The energy companies joined the AEC MOU in late 2006, and brought a research focus on fuel effects on advanced combustion strategies. The MOU was recently unanimously renewed by the partners through 2013.

The fundamental combustion and emissions research-to-date under the AEC MOU has led to significant advances in the understanding of various strategies for achieving LTC. Critical aspects of how HCCI and diesel LTC combustion progress, how their heat release rate and combustion phasing can be controlled, the sources of HC and CO emissions when the LTC approaches are pushed to the limits of operation, and fuel effects on LTC are being unraveled. HCCI strategies applied in the laboratory environment using conventional gasoline have achieved light-load operation down to engine idle conditions, loads as high as 16 bar BMEP (limited by the laboratory engine head design), peak indicated efficiencies in a light truck size engine of 48% indicated, all with less than 2010-type emission levels and controlled heat release. Higher efficiencies in heavy-duty truck engines have also been shown in the laboratory. Recent laboratory research in heavy-duty engines with dual-fueled (gasoline and diesel fueled) HCCI/LTC approaches are indicating potential for thermal efficiencies above 50% in a single cylinder engine, controlled heat release rates, and 2010 emissions levels. Implementation of diesel LTC approaches has also begun in heavy-duty diesels for a portion of the fuel burned during almost any engine cycle and over moderate to light-load parts of the engine operating range, providing significant engine-out emissions reduction. In general, higher injection pressure, multi-pulse injection, and EGR use have allowed a greater fraction of the reactive mixtures during diesel combustion to push toward LTC conditions, contributing to the lower engine-out emissions that have been achieved. The improved fundamental understanding has also advanced computational tools for engine design. Most engine designers are increasingly and aggressively using computational tools developed through DOE/VT supported experimental research and engine CFD development efforts. Growing use of computational tools for engine design is exemplified by Cummins' introduction of the ISB 6.7 liter light-truck diesel in 2007. This diesel engine was computationally designed with much reduced testing to confirm performance. The design process led to reduced design time and a more robust design with improved fuel economy meeting 2007 emissions standards. The future introduction of more robust computational design tools able to simulated the full range of engine combustion approaches (conventional mixing-controlled diesel combustion, premixed and stratified flame propagation, and LTC bulk ignition and combustion processes has very strong potential to lead to even faster evolution and improvement of cost effective engine designs.

Diesel engine manufacturers have continued their participation with DOE laboratories, catalyst suppliers, and universities in an aggressive effort to improve computational simulations and scientific understanding of diesel emission control systems (largely catalytic devices) to aid in improving engine system efficiency while meeting 2007-2010 regulations. Known as CLEERS (Cross-cut Lean Exhaust Emission Reduction

Simulations), this collaborative forum has fostered numerous contributions to NOx and PM control technologies and guides much of DOE-sponsored research in this field. A few examples of progress for 2007-2010 include:

- LNT models founded in CLEERS have been restructured to a lower order to run in PSAT vehicle simulations to allow study of impacts on fuel consumption
- An improved understanding and modeling of ammonia chemistry in LNTs has been developed
- Through application of DRIFTS spectroscopy, a better understanding of HC poisoning on SCR catalysts was gained
- Showed that dopants such as calcium could improve the sulfur tolerance and desulfation of LNT materials
- Developed a transient protocol for characterizing SCR catalysts in laboratory reactors

A new collaborative study on EGR cooler deposits and corrosion has emerged from the Diesel Crosscut Team. Utilizing primarily the engine and materials laboratories at ORNL, the properties of the fouling layers and process of fouling and corrosion are being determined. Ten industry firms are participating, and eight companies have provided field-aged coolers for characterization that included neutron imaging as well as electron microscopy.

The DOE's Heavy Vehicle Propulsion Materials Team has also been instrumental in developing commercial materials solutions being introduced in 2007 engines. A number of these materials, such as CF8C stainless steel which is already in commercial use, have been identified as enablers of still higher efficiency engines.

The DOE-industry project on fuels for advanced combustion engines (FACE) continued under a working group of the Coordinating Research Council (CRC). This effort seeks to provide a greater understanding of fuel property effects on various LTC modes starting with design of a standard set of research fuels. A set of nine research fuels in the diesel range were designed, produced, and characterized through standard ASTM methods as well as some of the latest analytical chemistry approaches such as two-dimensional gas chromatography. The nine fuels have been studied in at least four different engine platforms and data analysis are in progress. With a variety of approaches used in these engines to sustain LTC modes, the nine fuels exhibited distinct effects on operating ranges and emissions, especially PM.

DOE and NREL had a significant role in developing ASTM standards for biodiesel fuels. Fuel quality surveys have shown continued improvement in biodiesel fuel adherence to specifications.

1.5. Major Barriers

The technical barriers presented here, though described in three categories for simplification, are recognized as being highly interdependent and thus will be approached accordingly.

1.5.1. Barriers to Achieving Efficiency Goals

In general, it is recognized that customer demand for very high reliability, cost effectiveness, and proven durability is a major impediment to complex new systems to improve efficiency. More specifically and technically, barriers to improving diesel engine efficiency fall into the following categories:

- Efficiency is typically reduced by measures to reduce NOx emissions either in-cylinder or by aftertreatment, though the tradeoffs have been much improved through combustion developments and the deployment of urea SCR.
- Lack of an advanced component supplier base. Needed are suppliers of high efficiency boosting machinery, effective/efficient EGR cooling devices, faster response and reliable actuators and control valves, etc.
- Inadequate combustion understanding and robust simulation capability, especially across the full range of combustion approaches from conventional diesel combustion, to premixed and stratified flame propagation, to new combustion regimes such as HCCI, LTC.
- Poor cost-effectiveness of known exhaust-heat-utilization systems.
- Cost of advanced materials and their processing.
- Aftertreatment system energy penalties that reduce the overall engine/aftertreatment system energy efficiency, though not as great as once anticipated.
- Material needed for advanced technologies - higher peak temperature capability and strength at which critical engine components can operate.
- Limitations of coolants.
- Tribological limits of current materials and lubricants.
- Lack of cost-effective controller management and calibration techniques.
- Inadequate durable and accurate sensors.
- Limitations of current air-handling components and systems.
- Lack of full electronic management (i.e., smart motors in place of belts and gears to drive accessories, flywheel starter motor/generator, etc.).
- Lack of investment in improving the traditional reciprocator platform.
- Lack of investment and development of innovative engine processes and architectures that substantially improve the conversion of fuel chemical potential to useful work, such as via recuperation, extreme expansions, friction control, and thermal management.
- Cost, weight, package space, and cooling requirements that may offset engine benefits.

1.5.2. Barriers to Achieving Cost Effective, Durable, Emission Control (Enabling Maximum Fuel Efficiency)

Now that improved combustion systems and new aftertreatment systems have been introduced that allow 2010 emissions to be met, R&D will emphasize optimizing the fuel consumption of engine-aftertreatment systems and striving to greatly improve the overall cost effectiveness. Current aftertreatment systems introduced have as much as doubled the cost of an emission compliant engine/aftertreatment system and LNT systems and have introduced fuel economy penalties. Additionally, regulatory requirements for on-board diagnostics are challenging and need further development.

The following are the key barriers to achieving the technical targets for compliant emission control enabling maximum fuel efficiency from heavy duty diesel engines. Components technologies (e.g., fuel system, air handling, etc.) are necessary for achieving efficiency goals and are included below for completeness. Common to each is a lack of adequate simulation capabilities and readily implemented sensing and process control systems. Improved simulation capabilities are needed both to optimize the combustion and aftertreatment systems so to transform a 'statically' integrated system into an optimized overall engine/aftertreatment package that results in maximum efficiency and performance and minimum emissions. In turn, a mature and robust sensing and control system will monitor and navigate these multiple systems over the complex 'dynamics' of normal over-the-road vehicle operation, while yielding the best vehicle fuel economy, performance, and emissions.

- NOx/PM/efficiency trade-off during combustion—that is, maintaining efficiency and low NOx while keeping PM down:
  - Limitations of air-handling system;
  - Limitations of fuel-injection technology;
  - Incomplete optimization of cooled EGR and resolution of durability concerns;
  - Incomplete development of low-temperature combustion technologies, such as HCCI, resulting in limited range of operation;
  - Incomplete understanding of in-cylinder combustion and emission formation processes and inadequate simulation capabilities;
  - Limited effectiveness of cost-effective fuel additives and reformulation; and
  - Inadequate means to sense and control combustion timing.
- Aftertreatment system limitations
  - Degradation from sulfur in fuels (even at 15 ppm) and lubricants and long term durability;
  - Effectiveness over a wide enough engine load range (i.e., temperature range) and during transients;
  - Incomplete development of OBD methods and systems
  - Inadequate sensors for process control or diagnostics;
  - Inefficient management of engine exhaust temperatures for optimum catalyst efficiencies
  - Incomplete understanding and optimization of catalysts;
  - Fuel economy penalties;
  - Inefficient engine management for regeneration and desulfation of NOx traps
  - Regeneration of DPFs subjected to extended low-temperature operation;
  - Possible generation of unregulated toxic emissions;
  - Deficiencies in the fundamental understanding and modeling capabilities needed for designing effective catalysts and catalyst-based aftertreatment systems through means other than trial-and-error;
  - Back pressure from aftertreatment and the negative impact on engine efficiency; and
  - Packaging constraints on the vehicle, including need to preserve efficient aerodynamic features.
- Immature simulation and control systems integration, as well as static and dynamic optimization of multiple emission reduction systems.
  - Integration of new combustion regimes and aftertreatment at early stages
  - Complying with the CO and HC emission regulations will primarily be challenging when LTC modes of combustion, such as HCCI, are employed for NOx and PM control.
  - Close attention also will be applied to ensure that alternative combustion regimes and aftertreatment systems do not increase "toxic" unregulated emissions.
  - Limited simulation capability for these types of systems.

1.5.3. Barriers to Broader Use of Non-Petroleum Fuels

Barriers to wider use of renewable fuels such as biodiesel and next generation biofuels are their higher cost, different physical and chemical properties, and lesser known combustion and emission formation characteristics. When used in low-level blends, compatibility of these fuels with existing engine materials and systems has mostly been determined to be satisfactory. Uncertainties remain regarding the optimization of the engine combustion and aftertreatment systems for each fuel type. Moreover, the barriers to higher diesel engine efficiency generally apply equally to conventional diesel fuel and to most potential liquid alternative fuels. Synthetic fuels such as Fischer-Tropsch liquids and renewable (hydrogenated) diesel provide well-controlled paraffinic chemistry, but at high cost and with limited supply. Natural gas is being discovered and extracted in abundant quantities and may become an interim alternative to renewable fuels.

- Need continuing improvement of fuel quality and compatibility (lubricity for example) with engine systems (especially biodiesel blends)
- Need better understanding of composition range of non-petroleum fuels and impacts on advanced combustion regimes
- Need understanding of fuel property effects on NOx and particle emission characteristics and implications on DPF operation
- Need cost effectiveness in fuels, including impacts of energy density
- Need fuel type and quality sensors

1.6. Approach to Reaching Goals

The 21st Century Truck Partnership presents an opportunity to address key barriers to clean, higher-efficiency diesel engines. A highly integrated approach involving fuel formulations, engine technology, combustion, emissions controls, and materials is essential in meeting the 21CTP vision in this strategic element. Comprehensive R&D programs involving fundamental-to-applied research in National Laboratories and Universities, coupled to broad development and commercialization efforts in industry have been effective in progress thus far. Continuation of this overall collaborative approach is expected.

1.6.1. Efficiency

Approaches to improve engine efficiency are effectively guided by understanding the losses of energy and exergy. The combustion process, mechanical friction, heat transfer, air handling, parasitics, and exhaust losses are all key elements of a technical strategy to improve efficiency. Parasitic losses of water and oil pumps, alternators, compressors, etc. are highly significant and are addressed as a separate topic of the 21CTP vision.

Major elements of the technical strategy include the following:

- Define baseline engine designs in sufficient detail to delineate the areas of required technology advancement. This would be a guide for enabling technology projects. Conduct, on a continuing basis, analysis and supporting validation tests to assess progress toward goals.

- Optimize mechanical design and combustion system for increased expansion ratio and thermodynamic efficiency with considerations of emissions targets.
- Develop and integrate cost-effective exhaust energy recovery technologies into the engine system.
- Improve the fundamental understanding of diesel combustion/emissions formation processes and exhaust aftertreatment systems and the predictive simulation capabilities for these processes and systems needed to more effectively optimize performance.
- Develop and exploit advanced fuel injection and engine control strategies and new low-temperature combustion regimes for their potential efficiency gains, with modeling and simulation as an integral component of the system design strategy.
- Improve turbocharger and/or air-handling systems and controls, and trade-offs between efficiency and transient response. Develop new low-inertia materials and response-enhancing technologies. Emphasis on turbine and compressor efficiency, increased pressure ratio, and turbocharger map width.
- Continue refinement of piston/cylinder designs, valve trains and other mechanical components for reduced friction losses.
- Develop and apply reliable, low-cost methods for fully variable valve timing to enhance low temperature combustion, aftertreatment, air handling, and compression braking. Develop optimum control strategies.
- Develop accurate and robust sensors for control systems, such for NOx and start of combustion.
- Pursue reduction in parasitic losses of water and oil pumps, alternators, and compressors.
- Perform materials R&D in support of engine efficiency. Several pathways to more efficient engines rely heavily on the development and application of advanced materials.
    - *Valve train.* Materials with greater wear resistance
    - *Major Engine Components*. Cost-effective materials with higher strength and fatigue resistance for engine blocks and cylinder heads to enable higher peak cylinder pressures: e.g., higher-quality cast iron or high-strength materials to reinforce highly stressed areas in conventional cast iron. Improve the tribological characteristics of materials in piston- ring-liner systems, bearings and bushings, and gear systems. Materials and coatings for thermal management which can provide lower heat transfer to coolant and higher exhaust temperatures for after treatment or energy recovery.
    - *Air Handling*. Deposition and corrosion-resistant materials for EGR system components. Higher strength materials for turbocharger components, including lower mass for the rotating parts and greater strength for housings. Reduced bearing friction can enhance efficiency.
    - *Improved exhaust manifold materials and sealing methods to handle increased exhaust pressure and heavier turbochargers*
- Heat exchanger development for extraction of exhaust and EGR energy with minimum back-pressure.
- Exploration of alternative engine architectures (advanced two-stroke, Atkinson, etc.)

1.6.2. Emissions

Even with technologies now commercialized that meet NOx, PM, and HC standards, the intersection between these criteria emissions and engine efficiency remains critical, since efficiency will govern the ability to meet GHG goals. Concurrent efforts at the system, component, and scientific foundation levels need to proceed in each of these areas.

Simultaneous attainment of future emission-reduction and thermal-efficiency targets requires unprecedented attention to the integration of multiple, new system technologies. At the historical and most fundamental level, systems optimization and component performance was/is accelerated through the application of computer simulations. High order “off-line” calculations are emphasized and crucial to understanding and defining the basic engine configuration and its performance and emission signature. However, with the number of prerequisite systems and many additional orders of complexity relative to the historical engine, new techniques are required to enable implementation of a coherent multi-system integration. Simulation and control techniques are active companions in the diesel engine development and operational process. However, advancement of computational simulation capabilities for all systems is a high priority need. Major elements of the technical strategy to meet emissions targets additionally include:

- High efficiency SCR to minimize compromises associated with in-cylinder NOx control.
- Further develop flexible fuel-injection systems and engine control strategies and new combustion regimes for their emissions reduction potential, with modeling and simulation integrated with engine controls development.
- Optimize cooled EGR for maximum NOx reduction and minimum PM emission mitigating durability concerns with EGR through materials engineering and operational controls. Focus on EGR cooler efficiency, package size, reliability, durability, and fouling, enabling cooler intake manifold temperatures and greater efficiency.
- Improve the fundamental understanding of diesel combustion/emissions formation processes and exhaust aftertreatment systems and the predictive simulation capabilities for these processes and systems needed to minimize emissions.
- Resolve remaining issues for DPF regeneration, ash loading and removal, and aging.
- Develop strategies for mitigating sulfur effects on aftertreatment, including catalyst tolerance, regeneration, and further reducing sulfur sources (lubricants).
- Improve the scientific foundation of NOx adsorber-catalyst performance and degradation mechanisms. Improve the catalyst materials and systems for lean NOx catalysis with urea and alternative reductants for performance over wider temperature range while minimizing ammonia slip.
- Develop improved technologies and procedures for urea supply for SCR systems.
- Develop and apply reliable, low-cost methods for fully variable valve timing to enhance low temperature combustion, aftertreatment, air handling, and compression braking. Develop optimum control strategies. Same is in engine efficiency section
- Develop monitors and thresholds for sensors in controls and diagnostics in conjunction with OBD. Develop and use fundamental knowledge of catalysts and sensors for OBD methods.
- In the development of emissions control devices, include features necessary to make the devices suitable for retrofit on existing trucks.
- Materials R&D in support of emission reduction.
  - *Fuel Injection*. Low mass, low wear, fast acting injector actuator and valving systems to coincide with the emerging emission control techniques. This includes new materials and processes for cams, roller or sliding followers, and axles (for rollers) to allow increased

injection pressure and rate shaping, valve timing control, and compression braking optimization within packaging constraints.

- *Exhaust Aftertreatment.* Catalysts and filters with stable microstructures that can operate at high efficiency over a wide range of exhaust conditions with lowest back pressure and space requirements and at least one million mile durability.
- *Sensors*. Robust sensor materials that survive the severity of the diesel engine environment. Direct sensing of the emission constituents of interest (e.g. NOx) is a challenging, yet valid technological objective. A minimum predictable life expectation of one million miles is a prerequisite.
- *Lubricant control*. New materials and surface treatments for valve stem–valve guide seals and at the ring-liner interface to control lubricant entry to the combustion chamber and thus control PM emissions.

1.6.3. Fuels as Enablers

The introduction of ultra-low sulfur diesel fuel in 2006 is one of the more conspicuous examples of how fuel properties can enable certain engine technologies, in that case clean diesel engines. DOE had a significant role there in generating data for the EPA rule. For the last few years, resources have been more devoted to understanding how fuel properties may enable greater utilization of high-efficiency clean combustion modes. There are still issues of fuel property impacts on emission controls that deserve attention. In R&D dealing with a wider range of fuels properties, fuel companies should remain involved and the total "well-to-wheels" system should be considered.

- Develop fundamental understanding of fuel effects on in-cylinder combustion and emissions formation processes in advanced combustion regimes through experimental and modeling approaches
- Develop predictive tools that relate molecular structure to ignition behavior and heat release for fuels used in advanced combustion engines
- Evaluate new fuels and fuel blends for efficiency, emissions, and operating stability with advanced combustion regimes
- Evaluate the potential of reforming small amounts of fuel to generate additives that can be used to achieve fast control in low temperature combustion (LTC) modes
- Evaluate the performance of traditional lubricant formulations in engines using advanced combustion regimes and identify any performance deficiencies
- Determine effects of fuel composition, including non-petroleum fuels, on degradation of EGR system performance.

1.6.4. Non-Petroleum Fuels

The strategy and approach to expand the use of non-petroleum fuels is a complex situation requiring incentives for suppliers and consumers to realistically make a dent in petroleum imports. Policy-making and economic incentives may be beyond the scope of 21CTP. However, the partnership can take steps to ensure that technology is at least compatible and preferably enhanced by non-petroleum fuels. For example, the impacts of biodiesel on DPF regeneration processes have been clarified, and this fuel's impacts on EGR cooler fouling has been documented.

- Study combustion and emissions-formation processes of non-petroleum based fuels and blending components using experimental and modeling approaches
- Identify renewable and synthetic fuel blending components that provide enhanced efficiency, performance, and emissions characteristics
- Quantify the potential for improving engine and/or vehicle fuel economy through the use of renewable biolubricants
- Identify fuel properties other than sulfur that are critical to improving the efficiency, performance, and emissions of diesel engine and aftertreatment systems
- Perform RD&D to support appropriate codes and standards to increase the availability of petroleum displacement fuels
- Develop collaborations with biofuel R&D initiatives and programs to enable synergistic co-development of fuels (properties) and engines
- Develop high efficiency methane engines and systems while minimizing methane release in operation, storage, and handling.

1.6.5. Summary of Approach

An integrated systems approach involving engine design, fuels, and aftertreatment technologies is required for the 21CTP vision in fuel efficiency and emissions. R&D in combustion, materials, fuels, and aftertreatment devices provide the foundation for technology advancement, including simulations (virtual labs) in concert with controls development and experimentation. Industry, universities, and National Laboratories working within the context of a multiagency partnership are among keys to success.

Table 1. Schedule of Major Activities and Milestones

	10	11	12	13	14	15	16	17	18
Engine Efficiency*									
1. Demonstrate a 50% brake efficiency engine in truck at cruise condition	○					◆			
2. Laboratory demonstration of 55% peak efficiency engine	○					◇			
Emission Control Technology*									
1. Improve performance, durability and cost effectiveness of NOx and PM control technology through improved EGR and aftertreatment systems				◇					
Fuels*									
1. Through experiments and models with FACE fuels and other projects, determine the most essential fuel properties, including renewables, needed to achieve 55% engine brake efficiency.					◇				

○ Begin activity ◆ Major milestone ◇ Key intermediate milestone

*Although efficiency, emissions, and fuels are charted as separate activities, the R&D program is highly integrated

2. Advanced Heavy-Duty Hybrid Propulsion Systems

Promote research focused on advanced heavy-duty hybrid propulsion systems that will reduce energy consumption and pollutant emissions.

2.1. Executive Summary

The 21st Century Truck Partnership has established challenging goals for improving fuel economy and pollutant emissions from heavy-duty vehicles. In the context of 21CTP, "heavy-duty" (HD) vehicles are often defined as Class 2b through Class 8. This definition includes a diverse set of vehicles ranging from approximately 8,500 pounds GVW to 100,000+ pounds GVW. In addition, this set of vehicles consumes over 30% of the nation's total fuel consumed in motor vehicles.

Hybrid electric vehicle (HEV) technology is a key enabler that will help 21CTP achieve its goals. It allows truck and bus manufacturers to simultaneously improve fuel economy, emissions, and performance. In addition, HEV technology could provide a technological and commercial bridge from today's conventional powertrains to future fuel cell powertrains. No other technology can support such aggressive claims. The National Research Council in its first review of 21CTP recommended that it was "appropriate to continue funding and conduct sufficient research and development to demonstrate prototypical success in heavy-duty applications, or identify areas for continued research (Recommendation 4-2)."

For the purposes of this chapter, an HD HEV is one that features both an internal combustion engine (typically diesel) and a rechargeable energy storage system (typically batteries and/or ultracapacitors) and can absorb or deliver torque from the drivetrain using electric motor/generator(s). HEV systems have received a great deal of coverage in consumer and technical publications. Despite the emerging presence of hybrid electric technology in the passenger car industry, heavy-hybrid technology for commercial trucks and buses needs significant research and development (R&D) before it will be ready for widespread commercialization at prices that can be borne by the vehicles' operators.

Hydraulic hybrid technology is also of interest to 21CTP for commercial truck applications. Hydraulic hybrid technology uses hydraulic pumps and motors with low-pressure and high-pressure reservoirs to absorb and deliver torque from the drivetrain. This technology also needs R&D investment to be commercialized at prices appropriate for vehicle operators.

This chapter seeks to highlight the benefits of these technologies for heavy-hybrid vehicles. It also describes key research priorities where industry and government need collaborative investments.

The top priority HEV R&D areas that require government funding to meet 21CTP's goals include:

- Drive unit optimization;
- Drive unit cost;
- Energy storage system reliability;
- Energy storage system cost;

- Ability to attain fuel economy improvements (compared to today's conventional, non-hybridized heavy-duty vehicles) in a commercially viable manner.

2.2. Strategic Approach

The 21st Century Truck Partnership focuses on research and development of advanced heavy duty (HD) hybrid propulsion systems that will reduce energy consumption and pollutant emissions, and increase the nation's energy security. The strategic approach for this effort is to:

- Develop hybrid propulsion systems for HD vehicles, including trucks and buses. The specific vehicles defined as HD under 21CTP are Class 2b–Class 8 (vehicles >8,500 pounds gross vehicle weight [GVW]).
- Overcome the technical barriers that inhibit the technologies. Establish common objectives where federal assistance can be used to accelerate the introduction of HD hybrid technologies.
- Educate interested parties on the importance of HD hybrid systems and the differences between HD hybrids and hybrid systems for cars, light-duty trucks, and sport utility vehicles (SUVs).
- Stimulate market demand for HD hybrid products and describe how governments at all levels can help overcome the barriers to widespread deployment of these technologies.
- Establish confidence in HD hybrid technologies by providing unbiased testing and evaluation of HD hybrid vehicles and improve industry's ability to simulate and model such vehicles by validating models with actual test data.

2.3. Introduction and Background

The strategic approach to promote research on advanced HD hybrid propulsion systems is included as a major focus area for 21CTP because:

- It is a key technology that enables truck and bus emissions, performance, and fuel efficiency goals to be met simultaneously (without sacrificing one for the other).
- Hybrid electric technology is well aligned with the DOE light-duty program and DOE's long-range technology roadmap for passenger cars and heavy vehicles.
- Hybrid electric architecture is an integral part of the technology roadmap for fuel cell-powered, plug-in hybrid and all-electric trucks and buses.
- HD hybrid propulsion systems are key to Japan's strategic technology roadmap for trucks. 21CTP focuses on technical advancement that allows the United States and its heavy vehicle industry to be globally competitive in all areas.

2.4. Justification for Including Strategic Approach Aspect in 21CTP

2.4.1. The Challenges Facing Heavy-Duty Trucks

The 21st Century Truck Partnership is uniquely structured to coordinate efforts to improve the efficiency, emissions, and safety of class 2b to 8 commercial trucks and buses. Members include original equipment manufacturers and, unique to a public-private partnership, also includes key suppliers including heavy-duty diesel engine manufacturers and major component suppliers. Member companies are all multi-national with major U.S.-based research and development activities as well as domestic manufacturing capabilities.

The industry objective is to assure sustainable, cost-effective freight transport in an environment of limited petroleum supply and carbon emissions constraints. This means we need technology development plus related infrastructure and policy enablers to greatly improve vehicle and freight system efficiency and to develop low-carbon fuel sources.

To carry out this objective, the industry members are also joined by relevant federal agencies; the Department of Energy, the Department of Transportation, the Department of Defense and the Environmental Protection Agency. The Partnership has strategic alliances with the Engine Manufacturers Association (EMA) and the Truck Manufacturers Association (TMA), who serve on the industry's federal policy group, and the Hybrid Truck Users Forum (HTUF) with whom 21CTP shares six industry partners (Meritor, Eaton, Daimler Trucks, Navistar, PACCAR, and Volvo).

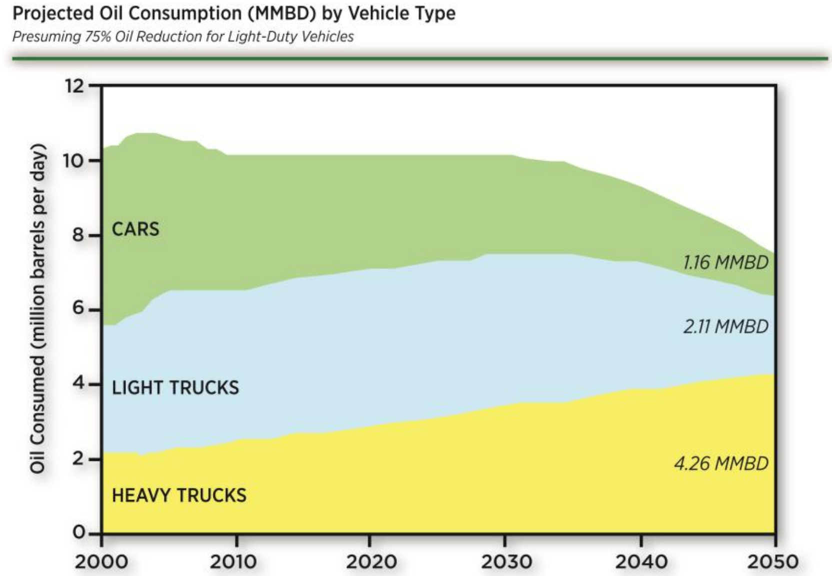

Figure 15. Projection of Transportation Fuel Use to 2050
Source: Internal DOE analysis, August 2008, comparing Heavy Truck oil consumption at AEO 2008 reference case levels with a 75% reduction in light-duty oil consumption relative to EIA's AEO 2008 reference case due to significant light-duty fuel economy gains and fuel switching.

In addition, fleet customers and small suppliers gain access to 21CTP programs by working through any of the partner companies. As a recent example, suppliers shared in an award given to Navistar. The National Laboratories also play a key role in working within 21CTP programs.

2.4.2. Technology Development Needs Exist in Several Key Areas

Requirements for heavy duty vehicles are markedly different from those of light duty, and unique solutions are required. Furthermore, the demand for freight movement is directly tied to economic growth which is expected to grow at 2 to 2.5% for the next 20 years. Recent DOE projections show that, if light duty fuel use targets are met and heavy duty trends continue, HD fuel use will exceed LD by 2040 (see Figure 15). These facts demand a major focus on efficient freight movement, combining strong government and industry efforts.

Many technologies that apply to cars do not apply to HD trucks, and an HD hybrid initiative is needed to round out DOE's energy security portfolio. An HD hybrid systems initiative, targeted at HD vehicles, is needed to complement DOE's passenger car targeted partnership initiative. There is a common perception that investments in passenger car (light-duty [LD] vehicle) technology benefit HD trucks. This is not entirely true. First, LD vehicles (including trucks) fall into Classes 1 and 2a, which contain passenger cars, light trucks (such as the GMC/Chevy 1500 series pickup truck), minivans, and most SUVs. HD trucks are everything else—all vehicles that exceed 8,500 pounds GVW, which are Classes 2b–8. This group of vehicles is very diverse and includes tractor-trailers, refuse and dump trucks, package delivery vehicles (e.g., UPS and FedEx), buses (e.g., city transit, school, shuttle, paratransit, demand response). Even large pickup trucks such as the GMC/Chevy 2500 and 3500, Ford F250 and F350, and Dodge Ram Heavy Duty 2500/3500 are in the HD class.

Table 2: Comparison of Heavy-Duty and Light-Duty Vehicle Characteristics

Characteristic	Heavy Duty (HD) Vehicles	Light Duty (LD) Trucks
Gross Vehicle Weight (GVW)	8,500 to 200,000 lbs.	Up to 8,500 lbs
Duty cycle	Continuous daily operation	Intermittent light duty
Peak horsepower	150 to 600	70 to 300
Continuous horsepower	100 to 600	25 to 60
Annual mileage	20,000 to 250,000 miles	8,000 to 20,000 miles
Expected lifetime	250,000 to 1,000,000 miles	150,000 miles
Purchase price	$60,000 to $250,000+	$12,000 to $40,000
Market volume (N.A. annual)	800,000	3,000,000
Number of configuration variants	Millions	A few thousand
Fuel of choice	Diesel	Gasoline
Fuel consumption	5 to 15 MPG	14 to 20 MPG
Who typically buys/owns it	The fleet manager/company	The driver
Who typically drives it	A hired driver	The owner
Buyer's priorities	Reliability, low cost of ownership, long life	It looks good, I like it/want it and I won't have to fix it too much
Emissions certification	Engine dyno, measured in grams per brake horsepower hour (g/bhp-hr)	Vehicle level, chassis dyno, measured in grams per mile (g/mi)
Certification responsibility	Engine manufacturer	Vehicle manufacturer

Table 2 compares some differentiating characteristics of LD and HD vehicles in North American markets. Key differences include:

- The annual sales volume for HD trucks is about a twentieth that of cars, and they can be bought in a thousand times more configurations. This means that components designed for the mass car market cannot, in many cases, be made commercially viable for HD trucks because the annual volumes do not support the required development and manufacturing costs.
- The HD truck market has a different set of drivers than the car market. HD trucks are typically bought to make money for the owner and are driven by a paid driver; cars cost their owners and drivers money. Generally speaking a HD truck buyer prioritizes reliability and low cost of ownership; a car buyer prioritizes styling and performance.

- A HD truck weighs 1–112 times more, has peak horsepower twice that of cars, and burns 3–4 times more fuel per mile driven, than a car.
- The payload of a HD vehicle is designed to exceed vehicle curb weight by a factor of approximately two; passenger car payload rarely comes near the vehicle curb weight.
- The life expectancy and duty cycles for HD vehicles are about ten times more demanding than those for light-duty vehicles. Therefore, HD hybrid technologies and solutions must be about ten times as durable as those being developed for LD hybrid applications.
- The exhaust emissions of an HD truck are generally certified and guaranteed by the engine manufacturer; the vehicle manufacturer is responsible for the emissions certification of a car.

These factors considered together have caused HD truck and LD vehicle markets and industries to behave very differently. The markets, products, business models, revenue streams, and regulatory environments are completely dissimilar. Technologies resulting from basic research can be transferable between the industries, but the products of applied research and beyond are market specific. In summary, the HD truck and LD vehicle technologies and corresponding investments in them leverage each other only at the most basic level. Because of this, a program complementary to US DRIVE is needed to address the unique technology needs of heavy duty vehicles.

2.5. The Importance of Heavy-Duty Hybrid Trucks

HD hybrid systems make trucks cleaner and more efficient. In an era of increasing ton-mile shipping volumes, powertrain efficiency is a very important consideration. Current HD HEVs can reduce oxides of nitrogen (NOx) as much as 50% and improve fuel economy 10%–50%, depending on the driving cycle. Other technologies that improve emissions but degrade fuel economy, such as exhaust gas recirculation (EGR), have been introduced to meet EPA 2007 and 2010 emission regulations. In contrast, HD hybrids not only provide improved fuel economy, but also a corresponding reduction in emissions. The technology thus offers improved operating efficiency to fleets while addressing the societal objectives of reducing emissions and also reducing dependence on foreign oil.

Hybrid vehicles have the potential to have greater energy efficiency than vehicles with conventional power trains. In many HD hybrid vehicles, the power plant can be used at its most efficient operating condition and often can be downsized. This is not due as much to engine horsepower reduction as it is to torque reduction. High torque rise engines are needed less often for HD hybrid vehicles, which allows for the use of higher speed, lower displacement engines that may have fewer cylinders and as a result are lighter weight and generally more fuel efficient. Moreover, the system can be used to slow the vehicle and to recover and store braking energy that can be used to propel the vehicle during accelerations. Hybrid propulsion systems can supplement or replace engine brakes and driveline retarders that dissipate braking energy as waste heat.

HD Hybrid technology is NOT mature and can realize significant benefit from technology investments. HD hybrid technology is far from mature, creating tremendous potential to improve component and system performance and efficiency through computer-aided design and systems optimization through advanced simulation techniques. The availability of a new generation of optimized components that are more reliable and lower cost will promote the use of hybrid propulsion systems in all commercial and military vehicle applications. Many of today's HD hybrid vehicles have used components that are commercially available but were not designed or optimized for on-road HD hybrid vehicles. Some HD hybrid components cannot be found elsewhere and must be custom designed for the application. These will be costly due to low production volumes that have not justified the development of high volume manufacturing tools and processes to produce them economically.

A multifaceted R&D effort is needed to develop enabling technologies for hybrid propulsion systems. For hybrid electric systems, electric motors, electrical energy storage, power electronics, electrical safety, regenerative braking, and power-plant control optimization have been identified as the most critical technologies requiring further research to enable the development of higher efficiency hybrid electric propulsion systems. Development of improved electrical energy storage systems and power electronics is especially important because of the high cost and limited availability of new components and subsystems. HD hybrid propulsion systems must also be optimized for a family of applications as part of the R&D effort.

HD hybrid electric systems are integral to the technology roadmap for all-electric HD trucks and buses and the future Smart Grid infrastructure. Electric vehicle and Smart Grid compatibility are clearly on the technology roadmap. However, advancements in both hybrid electric vehicle and battery technology are still required before electric vehicles will be dominant in any commercial vehicle application. Although the US DRIVE initiative was conceived to accelerate this transition for passenger cars, a complementary initiative is needed for HD vehicles. This gap should be filled with a HD hybrid technology development initiative.

Foreign competition is moving ahead with HD hybrid technology. The Japanese trucking industry is already moving ahead with HD hybrid systems, spearheaded by a Ministry of Economy, Trade and Industry (METI) initiative (formerly MITI, the Ministry of International Trade and Industry, until its reorganization in 2001). This is a strong motivating factor because of its impact on the ability of the United States to compete globally. Without a focus on this technology in the United States, Japanese companies will be more successful to commercialize fuel-efficient, clean-running hybrid trucks, leaving U.S. manufacturers scrambling to compete. Government support for the U.S. HD hybrid industry can level the playing field against government-funded global competitors and help the United States to maintain the lead in hybrid technology for heavy duty commercial vehicles. Will the Government address this issue proactively, or wait until a crisis (like $4.00 -$5.00 per gallon fuel prices) provides a much needed wake-up call, and then be forced to react after it is too late?

2.6. Description of Research Progress and Connection of Progress with Partnership Activities

The research advances in this strategic approach are in alignment with 21CTP's goals. Bringing complex commercial products, such as HD hybrid propulsion systems, to market can cost hundreds of millions of dollars per company and take as long as 10 years. DOE has budgeted between $1.0 and $1.5 million per year since FY 2007 for research and development activities at the National Labs related to MD and HD hybrid analysis, modeling and testing activities. In addition to this research funding, DOE funded the Technology Acceleration and Deployment Activity (TADA) in FY09 for $10 million, and the Transportation

Electrification MD projects under American Recovery and Reinvestment Act (ARRA) in FY10 for approximately $138 million. HD hybrid activities were also funded by DOE under the SuperTruck project in FY10 for approximately $115 million.

Even with the large amount of ARRA funding made available in FY10, there is a very large gap between the government's planned investment and the investment required to make this technology a reality. The government can help by funding the R&D and demonstration phases of these developments. The major HD hybrid developers in the United States will lead this work in partnership with the major engine manufacturers and truck OEM's.

U.S. Department of Energy (DOE): DOE's Vehicle Technologies Office has funded various research projects aimed at overcoming barriers of hybrid adoption noted in Section 2.8. These DOE funded projects include efforts such as simulation and optimization of heavy duty hybrid powertrains, laboratory testing and field testing and demonstrations of various hybrid systems and also deployment related funding and data collection activities.

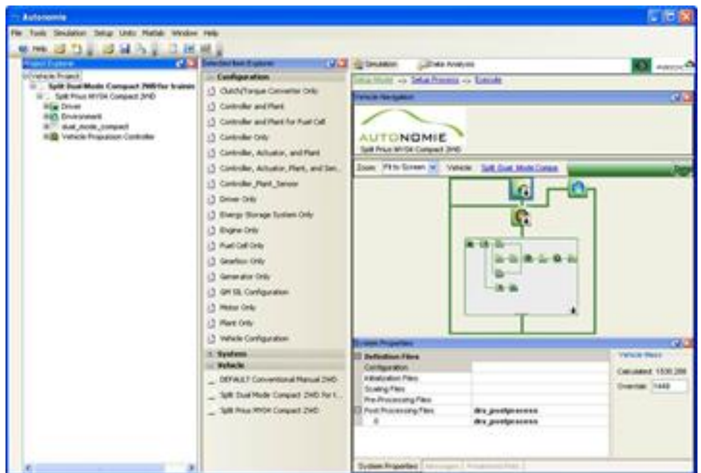

Figure 16. Screen Shot of Autonomie
Source: Argonne National Laboratory

Simulation/Modeling & Analysis: In 2007, Argonne National Laboratory began ramping up efforts to work with numerous OEMs engaged in hybrid activities, including Allison Transmission, Cummins, John Deere, PACCAR as well as government agencies (U.S. EPA) to develop specific features for Medium and Heavy Duty applications in Autonomie, Argonne's new vehicle simulation tool (see **Error! Reference source not found.**). State-of-the-art component data were first implemented through NDA's into Autonomie to model specific medium duty and heavy duty components, especially engine, transmission and vehicle aerodynamics. Specific control strategies, both for components (i.e., shifting) and vehicles (i.e., hybrid line haul) were then developed in collaboration with various OEMs. Several applications were finally validated using test data provided by the U.S. EPA (i.e., line haul, Class 4 P&D). The close collaborations with OEMs have allowed Argonne to significantly accelerate the development of medium and heavy duty features of Autonomie into 2010 and beyond.

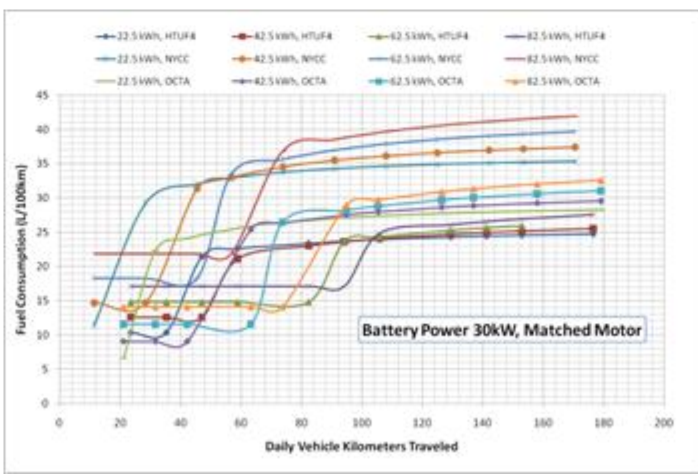

Figure 17. Energy Storage Sizing vs. Fuel Consumption for Various Drive Cycles
Source: National Renewable Energy Laboratory

In 2008, the National Renewable Energy Laboratory (NREL) began efforts to utilize existing simulation and modeling techniques and analyze how medium duty hybrid vehicles are used in a broad array of fleet applications, including parcel delivery and school buses. To fully understand and analyze these medium duty vehicles, NREL first collected and characterized vehicle usage patterns; most notably daily distance driven and drive cycle intensity. Second, drive cycle analysis results framed the selection of drive cycles used to test vehicles on a chassis dynamometer. Measured fuel consumption results were then used to validate fuel consumption values derived from dynamic models of the vehicles. For the final analysis of these medium duty architectures, NREL swept a matrix of 120 component sizes, usages and cost combinations to assess control strategies and component sizes that minimize fuel consumption and vehicle cost, while maintaining vehicle performance (see Figure 17 for an example output of energy storage analysis). Results illustrate the dependency of component sizing on drive cycle intensity and daily distance driven, and may allow fleets to match the most appropriate electric drive vehicle to their fleet usage profile.

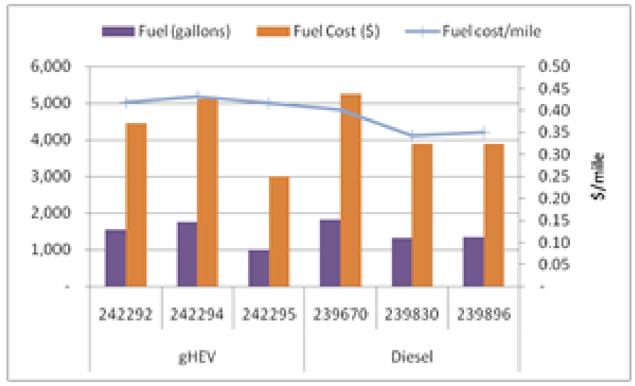

Figure 18. HEV Delivery Truck On-Road Results Source: National Renewable Energy Laboratory

Laboratory and Field Testing of MD and HD Hybrids: DOE's Advanced Vehicle Testing Activity has funded in-use and laboratory testing of advanced technology MD and HD vehicles for over 10 years. NREL's Fleet Test and Evaluation team has on-going efforts to assess hybrid electric drive systems in MD and HD vehicles. These systems combine a primary power source, an energy storage system, and an electric motor to achieve a combination of emissions, fuel economy, and range benefits unattainable with any of these technologies alone. The Fleet Test and Evaluation team works with industry partners to evaluate hybrid electric drive systems in buses and the results are valuable to provide an un-biased, third party assessment of real world operation and is used to focus future efforts to further improve performance. Typical on-road evaluations involve DOE funded efforts to work directly with commercial fleets that utilize hybrid vehicles to collect on-road vehicle use data to provide a basis for analysis in comparison to a conventional vehicle. Vehicle performance is tracked over a period of time at the fleet and vehicles are also tested on a chassis dynamometer such as the ReFUEL laboratory at NREL. Results showing long term on-road performance of the hybrids (fuel economy, emissions, operational cost and reliability – see Figure 18) as well as laboratory testing (fuel economy and emissions – see Figure 19) are published at the end of each project. Recent MD and HD testing and evaluation projects since 2007 include:

Drive Cycle	HEV Fuel Consumption (liter / 100km)
HTUF4	22.5
OC Bus	27.3
NYCC	34.9

Figure 19. HEV Delivery Truck Testing at NREL's ReFUEL Laboratory

- GM Allison's HEV transit bus in operation in Seattle, WA (2007)
- ISE's series HEV Transit Bus in operation in Long Beach, CA (2008)
- BAE's HEV system in operation in NY City, NY (2009)

- Eaton's HEV system in operation in the UPS fleet in Phoenix, AZ (2009)
- Enova's Plug-In HEV system in IC Corporation's school bus (2009)
- Azure's hybrid system in operation in the Fed Ex Los Angeles delivery fleet (2010)
- Eaton's HEV system in a class 8 tractor in operation at Coca Cola Enterprises beverage delivery fleet in Miami, FL (2010)

DOE funded deployment and field data collection efforts for MD and HD vehicles: In FY 2009 and FY 2010, DOE funded development and deployment funding to various PHEV and EV powered MD and HD vehicles. In FY2009, the Technology Acceleration and Deployment Activity (TADA) funded the development and deployment of the next generation Navistar PHEV school bus. This activity will fund development and deployment of PHEV school buses to improve the performance of IC Corporation's first generation design and will help move technologies from the laboratory to the marketplace by improving their durability, reducing their costs, and validating their performance in real-world settings. Improvements will include electric accessories to enable engine off operation and improved control strategies as well as improved energy storage approaches.

In FY2010, DOE, under the American Recovery and Re-investment Act (ARRA) – Transportation Electrification activity, was able to fund the development of 4 additional PHEV and EV platforms. Over 1,800 vehicles are being funded by the DOE to develop and demonstrate plug-in HEV and full EV operation in commercial fleet locations around the United States. These projects, selected through a highly competitive process by the Department of Energy, will accelerate the development of U.S. manufacturing capacity for batteries and electric drive components as well as the deployment of electric drive vehicles. Selected MD and HD projects under this grant will include:

- Smith Electric Vehicles – Develop and deploy up to 500 all -electric 'Newton' class 3 box trucks
- Navistar, Inc. - Develop, validate and deploy up to 950 class 2b/class 3 battery electric delivery trucks
- Eaton Corporation and Azure Dynamics under an award to the South Coast Air Quality Management District to develop and deploy 378 trucks and shuttle buses respectively.

Also in FY10, DOE announced several SuperTruck projects aimed at improving the efficiency of Class 8 long-haul freight trucks by 50%. These projects will develop and demonstrate systems-level fuel efficiency technologies by 2015, including improved aerodynamics, reducing engine idling technologies, waste heat recovery to increase engine efficiency, advanced combustion techniques, and powertrain hybridization. Selected projects under this grant program will include:

- Cummins Inc. - Develop and demonstrate a highly efficient and clean diesel engine, an advanced waste heat recovery system, an aerodynamic Peterbilt tractor and trailer combination, and a fuel cell auxiliary power unit to reduce engine idling.
- Daimler Trucks North America, LLC - Develop and demonstrate technologies including engine downsizing, electrification of auxiliary systems such as oil and water pumps, waste heat recovery, improved aerodynamics and hybridization.

- Navistar, Inc. - Develop and demonstrate technologies to improve truck and trailer aerodynamics, combustion efficiency, waste heat recovery, hybridization, idle reduction, and reduced rolling resistance tires.
- Volvo Trucks North America, Inc. – Develop and demonstrate technologies including next generation engine platforms, parallel hybrid systems, waste heat recovery, vehicle lightweighting, aerodynamics, and idle reduction.

Department of Transportation (DOT): DOT has been involved in funding HD hybrids by providing most of the incremental cost of the hybrid buses for public transit agencies around the United States. In addition to this and the Federal Transit Administration's (FTA) general funding of capital bus purchases (which has included many hybrid buses), there have been several recent initiatives that include hybrid bus work. Of note are:

National Fuel Cell Bus Program – Funded at $49 million over 4 years with an FY2006 start, this project pushes Fuel Cell Bus technology, which includes hybrid electric drivetrains, and is developing many components that could be used on any hybrid configuration including drive motors, energy storage systems and power electronics. DOT also has sponsored the National Fuel Cell Bus Program which consists of $45 million in funding between FY06 and FY09. The NFCBP will facilitate the development of commercially viable fuel cell bus technologies and related infrastructure for application in transit revenue service operations. The primary focus of the NFCBP is on fuel cell bus technologies since the Department of Energy is actively engaged in the research, development, demonstration and deployment of related hydrogen infrastructure. The workhorse vehicle for transit agencies in the United States remains the 40-foot, heavy-duty transit bus. The NFCBP's focus is on advancing the commercialization of 40-foot, heavy-duty, fuel cell transit buses.

Transit Investments for Greenhouse gas and Energy Reduction (TIGGER) – This project funds the development of on-board energy management systems (energy storage, regenerative braking, fuel cells, turbines, engine start stop, and hybrids), as well as electrification of accessories to enable hybrid operation. Round 1 consisted of $100 million in ARRA funding, 43 projects selected, many of which included battery or hybrid buses. Round 2 consisted of $75 million of discretionary funds for similar projects; special emphasis on innovation and electric drive technologies.

Emissions Certification Support for Hybrid Buses - The Center for Alternative Fuels, Engines and Emissions (CAFEE) at West Virginia University (WVU) is conducting a research program for the Department of Transportation (DOT), Federal Transit Administration (FTA) to investigate the need and advantages of emissions certification of hybrid buses. The objective of the project is to enable transit fleets to obtain credits and advantages for the investments they make in new technology buses, which have levels of exhaust emissions lower than required by Environmental Protection Agency (EPA) standards. Transit fleets may purchase new hybrid buses which have a higher original capital cost than conventionally powered buses but which have lower exhaust emissions of oxides of nitrogen (NOx) and particulate matter (PM) and lower greenhouse gas (GHG) production than conventional buses. The objective of this project is to establish emissions certification and verification procedures and a test protocol so that transit fleets can obtain credits or other benefits for the lower emissions levels. This information will allow transit fleet operators to establish and quantify emissions credits when deploying hybrid and advanced technology buses.

Department of Defense (DOD): Department of Defense (DOD): To date, DOD has spent a considerable amount of funding on MD and HD hybrid demonstration programs. DOD has taken leadership in the area of hybrids for combat vehicles and MD and HD tactical trucks. DOD promotes the development of dual-use technologies for both military and commercial vehicle applications. The U.S. Army has sponsored numerous hybrid programs, predominately through TARDEC (Tank-Automotive Research, Development and Engineering Center) and CERDEC (Communications-Electronics Research, Development, and Engineering Center). One such project developed under the DOD funding included the Oshkosh ProPulse diesel electric drive system, which provides electric propulsion power as well as 100kW of clean exportable military-grade AC power. This technology became part of the HEMTT A3 platform.

Environmental Protection Agency (EPA): EPA has sponsored an effort under its Clean Automotive Technology program based at its National Vehicle and Fuel Emissions Laboratory in Ann Arbor, Michigan to develop and demonstrate hydraulic hybrid propulsion technology, an alternative, hydro-mechanical approach to HD hybrid electric propulsion. EPA has several technology transfer partnership projects involving industry (UPS, Eaton, Navistar/IC Bus, FedEx, Parker, Freightliner and Kalmar) to demonstrate the ability of series hydraulic hybrid vehicle (HHV) technology to increase fuel economy and reduce emissions in numerous commercial trucks (as well as with Ford, Chrysler and Eaton on light-duty pickup/SUV and minivan applications). Demonstration projects of particular note are a class 6 series HHV UPS truck, a class 7 series HHV Yard Hostler, a class 6 series HHV shuttle bus (powered by a full gasoline HCCI engine), a class 6 series HHV midibus for transit, a class 2b SUV/pickup, and a family-sized minivan. All of these proof-of-concept vehicles have been tested on laboratory dynamometers and several have been evaluated in commercial service. Figure 20 shows the latest fuel economy improvement results (percent mpg) of EPA series hydraulic hybrid technology laboratory tested on various city driving cycles. Refer to EPA's web site (www.epa.gov/otaq/technology) for more details about the results of these demonstration vehicles.

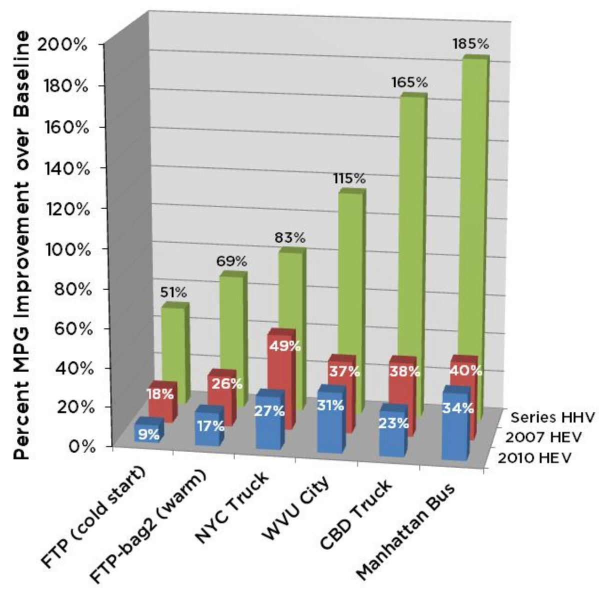

Figure 20. Hydraulic Hybrid Comparative Results Source: EPA

2.7. Technology Status and Plans

2.7.1. Drive Unit (Electric Traction, Motor, Transmission, Generator, Inverter, Controller and Cooling Devices)

Given the wide range of vehicle types and duty cycles, certain types of drive units may work better than others for specific vehicle applications or performance requirements. Several types of motors and generators have been proposed for hybrid-electric drive systems, many of which merit further evaluation and development. Motor generators can be configured before or after the transmission. Series HEVs typically have larger motors with higher power ratings because the motor alone propels the vehicle. In parallel hybrids, the power plant and the motor combine to propel the vehicle. Motor and engine torque are usually blended through couplings, planetary gear sets and clutch/brake units. Interestingly enough, the same mechanical components that make parallel HD hybrid drive units possible can be designed into series HD hybrid drive units to decrease the size of the electric motor(s) and power electronics.

2.7.2. Electric Machines

There are no easy answers for electric machine selection and design for HD hybrid applications. This choice must be made based on extensive trade studies relative to the requirements and priorities for the specific application. Motor subsystems such as gear reductions and cooling systems must be considered when comparing the specific power, power density, and cost of the motor assemblies. High speed motors can significantly reduce weight and size, but they require speed reduction gear sets that can offset some of the weight savings, reduce reliability and add cost and complexity. Air-cooled motors are simpler and generally less expensive than liquid-cooled motors, but they will be larger and heavier, and they require access to ambient air, which can carry dirt, water, and other contaminants. Liquid-cooled motors are generally smaller and lighter for a given power rating, but they may require more complex cooling systems that can be avoided with air-cooled versions. Various coolant options, including water, water-glycol, and oil, are available for liquid-cooled motors.

2.7.3. Power Electronics

This may also play a crucial role in converting and distributing power and energy in automotive applications. U.S. industries currently supply power electronic products for commercial and military HEV applications; however, no manufacturers in the United States can supply the high-power isolated gate bipolar transistors (IGBT's) required for these products. Selecting the correct power semiconductor devices, converters/inverters, control and switching strategies; packaging and cooling the units; and integrating the system are very important to developing an efficient and high-performance system.

2.7.4. Electrical Energy Storage

This technology has seen a tremendous amount of improvement over the last decade. Advanced battery technologies and other types of energy storage are emerging to give the vehicle its needed performance and efficiency gains while still providing a product with long life. The focus would be on the more promising energy storage technologies—nickel metal-hydride (NiMH) and lithium technology batteries and ultracapacitors. Other less-mature technologies, such as flywheels, will have a lesser focus, but will be considered as they reach sufficient levels of robustness for mobile applications.

An electrical energy storage system is needed to capture energy from the generator, to store energy captured during vehicle braking events, and to return energy when the driver demands power. Pure electric vehicles (EVs) rely on the energy storage system's energy content as their primary source of fuel, and as a result, the priority for EV energy storage systems is high energy for long range between recharges. Hybrid electric vehicles (HEVs) carry their primary energy in the form of liquid fuel that is converted into electrical energy by an internal combustion engine and electrical generator. Therefore, HEVs require only limited high-energy electrical storage capacity. HEVs need high-power storage systems because they typically use the energy storage system only as a temporary holding place for acceleration or deceleration energy. The priority for HEVs is to get energy in and out of the storage system efficiently and at high rates to enable the maximum fuel economy and emissions improvement. Electrical energy storage systems currently consist of battery and ultracapacitor packs that have electrical, thermal, and safety control features.

The two major electrical energy storage systems that are being considered for hybrid electric propulsion systems are electrochemical batteries and ultracapacitors. Over the past six years, government and industry programs and initiatives have supported R&D of electrical energy storage systems for LD vehicles. These programs and initiatives directed most of their resources to batteries because of the better potential for short-term commercialization, and established technical targets for hybrid battery development efforts for power-assist and dual-mode HEVs. Recent developments in the LD vehicle energy storage industry have enabled more opportunity for MD and HD pack development. A123 Systems has recently offered a large transit bus sized lithium ion battery pack for new bus purchases through the HEV manufacturer BAE Systems. A123 recently began offering a 26650 cell built into a 690 volt pack specifically designed for transit bus operations and offered as a replacement for older less reliable lead acid packs. Eaton Corporation also offers a lithium ion pack supplied by Hitachi for all their HEV powertrains. A123 has also supplied 80 kWh battery packs to Navistar for the eStar vehicles deployed under the Recovery Act. Valence will produce lithium ion phosphate batteries for Smith Electric Vehicles in the United Kingdom and the United States under the ARRA program.

Key challenges for any type of HEV energy storage system that must be addressed are:

- Cost, both procurement and life cycle;
- Weight and space claim;
- Life expectancy (in an HD drive-cycle);
- Energy and power capacity for a HD hybrid application;
- Suitability for the HD vehicle environment and cooling techniques;
- Architecture/modularity;
- Safety/failure modes;
- Maintainability;
- Management and equalization electronics and algorithms; and
- Supplier base for the storage elements.

2.7.5. Electric Hybrid Systems

First-generation HD HEVs have met or exceeded expectations for fuel economy and emission reductions. Most HD HEVs produced to date use commercially available internal combustion engines for on-board power generation. The engine's displacement and torque rating is generally lower for HEVs because electric motors have speed torque characteristics that are ideally suited for vehicle operations. Unlike an Internal Combustion Engine (ICE), an electric motor has full torque at zero speed. A properly designed HD hybrid system relieves the ICE from a heavy torque load and instead allows it to be used primarily as a power source. Additional torque is provided by electric machines either directly or through a parallel drive unit. This may allow use of a lighter duty, lower torque, and more fuel efficient internal combustion engine to perform the job of a larger, heavier engine. (For longer distance regional haul or line haul applications, the engine must be sized to deliver sufficient power to maintain a desired vehicle speed for a sustained period of time). The energy storage system provides stored braking energy during accelerations or peak power demands. In addition, it gives the system designer a degree of freedom in selecting the engine's operating point to prioritize fuel economy and emissions performance higher than drivability. A significant number of diesel-electric and natural gas-electric hybrids have operated successfully in commercial fleets.

As described above, engine operating conditions may differ significantly for conventional vehicles and HEVs. There are opportunities to design a purpose-built engine for use in hybrid electric propulsion systems to improve fuel efficiency. For instance, electronic controls can be used to shape the engine's load profile such that it generates electrical power near peak efficiency and seldom operates at low-load and high-speed or high load low speed conditions, where efficiency is low and emissions are high. With a properly integrated energy storage system, emissive and inefficient transient engine operation can be significantly reduced by providing transient energy from the energy storage system rather than the engine.

First-generation HD HEVs were built with predominantly "off-the-shelf" commercial components, including the engine, battery, and generator. Although these components have worked in the new hybrid application, further energy efficiency gains may be realized when components and controls are designed with the hybrid system in mind. Cost and efficiency gains may be realized if components can be combined into fewer, more integrated packages.

Various hybrid propulsion technology approaches

Hybrid electric propulsion systems may be needed to meet performance and efficiency goals for both commercial and military vehicles because HEVs feature a power plant in combination with an electric motor(s) and electrical energy storage system. Other alternative system configuration options, including hybrid hydraulic systems, could meet some specific vehicle system, customer, or market requirements. Many series, parallel, and power-split hybrid propulsion system configurations are possible. The optimum propulsion system configuration depends on vehicle performance goals, efficiency goals, duty cycle, and other practical considerations, including manufacturing cost, serviceability, market differentiation, and customer acceptance.

2.7.6. Powertrain Modeling Tools to Enhance Development Efficiencies

Building hardware is expensive. Traditional design paradigms in the automotive industry often delay control system design until late in the process — in some cases requiring several costly hardware iterations. To reduce costs and improve time to market, it is imperative that greater emphasis be placed on modeling and simulation.

Autonomie is a plug-and-play powertrain and vehicle model architecture and development environment to support the rapid evaluation of new powertrain/propulsion technologies for improving fuel economy through virtual design and analysis in a math-based simulation environment.

Autonomie will support the rapid integration and analysis of powertrain/propulsion systems and technologies for rapid technology sorting and evaluation of fuel economy improvement under dynamic/transient testing conditions. The capability to sort technologies rapidly in a virtual design environment results in faster improvements in real-world fuel consumption by reducing the time necessary to develop and bring new technologies onto our roads.

In addition to applications of the Autonomie software, projects that use the modeling expertise at both the national labs and industry to apply systems engineering and robust design to address barriers to the commercial viability of energy saving components and systems is highly beneficial. Examples of this type of work include projects to better understand the heavy vehicle's duty cycle and the in-use performance of hybrid and other energy saving technologies, robust design of hybrid system components to enhance their commercial viability, and specific physical analyses of specific component issues in energy storage and power electronics. An analysis/optimization approach using a combination of simulation and hardware testing (such as "hardware in the loop") could enable quicker and more cost-effective hardware and control system development.

In the hybrid electric system architectures, technical approaches must be developed to generate high-grade electrical energy from several vehicle sources to charge energy storage systems and potentially operate auxiliary load components. Electrical energy generation technologies technical goals include:

2.7.7. Regenerative Braking

HD hybrid vehicles use regenerative braking for improved fuel economy, emissions, brake heat, and wear. A conventional heavy vehicle relies on friction brakes at the wheels, sometimes combined with an optional engine retarder or driveline retarder to reduce vehicle speed. During normal braking, the vehicle's kinetic energy is wasted when it is converted to heat by the friction brakes. The conventional brake configuration has large components, heavy brake heat sinks, high temperatures at the wheels during braking, audible brake squeal, and consumable components requiring maintenance and replacement.

Hybrid electric systems recover some of the vehicle's kinetic energy through regenerative braking, where kinetic energy is captured and directed to the energy storage system. The remaining kinetic energy is dissipated through conventional wheel brakes or in a driveline or transmission retarder. Regenerative braking in a hybrid electric vehicle can require integration with the vehicle's foundation (friction) braking system to maximize performance and safety. Today's systems function by simultaneously using the regenerative features and the friction braking system, allowing only some of the kinetic energy to be saved for later use. Optimizing the integration of the regenerative braking system with the foundation brakes will increase the benefits and will be a focus for continued work. This type of hybrid regenerative braking system helps fuel economy, emissions, brake heat, and wear.

2.7.8. Electrical Systems Safety

Electrical safety requirements must encompass acceptable design practice, accessibility, and durability of safety provisions, human factors, and risk management. Electrical vehicle technology has led the way for the development of hybrid vehicle safety technology to a substantial extent. Electrical safety can be considered in the two subcategories shown below.

- Functional safety includes establishing a product safety checklist and design practice, ensuring crash/rollover isolation, integrating low-voltage accessories, and conducting failure effects and sneak-path effects analysis.
- Personnel safety includes consideration of emergency disconnects, access door/cover/power interlocks, high-voltage cable/harness routing, high voltage cable/harness unique identification, maintenance and emergency personnel training, and warning labels.

2.7.9. Test and Evaluation/Certification Status

Internal combustion engine power plants for HD vehicles are certified for exhaust gas emissions by operating over a combination of a highly transient cycle and a series of steady-state operating modes on an engine dynamometer which is designed to map the emissions of an engine throughout an operating range (unlike a LD vehicle where the engine is tested in a vehicle on a chassis dynamometer). These HD test procedures, defined by the U.S. Code of Federal Regulations as the Federal Test Procedure (FTP), have been developed for engines that are designed to be directly coupled to the drive axle(s) through the drivetrain of a vehicle. Calibration of the engine controls to meet these emissions standards, as well as performance, drivability, and durability requirements, is a major part of the development effort of an engine.

Hybrid powertrains can take many forms, but in all cases the direct link between the engine and the drive axle is either altered by additional motive components (parallel), or severed entirely (series), in order to improve vehicle performance. The new configuration could allow the engine to be calibrated for better efficiency and reduced emissions in a more narrowly defined operating regime. Depending on the hybrid configuration and vehicle use patterns, the engine may be optimized for far fewer operating modes, and the severity of transients (a major source of emissions) may be significantly reduced. However, if the test procedures are not updated to reflect the advantages of hybridization, manufacturers will be required to calibrate the engine

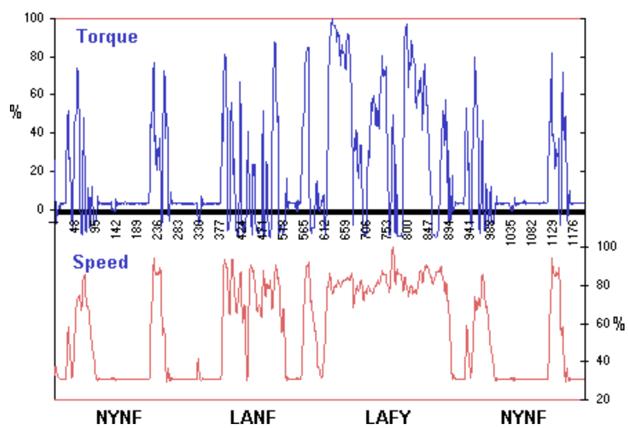

Figure 21. Heavy-Duty Federal Test Procedure Cycle

control system in order to certify the entire FTP cycle, at great expense—but of no value to actual hybrid vehicle operation whatsoever as it does not recognize the hybrid system benefits. **Therefore the need to establish new test protocols for heavy hybrid vehicles is a major factor in establishing the genuine benefit of this new technology.**

Tools needed to develop these test protocols may not be available, at least in a standard form. Chassis dynamometers for heavy duty vehicles and on-board emissions measurement systems, currently research tools, may be required to characterize the actual benefits of hybrid systems in operation. According to a Transportation Research Board report:[5]

> *Fuel consumption and emissions to measure performance of a hybrid may be measured directly from a vehicle on the road, a test track, or a chassis dynamometer. It is important to distinguish between comparative testing, where fuel consumption values used by two trucks of different technology are compared, and absolute testing, where fuel consumption is measured using a standardized procedure so that the results may be compared with results from tests conducted at different times or in different locations. If onroad measurement is conducted over a long distance or long period of time, the resulting average fuel consumption values may be compared fairly with those from another vehicle operated over a sufficiently similar route with sufficiently similar operating conditions. The purpose of a test track is to provide sufficiently repeatable conditions and vehicle activity that a comparison between the performances of two vehicles is possible with a reduced distance or time of operation relative to less controlled on-road tests. It should also be noted that the fuel efficiency of a truck is not readily characterized by a single number, but rather by a curve against average speed. If varying operating weight is also considered a factor, fuel efficiency information forms a surface of values against the axes of average speed and operating weight. Creating curves or surfaces of this kind would require exhaustive chassis dynamometer measurements, but they may also be created using models that are calibrated with more limited chassis dynamometer data. Curves or surfaces would show that some technology has low-speed benefits and some has high-speed benefits and that some technology is more sensitive to payload than other technology.*

The U.S. Environmental Protection Agency (EPA) is currently drafting vehicle level test procedures. The EPA has been requested by the President to institute GHG standards for HD vehicles and released this rule in August 2011. In general, in California, LD/MD hybrids must be vehicle-certified, while HD hybrids only need an engine cert. There is a voluntary interim hybrid HD vehicle cert procedure in California that was approved in 2002, based heavily on SAE J2711.[6] This procedure was approved on an interim and voluntary basis for fleets complying with ARB's transit bus rule, so it only specifically addresses NOx, and uses the OCTA and UDDS duty cycle. All this work is aimed at quantifying the improvement in fuel economy and emissions due to hybridization but at this time procedures are in draft form and voluntary and not finalized. SAE's J2711 is final and is a standard test procedure widely used by industry on a chassis dynamometer, but loads and cycles are still being finalized in conjunction with that procedure. SAE's J1321

---

[5] National Research Council, *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles*, 2010.

[6] See http://www.arb.ca.gov/regact/bus02/appb.pdf

Type II test procedure is also widely used but again, no industry standard cycle or certification process exists for MD and HD vehicles so a fully integrated system does not receive the credit due at a vehicle level as emissions and fuel consumption continue to be measured at the engine level.

Industry worked closely with both NHTSA and the EPA in the development and final release of new GHG and fuel consumption regulations. Recommendations coming from that recent work include the following:

- **Recognize Fleet Diversity:** The rule should align any standards with the technology needed for different applications. Fleets are diverse in terms of weights, sizes and capabilities in order to perform the wide range of tasks required of these vehicles. The rule should maximize achievable gains in medium-and heavy-duty vehicle fuel efficiency and GHG emission reductions by taking advantage of the technology improvement opportunities across the entire vehicle and its operation.
- **Avoid Unintended Consequences:** The rule should seek to avoid unintended consequences by building on existing programs, including the use of proven protocols. The rule should recognize current market structure. It should achieve significant short-term fuel efficiency improvements without restricting customer choice of product specifications to perform the actual work needed.
- **Supplemental Certification:** Existing certification test methods should be supplemented to recognize the efficiency improvements of technologies not accounted for at this time. Some hybrid systems, for example, deliver greater fuel efficiency and GHG reduction benefits than would be estimated based on current engine test protocols. New supplemental testing and certification procedures should be capable of differentiating fuel efficiency across novel technologies.
- **Harmonized Program:** Inconsistencies between regulatory agencies must be avoided. A single national MDV/HDV fuel efficiency/GHG program is essential to provide vehicle manufacturers, suppliers and the user community with the certainty necessary for capital investment. A patchwork of different state requirements or conflicting standards for GHG and fuel efficiency will compromise the achievement of improvement goals as well as program compliance.
- **Complementary Policies:** Financial and other incentives—including investment tax credits; accelerated depreciation of new capital investment; increased highway infrastructure spending and increased size and weight of vehicles—will accelerate the deployment of new, more fuel efficient trucks. These policies and others (decreased speed limits, driver training and congestion mitigation) will drive environmental, economic and energy security benefits and will greatly assist rapid fleet turnover of existing stock.

2.8. Technical Barriers

This section addresses the barriers to widespread acceptance of technologies associated with the strategic approach outlined in Section 2.1.

Industry/market characteristics that are considered barriers include low truck market volumes, high R&D costs, challenging reliability requirements, minimal technology crossover from cars, and razor thin margins in the trucking industry. These result in:

- Inability to collect a substantial differential cost for HD hybrids;
- Lack of reliable third party data on new propulsion technology;

- Lack of certification procedures and emission credits for the hybrid propulsion systems; and
- Lack of progress in HD hybrid product development.

Key ***heavy hybrid vehicle technical barriers*** emanating from these industry/market characteristics include:

- Initial and life cycle component costs;
- Component and system performance;
- Lack of high temperature, low cost power electronics and energy storage elements;
- Weight and space claim;
- Scalability and modularity;
- Lack of component standards;
- Insufficient vehicle test procedures;
- Integration/optimization of advanced vehicle technologies; and
- Infrastructure development (supplier base, manufacturability, process certification).

2.9. Component-specific barriers

2.9.1. Energy Conversion Technology Barriers

For hybrid electric propulsion systems, most components were not designed or optimized for use in on-road HEVs. Electric components can be costly because precision manufacturing tools are needed to produce the components, and production volumes are low. A new generation of components is needed for commercial and military HEVs. Electric motors, power electronics, electrical safety, regenerative braking, and power-plant control optimization have been identified as the most critical technologies requiring further research to enable the development of higher efficiency hybrid electric propulsion systems. The major barriers associated with these items relate to weight and cost reduction.

Drive units. The major barriers to introducing hybrid electric drive units for HD trucks include system (life cycle) cost, system reliability, and system durability. Safety concerns and system complexity as they relate to maintenance are also issues. The rigorous duty cycles and demands placed on HD vehicles necessitate a high degree of component reliability. In the lower volume market of heavy hybrid vehicles, cost reduction will be a challenge.

Power electronics. The barriers for introducing improved power electronic systems for truck applications are the cost, complexity, reliability, and the operating environment. Current power electronic converters and motor controllers that meet size and weight requirements are not rugged or reliable enough for 1,000,000-mile vehicle lifetimes and harsh trucking environments.

Other barriers are thermal management systems for fast, energy-efficient heat removal from device junctions and components, control of electromagnetic interference generated when the devices are switched, and achieving a low-inductance package for the power inverter. Generally, silicon operates too cold for efficient heat removal if the power electronics cooling system draws coolant from the engine, which would expose the electronics to relatively high water-ethylene glycol temperatures. As a result, silicon carbide is a preferred technology for more efficient heat removal. The task of packaging power electronics to satisfy the multiple extreme environments and ensuring reliable operation with proper function is a barrier. (The packages that are available are generally not suitable for vehicle applications.) Additionally, there is a limited domestic supplier base for high-power switch devices.

Safety risks may be higher for prototype HEVs that have not been subjected to rigorous hazard analysis.

2.9.2. Energy Storage Barriers

The primary barriers for electrical energy storage systems are achieving high power densities with high available energy, reliability, safety, and cycle life. Battery and life cycle costs are critical issues that could influence market acceptance for heavy vehicle applications. Many battery materials are currently too expensive. The chemicals used in many types of batteries need to be more stable to avoid self-discharge. Long, shallow discharges can cause chemical instability. The chemistry and materials in each technology can be improved. Lithium ion batteries have potential safety issues. Other barriers are proper integration of batteries in a pack within the vehicle, thermal management, and control systems.

2.9.3. Power Plant and Control System Optimization Barriers

Most components used in today's hybrid vehicles are commercially available. However, they are not optimized for on-road heavy hybrid performance. Electric components can be costly to produce and have low production volumes. Hybrid propulsion components are high weight and high volume. Integrated generator/motors need higher specific power, lower cost, and higher durability.

Alternative power plants, such as fuel cells and gas turbines, are much less mature than mass-produced internal combustion engine technology. These plants will require extensive R&D to match diesel engine efficiency, reliability, and operating cost.

2.9.4. Electrical Energy Generation Barriers

<u>Regenerative braking systems.</u> Current power electronics and energy storage systems may be too inefficient and slow to capture all available kinetic energy from the vehicle.

<u>Generators/Motors.</u> Current offerings from OEM's are low volume and high cost. More lower cost, high efficiency and high power density options need to be made available to the market.

<u>Waste heat recovery systems.</u> These have high cost and high volume issues. In addition, system integration is challenging because of its high speed, high power, and higher frequency power electronics needs.

2.9.5. Auxiliary Load Electrification Barriers

Fuel efficiency could be significantly improved (by 8% to 12%) by electrifying many of the accessories in a truck in a systematic, system-wide fashion. However, research is needed in the system development and integration, modeling, component development, and technology demonstration.

2.9.6. System Safety Barriers

The vehicle electrical system architecture has safety risks that may be higher for prototype HEVs that have not been subjected to rigorous hazard analysis. The greater extent and complexity of high-voltage components and cabling in HEVs requires extended safety practices. (For purposes herein "high voltage" shall be considered to be any voltage exceeding 50 volts DC or 50 volts rms AC.)

2.9.7. Test and Evaluation/Certification Barriers

Currently, there is no official hybrid testing protocol for fuel economy and emission certification procedures. Testing will require sophisticated equipment (chassis dynamometer and appropriate analysis equipment), protocols, and facility preparation. The approaches for vehicle certification, or at least a process for justifying a waiver from conventional engine certification procedures for HD hybrids, need to be studied.

2.10. Goals and Objectives – Electric Hybrid

2.10.1. Stretch Goals for the Hybrid Group

This section addresses the technical goals for HD hybrids defined by the 21CTP, and support the strategic approach outlined in the first section of this discussion. It should be noted that these are in fact stretch goals and can only be accomplished with increased funding through the 21st Century Truck Partnership.

Goal 1 - E-machines: Develop advanced motor technology that will deliver e-machines with improved durability, lower cost, better power density, and alternatives to rare earth permanent magnets.

- Design life for hybrid drive systems that are comparable to other components in the vehicle. For example, greater than one million miles (Class 8 line haul application) or 15 years of life (vocational applications).
- Power density, expressed in terms of kilowatts per kg, should be improved in order to reduce the significant weight penalty associated with some hybrid systems. Today, power density for some motor designs is in the range of 0.5kW/kg. The objective is to nearly double the power density to approximately 1kW/kg. This reduces cost, size, and weight, provides a more robust design, improves packaging, and facilitates higher vehicle payload capacity. A cost target of $23/kilowatt has been established by 2016.
- Motors and generators are already highly efficient, typically in the range of 94%. Even modest improvements to motor and generator efficiency result in a measurable reduction in fuel usage. Overall efficiency of the generator-battery-motor system is multiplicative, thereby magnifying the benefit of improved e-machine efficiency. Obtain design changes that would reduce losses and drive efficiencies up to the range of 96-97% by 2016.
- Permanent magnet motors are used in several hybrid systems today. Concern is increasing that higher hybrid volumes will create significantly higher demands for rare earth magnet material that is predominantly supplied by China. Development of alternate motor designs that do not depend on a commodity supplied primarily by a single foreign power is deemed to be in the best interests of

the United States. Demonstrate a non-permanent magnet motor technology in a commercial vehicle application that would equal or meet current hybrid system requirements by 2013.

Goal 2 - Inverter Design/Power Electronics: Develop technologies that will improve the cycle life of critical components within the inverter and other power electronics within the hybrid system.

- Silicon-based insulated gate bipolar transistors (IGBT's) are today one of the main components of the inverters used in heavy duty hybrid systems. Temperature control of these devices in an inverter that shares coolant with the engine can be problematic due to the relatively high engine coolant temperatures. This issue can be mitigated by increasing the allowable temperature range of the IGBT's. Alternately, integration of improved heat transfer mechanisms such as cooling plates to the IGBT chip base can facilitate cooling, whether coolant is shared with the ICE or an independent inverter coolant circuit is available. Another area of focus is the development of IGBT's with higher switching frequencies, which would allow smaller capacitor banks in the inverter and also reduce power losses. Technology developments focused on these areas will improve system life, simplify cooling requirements and drive down total lifecycle cost. An objective is to develop improved switching devices (IGBT or other) that have a broader operating temperature range, improved heat transfer capabilities, and higher switching frequencies. Develop this improved switching system and demonstrate benefits by 2016.
- Reduce overall weight of inverter designs by 20% through higher efficiency of switching devices with higher operating temperatures and potential integration with engine cooling systems by 2016.

Goal 3 - Energy Storage Systems: Develop an energy storage system with 15 years of design life, a broader allowable temperature operating range, improved power density and energy density, and significantly lower cost.

- Develop a system that can provide a cycle life of 5000 full cycles which should achieve the targets of 1 million miles (on highway) or 15 years (vocational). More work is required to better understand the cycle life of lithium ion batteries in actual vehicle applications. This is somewhat of an unknown, due to the fairly recent introduction of these chemistries into vehicle production.
- R & D efforts should also focus on expanding the acceptable operating temperature range for lithium ion batteries, currently at 0 to 55 degrees Celsius. Successful efforts could simplify battery pack cooling requirements and address cold weather operating concerns by 2017.
- Develop battery technologies that will significantly increase power and energy densities - The future battery technology of choice will likely utilize one of several lithium ion chemistries, which are believed to offer the best power and energy density. The result will be smaller, lighter batteries that simplify packaging and reduce vehicle weight. With continued, accelerated R&D efforts, improvements to cell and pack designs could potentially increase densities by up to 50% by 2017.
    - Explore alternate approaches to achieve both improved energy and power capabilities. Utilize either mixed battery chemistry or a "mixed energy storage" device (for example consisting of both batteries and ultracapacitors) to create a storage device that will not require the compromise between high energy density and high power density that is required by today's technology.
- Proposed Cost Targets

  - $45 per kW and/or $500/ kW- hour for an energy battery by 2017
  - $40 per kW and/or $300/ kW- hour for a power battery by 2020
- By 2016, cost of overall battery pack should not exceed cost of the cells themselves by more than 20%.
- Establish a solid "end-of-life" strategy for advanced batteries and provide necessary funding related to either the remanufacturing or recycling of batteries by 2017.

Goal 4 - Hybrid System Optimization – Medium Duty: The goal is to develop and demonstrate medium duty hybrid system technology that can deliver substantial increases in fuel economy, beyond what is available with today's systems. Potential applications for demonstration include medium duty shuttle buses, vocational trucks, or on/off highway medium duty work trucks. A vehicle demonstration program that provides a platform for developing these medium duty technologies (similar to the SuperTruck project for heavy duty) is one potential approach with development and demonstrations to be completed by 2017.

Goal 5 - Hybrid System Optimization – Heavy Duty: An overarching goal is to develop and demonstrate heavy duty hybrid system technology that can deliver substantial increases in fuel economy. For urban, heavy start and stop driving cycles, a stretch goal of 60% has been identified. For regional haul and line haul applications, the percentage improvements would be more modest, but would still result in significant fuel savings, based on total fuel consumed in these higher mileage applications with a stretch goal of 25%. To meet these stretch goals the areas of emphasis would be:

- Develop an optimized hybrid system that would consider multiple factors, including size of major components (IC engine, e-machines, and battery), regenerative braking strategies, and methodologies for coordinating the hybrid drive unit and IC engine operation. This integration would decrease the overall cost and weight of the systems without effecting vehicle performance. Today's simulation tools can provide significant insight into sizing and control strategies. For optimum performance, the hybrid cannot be treated as a "bolt-on" component to a conventional vehicle, but a system that has been carefully integrated into the powertrain. Extensive simulation work must be followed up with controlled testing in vehicles, as well as real world on-road fleet operation. Additional review and development needs to be considered for those vehicles that would possess alternative anti-idling devices that could be provided without additional infrastructure changes.

Goal 6 – Electrified Power Accessories: Develop robust, durable, efficient electric power accessories for use with medium and heavy duty hybrid systems.

- Electrifying accessories such as power steering, air compressors, and AC compressors can achieve significant reductions in parasitic losses, by powering them "on demand." In addition, electrified accessories are a requirement for hybrid systems that are capable of operation in an "engine off" mode, utilizing only electric power for propulsion. Currently, there is a very limited supply base for such electric accessories. Due to low volumes and limited development, they are typically bulky, expensive, and may lack the reliability needed for heavy vehicles.

The Hybrid Team, in concert with the Vehicle Power Demands Team, should oversee R&D focused on developing such accessories for heavy duty vehicles that will drive cost down, reduce weight, improve reliability and potentially contribute several percent of improvement in fuel economy. Targeted availability of such improved accessories would be in 2016.

Summary – Significant progress has been made to date in the development of hybrid components and systems for heavy duty vehicles, yet much work remains to make such systems technologically practical and commercially viable. A significant portion of the development cost to date has been borne by private industry, with assistance from federal agencies such as DOE. The SuperTruck project is an excellent example of research and development efforts being accelerated by the influx of additional funding from DOE. At least two of the four SuperTruck development teams are exploring advanced hybrid technologies as one means of achieving the required 50% improvement in fuel efficiency.

Additional funding can be a very effective catalyst for exploring, selecting, and industrializing advanced technologies for hybrid vehicles. Such funding, along with the strong contributions of the National Laboratories, will facilitate private industry's efforts to make a number of these promising technologies reality. Federal Government funding will be critical to the success of the President's target of 1 million electric vehicles on the road in the United States by 2015.

The OEMs and major suppliers on the 21st Century Truck Partnership share a number of common technological and commercial challenges related to hybrid system development. By coming together and identifying the most pressing needs for continued progress, our combined voice can be most effective in recommending to DOE those advanced R&D initiatives that will pay the greatest dividends in advancing the state of our national hybrid industry.

Final Note on the Relationship Between 21CTP Hybrid Goals and EPA / NHTSA Regulations – The EPA, NHTSA, CARB, and IRS provide incentives for hybrids in certain applications (*e.g.*, page 151 of the EPA / NHTSA NPRM). Additional research and development is necessary to develop an array of HD hybrids with vocational coverage, fuel savings and cost-effectiveness, and durability that are sufficient to allow HD hybrids to cover a broad range of the HD vehicle market. Developing standardized, cost-effective validation techniques, specific to applications and use patterns, including mission profiles that involve non-driving intervals, will provide industry and regulators the tools needed to evaluate these emergent technologies in an efficient, cost-effective manner.

2.11. Technology Status and Plans for Hydraulic Hybrid Systems

Between 2009 and 2010 three hydraulic hybrid suppliers began their field trials of pilot fleets of the first parallel and series hydraulic hybrid technology in commercial refuse trucks in several cities across the US (New York, Miami, Houston, Los Angeles, etc.). The hydraulic hybrid systems delivered fuel efficiency results between 20% and 70% (depending upon parallel/series configuration and route), and cost is still a challenge to high market penetration since sales volume is still very low. Early field trials for class 6 hydraulic hybrid delivery trucks should begin in 2012. There are a large number of proof-of-concept and pre-production demonstration programs underway by several companies for both heavy and light duty vehicles.

2.11.1. Hydraulic Hybrid Drive Units

Currently, there are a number of different hydraulic hybrid drive unit technologies (e.g. swash-plate, bent axis, and radial hydraulic pump-motors) employed in production and demonstration programs. The large number of hydraulic hybrid vehicle applications will require various different solutions for the drive and engine pump-motor configurations. The existing technology will be leveraged, but several improvements are needed to transfer hydraulic pump-motor technology from the off-highway applications where it dominates today to the on-highway market. For example, increasing the maximum pressure of the system can increase energy density, thus increasing system performance. Current non-road hydraulic pump-motors are rated at 5,000 psi, and the goal for on-road applications would be to double this pressure rating to improve energy density, efficiency and reduce weight. In order to optimize system performance over the wide range of on-highway vehicle applications, subsystems such as integrating hydraulic drives with rear drive and gear reductions will need to be developed. Another example of pump-motor research that is needed is in the area of noise reduction. These types of pump-motors are in production today, but they must be redesigned in order to cost-effectively meet the performance, durability, reliability and noise requirements of the on-highway truck industry.

2.11.2. Hydraulic Hybrid Energy Storage

The typical method to be used for storing hydraulic energy in a heavy hybrid hydraulic vehicle is a hydro-pneumatic accumulator. Energy is stored when hydraulic fluid is pumped into a high pressure vessel and compresses an inert gas like nitrogen. These energy storage devices have been commercially available for decades, but the technology will need to be made lighter and optimized for on-highway vehicle applications. One of the key advantages of hydraulic accumulators is that they are designed to last the life of the vehicle and do not require replacement. Increasing the maximum system pressure above 5,000 requires advances to the accumulator, hose/connector and oil/gas barrier technologies. Developing these technologies, the manufacturing processes needed for high-volume production, and the associated supplier base, as well as demonstrating its durability for the heavy truck market will be the focus of this research.

2.11.3. Hydraulic Hybrid Control Systems

Advanced hydraulic hybrid control systems derive their fuel economy improvement from the use of three design and control strategies: 1) recovery and reuse of over 70% of braking energy (known as regenerative braking), 2) optimization of engine operation near the best efficiency “sweet” spot, and 3) reduction of engine operation (e.g. shutting-off when it is not needed to make power such as when the vehicle is braking or stopped, so there is never any engine idling). Early parallel hydraulic hybrids sold in the market place will likely be designed to only benefit from the first one or two strategies (e.g., designed only with hydraulic regenerative braking systems with little or no engine control optimization). These types of systems are in the evaluation vehicle stage today and are nearly ready for commercialization. Hydraulic hybrid “regen-only braking systems” have demonstrated 15-25% improvements in fuel economy in heavy vehicle applications (depending upon the drive cycle). Currently, several companies and government agencies have active hydraulic hybrid development programs looking at efficiency improvements using the first three design strategies. Advanced full-series hybrids which do not have a conventional mechanical drivetrain between the engine and the wheels are targeting 60-100% fuel economy improvements.

2.11.4. Hydraulic Hybrid Regenerative Braking

Hybrid hydraulic regeneration systems have very high power density allowing them to capture and re-use a very high percentage of the vehicle's kinetic energy. For heavy hybrid hydraulic vehicles, it is possible to capture and re-use as much as 70% of a vehicle's kinetic energy when the regenerative braking system is properly integrated. Modeling and testing indicate that fuel economy improvements (on a percentage basis) tend to increase with increasing vehicle GVW. Also, since much of the braking energy of the vehicle is captured and not wasted by the vehicle's friction brakes, brake life is extended substantially resulting in lower operating costs for the end user. Examples of vehicles with heavy urban start-stop duty cycles that can benefit from these hydraulic hybrid regeneration systems designs are pickup & delivery vehicles, shuttle buses, city transit buses, and refuse trucks. Although the technology is approaching a point where it can be commercially viable in some applications, additional development is required to optimize the system and components in order to make the technology viable to a wider range of vehicle applications. The high power density of hydraulic components provides a technology that is extremely scalable. In addition, the high power density facilitates the rapid recovery of the vehicle's kinetic energy during braking, thus allowing a very high percentage of that energy to be regenerated. There is no question that hydraulic hybrid systems can be created to cover the entire range of Class 2b to Class 8 vehicles. Prototype systems have already been created, installed, and tested in vehicles covering that entire range.

2.11.5. Hydraulic Systems Safety

Hydraulic hybrid devices currently use accepted industry standards for pressure vessels (e.g., ANSI/AIS NGV2-1998) and other components. The expected operating conditions of the hydraulic hybrid system (e.g., temperature and pressure) are within the normal limits for similar hydraulic components and systems today. Safety-related issues on which resources will focus include designing the systems for occupant and maintenance provider safety, establishing maintenance procedures, creating maintenance provider training tools, and creating appropriate warning labels.

2.12. Technical Barriers for Hydraulic Hybrid Systems

There are no technical "barriers" that are show stoppers to bringing hydraulic hybrid technology to market. However, there are some technical and manufacturing challenges that still require research to improve efficiency, reduce noise, reduce gas permeation, and develop high-volume low-cost manufacturing techniques.

2.13. Goals and Objectives for Hydraulic Hybrid Systems

Hydraulic Energy Conversion Devices: Develop a new generation of hydraulic pumps and motors that meet the on-highway markets demands for performance, cost, durability, and reliability. Higher pressure limits (7,000-10,000 psi) and the optimization of efficiency, weight, and noise reduction will also be important areas of development. Axial piston, radial piston, bent-axis, and variants of these types and potentially other types of pumps and motors will be studied to determine their suitability for heavy hydraulic hybrid systems. It is likely that a family of devices will be needed to adequately cover vehicle applications ranging from Class 2b through Class 8.

Hydraulic Energy Storage: Develop energy storage systems that meet the life targets of the vehicle. Develop storage devices with higher specific energy and energy density (e.g., higher maximum pressure, lower weight, etc.). Develop the manufacturing processes needed for high-volume production and the associated supplier base.

Hydraulic controls: Develop valves capable of higher operating pressures while maintaining low cost, high efficiency, and high reliability. Develop sensing solutions to lower cost and improve reliability. Optimize hydraulic circuit design to enhance system performance while maintaining simple system architecture.

Hydraulic Energy Transfer Fluids: Develop cost-effective fluids that meet the performance requirements of the system over the entire operating temperature range of the vehicles. Future fluids should also meet bio-degradability and fire resistance requirements. Many of these requirements are undefined and resources will be focused on both defining the requirements and testing the potential fluids to verify fluid life and component and system durability under anticipated environmental conditions.

3. Vehicle Power Demands

Promote research to reduce vehicle power demands to achieve significantly reduced energy consumption.

3.1. Introduction

Table 3. Energy audit and potential fuel efficiency improvements for line-haul trucks (Reproduced from 21st Century Truck Technology Roadmap)

Energy Loss Sources	Baseline
Engine losses per hour (kWh)	240
Auxiliary loads (kWh)	15
Drivetrain losses (kWh)	9
Aerodynamic losses (kWh)	85
Rolling resistance losses (kWh)	51
Total energy used per hour (kWh)	400

NOTE: Fully loaded on level road at 65 mph for 1 hour.

Table 3 presents an energy audit of a typical Class 8 vehicle operating on a level road at a constant speed of 65 mph with a GVW of 80,000 lb. Engine losses (240 kWh), account for approximately 60% of the total energy with the remaining losses associated with aerodynamic drag, tire rolling resistance, drivetrain losses and auxiliary loads. Collectively, these losses represent 40% (or 160 kWh) of the total energy losses. Improvements in aerodynamic drag and tire-rolling resistance can have a significant impact on fuel efficiency; improvements in driveline and accessory efficiency have a lesser influence on fuel efficiency. Proper management of thermal loads and overall vehicle weight also influence overall vehicle efficiency.

The basic configuration of a class 8 tractor-trailer has not changed over decades due to regulations and operational constraints. The 2006 statistics for combination trucks on the highway show that there are roughly 2.2 million trucks, each traveling an average of 65,000 miles/year and consuming 12,800 gallons of fuel per year. They consume roughly 12-13% of the total United States petroleum usage. At highway speeds, a class 8 tractor-trailer uses about 53% and 32% of the usable energy produced by the vehicle engine to overcome aerodynamic drag and rolling resistance, respectively. All vehicles will benefit from aerodynamic drag reduction. The higher the operating speed and the longer the drive duration, the greater the benefit will be. A 20% reduction in aerodynamic drag results in savings in fuel consumption for steady highway travel in the range of 10 to 15%. A 10% fuel economy improvement translates into 2.8 billion gallon of diesel fuel saved per year which is roughly equivalent to 2.5 million tons of CO_2 not released into the atmosphere.

Tire rolling resistance accounts for around 30% of the vehicle resistance to forward motion. Within the range of heavy vehicle tires, there are large variations in tire rolling resistance that can affect energy losses and fuel efficiency. Wide spread adoption of newer wide base single tires represents an opportunity to reduce rolling resistance of the vehicle, and at the same time reduce vehicle weight. However, there remain barriers to the use of wide-base singles that must be addressed in order to increase fleet usage. A 50%increase in tread depth translates into a 12% increase in rolling resistance – and by the end of life rolling resistance is reduced 25% versus a new tire. New compounding for improved wear and performance has shown that tread depth can be reduced to improve rolling resistance while not giving up other required performance metrics. Further, if future supplies of natural rubber run short and have to be replaced by synthetics, this will result in a 25% increase in rolling resistance. Hence, many factors need to be traded off in a systems context in order to maximize fuel economy and maintain other performance metrics.

Auxiliary power management is a crosscutting technology area that addresses the efficient and practical management of both electrical and thermal management requirements for all classes of heavy vehicles. Auxiliary power is required during both drive and idle periods for heavy vehicles. Power requirements are derived from many vehicle functions, including engine and fuel heating; HVAC; lighting; auxiliary components (e.g., pumps, starter, compressor fans); and hotel loads (HVAC, computers, entertainment systems, and on-board appliances like refrigerators, microwaves, coffee pots, and hot pads), as well as work function loads such as trailer refrigeration and the operation of power lifts and pumps for bulk fluid transfer. Currently, up to 30 kW of auxiliary power is required for transit buses. Class 8 tractor-trailers can require up to 15 kW of auxiliary power and an additional 30kW to power trailer refrigeration units. Other sources for auxiliary power to run electrical loads include use of waste heat recovery from application of the Rankine bottoming cycle.

A fully loaded tractor-trailer combination can weigh up to 80,000 pounds. Reduction in overall vehicle weight could enable an increase in freight delivered on a ton-mile basis. Practically, this enables more freight to be delivered per truck and improves freight transportation efficiency. New vehicle systems, such as hybrid power trains, fuel cells and auxiliary power will present complex packaging and weight issues that will further increase the need for reductions in the weight of the body, chassis, and power train components in order to maintain vehicle functionality. Material and manufacturing technologies can also play a significant role in vehicle safety by reducing vehicle weight, and in the improved performance of vehicle passive and active safety systems.

Thermal management focuses on minimizing the auxiliary load requirements for heating, ventilation, and air-conditioning (HVAC) systems while maintaining the thermal comfort of the vehicle occupants. Additional benefits in fuel efficiency can be achieved through the development of high-performance heat exchangers and cooling media (fluids), which will reduce the need for high-output engine water pumps. Technologies for reducing the vehicle thermal (solar) loads include advanced window glazing, thermal insulation, and ambient cooling and ventilation systems. Additionally, heat generated in the vehicle cabin can be used in various cooling techniques, including metal hydride systems, absorption, desiccant systems, and exhaust-heat waste-recovery systems. Recent developments in waste heat recovery and thermoelectrics offer new opportunities to recover energy from the exhaust stream and exhaust gas recirculation system. Reductions in friction and wear in drivetrain components can reduce frictional losses in transmissions, drivelines, and drive axles, contributing to reduced vehicle power demands.

3.2. Technology Goals

Vehicle power demands due to aerodynamic resistance, tire rolling resistance, accessory loads, vehicle weight, under hood thermal loads, friction, and wear collectively reduce the overall efficiency of heavy vehicles. Five primary technology goals have been identified for the partnership to address over the next ten years.

- **Technology Goal 1:** Develop and demonstrate advanced technology concepts that reduce the aerodynamic drag of a Class 8 highway tractor-trailer combination by 20% (from a drag coefficient of 0.69 to 0.55). Evaluate a stretch goal of 30% reduction in aerodynamic drag (from C_d=0.69 to C_d=0.48). The baseline for this goal is the proposed EPA/NHTSA baseline of C_d=0.69 with 9.2 m^2 frontal area for a conventional Class 8 tractor with high roof sleeper.
- **Technology Goal 2:** Develop and demonstrate low rolling resistance tires that can reduce vehicle rolling resistance and wheel weight for a Class 8 tractor-trailer. Demonstrate 35% reduction in rolling resistance from C_{rr}=8.2 kg/metric ton for drive wheels to a goal of C_{rr}=5.33 kg/metric ton. The baseline for this goal is the EPA/NHTSA proposed baseline for a Class 8 tractor/trailer equipped with low rolling resistance dual tire drive wheel configurations having C_{rr}=8.2 kg/metric ton.
- **Technology Goal 3:** Develop and demonstrate technologies that reduce essential auxiliary loads by 50% (from current 20 horsepower to 10 horsepower) for Class 8 tractor-trailers. The baseline for this goal is a Class 8 highway tractor/trailer with sleeper operating 5 day over-the-highway operations at 36,000 kg (80,000 pounds) CGVW.
- **Technology Goal 4:** Develop and demonstrate lightweight material and manufacturing processes that lead to a 10% reduction in tare weight for a 15,500 kg (34,000 pounds) tractor/trailer combination. Establish a long-term stretch goal of reducing combined vehicle weight by 20%. The baseline for this goal is a Class 8 highway tractor/trailer with high roof sleeper and dry van trailer capable of 36,000 kg CGVW.
- **Technology Goal 5:** Thermal Management & Friction and Wear. Increase heat-load rejected by thermal management systems by 20% without increasing radiator size. Develop and demonstrate parasitic friction reduction technologies that reduce driveline losses by 50%, thereby improving Class 8 fuel efficiencies by 3%. The baseline for this goal is a Class 8 highway tractor/trailer with sleeper operating at steady state 65 mph at 36,000 kg CGVW.

The goal of the 21st Century Truck Partnership is to conduct research and development, demonstrations, validation and deployment of cost effective, reliable and durable technologies that reduce vehicle power demand requirements. The partnership will utilize a vehicle system approach to continually track overall benefits of individual technologies on overall vehicle efficiency and performance.

3.3. State of Technology

3.3.1. Aerodynamics

Industry currently determines the aerodynamic characteristics of a truck design by using several techniques, including wind tunnel testing on reduced-scale models, full-scale trucks, and vehicle components (e.g., mirrors), track testing, and on-road testing. Industry has also begun to use simulations to guide experiments and design. Joint experiments and simulations are critical in developing an understanding of the key physics drivers and for the development of effective design concepts.

The effective approach in aerodynamic drag reduction is through the control/modification of the tractor-trailer flow field using passive or active add-on devices. There are three critical flow regions around the vehicle that should be treated: the gap between the tractor and the trailer, the underbody, and the base of the trailer. In addition, significant aerodynamic drag reduction can be achieved by use of geometry integration. These are essential components to develop and design the next generation of highly aerodynamic/fuel efficient class 8 heavy vehicles.

Current add-on devices can achieve significant reductions in drag (with devices like baseflaps, skirts, and side extenders). However, these devices often pose operational and maintenance issues that hinder their acceptance and use by fleet owners and operators. The objective for future efforts is to develop and implement more integrated and less obtrusive drag reducing concepts that are practical and affordable. This will require a well-organized and prioritized plan with the full participation of the partnership. Critical elements include experts in aerodynamics R&D working in conjunction with manufacturers and fleet operators providing the practical industrial experience. This effort includes a joint simulation and experimental (laboratory and track) with the use of optimization tools and techniques for efficient design, as well as field testing in real world applications. As part of a proposed rulemaking on heavy vehicle fuel efficiency, EPA/NHTSA have established a baseline C_d=0.69 with a frontal area of 9.2 square meters for a Class 8 tractor/trailer combination.

3.3.2. Tire Rolling Resistance

Tires affect vehicle fuel economy mainly through rolling resistance. As a tire rolls under the vehicle's weight, its shape changes repeatedly as it experiences recurring cycles of deformation and recovery. In the process, mechanical energy otherwise available to turn the wheels is converted into heat and dissipated from the tire. More fuel must be expended to replace this lost energy. Combinations of differences in tire dimensions, design, materials, and construction features will cause tires to differ in rolling resistance as well as in many other attributes such as traction, handling, noise, wear resistance, and appearance. Once they are placed in service, tires must be properly maintained to perform as intended with respect to all attributes. The maintenance of proper inflation pressure is especially important.

The characteristics affecting hysteresis are a tire's design and construction and the material types and quantities used. The beneficial effect of radial-ply constructions in reducing tire rolling resistance is an example of the influence of tire construction on hysteresis. In comparison with the bias-ply tire, the steel-belted radial tire reduced the deformation of the tread in the contact patch. Hence, in addition to affecting tire handling, endurance, and ride comfort, the changeover from bias-ply to radial-ply tires during the 1970s and 1980s reduced tire rolling resistance by an estimated 25 percent without requiring major changes in the polymers used.[7]

There are several measures of the geometry of a tire, including its outer diameter, rim diameter, and width. Reducing a tire's aspect ratio—that is, its section height relative to its section width—should reduce hysteresis if it is accomplished by shortening and stiffening of the sidewalls. The aspect ratio, however, can be altered in other ways—for instance, by changing the tire's outer diameter, width, rim diameter, or all three dimensions. Moreover, changing tire geometry is difficult without changing other characteristics of the tire that influence hysteresis, such as mass, material types, and construction features. As a result, it can

---

[7] Schuring, D.J., "The Rolling Loss of Pneumatic Tires," Rubber Chemistry and Technology, Volume 53, number 3, 1980, page 601.

be difficult to know, a priori, how specific changes in tire dimensions will translate to changes in rolling resistance.[8]

For heavy duty vehicles, low rolling resistance dual wheels and the wide base single tire for use on drive and trailer axles is representative of current state-of-the technology. Wide base single tires reduce rolling resistance, and at the same time reduce vehicle (unsprung) weight by up to 75 pounds per pair of conventional dual tires replaced. Resistance in the market place, driver and fleet owner perceptions, and other factors have limited widespread adoption of low rolling resistance dual wheels and wide base single tires. As part of a proposed rulemaking on heavy vehicle fuel efficiency, EPA/NHTSA have established a baseline rolling resistance for drive wheels of C_{rr}=8.2 kg/metric ton.

3.3.3. Auxiliary Load

Auxiliary power management is a crosscutting technology area that addresses the efficient and practical management of both electrical and thermal management requirements for all classes of heavy vehicles. Auxiliary power is required during both drive and idle periods for heavy vehicles. Power requirements are derived from many vehicle functions, including engine and fuel heating; HVAC; lighting; auxiliary components (e.g., pumps, starter, compressor fans); and hotel loads (HVAC, computers, entertainment systems, and on-board appliances like refrigerators, microwaves, coffee pots, and hot pads), as well as work function loads such as trailer refrigeration and the operation of power lifts and pumps for bulk fluid transfer. Currently, up to 30 kW of auxiliary power is required for transit buses. Class 8 tractor-trailers can require up to 15 kW of auxiliary power and an additional 30kW to power trailer refrigeration units.

The overwhelming majority of trucks and buses on the road today derive auxiliary power from belt- or gear-driven systems. These systems convert fuel energy to mechanical and electrical energy. Mechanical energy is used to operate mechanical-based auxiliaries (such as pumps and compressors); electrical energy is used for lights, ignition, fans, radio, and other electrical components. Although they are reliable, durable, and commercially cost-competitive, belt- and gear-driven systems inefficiently convert fuel energy to electrical or mechanical energy and tend to have constant outputs rather than supplying power on demand.

The long-term objective is complete electrification of the total vehicle. This will require removing auxiliary loads from the truck engine by transitioning from today's belt- or gear-driven technology to an electrical "power on demand" system. Managing where and when power is needed can provide many benefits, such as fuel savings, emissions reductions, and productivity enhancements. In addition, the overall system derives a number of benefits from the ability to provide flow, pressure, or power where needed for an engine function and from continuous adjustment to different operating modes.

Specific fuel cell goals have been identified that address auxiliary power unit applications for idling reduction and heavy vehicle electrification. Consistent with both the Fuel Cell Technologies Program and SECA goals, the Partnership supports the development of a $400/kW fuel cell system for auxiliary power units (3 to 30 kW) with a specific power of 150 W/kg and a power density of 170 W/L by 2010. In 2005 a

---

[8] National Research Council, *Tires and Passenger Vehicle Fuel Economy: Informing Consumers, Improving Performance – Special Report 286*, 2006.

project was awarded by the DOE EERE Fuel Cell Technologies Program to develop solid oxide fuel cells for heavy vehicle auxiliary power applications. An additional approach for supplying electrical energy for vehicle electrical loads would be through application of the Rankine bottoming cycle for thermal energy recovery. Instead of providing recovered energy back to the engine in the form of mechanical power, the Rankine bottoming could be used to generate electrical power for vehicle electrical loads.

3.3.4. Lightweight Materials

A fully loaded tractor-trailer combination can weigh up to 36,000 kg (80,000 pounds). Reduction in overall vehicle weight could enable an increase in freight delivered on a ton-mile basis. Practically, this enables more freight to be delivered per truck and improves freight transportation efficiency. In certain applications, heavy trucks are weight-limited (i.e. bulk cargo carriers), and reduced tractor and trailer weight allows direct increases in the quantity of material that can be carried. New vehicle systems, such as hybrid power trains, fuel cells and auxiliary power will present complex packaging and weight issues that will further increase the need for reductions in the weight of the body, chassis, and power train components in order to maintain vehicle functionality. Material and manufacturing technologies can also play a significant role in vehicle safety by reducing vehicle weight, and in the improved performance of vehicle passive and active safety systems. Finally, development and application of materials and manufacturing technologies that increase the durability and life of commercial vehicles result in the reduction of lifecycle costs.

In support of the overall goal to cost-effectively enable trucks and other heavy vehicles to be more energy-efficient and to use alternative fuels while reducing emissions, the 21st Century Truck Partnership seeks to reduce energy losses due to the weight of heavy vehicles without reducing vehicle functionality, durability, reliability, or safety, and to do so cost-effectively. In addition, it is recognized that improved materials may enable implementation of other technologies that can further improve the fuel efficiency of the vehicles. Weight reduction goals vary according to the weight class of the vehicle. However, the targets for all classes range between 10 and 33% reduction in weight. For example, a more specific goal of a 10% weight reduction with a long-term stretch goal of 20% reduction has been chosen for Class 8 tractor-trailer combinations. This is consistent with the 1,550 kg (3,400 pounds) reduction for a baseline tractor/trailer combination (with 150 gallons of fuel) weighing 15,450 kg (34,000 pounds). The weight targets for each vehicle class depend on the performance requirements and duty cycle. The targets reflect the goal for total vehicle weight. It is recognized that, in some cases, the weight reduction in the body and chassis will likely be significantly higher. It is important to note that materials or technologies developed for a particular vehicle class are not necessarily limited to that class. For example, materials developed for lightweight frames for pickup trucks, vans, or SUVs will eventually be used in Class 3-5 vehicles, and materials developed to meet the demanding performance requirements for Class 7 and 8 trucks will find application in smaller vehicles. In recent years, there has been increased focus on manufacturing technologies that reduce the cost penalty associated with more expensive lightweight materials by conducting research in manufacturing technologies that are adaptable to the lower production volumes associated with heavy duty commercial vehicles. Weight reduction must not in any way sacrifice the durability, reliability, and performance of the vehicle. Attaining these goals by reducing inertial loading will yield substantial benefits: increased fuel efficiency with concomitant reductions in emissions; increased available payload capacity for some vehicles; reduced rolling resistance; and optimized safety structures and aerodynamic drag reduction systems.

3.3.5. Thermal Management, Friction and Wear

Thermal management also focuses on minimizing the auxiliary load requirements for heating, ventilation, and air-conditioning (HVAC) systems while maintaining the thermal comfort of the vehicle occupants. Additional benefits in fuel efficiency can be achieved through the development of high-performance heat exchangers and cooling media (fluids), which will reduce the need for high-output engine water pumps. Numerous technologies have been identified, including direct heating and cooling of the vehicle occupants, eliminating in-dash venting systems, reducing vehicle peak and steady-state thermal loads, and employing heat-generated cooling techniques. Technologies for reducing the vehicle thermal (solar) loads include advanced window glazing, thermal insulation, and ambient cooling and ventilation systems. Additionally, heat generated in the vehicle cabin can be used in various cooling techniques, including metal hydride systems, absorption, desiccant systems, and exhaust-heat waste-recovery systems.

Friction, wear and lubrication are important considerations in reducing driveline losses in commercial vehicle applications. Advanced coating and lubricants will be needed to minimize friction losses in transmission gear sets, shafts and lubricating systems, as well as reducing friction in drivelines and drive axles.

A long-term need is the development of tools and technology to reduce parasitic friction losses in driveline and auxiliary components. Analytical tools based on mechanistic friction models are used examine the impact of boundary friction and lubricant viscosity on fuel economy. Detailed analysis of the results help identify the specific components that have the biggest impact on fuel economy, and the levels of improvements in friction needed to achieve a specific fuel economy. Figure 22 illustrates the overall impact of reducing boundary friction and lubricant viscosity on fuel consumption for a Class 8 truck running over an FTP driving cycle.

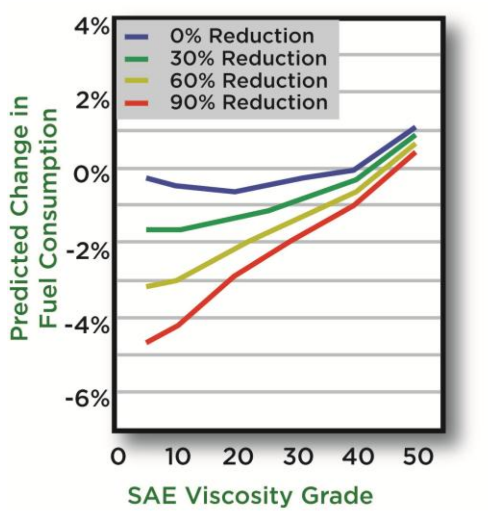

Figure 22. Reduction in Fuel Consumption as Function of Boundary Friction Reduction and Oil Grade

3.4. Research Progress in the 21st Century Truck Partnership

3.4.1. Aerodynamics

The DOE Consortium for Aerodynamic Drag of Heavy Vehicles has made considerable progress towards the goals of the 21st Truck Partnership over the last few years. More discussion of the progress and possibilities in aerodynamic drag may be found in Chapter 6, Efficient Operations.

3.4.2. Tires

Major tire manufacturers continue to introduce new tires and wheel systems based upon internal research for all vehicle vocations in the areas of tire structure, material compounding, tire sizes, tread design resulting a variety of customer tradeoffs to name a few such as wear, traction, rolling resistance and price.

Recently, Cooper completed a white paper for the DOE titled "Assessment of Petroleum Dependency of the U.S. Tire Industry" by Dr. Hyeonjae Kim, Dr. William Ferng, and Greg Bowman. This study highlighted the vulnerabilities to the industry with regard to oil dependency and outlined several issues and opportunities with regard to materials research and the impact on the natural rubber supply for tires worldwide. Should natural rubber for whatever reason become in short supply, alternative replacement options (including synthetics) would have a dramatic negative effect on tire rolling resistance.

3.4.3. Auxiliary Loads

The majority of activity in this area has focused around three areas: 1) the electrification of heavy vehicle components or "the more electric truck" 2) fuel cell auxiliary power and 3) waste heat recovery using advanced thermoelectric and turbo-charging. The projects in these areas have included coordination and integration between projects across DOE EERE, FE and DOD. For example, joint workshops on thermoelectrics have been held between DOE and DOD and funded projects have been coordinated across agencies. The FE sponsored Solid-State Energy Conversion Alliance (SECA) has coordinated fuel cell development for heavy vehicle applications with DOE EERE and DOD. Projects in the partnership have been competitively awarded and undergone annual peer review. Many of the milestones and deliverables have been adjusted over the last couple of years to better match available funding resources. The fuel cell auxiliary power programs have been coordinated with the Idle Reduction activities outlined in the Idle Reduction section of this roadmap document.

3.4.4. Lightweight Materials

The 21st Century Truck Partnership formed a Materials Team in 2001 and published a Research and Development Plan for Materials in December 2001 (21CT-002). During the time period from 2003 to the conclusion of the High Strength Weight Reduction (HSWR) Materials Program at the end of FY2006, the program focused on development and demonstration of lightweight materials and manufacturing technologies in partnership with the heavy vehicle manufacturers, their suppliers, and the DOE National Laboratories. Similarly, DOD, through programs at NAC, was also seeking to develop lighter weight military vehicles. New lightweight materials projects are planned under the Lightweight Materials program that supports both light- and heavy-duty vehicle materials needs.

Projects in the area of thermal management, friction and wear have been coordinated with the DOE Heavy Vehicle Systems Optimization Program. Program focus has been on reducing truck radiator size through efficient cooling systems, advanced nanofluid coolants and improved underhood design through modeling.

A new heavy vehicle lightweight materials technical roadmapping effort is currently planned by the Materials Technology office in FY2012. This roadmap effort will update the existing roadmap and solicit updated input from heavy vehicle OEM's, engine manufacturers and industry suppliers.

3.4.5. Thermal Management, Friction, and Wear

Projects in the area of thermal management, friction and wear have been coordinated with the DOE Heavy Vehicle Systems Optimization Program. Program focus has been on reducing truck radiator size through efficient cooling systems, advanced nanofluid coolants and improved underhood design through modeling.

3.5. Major Barriers

3.5.1. Aerodynamics

Perhaps the greatest barriers to reducing aerodynamic drag are related to the restricting operational factors in the transport of freight. The capacity of the cargo carrying trailer needs to be maintained and the trailer needs to be box shaped so that aerodynamic contouring of a trailer is limited. The trailers are fully interchangeable (i.e., a tractor does not always pull the same trailer) and there are several trailers for every tractor so that aero devices on a trailer provide more of an economical challenge than those on a tractor. Heavy vehicles must be maneuverable on country roads and negotiate sunken docks which restrict tractor-trailer gap treatments to those that will not limit turning radius or restrict trailer underbody treatments to those not causing high-centering. Trailers typically have trailing-edge access with swinging or roll-up doors so trailer base treatments must not restrict ease of opening or be prone to damage when trailers are closely packed into a parking or storage area.

3.5.2. Tires

The industry faces many barriers in the development of higher performance, lower rolling resistance tire systems. They must consider hundreds of compounding options and make tradeoffs between wear, traction and rolling resistance – but also are being challenged by new or existing federal and state regulations. An example cited that in one particular instance of a single wide- based tire (that replaces two trailer tires) was not legal in certain states due to the perception that contact stresses increased road repair. In another example a typical owner/operator may have always purchased a selected tire tread depth, and demands that for his new tires, when in fact new compounding with less tread depth would not only save money but improve fuel efficiency and performance. These examples show that technology improvements are needed along with training and education for the consumer.

Credible and repeatable third party test results are also needed as there are too many options with too much conflicting information as to what works and what does not. Various states are introducing labeling laws to better inform the buyer.

Finally there are a number of new opportunities, mostly in the instrumentation and measurement areas in which significant data and information could become available as feedback to the truck "system" so as to improve fuel economy (for example continuous tire pressure monitoring) and well as for safety (road patch measurement to indicate freeze onset). The barrier to many of these new technology options has always been cost. As vehicles become more electrified, sensors, data collection, on board analysis in real time will become the norm as volumes increase and cost becomes affordable.

3.5.3. Auxiliary Loads

There are several barriers to the development of auxiliary power technologies that will efficiently meet current power needs, address anti-idling issues, and meet future truck and bus power requirements. The trucking industry operates on small profit margins. Fuel costs and payload weights are important factors that directly affect profitability in the industry. Although many existing technologies have been demonstrated, the technology development process must focus on technology options that ultimately can be commercially viable. This includes the development of cost-competitive, safe, reliable, and durable technologies. Existing technologies, such as a small combustion-engine or fuel cell APU, can play a significant role in reducing fuel usage and emissions only if they are utilized by the trucking industry. Technologies must be developed to reduce fuel utilization, minimize weight, and meet all current codes and regulations. Complete electrification of the truck will require the development of energy-efficient and cost-competitive technologies as the industry transitions from belt- or gear-driven technologies to electrically driven components. This same technology is also directly applicable to and will benefit many other markets that utilize the same basic engines, such as buses, construction equipment, marine equipment, and military equipment.

3.5.4. Vehicle Weight Reduction

The principal barriers to overcome in reducing the weight of heavy vehicles are associated with the cost of lightweight materials, the difficulties in forming and manufacturing lightweight materials and structures, the cost of tooling for use in the manufacture of relatively low-volume vehicles (when compared to automotive production volumes), and ultimately, the extreme durability requirements of heavy vehicles. While light-duty vehicles may have a life span requirement of several hundred thousand miles, typical heavy-duty commercial vehicles must last over 1 million miles with minimum maintenance, and often are used in secondary applications for many more years. This requires high strength, lightweight materials that provide resistance to fatigue, corrosion, and can be economically repaired. Because of the limited production volumes and the high levels of customization in the heavy-duty market, tooling and manufacturing technologies that are used by the automotive industry are often uneconomical for heavy vehicle manufacturers. Lightweight materials such as aluminum, titanium and carbon fiber composites provide the opportunity for significant weight reductions, but their material cost and difficult forming and manufacturing requirements make it difficult for them to compete with low-cost steels. There is a need to overcome these barriers by the introduction of lower-cost lightweight materials, and most important, innovative forming and manufacturing technologies that are tailored for lower-volume, high durability vehicle structures, and that use low-cost tooling and assembly technologies that are suitable for heavy vehicle production volumes.

The principal barriers to overcome in reducing the weight of heavy vehicles are listed below.

Cost. The current cost of light weighting materials (compared with plain carbon steel and cast iron) impedes their widespread use in heavy-vehicle structural applications.

Design and simulation technologies. Adequate design data (e.g., materials property databases), test methodologies, analytical simulation tools, and durability data do not exist for many lightweight materials and manufacturing technologies. Current manufacturing processes for lightweight materials lack design flexibility and do not optimize the use of the materials for body structures.

Hybrid Materials and Structures. Hybrid materials and structures that use the optimum material for each application are not feasible with the current design and manufacturing knowledge base.

Manufacturability. Methods for the cost-competitive production of components for heavy vehicles are not sufficiently well developed. They also must be made compatible with heavy-vehicle manufacturing procedures and volumes.

Tooling and prototyping. The cost of tooling for forming components made with lightweight materials is too high in the volumes typical for the heavy-vehicle industry. The development and fabrication time required for prototyping components is too long.

Joining and assembly. High-yield, robust joining technologies for lightweight materials are not sufficiently developed. Assembly and joining techniques for dissimilar materials and hybrid structures are inadequate.

Vehicle corrosion. Many lightweight materials and light weighting approaches cannot be used in commercial vehicles because of significant corrosion and maintenance issues. Corrosion is a significant contributor to the cost of maintenance of heavy vehicles. Research is needed to develop materials that are resistant to both general and galvanic corrosion. Low-cost, durable coatings are needed.

Maintenance, repair, and recycling. Technologies for cost-effective maintenance and repair are inadequate for many lightweight materials. Recycling methods for lightweight materials are not as well developed as those for ferrous materials. Infrastructure and markets for efficient use of recycled composites are inadequate. Damage resistance and tolerance are not well developed for many lightweight materials.

3.5.5. Thermal Management

Many thermal-management issues are common between present-day vehicles and the advanced concepts under consideration. For example, on most vehicles, and especially on large trucks, the size of radiators and coolers dictates the front-end design which contributes significantly to the drag coefficient, and thus to fuel economy. Exhaust gas recirculation (EGR), which is a widely-used strategy for reducing NOx emissions, can add a 20 to 50% heat load to heat-rejection systems. Unfortunately, many conventional cooling-system components such as radiators, oil coolers, and air-conditioner condensers, are already at or are approaching their maximum practical size and functional limits.

The trend toward hybrid and fuel-cell vehicles is expected to further increase the demand on coolant heat-rejection systems. In fuel-cell vehicles, the exhaust of the fuel cell contains water vapor that needs to be recovered to reduce the amount of water carried onboard. Minimizing the size of the heat exchanger to accomplish this is a challenge. In diesel hybrids, there may be up to five separate cooling systems (for engine, batteries, motors, electronics, and charge air), and optimization of this design is a complex task. Many thermal management issues are also specifically associated with advanced concepts or with military applications. For military operations, any increases in radiator size will not only affect aerodynamics and parasitic energy losses, but also limit any decrease in cab size that is desirable for space savings in airlift operations. All of these demands have created a need for new and innovative thermal management technologies that will require long-term R&D.

3.5.6. Friction and Wear

Several barriers/challenges in friction and wear include: improving fuel efficiency without sacrificing durability and reliability, and development of cost-effective technologies to reduce friction and wear in driveline components.

- Reducing the viscosity of drivetrain fluids significantly reduces viscous and windage losses. Current designs, materials, and lubricants are inadequate to maintain component durability and reliability when used with low-viscosity fluids.
- Cost-effective, high-volume manufacturing of low-friction, wear-resistant materials, surface treatments, and additives are lacking.
- Integration of component designs with advanced materials, engineered surfaces, and lubricants into complete systems is poor.

3.6. Approach to Reaching Goals

3.6.1. Aerodynamics

The challenge of reducing Class 8 truck aerodynamic drag requires a highly-directed systems approach to the engineering task. Considering the tractor-trailer as a total system will gain the most benefit from aerodynamic improvement; thus it is imperative that fleet owners and operators, tractor and trailer manufacturers, along with R&D experts in aerodynamics simulation and experimentation, all be part of this program.

The areas in which improvement in aerodynamic drag of Class 8 trucks can be realized are:

- Investigation of new, innovative drag reducing concepts based on a design approach that utilizes knowledge of the flow physics (based on simulations and laboratory experiments) with consideration of vehicle operation restrictions.
- Refinement of tractor designs and system modifications including repositioning of components (e.g., remote mounted cooling system) through the use of flow simulations in conjunction with advanced optimization tools with laboratory validation experiments.
- Address vehicle operation issues with current devices (e.g., baseflaps, skirts, gap splitter plate) or alternate component options (e.g., mirror replacement with camera system, dual tire replacement with super singles).
- Integrated approach to heavy vehicle system design may consider interaction of components and operational impacts.
    - Power-train integration: Engine, drive train components, and road/vehicle interface (tires)
    - Highway integration: Roadway design and use and tire/road integration
    - Flow conditioning integration: Components which alter flow fields to improve performance
    - Geometric integration: Integration of tractor and trailer bodies

The goal of reducing aerodynamic drag must be considered in light of other vehicle requirements. In particular, the addition of exhaust gas recirculation (EGR) systems will put additional requirements on cooling systems, including pumps, fans and radiators. These components impact the under hood space requirements and work in opposition to the need to reshape the front-end of the vehicle for drag reduction. In addition, the competition for space between cooling systems and front end shaping may also affect the need for improved front-end energy-absorption systems. These seemingly contradictory requirements underscore the need for a systems approach.

3.6.2. Rolling Resistance

The following activities could greatly accelerate the introduction of new highly efficient tire systems and help the industry prepare for increased raw material supply constraints which could have a 25% negative impact on fuel economy.

- Encourage SuperTruck teams to have access to the latest and best tire system technology possible
- Develop domestic material alternatives to natural rubber at equivalent performance metrics for tire performance
- Work with states that are introducing tire labeling laws, conduct independent testing, and publish unbiased results for each tire normalized on the basis of energy efficiency and other performance metrics
- Encourage projects with tire OEMs that obtain real time direct feedback electronics for "smart tire systems"
- Since most tires will be replaced in a few years, conduct third party education seminars with literature to dispel myths from facts on energy efficiency so that future buying decisions enhance and upgrade the existing vehicle tire stock.
- Utilize National Laboratory computing facilities to work with OEMs to produce and test state of the art designs at a multi-physics based approach to solve material, structural, thermal - simultaneous problem solvers with optimization schemes.

3.6.3. Auxiliary Loads

The technical approach to addressing current auxiliary power requirements will include the following steps:

- Conduct system analysis to evaluate potential technologies that support the electrification of auxiliaries and reduce electrical requirements.
- Develop and demonstrate cost-effective technologies that will enable the electrification of auxiliaries by means of stationary power sources.
- Support development of industry standards for electrical system designs for heavy-duty vehicles to assist in establishing criteria such as uniform voltage levels.
- Assist in establishing industry standards for uniform connector and power level for electrical power connections at truck stops.
- Determine system requirements for fuel cell APUs for heavy duty vehicles.

- Develop miniature fuel processors for polymer electrolyte membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) systems.
- Develop and verify fuel cell technologies for APUs (to 30 kW) and off-road systems.
- Develop diesel reforming capability for auxiliary power units.
- Test and evaluate fuel cell APUs for heavy-duty vehicles under simulated duty cycles and rigorous durability cycles.
- Develop high specific power, high durability 1-30 kW solid oxide fuel cell system that will meet technology targets.
- Investigate the application of Rankine cycle bottoming for waste heat recovery and conversion to electrical energy for further truck electrification.
- Develop motor/generator technology to reduce size, increase efficiency and reduce cost for heavy vehicle applications.
- Continue development of higher efficiency thermoelectric conversion from exhaust and EGR heat sources.
- Alternative air conditioning technologies that eliminate the need for an engine driven refrigerant compressor.
- Research and development for battery technologies for hybrid heavy vehicle powertrains.

3.6.4. Vehicle Weight Reduction

Lightweight materials and manufacturing R&D in the 21st Century Truck Partnership will focus on developing technologies that are aimed at addressing the barriers listed for lightweight materials to permit their accelerated development and introduction into the trucking industry. Materials and manufacturing technology development during the period from 2010 going forward is focused on:

- Development of technologies for enhanced manufacturability of lightweight components for trucks and buses;
- The introduction of lower cost carbon fiber and hybrid composite materials for heavy trucks;
- Lower-cost tooling and assembly technologies to reduce component part-count and resulting tooling cost;
- Adapting established heavy vehicle materials and manufacturing technologies, such as Sheet Molding Compound and compression molding to lighter weight carbon fiber and hybrid composite materials;
- Development of design concepts and material data bases to provide design engineers the flexibility to consider lightweight materials in vehicle design; and
- Development of technology in support of advanced materials, joining, maintenance, and repair.

The greatest weight reductions are foreseen through the use of high-strength steel, aluminum alloys, and polymer matrix composites in frames and bodies and, in lesser quantities, in wheels, cabs, transmission housings and shafts, and suspension components. Ultra large, thin-wall aluminum and steel castings, superplastic forming of aluminum, and integrated composite manufacturing technologies will reduce part count and thereby weight and cost. Hybrid composite materials that utilize lower-cost glass fiber and core materials in combination with carbon fiber reinforcements can meet structural requirements while reducing the amount of more expensive carbon fiber. Other weight reduction opportunities include stainless steel in frames, reinforced aluminum blocks in light-duty engines; sandwich, cored, and foam materials for body panels; and metal matrix composites, titanium, and magnesium alloys for specialized components.

3.6.5. Thermal Management

A key goal for thermal management activities is to increase heat-load rejected by thermal management systems by 20% without increasing radiator size. Exhaust gas recirculation (EGR) is the most popular near-term strategy for reducing NOx emissions, but can add 20-50% to coolant heat-rejection requirements. There is also a need to package more cooling in a smaller space without increasing cost. These new demands have created a need for new and innovative technologies and concepts that will require research and development. This will include advanced concepts for increasing heat transfer in both coolant fluids and advanced heat exchangers.

Several research areas identified by industry and government researchers can provide both near-term and long-term solutions to many of the next management problems. The research areas are identified as follows:

- Intelligent thermal management systems for more electrical vehicle systems and components
- Advanced heat exchangers and heat-transfer fluids, including nanofluids, carbon foams, and cooling system components
- Advanced thermal management concept development including heat pipes and waste heat recovery
- Simulation-code development for computational fluid dynamics simulations for use in modeling airflow, fluid flow, underhood aerodynamics and cooling system components

3.6.6. Friction, Wear, and Lubrication

Major topics identified by industry and government researchers include near-term and long-term solutions to improve fuel economy, while maintaining system durability & reliability:

- Integration of mechanistic friction and wear models into codes to predict and mitigate parasitic energy losses in driveline components
- Advanced materials and coating technologies that lower friction, reduce wear, and improve reliability
- Engineered surfaces – modeling, development, and testing of textured surfaces to improve friction and lubrication properties, including laser and mechanical texturing and coatings
- Boundary layer lubrication – fundamental studies of phenomena that control friction, durability and reliability of driveline components

Table 4 - Schedule of Major Activities and Milestones

	06	07	08	09	10	11	12	13	14	15	16	17	18
Aerodynamics													
Demonstrate computational-based design tools for integrated applications of drag reducing technologies													
Perform system study for "clean sheet" power tractor design optimized for reduced aerodynamic drag (30% reduction)													
Perform vehicle OEM on-road demonstrations of selected aerodynamic reduction technologies to validate operation													
Tire Rolling Resistance													
Complete on-road demonstration of low rolling resistance tire systems with selected Super Truck teams													
Conduct educational programs promoting low rolling resistance tire technologies and their fuel savings benefits													
Competitively fund development of domestic alternative tire materials, including alternative natural rubber materials													
Auxiliary Loads													
Complete systems studies to identify electrification candidates and heavy vehicle electrical requirements													
Conduct alternate fuel cell technology demonstrations for PEM and solid oxide fuel cells													
Demonstrate Rankine bottoming cycle technology for electrical generation and vehicle electrification													
Complete competitive development and demonstration of high power, compact and low-cost motor/generator systems.													
Lightweight Materials													
Complete update of Heavy Vehicle Lightweight Materials roadmap (in conjunction with Materials Tech. office)													
Develop low-cost forming and tooling technologies for advanced aluminum, steels, magnesium and composites													
Demonstrate hybrid fiber reinforced composites using carbon, glass and natural fibers for reduced cost and improved performance													
Demonstrate production capabilities for advanced casting, including ultra-large castings													
Thermal Management and Friction and Wear													
Demonstrate waste heat recovery technologies for exhaust and EGR													
Integration of friction and wear models to reduce powertrain loss													
Develop advanced coatings for reduced friction and wear													
Downselect and demonstrate engineered surface applications for reduced wear and friction													

4. Idle Reduction

Promote the development and deployment of engine idle reduction technologies that substantially reduce energy consumption and exhaust emissions due to heavy vehicle idling.

4.1. Introduction and Background

Long-haul trucks idle a significant portion of the time. A typical long-haul truck idles anywhere from 1,400-2,400 hours per year when parked overnight at truck stops and other idling areas like warehouses and terminals. Nationally, a significant amount of fuel is consumed unnecessarily this way – Class 7 and 8 trucks alone consume about a billion gallons of diesel fuel annually during overnight idling. Drivers have many reasons for keeping the diesel engine running in a tractor-trailer: (1) to keep the cab and/or sleeper heated or cooled, (2) to keep the fuel warm in winter, (3) to keep the engine warm in the winter to permit easier startup, (4) to provide power to operate electrical appliances such as microwaves and TV sets, (5) to keep the batteries charged, and (6) because the other drivers do it. Until now, the focus has been on overnight idling, which represents a very visible target for conservation and emission reduction efforts. In addition, commercial vehicles of all sizes also idle for extended periods during their workdays, often creeping along in queues at ports and depots, and the quantity of petroleum used for workday idling may be far greater than that used by sleepers overnight. The sum of overnight and workday idling of trucks is estimated to consume well over 2 billion gallons of diesel fuel annually in the United States.[9] Other vehicles with diesel engines are also idled for long periods: school bus drivers idle their buses in the morning to defrost the windshield and heat the bus, and transit and tour bus drivers idle their buses to heat or cool the bus while waiting for passengers. Off-highway vehicles and locomotives are idled to keep the engine and fuel warm in cold weather. Military vehicles also spend a significant amount of their engine on-time idling, usually as part of a silent watch and/or to provide power to their hotel loads, communication, and weapons.

Idling produces airborne emissions and noise in addition to excess fuel consumption. Air quality at and around truck stops, and in the truck cab itself is often poor,[10] and noise levels make it difficult for truckers to sleep. A number of cities and municipalities have banned or restricted idling to reduce these impacts. Since the last report to the National Academy of Sciences, the number of states and localities that have enacted anti-idling regulations has greatly increased. The latest compendium of the American Transportation Research Institute (ATRI)[11] now shows that idling is restricted in at least 12 more areas, bringing the total number of states and jurisdictions to at least 46. Many states have strict regulations in

---

[9] L. Gaines, A. Vyas, and J. L. Anderson, Estimation of Fuel Use by Idling Commercial Trucks, Transportation Research Board Annual Meeting, January 2006

[10] P. Doraiswamy, et al., Measuring Air Pollution Inside and Outside of Diesel Truck Cabs, for the U.S. Environmental Protection Agency (November 4, 2005) http://www.epa.gov/SmartwayLogistics/documents/incabairquality-110405.pdf

[11] American Transportation Research Institute, Compendium of Idling Regulations, June 2010.

, http://www.atri-online.org/index.php?option=com_content&view=article&id=164&Itemid=70

more than one city, while others are statewide; sometimes the regulations for the city are different from those of the state. The California Air Resources Board adopted a rule that has not only limited idling to 5 minutes since 2007, but also requires automatic shut-off devices. In addition to this confusion, these regulations are unevenly and irregularly enforced; in New York City, for example, city parking monitors could not write tickets until recently because their hand-held computers did not have a code for idling. On the other hand, Region 1 (the New England states) of the U.S. Environmental Protection Agency (EPA) handles enforcement because idling reduction is a part of that region's State Implementation Plan required by EPA.

For example, Philadelphia bans idling of heavy-duty diesel-powered motor vehicles, with exceptions made during cold weather. Some of the states and districts with idling regulations include: California, Colorado, Connecticut, Hawaii, Illinois Maryland, Massachusetts, Minnesota, Missouri, Nevada, New Jersey, New York, Pennsylvania, Texas, Utah, Virginia, and Washington, D.C. Although many of these ordinances are not strictly enforced, Boston and New York City are among the localities that have started enforcing anti-idling regulations more aggressively.

Extended idling by commercial trucks costs truck owners about $6 billion annually and wastes over 1% of our petroleum usage. Much of this petroleum use could be avoided by installing idle reduction technologies, adopting more efficient freight scheduling policies, or in some cases, simply turning the trucks off. Reducing idling would improve the durability of the vehicles and result in maintenance cost savings by reducing engine-on time and the frequency of oil changes, as well as increasing the interval to engine overhaul. But the main reason for interest in idling reduction is that idling wastes diesel fuel, and the price of diesel fuel is high and extremely unpredictable. In order to combat the high cost of diesel fuel and maintenance, truck owners have started installing idling reduction devices such as stand-alone battery-powered air-conditioners and direct-fired heaters, or on-board auxiliary power units (APUs) that generate electric power at a fraction of the amount of fuel used by idling the truck's main engine. A survey conducted in February 2006 by ATRI of 55,000 truckers found that 36 percent of respondents with sleeper cabs currently use on-board idle reduction technologies. The most prevalent on-board technology determined by the survey was direct fired heaters (32%), followed by battery-powered air-conditioners (24%), while APUs were used by 12% of respondents.[12] One of the measures of accomplishment for the 21CTP's R&D effort in this area has been increased customer demand for idle reduction devices that has led most truck manufacturers to offer these components as OEM options, coupled with improved cab insulation in some models. Truck manufacturers have also related that another popular OEM idle reduction option ordered on new model trucks was shore-power kits for plugging in at truck stops/rest areas. These included electric air-conditioners and heating units located in the sleeper compartment.

4.2. Goals and Objectives

To date, 21CTP has not been able to carry out the necessary surveys to quantitatively measure the progress being made in reducing idling fuel consumption due to an absence of funding for such studies. Only

[12] American Transportation Research Institute, **Idle Reduction Technology: Fleet Preferences Survey,** February 2006. http://www.atri-online.org/research/results/Idle%20Reduction%20Technology%20Fleet%20Preferences%20Survey.pdf

qualitative observations can attest to the increased adoption rate of these devices for which the primary drivers have been (1) the high cost of diesel fuel and (2) regulatory measures adopted in some states and cities to reduce idling. Therefore, it is recommended that the following list of accomplishments/goals be budgeted in the upcoming fiscal year:

- Goal 1: Work with OEM truck manufacturers to obtain data on the number of new trucks being ordered with IR options.
- Goal 2: Conduct a fleet survey to gather data on the amount of in-use idling hours that are accumulated by type of heavy-duty vehicle.
- Goal 3: Acquire data from the EPA SmartWay Program to measure fuel savings and emissions reductions associated with the various type of IR equipment available.
- Goal 4: Establish a nationwide multi-mode IR education program.
- Goal 5: Promote the incorporation of IR equipment on new trucks as fuel saving devices as they are identified through the DOE SuperTruck project.

Without funding dedicated to this effort, it is quite difficult, if not impossible, for the 21st Century Truck Partnership to accomplish these goals.

Assuming there is funding, the action items below lay out a path to accomplishing the stated objective. The first four activities that will enable achievement of truck idling reduction have been grouped together because they are interrelated. These action items are to:

- Continue industry/government collaboration to promote the development and deployment of cost-effective technologies for reducing fuel use and emissions due to idling of heavy-duty diesel engines.
- Expand the current educational programs for truck and bus owners and operators to implement enabling technologies and operational procedures to eliminate unnecessary idling.
- Investigate a mix of incentives and regulations to encourage trucks and buses to find other more fuel-efficient and environmentally-friendly ways to provide for their power needs at rest.
- Promote the development and demonstration of cost-effective add-on IR equipment that meets driver cab comfort needs, has a payback time of 2 years or less, and produces fewer emissions of NOx and PM than a truck meeting 2010 emission standards.
- Reduce the thermal load of the truck heating, ventilating, and air-conditioning (HVAC) system during driver rest periods through implementation of efficient cab insulation systems and low thermal transmission glazing. Reduction of cabin energy load, through the addition of insulation and window glazing, coupled with controls to reduce peak energy loads, could enable downsizing of APUs and battery-powered systems to reduce cost and weight while enhancing their performance.[13]
- Produce a truck with a fully-integrated electrically-powered truck cab HVAC system to reduce IR system component duplication, weight, and cost by 2017.

---

[13] National Renewable Energy Laboratory's (NREL) study, *CoolCab: Reducing Thermal Loads in Long-Haul Trucks*, February 2010. http://www.nrel.gov/vehiclesandfuels/fleettest/pdfs/47415.pdf

- Develop and demonstrate viable fuel cell APU systems for military and other users, in the 5-30kW range, capable of operating on JP-8 fuel with 35% efficiency (based on the fuel's heating value) by 2015.

4.3. Remaining Barriers to Achievement of the Goal and Objectives

1) Availability of OEM installed units with improved performance and lower cost. R&D activities may improve the effectiveness of the IR technologies, but market acceptance will depend primarily on the perceived economic benefit of the technology. The cost of integrating IR devices into new trucks needs to be reduced to where truck purchasers can see a payback of 2 years or less for their added investment. Since the vast majority of trucks are purchased by independent owner-operators, confidence in a rapid payback is critical to the economic viability of any new technology.

2) Availability of cost-effective retrofit units. Market penetration of IR technology began slowly, but recent high fuel prices are encouraging equipment purchases, and a growing number of states and metropolitan areas with anti-idling regulations are forcing the decision to retrofit IR equipment on existing trucks. R&D breakthroughs, in conjunction with equipment manufacturers' ingenuity to make these retrofit IR units smaller, cheaper, less time-consuming to install, and more reliable will increase actual benefits and could hasten market acceptance. In addition, truck resale value is a top priority with independent truck operators, who may have not yet recognized the added value IR equipment represents.

3) Most places trucks stop during rest periods do not provide electrical outlets. New IR technologies enable the driver to shut off the main engine while parked and instead use electricity from an off-board electrical connection known as "shore power" to power equipment and appliances in the truck cab. A 2006 study by the Electric Power Research Institute (EPRI) observed that the savings in fuel costs alone could amount to more than $1 per hour or approximately $2,000 per year per truck without sacrificing driver comfort.[14] However, the barrier to widespread adoption is the fact that the number of "resting" trucks far outnumbers the amount of parking spaces in both state-maintained rest areas and privately owned truck stops combined. Moreover, only a small fraction of these rest spaces have electrical infrastructure available to plug in such on-board shore power systems.

4) IR technology to address workday idling fuel usage. Fleet studies are needed to better characterize the magnitude and causes for workday idling and devise proposed solutions. The development of an energy-storage system and motor to enable vehicles to operate in creep mode, with the main engine off, would be useful in addressing the workday idling fuel usage problem, i.e. a lower cost version of a heavy-hybrid powertrain would be one way to accomplish this.

5) Lack of analysis tools and test data to quantify the benefits of thermal load reduction technologies. There is a need within the truck manufacturing industry for analysis tools that can quickly and accurately predict the impact of thermal load reduction technologies on HVAC thermal load and idle

[14] Electric Power Research Institute, *Case Study: Diesel Engine Idle Reduction in Class 8 Trucks Using On-Vehicle Equipment with Optional Shore Power*, August 2006.

fuel use. Without a clear understanding of potential benefits, manufacturers are hesitant to incorporate new IR technologies, and truck cab buyers do not know if the new features will offer a short payback time.

6) Lack of consistent regulations. Uniformity and better enforcement of existing regulations would provide an increased disincentive for idling. The EPA, with input from other 21CT partners, promulgated a model law to enable regulatory consistency, but idling laws still vary widely from state to state. A major impediment delaying mainstream market acceptance of IR technology is uncertainty about idling legislation that would mandate or preclude specific devices. There are no national standards for on-board IR equipment, and equipment purchased and installed in most parts of the United States might not be legal everywhere. For example, California requires a particulate control system (not yet available) on the APU for 2007 MY and later trucks that outlaws the use of APUs without particulate filters in that state. Moreover, the California regulation serves as a disincentive to any 50-state freight carriers for purchasing APUs, and APUs can be perceived as a negative impact on truck resale value. Development of a low-cost diesel particulate filter for small auxiliary engines would enable compliance in California, but there is no assurance that similar inconsistencies would not cause problems in the future.

7) Public awareness and truck fleet education programs. Increasing public/industry awareness and education of end-users, as exemplified by the U.S. Army's former SunLine Transit fuel cell APU demonstration program, would help generate the public and fleet-owner awareness of IR technologies. In addition, dissemination of information on the comparative benefits of competing technologies would reduce buyer confusion about the plethora of available technologies (see Appendix).

8) Increased financial incentives. Even if rapid payback is assured, many heavy vehicle owners do not have the capital to invest upfront. We have examples of large fleets implementing IR technologies without the use of incentives, based only on the merits of the benefits derived from reduced fuel use, emissions, maintenance, and driver comfort. However, for the majority of fleets, the early adoption of IR technologies can be accelerated by continued assistance through appropriate government subsidies or other financial incentives. Such incentives should include additional tax credits or low-interest loans, and would include extending R&D grants to support government-industry partnerships to develop some of the improved IR technologies mentioned here. Many incentive programs are only available for trucks that remain within a specific geographical area (and all of them are oversubscribed), but most long-haul trucks travel widely. Therefore, more programs need to be regional or national in scope. There has been some legislation in the past several years related to idling reduction. The exclusion from Heavy Truck Tax for Idling Reduction Units and Advanced Insulation[15] allows for APUs and advanced insulation having an R-value equal to or more than R-35 to be exempt from paying the 12% Federal excise tax. The Emergency Improvement and Extension Act modifies the Internal Revenue Code to allow this exemption.

In recognition of this need for financial incentives, DOE, DOT and EPA projects funded by the American Recovery and Reinvestment Act of 2009[16] (known as the "stimulus") awarded approximately $225 million devoted to the purchase and installation of various types of fuel-efficient technologies of which truck idle

[15] Section 206 of the Emergency Improvement and Extension Act (EIEA) of 2008 (Public Law 110-343)

[16] Public Law 111-5

reduction was a key component. DOE used block grants and solicitations to make awards to states and localities to reduce idling, among other projects. Part of DOE's SuperTruck projects (which will be discussed later in this document) used stimulus funding, and all the teams are incorporating idling reduction in their projects. Likewise, EPA stimulus awards from its National Clean Diesel campaign, of which the SmartWay Transport Partnership is a part, support idling reduction. Table 3 below shows how these DOE, DOT and EPA grants will foster idling reduction. Values shown include a range of technology development and deployment activities, of which idling reduction is a part. It is virtually impossible to tease out the exact amounts of funding for IR given the nature of the awards. Note that in most cases, idling reduction is just one element of the project.

Table 5. Summary of American Recovery and Reinvestment Act Funding for IR Related Projects

Activity	Project Description	Approximate Funding
Purchase and installation of IR equipment for on-road diesel vehicles, including school buses, and educational outreach about the benefits of idling reduction	APUs, fuel-operated heaters, battery-powered air-conditioners, engine block heaters, and engine start-up/shut-off idle control systems (and other emission reduction projects—such as engine repowers, replacements, or installation of diesel oxidation catalysts—in cases where bundled with IR projects)	>$65 million
Purchase and installation of IR equipment for nonroad vehicles (ports, railroads, airports, and agriculture)	Installation of shoreside electrical power and the retrofit of ocean-going vessels, "gensets" for locomotives, and electrification of ground-support equipment for airports	>$25 million
Truck stop electrification (TSE)	Wayside single-system (no onboard equipment required) and dual-system TSE projects	>$32 million
DOE "SuperTruck" development and demonstration projects that have an IR component	Cummins: Development and demonstration of a highly efficient and clean diesel engine, an advanced waste heat recovery system, an aerodynamic Peterbilt tractor and trailer combination, and a fuel cell APU to reduce engine idling Navistar: Development and demonstration of technologies to improve truck and trailer aerodynamics, combustion efficiency, waste heat recovery, hybridization, IR, and reduced rolling resistance tires	>$78 million
DOT projects with explicit congestion mitigation and idling reduction components	Grade separation (road and railroad) and highway improvements	>$55 million

4.4. Roles and Activities of 21st Century Truck Partners

All of the 21st Century Truck partners, both industry and government agencies, have important roles in developing and implementing a coherent program of IR. DOE analyzes technology needs and performs the appropriate R&D to help make cost-effective technology available for implementation. The results of the analysis enable a systematic comparison of potential strategies, including emission credits, positive incentives, and regulations to install appropriate IR technology. EPA and DOT have been named to lead the effort in implementation. A major goal of the DOD is to reduce the logistical footprint of deployed forces, primarily through savings in fuel consumption. Thus, DOD's goal overlaps with those of the other partners. For example, the U.S. Army RDECOM CERDEC lab is working in conjunction with the U.S. Army PM-HTV (Heavy Tactical Vehicles) to demonstrate the feasibility of a diesel engine APU on the M915A5 long-haul tractor. The 21st Century Truck industrial partners and their suppliers need to work together to make IR technologies an affordable and cost-effective part of their vehicles' design, seamlessly integrating their choice of technologies into the operation. Other stakeholders are working on the IR effort as well, with cooperation from 21st Century Truck partners. For example, local, state, and regional air quality agencies have teamed up with the EPA and DOE's Clean Cities coalitions to form regional collaboratives to address diesel engine emissions, with IR as a major component of their efforts. Two examples are the Mid-Atlantic Region Air Management Association (MARAMA) and the West Coast Diesel Collaborative. EPA's collaboratives publish solicitations on these topics as does DOE's Clean Cities Program. TSE awards are one type of project that has received funding from these programs.

DOE activities: The DOE provides the leadership for R&D and analysis activities that will enable advanced-technology solutions to the idling problem. In its labs, DOE has the skills and resources to focus on energy consumption and emissions reduction R&D through a blend of in-house and contract R&D and analysis activities. However, current R&D activity is at a reduced level due to heavy-duty vehicle sector funding constraints for the past 8 years. Accomplishments to date include the following activities:

- DOE analyzed how energy use and emissions of CO_2, NOx, and rural and urban PM_{10}, for idling and alternatives, varied with climate (more heating/cooling needed) and local electricity generation mix. Additional work compared costs of idling and alternatives as functions of idling duration, fuel costs, and device costs. Combined results of the two efforts enabled comparison of the effectiveness of IR strategies, in terms of both costs and emission reductions, and compared the economics of the different options for supplying cab comfort to truck drivers.[17] These results were published and disseminated.
  - For trucks that idle fewer than about 20 hours per week, technologies with low capital investment for the truck owner are the most attractive from a total cost perspective. These include electrified parking spaces (EPS) and idling. From an emissions standpoint, of course, idling is the least attractive alternative. Direct-fired heaters supply heat with the lowest cost impacts, and the most desirable methods for supplying air-conditioning are thermal storage air-conditioning units, if the truck is a 2007 or later model, or EPS.

[17] L. Gaines, C. J. Broderick Hartman, M. Solomon, *Energy Use and Emissions Comparison of Idling Reduction Options for Heavy-Duty Diesel Trucks*, TRB Paper 09-3395, Transportation Research Board Annual Meeting, January 2009

- For trucks that idle over 20-30 hours per week, technologies using on-board equipment, including dual-system EPS, result in the lowest total cost to the truck owner over 5 years of operation, while single-system EPS results in the highest total cost. NOx from pre-2007 trucks and CO_2 emissions can be reduced by air-conditioning via EPS, but this results in an increase in PM10 because of the use of coal in the grid mix in all states. However, most of these PM10 emissions are upstream in rural areas, leading to low population exposure and resultant health costs. One significant advantage of wayside systems is that they guarantee that local emission reductions occur at their locations, although this may be at the expense of emissions upstream.
- In summary, heating plus storage air-conditioning and dual-system EPS are among the options preferred on both economic and environmental grounds over a wide range of idling behaviors, regardless of location. Costs could be reduced by complete, non-duplicative integration of IR equipment into the original truck design. Effectiveness in reducing work-day idling could be improved by hybridization and by development of creep-reduction devices.

- In January 2010, DOE announced its commitment of $115 million for the SuperTruck project, which is a 5-year initiative to develop and demonstrate Class 8 trucks that can achieve a 50-percent improvement in freight-hauling efficiency. The manufacturers involved will explore fuel-efficiency gains through improved aerodynamics, engine IR technologies, waste heat recovery to increase engine efficiency, advanced combustion techniques, and powertrain hybridization. One of the anticipated outcomes of truck hybridization is its ability to move the vehicle at low speed with the engine off, i.e. adds creep capability.
- DOE, through the Clean Cities Program, has sponsored a whole suite of outreach activities to increase awareness of the benefits of IR. These activities have included preparation of white papers; production of webcasts; maintenance of a website; presentations to help educate Clean Cities coordinators and stakeholders; and presentations at various professional meetings about the issues involved and the technologies available. DOE has produced IR fact sheets and other educational materials for use by coalitions, local agencies, and trucking companies. Among these are handouts to give to drivers to make them aware of reasons not to idle. These materials are made widely available.
- Through Clean Cities, DOE's involvement in IR has been extended to include light- and medium-duty vehicles as well as heavy-duty. This broadening in scope greatly increases the potential benefits of DOE efforts on IR.
- The *National Idling Reduction Network News* is a DOE-sponsored electronic newsletter whose primary distribution each month reaches almost 1,500 readers. The newsletter is the major outcome of the National Idling Reduction Planning Conference held in May 2004. DOE's newsletter reaches many organizations interested in:
  - exchanging information on successful idling reduction programs
  - locating grants and financial incentives
  - tracking regulatory news and events
  - reading news about electrified parking spaces, alternative maritime power, and railroad idling
  - using idling reduction calculators.

Readership includes metropolitan planning organizations (MPOs); federal, state, and local energy, transportation, health, and environmental agencies; truck and engine manufacturers; non-governmental organizations; railroads; APU manufacturers and distributors; and many others. The newsletter is a useful tool for these organizations to exchange information, such as finding anti-idling commercials and looking for signage to be posted outside schools to reduce school bus idling.

- DOE also funded several other demonstration projects in which trucking fleets installed after-market on-board IR equipment. These demonstrations collected data from actual fleet operation and documented the performance and benefits, as well as driver acceptance and satisfaction with the systems. Another project with a 21st Century Truck partner demonstrated OEM installation.[18]
- To assess the HVAC load reduction potential in truck tractor sleeper cabins, DOE funded the development of CoolCalc, an analysis tool that allows users to create truck sleeper cabin models and predict cabin temperatures in different environmental conditions. The main objective of the project is to identify and evaluate design opportunities to reduce the thermal load inside truck tractor cabs and enable advanced IR technologies. Thermal soak test methods were developed to assess promising IR designs and quantify potential benefits.
- Additional research was aimed at development of solid-oxide fuel cell technology to supply clean and quiet power for APUs. This DOE research lead to the U.S. Army's demonstration of a fuel-cell APU in the SunLine Transit truck that toured various regions of the country.

EPA Activities: EPA and DOT coordinate their efforts to develop partnership agreements with trucking fleets, truck stops, and manufacturers of IR technologies (e.g., portable APUs, electrification) to install and use low-emission idling technologies. Since the last report in 2006, the EPA has undertaken the following steps to reduce engine idling emissions and fuel consumption from long-haul trucks:

- The EPA demonstrated the effectiveness of mobile and stationary IR technologies in reducing idling emissions and conserving fuel through over $6 million in grants, including several EPS projects. EPA awarded the EPRI a grant to implement IR technologies on trucks. They tracked fuel and maintenance savings and required re-investment of the savings in additional IR equipment. A list of completed projects can be found at http://www.epa.gov/smartway/idle-demo.htm.
- EPA continues work begun in 2005 with Texas A&M's Texas Transportation Institute (TTI) to develop a protocol to measure the long-duration emissions from IR systems mounted to a Class-8 tractor. EPA's goal is to demonstrate the draft IR protocol by 2011. This effort also includes developing a test cell that simulates a full range of environmental conditions (i.e., sunlight, cold, heat) while under a typical long-duration "hotel" load. This test cell is designed to allow a direct comparison of emission differences between a tractor's propulsion engine and an IR device. The protocol and the test cell could potentially be adapted to test other types of IR systems, truck configurations, and idling. The goal is to refine the SmartWay IR verification process by 2012. These efforts could inform EPA's voluntary and regulatory programs as well as interagency research collaborations like the 21CTP.
- Since 2008, EPA has supported the deployment of technologies, including IR systems, that save fuel and reduce diesel engine NOx and PM emissions through competitive grants programs. In the 2009-2010 competition, $120 million was awarded.

---

[18] National Renewable Energy Laboratory Report for the DOE Advanced Vehicle Testing Activity, *Idle Reduction Technology Demonstrations*, November 2004. http://www.nrel.gov/vehiclesandfuels/fleettest/pdfs/36717.pdf

- EPA, working with the DOT, states, and private lenders, is developing innovative, market-based and sustainable funding opportunities, such as low-interest loans through the EPA's SmartWay Finance Program, to replace traditional grants to allow the truck and rail industries to purchase and use IR technologies.

DOT Activities: Since 2007, DOT's Research and Innovative Technology Administration (RITA) has funded the Transportation Research Board (TRB) to carry out research projects to improve freight mobility and to mitigate the effects of freight transportation through establishing the National Cooperative Freight Research Program (NCFRP).

- In June 2009, the NCFRP convened Project Panel No. 28 in order to oversee a truck idling scoping study. The panel includes liaison representatives from DOT's Federal Motor Carrier Safety Administration (FMCSA) and Federal Highway Administration. NCFRP Project Panel No. 28 also includes representatives from EPA, the California Air Resources Board, and the Port Authority of New York and New Jersey. As a result of NCFRP Project Panel No. 28's deliberations, TRB awarded a 16-month, $200,000 contract to Booz Allen Hamilton for the purpose of preparing a truck idling scoping study. The study would develop a framework to provide a general methodology and cost estimates for obtaining national and regional data sets for the time trucks spend idling, by class of truck (e.g., gross vehicle weight, number of axles, Classes 2b-8), the type of operation (e.g., parcel delivery, service, truckload, pickup and delivery), and the causes of the idling (e.g., power take-off, climate control, and other hotel loads) during driver rest periods, queuing, incidents, and inspections). The study covers seven tasks: (1) review existing literature and data sources of idling data, (2) identify and evaluate potential new sources of idling data, (3) list the most important data elements and promising sources, (4) deliver an interim report summarizing results of the first three tasks, (5) develop a framework for obtaining national and regional data sets for the time that trucks spend idling, (6) validate the framework and estimate implementation costs, and (7) deliver the final report. As of June 2010, Booz Allen Hamilton submitted a work plan to NCFRP Project Panel No. 28 for the study.
- DOT's FMCSA promulgates and enforces safety regulations governing the operations and maintenance of trucks, tractor-trailers, and other commercial vehicles. FMCSA has jurisdiction over the equipment used on trucks, including IR equipment, such as APUs. Recently, FMCSA provided review comments to EPA on a list of approved IR equipment for trucks.
- The FHWA administers the Congestion Mitigation and Air Quality (CMAQ) improvement, which has supported transportation air-quality projects since its inception in 1991. Funding under the program is apportioned to the states, and eligible projects are selected by the state DOTs in cooperation with MPOs. The CMAQ program has funded numerous IR projects around the country including a host of EPS facilities totaling approximately $30 million. Also, the Safe Accountable Flexible Efficient Transportation Equity Act: a Legacy for Users (SAFETEA-LU)[19] provides explicit eligibility for IR technologies (i.e., APUs and truck stop electrification systems) under the CMAQ

[19] Section 1808 of SAFETEA-LU.

program. The FHWA's formal CMAQ program guidance[20] outlines a number of project types focusing on freight and diesel engine emissions mitigation.

- In addition to CMAQ, advanced TSE systems (single-system electrified parking spaces) are eligible for funding under SAFETEA-LU[21], and are defined as "a system that delivers heat, air-conditioning, electricity, or communications to a heavy-duty vehicle." [22] On-board systems are also eligible for funding. Finally, Surface Transportation Program (STP) funding from SAFETEA-LU is eligible for Transportation Control Measures (TCMs) [23], one of which is "programs to control extended idling of vehicles." [24]
- DOT, along with DOE, has supported EPA's public outreach efforts on IR by attending and presenting at various national conferences and meetings, and also supported EPA's regional diesel emission collaborative efforts. In addition, DOT developed a website[25] entitled "CMAQ and Idle-Reduction Techniques" as a public outreach tool in order to promote the use of CMAQ funds for cost-effective projects such as IR.

DOD Activities: The military specifically needs an APU to reduce in-field fuel consumption and related logistical costs, and to reduce thermal and audible identification signatures during silent watch, because APUs are quieter and have a reduced thermal signature than idling the primary engines, making the vehicles less detectable in the battlefield. For example, the U.S. Army RDECOM CERDEC lab is working in conjunction with the U.S. Army PM-HTV (Heavy Tactical Vehicles) to demonstrate the feasibility of a diesel engine APU on the M915A5 long-haul tractor. Reducing fuel use is key because approximately two-thirds of the ground fleet is used to deliver fuel to the other third in the battlefield.

The military has already made a transition to a "Single Fuel Forward" policy with jet fuel-based JP-8. This change reduced expenses by avoiding the need to support vehicles that ran on JP-8, diesel, or gasoline. Although this provided realized savings, it did not fully optimize performance and durability of the traditional internal combustion engines, primarily because of the lack of coordinated international fuel quality regulations. JP-8 is a petroleum-based fuel; petroleum is generally accepted as a finite resource that will eventually need to be replaced by renewable energy sources, such as solar, wind, and biomass or by an energy carrier like hydrogen that can be made from a wide variety of feedstocks. In general, the DOD is focused on increasing power generation from renewable sources that are safe for the soldier, provide better durability and fuel economy, and are not cost prohibitive.

---

[20] The guidance can be found at: http://www.fhwa.dot.gov/environment/cmaq08gm.htm.

[21] Section 1113(a)(1) of SAFETEA-LU, which amends Section 133(b) of Title 23 of the U.S. Code (Highways)

[22] Section 1122(b) of SAFETEA-LU

[23] 23 USC section 133

[24] Section 108(f)(1)(A) of the Clean Air Act

[25] http://www.fhwa.dot.gov/environment/cmaqpgs/idlereduct/index.htm

4.5. Next Steps

Cooperative action on the part of the 21CT partners will bring cost-effective IR technologies into widespread use as soon as possible. This strategy has several elements. First, remaining technological challenges must be addressed. Some developments that would enable faster implementation of cost-effective IR alternatives include measurement of long-duration idling and APU emissions using ultra low-sulfur fuel (so that appropriate regulations can be adopted), development of a low-cost diesel particulate filter for small auxiliary engines (to facilitate compliance with California rules), full integration of IR equipment into new trucks, and development of creep-mode technology (to address daytime idling at ports, depots, and borders).

DOE/EPA/DOT should cooperatively engage in funding an extensive survey of trucks and truck fleets to investigate the rate of adoption of IR technologies, examine user preferences for type of system adopted, geographic location, and list of primary reasons for adoption. The data collected would be instrumental in the directing the further development of cost-effective IR technologies that have a proven track record and serve as a means to accurate measure the cost-benefit of government funding and incentives programs being directed to programs that encourage reduced idling.

Next, the most cost-effective technologies for different types of situations must be identified, additional incentives for their deployment established, and finally, all of the stakeholders appropriately educated so they can make the best choices about where to invest their limited resources.

4.6. Description of Available Idle Reduction Technologies

There are several types of systems on the market that allow heavy trucks to reduce their long-duration idling while still maintaining cab comfort for the driver. Some are available as optional original equipment for purchase on new trucks, and all can be retrofitted onto existing trucks. The services provided vary from simply turning the engine off when it is not needed to the full range of hotel and engine services. Devices are available for stand-alone installation on-board the truck or to plug into wayside installations.

On-Board Devices are available wherever and whenever the truck is stopped. Although they add weight to the truck, the Energy Policy Act of 2005 includes a 400-pound weight waiver to prevent the additional weight from decreasing the revenue-producing load that can be carried. The following on-board technological alternatives could be used to avoid overnight idling

Automatic start/stop systems shut the engine down after a short, preset idling period. The system then monitors the condition of the engine and coolant, and restarts the engine as necessary to maintain acceptable temperatures. Energy use and emissions are reduced because the engine is only on part of the time. One disadvantage of these systems is that the starting and stopping disrupts the drivers' sleep. The State of California mandates automatic shut-off (only) devices for all medium and heavy trucks.

Direct-fired heaters can be used to heat the cab/sleeper and/or the engine. Commercially available direct-fired heaters use less than 10% as much fuel as the main diesel engine to provide heating, and also much less than an APU because they supply heat directly from a combustion flame to a small heat exchanger. These can be used overnight, but supply no cooling or electric power unless coupled with other devices.

Evaporative coolers are commonly called "swamp coolers." Air blown across the surface of water from the device's reservoir (which must be refilled periodically) evaporates some of the water, which thereby removes heat from the air. Unfortunately, the rate of evaporation decreases as the humidity rises, so evaporative cooling is only effective in areas where the ambient humidity is low. They can be installed alone or in conjunction with heaters.

Air-conditioners are suitable for cooling regardless of humidity. Various technologies can be used, from thermal storage to vapor compression to heat pumps. They can be run off the truck's existing batteries or from additional batteries or thermal storage. The energy for cooling is supplied to the storage device when it is recharged by the truck's engine during operation, using a small quantity of extra fuel.

Auxiliary power units (APUs) and generator sets, now available as an option on some new trucks, supply all of the services the trucker requires to be comfortable anywhere in any weather: heat, air-conditioning, and electric power. These devices consist of a small diesel-fueled internal combustion engine equipped with a generator to provide electricity and heat. An electrically powered air-conditioner unit is normally installed in the sleeper area, although some units use the truck's existing air-conditioning system. Cab/sleeper heat is provided by an electric heater in the unit or a supplementary diesel heater.

In the future, it might be possible to use a fuel cell as an APU. A demonstration of a hydrogen-fueled and a methanol-reformer polymer electrolyte membrane (PEM) fuel cell was conducted by one of the 21st Century Truck partners. DOE is investigating SOFC technology for this application. EPA had a methanol-reformed fuel cell APU project with industry. U.S. Army RDECOM TARDEC National Automotive Center demonstrated two fuel cell APUs on Class 8 vehicles: a direct-methanol SOFC and a direct-hydrogen PEM, both integrated into vehicles with diesel-fueled primary ICEs. U.S. Army RDECOM CERDEC is in the process of demonstrating the feasibility of a diesel engine APU on a Class 8 M915A5 Army tactical long-haul truck.

Electrified truck parking spaces (EPS) can provide parked vehicles electricity for heating, cooling, and other purposes. This type of system is often referred to as truck stop electrification (TSE), but some industrial stakeholders object to this term because it implies that the applicability is limited to truck stops. These **wayside units** add little or no weight to the truck and cause no local emissions. They are available at a few dozen truck stops so far. Even if such installations are eventually widespread, there are likely to be times when a trucker is unable to find a place to plug in, and will therefore need a different alternative.

Two basic types of wayside units have been developed and demonstrated: a “single” system that supplies all needed services through a duct inserted into the cab window and a “dual” system that is simply a plug at a parking spot that enables the trucker to tap into the electric power grid. As of this writing, the single system is more widespread.

Single System Electrification. This parking space electrification concept requires no retrofit of the truck and therefore essentially no up-front cost by the user. An electrical HVAC unit that produces the conditioned air is installed on a gantry at the front of the parking space; conditioned air and electricity are fed through a filtered conduit ending in a service module that fits through the truck window. The service module includes a computer screen and access to the internet, phone, and cable television in addition to electric power. Other services, such as pay-per-view and training courses, are also available.

Dual System Electrification. The trucker would simply “plug in” the truck to outlets at the truck stop or depot to power on-board electrical devices. Electrification involves modifying the parking location by installing ground electric outlets (or plates in case of the induction power transfer approach) at each parking space. Construction is underway at several locations, mostly in the Pacific Northwest, but expanding across the country as a result of a stimulus grant from DOE. Dual system electrification also involves installing some combination of an inverter/charger, electric engine block heater, electric fuel heater, and electric heating/cooling device for cab and sleeper conditioning, and electric idle control on the truck.

5. Vehicle Safety

Promote 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.

5.1. Introduction and Background

Truck and bus manufacturers, industry suppliers and Federal Agencies that participate in 21CTP are working collectively to ensure that as fuel economy improvements are pursued through advanced technologies, safety goals remain uncompromised—and to even improve safety in the face of efficiency and mobility improvements.

A key strategy in this regard is to pursue solutions that help prevent crashes altogether-- either through collision warning systems, automatic vehicle control intervention technologies, and/or enhanced vehicle inspection and enforcement systems that help to identify and correct mechanical or operational conditions that could compromise safety.

Implementation of such technologies and systems is expected to help substantially in reducing fatalities and injuries, and will also have secondary benefits of reducing congestion and idling—thereby reducing fuel consumption and improving overall productivity of the trucking industry.

The overall progress toward improving truck safety has been encouraging throughout the past decade. Fatal collisions involving large trucks have dropped from about 5400 in 1998 to approximately 3400 in 2009. Even more importantly, the fatal crash rate has dropped from 2.75 fatal crashes per 100 million miles traveled in 1998 to about 1.2 fatal crashes per 100 million miles in 2009—and this is in spite of increasing truck traffic, whose growth rate is about 2.5 percent each year.

For heavy vehicle safety, a two-fold approach will be taken. First, the Partnership will conceive, develop and contribute to the deployment of future transportation technologies and operational concepts that will simultaneously contribute to enhanced safety, fuel efficiency, and productivity, while sustaining the economic viability of the trucking industry. Secondly, because safety is a crosscutting goal of the 21CTP and because of the potential for conflict between high-level goals (e.g. truck safety vs. regulated size and weight), a systems approach to safety is being supported to assure a balance in achieving all of the Partnership's goals.

5.2. Justification for Inclusion of Safety in 21CTP

Safety is a central element in the 21CTP vision—and truck manufacturers have stated on numerous occasions that safety is their number one priority. 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. While truck safety statistics have been improving steadily, crashes involving heavy trucks still account for about one out of ten motor vehicle fatalities in the United States.

Although secondary in significance to fatalities, crashes involving trucks also impose a variety of costs on society. Based on a study by the Pacific Institute, the estimated cost of police- reported crashes involving trucks with a gross weight rating of more than 10,000 pounds averaged $91,112 (in 2005 dollars). Crashes in which truck-tractors with two or three trailers were involved were the rarest, but their cost was the highest -- $289,549 per crash. The costs per nonfatal injury crash averaged $195,258, and fatal crashes cost more than any other crashes -- at $3,604,518 per crash.

In developing programs to improve vehicle safety, it is essential to consider the multiple factors impacting safe operation. These include:

- motor carrier management's commitment to safety and their safety management practices;
- driver skill, performance, and behavior;
- driver training;
- driver distraction, information overload,
- driver fatigue;
- roadway design and condition;
- traffic volumes and density;
- vehicle design, performance, and condition;
- loading and cargo securement; and
- Institutional issues such as motor carrier regulations and enforcement.

21CTP has previously focused on safety research involving vehicle design, performance and condition. New emphasis is being placed on vehicle dynamics and stability, collision warning and intervention technologies, enhanced roadside inspection systems, and improving driver performance.

Technologies that contribute to enhancing the safety of heavy vehicles can also contribute to enhanced fuel efficiencies, lower emissions, and enhanced productivity. Collision avoidance systems, for example, can help to minimize incidents/accidents that nearly always result in hours of congestion and increased idling times of all vehicles in the vicinity of the event.

5.3. Overview of Truck Safety Statistics

Combination trucks (defined as tractor-trailers, bobtail tractors, and single-unit trucks towing trailers) are involved in about three-fourths of the fatalities resulting from all types of medium/heavy trucks. Over 80% of these fatal crashes are multiple-vehicle crashes, and the vast majority of the fatalities (about 80%) are occupants of other vehicles. In about two-thirds of two-vehicle crashes involving combination trucks, the point of impact on the truck is the front. Over 60 percent these involve the front portion of the truck being struck or striking some portion of another (typically smaller) vehicle. The second most prevalent crash type is the front of the truck impacting the side of another vehicle.

In half (50%) of the two-vehicle fatal crashes involving a large truck and another type of vehicle, both vehicles were proceeding straight at the time of the crash. Most of the fatal crashes involving large trucks occurred in rural areas (64%), during the daytime (67%), and on weekdays (80%). During the week, 74 percent of the crashes occurred during the daytime (6 a.m. to 5:59 p.m.). On weekends, 63 percent occurred at night (6 p.m. to 5:59 a.m.).

The number of people killed each year in crashes involving medium-duty single-unit trucks is fairly small (about 300 for Classes 5 and 6 combined). This is primarily due to the fact that these trucks typically have much less vehicle miles traveled per year and operate in a lower-speed urban, daylight setting. About 20% of those fatalities are occupants of the truck, 70% are occupants of other vehicles involved in the same crashes, and 10% are non-occupants. Even though the operational use patterns of Class 5 and 6 trucks differ from that of the tractor-trailer platform, the crash avoidance safety issues are similar. The primary commercial truck safety focus should be on stability and rollover, collision warning and intervention systems, and driver performance.

5.4. Technology Goals

21CTP will work collaboratively with DOT to enhance safety primarily through a variety of crash avoidance strategies that include on-board vehicle technologies as well as operationally-focused programs designed to reduce crash risk. The overall goals of this collaboration are to 1) ensure that advancements in truck design and technology to improve fuel efficiency do not have any negative impacts on safety; and (2) conversely, to ensure that efforts to improve safety to not reduce efficiency—and, where possible actually contribute to improvements in overall motor carrier industry system efficiency. Key safety initiatives focused on heavy trucks are reviewed in the following sections.

5.5. Crash Avoidance Strategies

Among the many factors leading to truck crashes, vehicle design and maintenance characteristics play an important role, as does driver behavior and performance. Of particular interest in 21CTP are vehicle design and operational concepts that enhance truck stability and reduce the tendency of combination vehicles to jackknife or rollover. In addition, driver assistance technologies such as drowsy driver monitoring, impending collision warning, and driver performance monitoring are being investigated by DOT and its industry partners. For example, technologies and processes are being researched to improve the efficiency and thoroughness of in-service inspections to reduce the population of unsafe trucks on our highways. Although much of 21CTP principally addresses the vehicle, the scope of the safety emphasis in this Program includes the driver and infrastructure to the degree that they support the avoidance of crashes, the mitigation of congestion associated with such crashes, and the associated reduction in fuel consumption and emissions.

Crash avoidance initiatives fall into six primary categories: (1) improved braking performance including roll and stability control systems; (2) collision mitigation technologies that directly intervene to warn drivers and/or take control of the vehicle in collision imminent situations; (3) diagnostic technologies that improve the ability to maintain safety-critical systems; (4) human factors research to improve the driver-vehicle interface, identify sources of distraction and enhance driver performance through a variety of technology and operational strategies; (5) *SmartRoadside;* a program to improve how state, local and federal officials interact with commercial vehicle operators and drivers at the "roadside" to reduce down-time associated with vehicle inspections, port operations, border crossings and other venues. Components of this program include wireless roadside inspections, size and weight compliance, and other state-based programs, and: (6) cross-cutting research related to DSRC-based wireless communications –a set of technologies and applications focused on establishing standardized wireless communications between vehicles to support safety, mobility and efficiency within the motor carrier industry.

5.5.1. Improved Braking Performance and Stability Control

In 2009, NHTSA published a Final Rule amending FMVSS No. 121, Air Brake Systems, to improve the stopping distance performance of heavy commercial vehicle tractors. As a result of the amended standard, as of August, 2011, the majority of new commercial vehicle tractors are required to have the capability stop in not more than 250 feet when loaded to their GVWR and tested at a speed of 60 mph, which represents a 30 percent reduction in stopping distance compared to previous requirements. For a small number of very heavy severe service tractors, the new requirement is 310 feet under the same conditions. This improved brake performance can be accomplished through the use of larger more powerful conventional drum brakes, or the use of air disc brakes, or some mix of the two on tractor-trailer combination vehicles.

Over the last five years, truck OEMs have also begun to offer electronic stability control (ESC) on several truck models, and the technology has even become standard on select models from some manufacturers. ESC enables precise, computer-controlled braking at each wheel-end on a tractor to assist the driver in maintaining control in critical driving situations. Such braking systems monitor yaw rate, lateral acceleration, speed, steering input and other parameters to determine if the vehicle is about to experience a loss of control and enter into an oversteer or understeer situation. Braking is applied at the appropriate wheel-end during such aggressive steering maneuvers in order to bring the vehicle back into control. ESC capability is often combined with roll stability control (RSC) systems which estimate the center of gravity of the vehicle as well as lateral acceleration and yaw to determine if the vehicle is approaching its rollover threshold—and if necessary then applies the brakes to slow the vehicle and prevent the rollover. ESC and RSC braking systems prevent wheel lockup, skidding, loss of control and jackknifing during extreme braking and/or turning maneuvers.

Increased research and analysis on the use of disk brake systems for tractors and trailers is also supported by 21CTP. In addition to contributing to shorter stopping distances, the use of disc brakes will improve the thermal capacity (fade resistance) for new tractor trailer foundation brake systems. With proper design and materials, disk brakes also offer the potential for reduced weight which would support fuel efficiency goals. The biggest challenge will be to provide disc brake designs that are economically feasible and commercially acceptable.

An additional technology that is worthy of additional consideration for a 21st century truck design is the use of electronically controlled braking systems (ECBS). This technology replaces the pneumatic brake control systems on air brake systems with electronic control. The advantages include reduced latency of control commands (by eliminating delays inherent with mechanical air control), and more precise control of the braking application. The inherent delay in air control systems may be a particularly important concern in implementing fuel efficiency strategies centered on use of multiple trailers since the braking delay is exacerbated in such vehicle configurations. To this extent, ECBS (which would allow for precise and instantaneous control of braking force at all wheel-ends—even in multiple trailer configurations) can be thought of as an enabling technology for such high efficiency tractor-trailer configurations.

5.5.2. Collision Warning and Intervention Systems

Advancements in collision warning and avoidance systems for heavy trucks has continued over the past several years—and 21CTP supports continued research in this area as a potentially high-payback technology for improving safety. Warning systems available commercially include:

- Lane departure warning (LDW)
- Forward collision warning (FCW)
- Side object detection (blind spot monitoring, BSM) and lane change merge (LCM)
- Rear object detection and collision warning

The above systems utilize radar, lidar, video detection, ultrasonic, and other sensor systems—combined with sensor input analysis algorithms—to determine if/when a potential crash situation is developing, and then warn the driver appropriately. Warning mechanisms include audible tones, displays, and/or haptic feedback mechanisms (such a seat vibrations or “tugs” on the seatbelt). Several systems not only provide warnings, but are also capable of taking active control of the vehicle by de-throttling the engine, engaging the engine brake, and/or applying the foundation brakes depending on the deceleration rate called for by the system’s algorithm. Typical systems first warn the driver of a developing dangerous situation, but if the situation worsens and a crash is considered imminent the active control features are engaged.

The U.S. DOT is also sponsoring research on enhanced rear signaling systems (ERS) for trailers. Such systems incorporate rearward looking radar along with additional lighting fixtures on the rear of the trailer. If a following vehicle exceeds preset thresholds for closure rate, speed or distance, the lights on the back of the trailer are energized in an effort to gain the attention of the driver in the following vehicle. Early testing shows promise for this system.

In addition to the above discrete systems, suppliers and OEMs have combined multiple warning technologies into integrated safety systems. Further, the sensor data from such systems can be combined with speed, braking and other data already available on the vehicle’s high-speed databus to monitor the safety performance of the driver. For example, hard braking events, engagement of stability control or ABS, lane keeping behavior, and following distance can all be monitored by integrated systems. Performance histograms can then be developed based on various threshold settings—and the information off-loaded to fleet managers/dispatchers using a fleet’s existing telematic systems.

The use of these innovative collision avoidance and warning systems can play an important role in maintaining or even improving safety as heavy truck designs evolve to become ever more efficient.

5.5.3. Safety System Diagnostic Technologies

The 21st century truck must not only be designed to the highest levels of safety and productivity standards, but must also be able to be easily maintained in a cost effective and comprehensive manner. This is particularly true as new safety systems and technologies require precise calibration in order to operate optimally. The U.S. DOT and its industry partners are investigating selected maintenance and diagnostic systems to ensure safe operation of the vehicle throughout its useful life.

Tire Pressure Monitoring. The U.S. DOT has completed considerable research related to costs, benefits and operations of tire pressure monitoring systems and automatic inflation systems for trailers. Such systems are likely to be of particular importance and cost efficiency as the industry continues to transition to single wide based tires.

The objective of tire pressure monitoring systems is to improve commercial motor vehicle safety, and reduce total tire ownership costs by assisting drivers and fleet managers in monitoring and maintaining proper tire inflation pressures. By automatically measuring and indicating air pressure information to fleet operators and drivers, tire pressure monitoring systems can be valuable aids for proper tire maintenance that will enhance the safe and efficient operation of commercial motor vehicles.

Tire air pressure information can be indicated by different means. The interface for some tire monitoring systems provides information in the form of alerts from on-vehicle wheel-mounted or dash-mounted display units when tire pressure changes have occurred. Other systems involve the use of hand-held or drive-by readers to capture and instantly report tire pressure and possibly other maintenance information. The information from these systems can also be reported in a fleet-specific manner via an internet server to maintenance managers for tire monitoring and tracking purposes.

Vehicle tires that are improperly inflated can impact the life of the tire and lead to catastrophic tire failures. Through the aid of tire pressure monitors, tires can be properly maintained, and crashes caused by tire blowouts, vehicle handling characteristics, hydroplaning, and other tire-related issues can be prevented, resulting in savings of life, property damage, time, and congestion. Furthermore, fuel economy can be severely impacted by inadequate tire inflation, because additional power is required to move the vehicle due to the increased rolling resistance.

The U.S. DOT has sponsored both controlled test track testing as well as field operational tests of tire pressure monitoring systems in order to better document the costs and benefits for various types of fleet operations. An efficient, accurate and cost effective tire pressure monitoring system is consistent with the 21CTP vision for future trucks—particularly as the industry moves toward single wide based tires in the effort to attain enhanced fuel economy.

Brake System Sensors and Diagnostics. While the industry is moving forward aggressively with more powerful braking systems and more sophisticated braking control (see section 5.5.1), the effectiveness of such systems can be reduced or even negated if the fundamental brake system components are not in good working order and properly maintained. With 10 wheel-ends on a typical tractor-trailer, brake maintenance is a continuing challenge for most fleets—and is one of the highest cost maintenance elements. The U.S. DOT is sponsoring a variety of research on technologies that would allow for more reliable and efficient brake system diagnostics and maintenance. The leading brake diagnostic technology under consideration is on-board brake stroke monitoring.

On-board brake stroke monitoring systems enhance commercial motor vehicle safety by relaying critical information about air brake adjustment and operational status to drivers, inspectors, and maintenance personnel. These systems can detect major brake problems in real-time.

The sensitivity to brake system adjustments is compounded by the lack of feedback to the driver, since a driver cannot easily detect brake degradation related to an adjustment condition until he or she needs to make an emergency stop. Since drivers are often unaware of existing brake defects and reduced braking capability, brake monitoring systems provide valuable information to let the driver know when brakes are out of adjustment or not working properly so that corrective measures can be taken to maintain the vehicle's safe operation. If all of the brakes on a vehicle are not properly adjusted, then those in adjustment will take a disproportionate share of the load. In turn, this may cause them to fade prematurely and shift the load to other poorly adjusted brakes.

Brake stroke monitoring systems can aid carrier personnel in discovering air brake adjustment and operation problems due to the following defects:

- Worn, seized, or out of adjustment manual and automatic slack adjusters
- Slack adjusters that have not been installed properly
- Pushrods that have been cut too short
- Ruptured actuator diaphragms or leaking airlines
- Plugged or crimped airlines
- Frozen or stuck air valves
- Cracked or broken brake drums
- Brake shoes that may be "hung-up" due to other faults in the foundation brake system or slack adjuster faults
- Push rods that have not retracted due to components binding
- Broken parking brake springs
- Worn S-cams

In addition to brake stroke monitoring systems, DOT has previously investigated other advanced on vehicle brake diagnostic technologies including; strain gauges affixed to the anchor pin to determine radial and axial braking force; lining wear sensors; thermal sensors; as well as systems that compare brake system control pressure, wheel speed and deceleration rates to determine if the system is working properly and in calibration. DOT has also researched and developed performance specifications for performance based brake testers (PBBT) for use by commercial truck inspectors.

5.5.4. Improved Driver Behavior and Performance

The Large Truck Crash Causation Study (LTCCS), commissioned by the 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. The Study included an unprecedented level of information to be collected on each crash including interviews with parties involved, photographs, police reports, follow-up medical reports and high level accident reconstruction. Each crash involved at least one large truck and resulted in at least one fatality or injury. The total sample of 967 crashes included 1,127 large trucks, 959 non-truck motor vehicles, 251 fatalities, and 1,408 injuries. The Study generated tremendous insights into the causation of heavy vehicle crashes—and a key take-away from the Study is that action or inaction by the driver of either the truck or other vehicle was the critical reason for 88 percent of the crashes—thus highlighting the importance of the driver in safety.

The commercial truck driver also plays a critical role in achieving improvements in fuel efficiency. In a preliminary study conducted for DOE's Vehicle Systems Program, data that had been collected for the Heavy-Truck Duty Cycle Project was analyzed for fuel efficiency and driver behavior. Variations of up to 50% in fuel efficiency was seen where the primary difference was driver behavior on identical routes and identical cargo loads.

Such studies (LTCCS and DOE Duty Cycle Project) indicate that the behavior of the driver can have a significant role in the safety and fuel efficiency of heavy-trucks. Key areas of research related to the driver that will be addressed through 21CTP include: Distraction: Fatigue; and Eco-Driving.

Distraction. Driver distraction is an area that is receiving considerable current attention. For example, FMCSA has issued its final rule prohibiting texting by commercial vehicle drivers while operating in interstate commerce. The rule took effect in October 2010 and imposes sanctions, including civil penalties and disqualification of non-compliant drivers from operating commercial motor vehicles in interstate commerce. Additionally, motor carriers are prohibited from requiring or allowing their drivers to engage in texting while driving.

Three primary types of driver distraction tasks have been identified by DOT. They are:

- Visual distraction: Tasks that require the driver to look away from the roadway to visually obtain information
- Manual distraction: Tasks that require the driver to take a hand off the steering wheel and manipulate a device;
- Cognitive distraction: Tasks that are defined as the mental workload associated with a task that involves thinking about something other than the driving task.

NHTSA has engaged in a number of Driver Distraction research efforts. They include the following:

- Driver Cell Phone Use Observational Study
- Study of Driver Strategies for Engaging in Distracting Tasks Using In-Vehicle Technologies
- Driver Distraction With Wireless Communications and Route Guidance Systems
- The Impact of Driver Inattention on Near-Crash/Crash Risk/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data
- An Examination of Driver Distraction as Recorded in NHTSA Databases

In a recent study[26] of driver distraction in commercial vehicle operations it was found that drivers were engaged in non-driving related tasks in 71 percent of the crashes, 46 percent of near-crashes, and 60

[26] http://www.fmcsa.dot.gov/facts-research/research-technology/report/FMCSA-RRR-09-042.pdf

percent of all safety-critical events (4,452 safety critical events were studied). In addition, it was concluded that performing highly complex tasks while driving leads to significantly increased risk. Eye glance analyses examined driver eye location while operating a commercial motor vehicle. Tasks associated with high odds ratios (meaning an increased risk of a crash occurring) were also associated with high eyes-off-road times. Based on the results of the analyses, a number of recommendations were presented that may help address the issue of driver distraction in CMV operations. These included fleet recommendations for:

- Driver education and training
- Development of policies to minimize or eliminate the use of in-vehicle devices while driving
- Prohibiting texting while driving
- Prohibiting the manual dialing of cell phones while driving
- Prohibiting reading, writing and looking at maps while driving
- Better driver-system interface designs for dispatching devices and instrument panels

Driver distraction is a complex issue with numerous contributing factors. Nevertheless, it is clear that more integrated driver interface designs, as well as complimentary training and operating practices that focus on preserving the driver's attention on the road ahead, are important steps in minimizing distraction. These areas will continue to be of high priority for 21CTP members.

Fatigue Research

Operator fatigue and sleep deprivation have been widely recognized as a high priority commercial vehicle safety issue. Fatigue affects mental alertness, decreasing an individual's ability to operate a vehicle safely and increasing the risk of human error that could lead to fatalities and injuries. Fatigue slows reaction time, decreases awareness, and impairs judgment. Adding to the difficulty of understanding the fatigue problem and developing effective countermeasures to address operator fatigue is the fact that the incidence of fatigue is underestimated because it is so hard to quantify and measure. DOT has conducted studies focusing on recent developments in vehicle-based operator alertness monitoring technologies, and several promising state-of-the-art devices and technologies were identified and evaluated against a set of proposed design guidelines. Technological advances in electronics, optics, sensory arrays, data acquisition systems, algorithm development, and machine vision have brought the goal of providing unobtrusive, real-time, affordable, 24-hour driver alertness monitoring capability much closer to reality. Considerable development effort is taking place to demonstrate the scientific validity and reliability of these technologies. For example, DOT is preparing to implement a comprehensive examination of an on-board monitoring system on three test fleets comprising 270 vehicles.

Eco-Driving

As noted earlier, driving behaviors and driving "style" can have a major influence on fuel efficiency—particularly for manual transmission vehicles and for heavy trucks. Eco-driving involves throttle, shifting and braking behaviors that drivers can use to optimize fuel economy. The energy in fuel consumed in driving is lost in many ways, including engine inefficiency, aerodynamic drag, rolling friction, and kinetic energy lost to braking (and to a lesser extent regenerative braking). Driver behavior can influence all of these. While oversimplifying the issue, the basic concept is that the more a driver can maintain steady-state operations (in the face of changing traffic speeds and/or grade variations) and avoid heavy accelerations/decelerations, the higher fuel economy performance he/she can achieve.

Basically, a fuel-efficient driving strategy involves anticipating what is happening ahead, and driving in such a way so as to minimize acceleration and braking, and maximize coasting time. It is also important to note that this same driving “style” can promote (or is consistent with) safe driving. In both instances, the focus of the driver should be on anticipating upcoming events, traffic conditions and grade changes in order to modulate speed and minimize highly transient maneuvers. This focus on “anticipation” by the driver of what is ahead is also consistent with mitigating distraction as well as adhering to safe following distances, speed management, and braking actions—all of which support both safe as well as efficient driving.

Technologies are currently being developed that support eco-driving behaviors. These include providing information to the driver in real-time concerning the amount of fuel consumed, eco-driving style advisors, intelligent speed adaption, and advanced cruise control concepts.

5.5.5. Smart Roadside

FMCSA and FHWA are partnering in research related to improving how state, local and federal officials interact with commercial vehicle operators and drivers at the roadside. The focus is on improving both the efficiency and comprehensiveness of operations so that freight can flow more smoothly, but also to ensure the fleet operators are adhering to all applicable regulations. The *SmartRoadside* program includes research related to enhanced, wireless roadside inspections, electronic permitting and credentialing, virtual weigh stations, and enhanced vehicle and driver identification strategies.

In-service inspections are important in order to identify unsafe drivers, vehicles and carriers. Currently, there are a number of North American Standard (NAS) Driver/Vehicle Inspection Levels. The most intensive of these is a Level 1 inspection that includes an examination of the driver's license, medical examiner's certificate and waiver, if applicable, alcohol and drugs, driver's record of duty status as required, hours of service, seat belt, vehicle inspection report, brake system, coupling devices, exhaust system, frame, fuel system, turn signals, brake lamps, tail lamps, head lamps, safe loading, steering mechanism, suspension, tires, van and open-top trailer bodies, wheels and rims, windshield wipers, emergency exits on buses and hazardous materials requirements, as applicable.

Level 1 inspections require a significant amount of time (about 40 minutes in total). At current resource levels within the state-based commercial vehicle safety enforcement communities, about three million annual inspections are conducted each year. With about 3 million tractors in service (and another 4 million heavy straight trucks) this means that many vehicles will go more than a year without ever being inspected…and many will go for several years without an inspection. Moreover, the violation rate for those vehicles that do get inspected is high at about 73% (meaning some type of vehicle and/or driver violation is found on nearly 3 out of every 4 vehicles inspected).

Further, the likelihood of a roadside inspection is far less than for a truck being weighed; about 177 million weight inspections are completed annually with a violation rate of only 0.29%. It is reasonable to assume therefore that if the likelihood of an NAS inspection was increased, the violation rate would likely decrease. Because of this, FMCSA is engaging in a Wireless Roadside Inspection (WRI) Program. The WRI Program involves the transmission of driver, vehicle and carrier information to an inspection station (which may be either a fixed site or a mobile enforcement vehicle), and when received, linking with federal and state commercial motor vehicle safety data systems to extract historic information related to the driver, vehicle and carrier. This information, along with an electronic hours-of-service log is provided to the inspector, minimizing the time required to do this manually. As a result, inspections are conducted more expediently allowing more inspections to take place. At the current time, only inspection data is being addressed by WRI; however, information related to brakes, exhaust system, steering, wheels, wipers, suspension, fuel system, coupling, etc., has the potential for being gathered and transmitted as well. FMCSA is currently studying various communications modes including DSRC and commercial mobile radio services to determine their usability in the WRI Program.

5.6. Standardized Wireless Communications for Commercial Vehicles.

Over the past six years, 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 is being conducted to leverage the potentially transformative capabilities of dedicated, short range communication (DSRC) technology to make surface transportation safer, smarter and greener. If successfully deployed, such standardized communications will ultimately enhance the safety, mobility and quality of life of all Americans, 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 forward collision warning (FCW); lane departure warning (LDW); intersection collision avoidance; and several others.

5.7. Commercial Vehicle Size and Weight Research

The DOT recognizes the potential for increased efficiencies in the motor carrier industry with increased allowances for commercial vehicle size and weight. For example, increased commercial truck weight pilot studies were recently conducted in Maine and Vermont to determine potential safety and road maintenance issues with road and bridge infrastructure at combination vehicle weights up to 99,000 pounds traveling on the interstate system as compared to the current maximum weights of 80,000 pounds. Vehicle crash violation, weight, and other operational data were gathered and analyzed to determine the impacts on overall safety, infrastructure, and freight mobility.

6. Efficient Operations

6.1. Perspective

Heavy trucks and buses are responsible for about 24% of the energy consumed and CO_2 emissions generated in highway transportation in the United States.[27] The VMT for trucks is expected to increase at a rate significantly outpacing passenger VMT growth, which will result in a steady rise in the percentage of energy consumption (and emissions) attributable to trucks over the coming decades. Recent projections of truck and passenger car VMT and fuel consumption have indicated that the fuel consumption of trucks will surpass that of passenger vehicles by the year 2040.[28] These facts have sparked significant recent interest in truck fuel efficiency in the transportation community.

Reducing the fuel consumption of trucks can be achieved with better engine designs and improvements in other parameters of the drivetrain, aerodynamics, etc., but also through more efficient operations, logistics, and using improved speed control of vehicles either with improved driver training or automated vehicle control, or mandatory speed limits. Fuel consumption can also be decreased by reducing the weight and/or volume of freight that must be transported, for example by using reduced packaging in consumer products. Retailers can require that suppliers reduce extraneous packaging for improved efficiency, as Wal-Mart has recently begun. Carrying greater quantities of freight per truck can lead to improved efficiency and reduced fuel consumption, and this can be accomplished in several different ways.

Better supply chain management can improve freight efficiency significantly, and many companies have made remarkable gains through streamlining their operations and, in many cases, completely restructuring the way that they manage their goods transport. Wal-Mart, for example, pioneered the hub and spoke distribution system with the creation of its distribution centers and is widely renowned for the efficiency of its supply chain functions. These supply chain improvements can reduce overall fuel consumption significantly, and they provide a competitive advantage to the companies that employ them. For this reason, it is expected that the market itself will continue to make improvements in supply chain efficiency, although there may be particular actions that can be taken with incentives for improving efficiencies for particular aspects of supply chain management.

In addition to the above, the total distance that cargo is transported can be reduced if transportation networks are optimized to avoid unnecessary movements. Loads carried and distances traveled can also be reduced if multiple functions in the value added chain for any product can be performed at one location or at facilities that are in close proximity to one another, as opposed to performing related functions at different facilities. An example is the production of steel cable at a facility nearby to the factory that produces the bulk steel stock, as opposed to shipping it over greater distances before drawing the wire. While many industries have developed in a manner that these efficiencies are inherent to the operations,

---

[27] S.C. Davis, S.W. Diegel, R.G. Boundy. Transportation Energy Data Book, Edition 28, Oak Ridge National Laboratory, 2010.

[28] A. Greszler, "Technologies and Policies for Improving Truck Fuel Efficiency& Reducing CO_2," in *Transportation and Climate Solutions: Findings from the 2009 Asilomar Conference on Transportation and Energy Policy*, Edited by D. Sperling and J.S. Cannon, Institute of Transportation Studies, Davis, CA, 2010.

there are certainly many instances where raw materials or intermediate products are transported back and forth across the country or even around the globe due to sourcing issues, supply chain inefficiencies, or reduced labor or manufacturing costs. These examples show that changes to the structure of the supply chain network have the potential to improve freight efficiency by impacting the VMT, average size of loads carried, etc. It should be noted that best practices of business and manufacturing may occasionally conflict with highly efficient freight transport and some inefficiencies are inevitable. Seeking new approaches to further streamline supply chain operations can lead to more efficient freight transport.

Vehicle, container, and trailer tracking has brought an efficiency revolution to supply chain management. Tracking systems facilitate more efficient management of the fleet. Changes in supply and demand can be efficiently managed for long-haul trucking and more importantly for short haul Less-Than-Truckload (LTL) carriers. Interactive tracking at the operations center is usually integrated with routing and resource optimization algorithms for increased efficiency. This reduces the number of miles traveled for deliveries and deadheading (empty loads).

The growth of intermodalism has also resulted in significant fuel cost savings and reduced emissions. "Intermodal freight transport is defined as the use of two or more modes to move a shipment from origin to destination. An intermodal freight movement involves the physical infrastructure, goods movement and transfer, and information … under a single freight bill".[29] Intermodalism resulted from the development of a standardized container that could be used to ship cargo by water, motor carrier, and rail. Railroads can move 480 ton-miles to the gallon,[30] while a truck can move about 150 ton-miles to a gallon of fuel, based on a truck maximum load capacity of 80,000 pounds (corresponding to up to 25 tons of freight) with a fuel economy of 6 mpg. A container from China that is bound for a location in the U.S. Midwest or East Coast can be placed on a double stack rail car at its port of entry and moved to a rail yard near the destination. From there, it can be transferred to a motor carrier for the short distance move to the consignee. Such shipments, when practical, can reduce the total fuel consumption of the freight shipment by a factor of three or more.

The expansion of the Panama Canal for larger container ships will result in more freight that is bound for the East Coast traversing the canal and being off loaded at ports nearer their destination. This will also reduce fuel use and emissions since ship transport is considerably more efficient on a ton-mile per gallon basis than rail. Another trend that we may see in the future is short sea container shipping along the coast and/or inland barge container shipping. Traditionally, barges have been used mainly for bulk low value cargo, but there is the potential for substantial fuel savings and emission reductions with the use of coastal and inland marine shipping.

Infrastructure improvements and deployment of advanced technologies may be needed to achieve some of these supply chain efficiencies on a large scale, and it will take time and resources to implement such changes to achieve maximum impact. Nonetheless, there may be opportunities for federal agencies to

---

[29] W. DeWitt, J. Clinger, "Intermodal Freight Transportation," in *Transportation in the New Millennium: State of the Art and Future Directions*, Committee on Intermodal Freight Transport, Transportation Research Board, 2000. http://onlinepubs.trb.org/onlinepubs/millennium/00061.pdf. Accessed 2/10/11

[30] Association of American Railroads, http://www.aar.org/Environment/Environment.aspx.

influence the timeline for implementing such changes through incentives and funding to help support the deployment of advanced supply chain management approaches. Research that quantifies the benefits and further potential of supply chain improvements can help determine specific areas where government participation is needed to jump start activities that the freight transport industry is not able or willing to implement itself. Furthermore, research and planning are needed to determine the investments that can achieve the best payback with respect to fuel savings potential and to develop a long-term plan to implement the most beneficial solutions throughout the nation.

Following passage of the Energy Independence and Security Act of 2007 (EISA) the U.S. government commissioned a number of studies to better understand the fuel efficiency gains attainable in medium- and heavy-duty trucks.[31, 32] Results of these studies have indicated that very significant reductions in truck fuel consumption can be achieved both with technology and other operational changes, with some combinations of technologies providing estimated reductions in fuel consumption exceeding 50% in some applications. As mandated by EISA, new truck fuel efficiency standards were established by the National Highway Transportation Safety Administration (NHTSA), while the Environmental Protection Agency (EPA) proposed to regulate greenhouse gas emissions from medium- and heavy- duty trucks. The final standards, issued by NHTSA and EPA in September 2011, will go into effect beginning with model year 2014 vehicles. While this first-time creation of truck efficiency standards is a very positive step forward, it should be considered only as a first step. A longer term challenge that the industry should continue to pursue is implementing technologies and practices that will provide the greatest benefits across the very diverse and complex trucking industry. Given the stakes of the Department of Energy (DOE), DOT and EPA in regards to reducing truck fuel consumption, it is strongly felt by the 21st Century Truck Partnership that combined support and sponsorship of research and development activities from these three agencies is essential to ensuring that technology and operational solutions will be relevant in the U.S. trucking industry.

In the remainder of this chapter, several selected fuel efficiency technologies and other approaches that have the potential to significantly reduce fuel consumption in truck transportation will be reviewed, and aspects for which joint DOE, DOT and EPA involvement can have particular benefits will be highlighted. The estimated impact on fuel consumption that these technologies, operational changes, etc. can be expected to provide will be quantified where possible, based on prior forecasts. Important knowledge gaps pertaining to the current understanding of truck operations and the potential benefits of specific technologies will be identified along with approaches that can be followed in order to fill these gaps. Many of the technologies under consideration are not well-developed, and there can be major hurdles in deploying them in the U.S. trucking fleet either due to technological challenges, the current costs of the technologies, barriers imposed by existing regulations and policies or simply due to a lack of acceptance in the trucking industry. Various means by which such obstructions can be reduced or eliminated will be considered within the context of

---

[31] Transportation Research Board, *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles*. The National Academies Press, Washington, D.C., 2010. http://www.nap.edu/catalog.php?record_id=12845. Accessed 2/10/11

[32] C. Cooper, F. Kamakaté, T. Reinhart, M. Kromer, R. Wilson, *Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO_2 Emissions*, Edited by P. Miller, NESCCAF, ICCT, SwRI, and TIAX, 2009.

DOE, DOT and EPA influence. Based on an evaluation of what could likely be most effective in achieving significant reductions in fuel consumption, priorities will be set for research needs in which the agencies share a combined interest and authority. Where there are opportunities for the U.S. government to assist in providing funding for research, making changes to regulations or providing incentives that can enable more efficient trucking operations without compromising safety or transportation system robustness, the DOE and DOT can commit to supporting these goals. A key objective of this white paper is to identify specific opportunities and challenges with respect to advancing the state-of-the-art of truck fuel consumption and to highlight particular research needs that are seen as critical to maximizing the overall efficiency of freight movement and of trucks in general. It is proposed to develop a set of specific topics on which DOE, DOT and EPA can—and should—work together to further the goal of improved truck efficiency. Based on the priorities defined herein, a set of cooperative projects and paths aimed at significantly reducing fuel consumption in trucking will be established that are best addressed jointly by these agencies. This paper will focus on several existing and developing technologies that can have a significant impact on truck fuel economy but that require research to quantify the benefits of the technologies or to better understand in what applications they will provide meaningful benefits.

6.2. Technologies for Reducing Fuel Consumption in Medium- and Heavy-Duty Trucks

There are many elements that impact the fuel consumption of individual trucks. The engine efficiency, other design parameters of the truck, transportation network design and operation, and driver behavior all impact the efficiency of a given truck. This section focuses on specific technologies that are expected to yield significant improvements in truck fuel efficiency but for which additional research and/or regulatory changes are needed.

Figure 23. Power Use Diagram for a Class 8 Tractor-Trailer Shows a typical percentage distribution of the mechanical power losses for a long-haul usage (varies based on the particular drive cycle)

6.2.1. Aerodynamics

Aerodynamic drag is important for operations at high speeds but is relatively unimportant at the lower speeds typically encountered in urban driving. Therefore, depending on the truck application, it may or may not be a significant contributor to fuel consumption. Aerodynamic drag is responsible for about 50% of the total power that must be provided to the wheels for a fully loaded tractor trailer driving at highway speeds of 65 mph, , which equates to over 40% of the total engine output power, as shown in Figure 23. For long-haul tractor-trailers, the application that represent about 70% of the fuel consumed and emissions generated by all trucks, the majority of driving is done at high speeds on interstate highways or other primary roadways, so aerodynamic drag is very important in truck operations overall. For this reason, aerodynamics consistently receives a good deal of attention when considering truck fuel consumption.

Regulatory Issues

One issue regarding aerodynamic drag that is particularly relevant to the government agencies is how existing highway regulations may influence or constrain what can be achieved in terms of reducing aerodynamic drag. The role that existing regulations play in restricting vehicle design is an important consideration for future studies and technology development. The following technologies are high potential technologies for which some regulatory hurdles also exist:

1. There are various regulations limiting the total dimensions (length, width and height) that trucks can have. New aerodynamic drag reduction devices have been designed that can reduce aerodynamic drag considerably if additional hardware is attached to the exterior of the trailer. Such hardware additions can result in dimensional extensions beyond the current regulatory limits, depending on the trailer in use. One such device that serves as an example is the TrailerTail® from ATDynamics, shown in Figure 24.

Figure 24. TrailerTail® Aerodynamic Reduction Device

Although this device has been exempted from U.S. DOT length restrictions and is available for use by trucking fleets, the exemption process is not straightforward. It would be worthwhile for DOT to review its regulations and to determine if modifications are needed to allow more flexibility in allowing fuel efficiency devices to be used on combination trailers. It is noted that aftermarket modifications to vehicles do raise safety concerns with respect to structural integrity of the device and quality of the installation, and such concerns need to be addressed concurrently with the benefits that can be achieved with any new device.

2. Mirrors. The aerodynamic drag due to truck mirrors is significant since the mirrors extend beyond the main cross section of the truck and therefore increase the frontal area of the entire truck and considerably disrupt the airflow along the region where the mirrors are located.[33] Manufacturers have streamlined mirrors in recent years, but it is not expected that significant further reductions in aerodynamic drag are possible with mirrors. Typical mirrors contribute about 5%-9% to the total aerodynamic drag of a truck, and can be responsible for several percent of the total fuel consumption.[34] A logical approach to eliminating this issue would be to use cameras as an alternative to mirrors. In addition to the aerodynamic advantages, camera systems can also help to eliminate the significant "blind spot" problem of large trucks. However, current regulations specifically require external mirrors on all trucks. External mirrors have a very important advantage with respect to enforcement in that they are readily visible and their condition can be easily assessed while the vehicle is on the road. Nonetheless, given the reliability of modern electronics, the high quality of cameras that are currently available and the fuel savings that could be possible by eliminating mirrors, it seems appropriate to consider changes to this restriction and to study in

[33] M.G.L. Cresswell, P.B. Hertz, "Aerodynamic Drag Implications of Exterior Truck Mirrors," SAE Paper Number 920204, SAE International, 1992.

[34] *Ibid.*

detail the benefits and drawbacks of allowing cameras to replace external mirrors on commercial trucks. Empirical studies should be performed to directly quantify the fuel savings if mirrors are eliminated, but also to evaluate the impact on safety and to quantify the level of reliability that could be expected to be achieved with redundant camera systems. Indicators and measures to ensure proper functioning of cameras that would provide an adequate means of enforcement need to also be addressed.

Aerodynamic Testing Standardization

In addition to regulatory impacts on aerodynamic design for vehicles, the issue of standardization in testing is very important for having results that potential users of new technologies can understand and trust. Currently, there are no standardized test methods for aerodynamic devices used on medium- and heavy-duty trucks. This situation should be addressed with a focused standard development effort that will quantify the aerodynamic savings in a way that can be used directly to estimate the fuel economy benefits associated with any aerodynamic technology. Research is needed to determine the relative importance of different wind directions on the aerodynamic performance and the consequent fuel economy impacts. Furthermore, the relevance of wind tunnel testing with a fixed ground plane should be investigated, among other factors. An objective should be to develop a test method that could be used to provide a single metric of the effectiveness of aerodynamic drag reduction devices that trucking fleets and other operators could use to quantify the fuel savings possible with any aerodynamic technology.

6.2.2. Trailer Role in Fuel Consumption for Combination Vehicles

The role of the tractor in combination trucks is clearly very important, and a majority of the technology proposals for improving fuel economy of combination trucks have focused on the tractor. This is logical since it provides the power that drives the vehicle forward and the energy used is therefore derived from the tractor itself. However, the trailer also impacts the overall vehicle fuel economy in terms of aerodynamic influences; parasitic losses due to bearing friction; wheel alignment issues that lead to tire scrubbing and the accompanying increase in rolling resistance; brake drag; and of course the weight of the trailer itself. It is not known how significant these effects are for tractor-trailer fuel consumption, but the impact could be important overall. Considering that there is a ratio of over three trailers for every tractor in the United States, and the fact that many trailers are not owned by the same company that operates the tractor (and therefore the owners of trailers do not have a stake in the fuel costs), there are clearly economic reasons why trailer maintenance may not be performed as rigorously or frequently as for the tractors, and why innovative research and designs focused on trailers are slow to develop. Research to understand the variability in trailer parasitic losses would be beneficial for determining if stricter control of trailers is needed for maintenance, if design changes are in order, or if regulations regarding maximum allowable parasitic losses are appropriate.

6.2.3. Intelligent Transportation System (ITS) Technologies

The term Intelligent Transportation Systems (ITS) refers to efforts to add information and communications technology to both vehicles and the transportation infrastructure for the purpose of improving the performance of the overall transportation system. Some key areas that ITS has focused on include safety, efficiency, emissions reductions, capacity management, travel time and sharing of traveler information. A broad range of ITS technologies have been under development for years and new technologies are continually being deployed across the nation.[35] ITS includes everything from driver information systems, electronic toll collection and electronic screening for weight and safety inspections to traffic signal optimization and ramp metering (aimed at reducing congestion) and in-vehicle crash avoidance and mitigation devices, among others. These systems have already yielded many benefits in information sharing, safety and congestion mitigation, but the rapid advances in communication technologies offer the potential of much greater benefits as inter-vehicle communication and vehicle-to-infrastructure communications are adopted. The Connected Vehicle program sponsored by the DOT aims to enable safe, interoperable networked wireless communications among vehicles, the infrastructure, and passengers' personal communications devices. This effort has the potential to provide a quantum leap forward in the benefits that ITS technologies can provide to highway transportation and will open the door for a diverse set of new applications.[36]

A variety of advanced ITS applications have been proposed for improving fuel efficiency that will take advantage of connectivity among vehicles and with the transportation infrastructure. These applications will save fuel by reducing congestion, minimizing speed fluctuations characterized by unnecessary braking and accelerations, and optimizing vehicle operating conditions for peak efficiency using information of the current and expected traffic environment surrounding each vehicle. Relevant ITS applications and systems include adaptive signal timing, dynamic vehicle routing and advanced speed advisement and control.

One system believed to hold very significant potential for fuel savings is predictive-cooperative adaptive cruise control (predictive CACC). This advanced cruise control system will provide highly automated vehicle speed control by using information from other vehicles and connected transportation infrastructure in a way that allows the vehicle speed profile to be highly optimized for fuel efficiency. The predictive CACC system would provide automatic adjustments to a vehicle's speed to account for real-time traffic conditions, traffic signal timing, elevation variations, speed limit changes and any curves and turns along the route of travel. In freeway operations, the system would manage "vehicle platooning" (maintaining a short following distance of around 2-3 meters) between vehicles in groups of a limited number of vehicles), which can provide significant benefits in reducing aerodynamic drag as well as increasing traffic capacity. Additional functions could also be integrated with the predictive CACC system as its use becomes more widespread. For example, lane changes in traffic could be managed through a request and automated scheduling system, allowing vehicles to make lane changes more easily and in a manner that minimizes or eliminates disruptions to traffic and unnecessary braking.

The potential reduction in fuel consumption when vehicles take full advantage of shared traffic and infrastructure information is dramatic. In off-freeway settings, optimization of vehicle speeds by accounting for traffic ahead of a vehicle can reduce fuel consumption by up to 33%,[37] depending on the drive cycle. These benefits will not be achieved immediately when such devices are available since information sharing requires that a significant portion of vehicles be equipped with such systems.

---

[35] ITS Deployment Statistics Database, http://www.itsdeployment.its.dot.gov/. Accessed 2/10/11

[36] DOT Connected Vehicle Research, http://www.its.dot.gov/connected_vehicle/connected_vehicle.htm.

[37] C. Manzie, H. Watson, S. Halgamuge, "Fuel Economy Improvements for Urban Driving: Hybrid vs. Intelligent Vehicles," *Transportation Research Part C*, vol. 15, pp. 1–16, 2007.

Nonetheless, it is expected that significant improvements in fuel efficiency can be achieved even with deployments as low as 15-20%. Further research is necessary to better quantify the benefits achievable with ITS systems in real-world usage, particularly during the initial transition periods when only a limited number of vehicles are equipped with these ITS systems. There is a need to carefully assess which ITS technologies can provide the greatest benefits for the trucking sector and quantify the expected efficiency improvements and costs.

While ITS technology development is already strongly supported by DOT, most notably through the RITA Joint Program Office Connected Vehicle program, the primary focus has been on safety applications, and current funding for the Connected Vehicle program still remains heavily oriented toward the DOT-centric missions of safety and congestion mitigation. The 21st Century Truck Partnership recognizes that the inherent infrastructure to support Connected Vehicles should include the commercial vehicle sector as well as the passenger fleet. In addition, it acknowledges that there are multiple demonstrations occurring elsewhere in the world where Connected Vehicle systems are being utilized to improve fuel economy and air quality, mitigate congestion and the associated losses in productivity, etc. A case is made for initiation and future support of similar activities in the United States. under 21CTP aegis.

With our analysis-backed sense of the magnitude of potential energy savings available from ITS technologies and systems, it is important that DOE and DOT work very closely in this domain so that the magnitude of energy savings attainable with Connected Vehicle systems does not go untapped. Research and development of these applications must be sufficiently funded to assure attainment of the maximum benefits in fuel savings and emissions reductions, in addition to safety and mobility. DOE (as well as EPA) sponsorship of activities in support of other Connected Vehicle research is strongly recommended, and regular communications between the DOE and DOT regarding ITS advancement should be maintained.

6.2.4. New Generation Wide Base Single Tires

New Generation Wide Base Single (NGWBS) tires are a tire design innovation that yields a significant reduction in tire rolling resistance for heavy trucks. One NGWBS tire replaces a conventional dual tire set in a typical drive or trailer position on combination vehicles, and they can be used in some other truck applications as well. The NGWBS tire design can result in rolling resistance levels that are 20-35% lower than the dual tires they replace. Replacing all dual tires on a heavy truck with NGWBS tires can translate to fuel savings between 5 and 10 percent depending on the specific drive cycles that are driven.

Although the fuel efficiency benefits [38, 39, 40] have been well demonstrated in a number of studies, the use of NGWBS tires has been constrained by various regulatory restrictions applied to some state permit-

[38] T. LaClair, R. Truemner, "Modeling of Fuel Consumption for Heavy-Duty Trucks and the Impact of Tire Rolling Resistance," Presented at the Commercial Vehicle Engineering Congress and Exhibition, November 2005, SAE Paper 2005-01-3550, SAE International.

[39] G. Capps, O. Franzese, B. Knee, M.B. Lascurain, P. Otaduy, "Class-8 Heavy Truck Duty Cycle Project Final Report," Report number ORNL/TM-2008/122, August 2008.

[40] L. Bachman, A. Erb, C. Bynum, "Effect of Single Wide Tires and Trailer Aerodynamics on Fuel Economy and NOx Emissions of Class 8 Line Haul Tractor-Trailers," Presented at the Commercial Vehicle Engineering Congress and Exhibition, November 2005, SAE Paper 2005-01-3551, SAE International.

required vehicle operations, e.g. oversize, overweight, or longer combination vehicles, in the United States. These permit-required vehicle regulations were in place to ensure that loads could be adequately carried by dual tires, i.e. to prevent the practice of “singling out,” and to address the concerns of tire/pavement interaction of the earlier single truck tires, i.e. 65-aspect ratio. With the wider NGWBS tires, the tire contact area is similar to the area of a conventional dual tire set and the pressure on the ground does not differ greatly between NGWBS tires and duals. As a result, the tire/pavement interaction has been shown to be very similar whether dual tires or NGWBS tires are used.[41] No restrictions apply to truck operations within the legal size and weight limits, however some states have restrictions on the use of NGWBS tires in over-size and over-weight operations that require truck-trailer permits. Research is ongoing on the overall subject of vehicle/pavement and tire/pavement interaction, but further efforts are needed to demonstrate that the tire/pavement interaction with NGWBS tires is no more severe than for conventional dual tire sets, even for these permit-required over-size and over-weight operations. Such research will help to harmonize the regulations of different state DOTs so that no further restrictions regarding the use of NGWBS tires remain.

State regulatory restrictions * on NGWBS tire use e.g. 445/50R22.5, 455/55R22.5, 495/45R22.5	
Commercial vehicle operation within legal size and weight	No restrictions identified.
Commercial vehicle operation requiring state-issued permit	NY, MN, LA, SD, KS, OK, TX, MT, UT, NV, WA, CA

* State laws and regulations are subject to change at any time and state authorities need to be consulted for commercial vehicle operations.

- Commercial vehicle legal size and weight operation
  - No restrictions identified.
- State commercial vehicle permit-required operation
  - Forms of tire regulatory language
    - “ each axle (non-steering) must have 4 tires ”
    - “ two tires at each end of each axle ”
    - “ minimum axle width ”
    - “ tandem axle shall have tires of the same size and construction ”
    - “ limit to 500 lpi ”

6.2.5. Weight Limit Allowances for Fuel Saving Devices

While some technologies may impose no significant weight penalty (or even result in a vehicle weight reduction), many of the advanced fuel efficiency technologies do require hardware that can increase a vehicle’s mass. Legal restrictions for the maximum vehicle weight therefore act as an additional regulatory deterrent to the adoption of fuel saving technologies, particularly for those devices that are relatively heavy, since the additional weight of the device can limit the load carrying capacity of the vehicle. States can opt in to a national 400-pound exemption that is permitted for idling reduction devices under the Energy Policy Act of 2005, but there are several states that do not allow the exemption. For other fuel saving technologies, no such exemptions are currently in place. The DOE and DOT should consider means by which this regulatory barrier can be removed so that the implementation of fuel savings technologies will not be impeded as a result of weight limitations.

[41] I. Al-Qadi, “New Generation of Wide-Base Tire and Its Impact on Trucking Operations, Environment, and Pavements” Transportation Research Board 86th Annual Meeting, Paper No. 07-2432, January 21-25, 2007, Washington, D.C.

6.3. Information Gaps

Identifying and optimizing new technologies and making operational improvements that will have the greatest impact on truck fuel efficiency requires detailed knowledge of how trucks are operated on our nation's roadways. Data gathered from many different sources are needed to accurately quantify the gains that can be made by applying new technologies among the many very different uses of trucks. The available information needs to be further analyzed and assimilated so that the solutions with the greatest potential can be identified and further developed.

One issue that has arisen repeatedly when attempting to quantify potential fuel economy gains is that of realistic drive cycles of trucks. Depending on what drive cycles are used in an analysis or measurement, the estimated benefits of a given technology can vary dramatically. In order to develop a better understanding of technologies that will provide meaningful reductions in fuel consumption, it is necessary that a fundamental knowledge of how trucks are used be developed. This can be achieved by measuring the drive cycles of a broad variety of trucks and assessing the data statistically so that representative sets of drive cycles can be developed for use in truck performance assessment models. While there are a variety of drive cycles available in the literature and from sources like dieselnet.org, there is no widely accepted set of drive cycles that represent particular trucking applications that have been validated as truly characteristic of the usage of these applications. As a result, many modelers have selected drive cycles without a strong justification, and it is quite likely that many current estimates of the fuel savings that can be achieved with particular technologies include large errors simply due to the drive cycles assumed in the analyses. Even DOE did not provide guidance on this issue with the SuperTruck solicitation, in which the drive cycle used was left up to each organization that responded to the solicitation. This approach leaves the door open to analyses that are inconsistent in the benefits that particular technologies may provide for particular applications and vocations. Lack of well-defined, consensus-based drive cycles can also result in intentional misrepresentation of benefits by selecting a drive cycle that favors the technology selected. It is proposed that drive cycle data be collected for many types of vehicles as used in different vocational trucking applications and that the data be statistically analyzed to develop representative drive cycles for specific truck configuration-application combinations. Developing drive cycles that are relevant for the many different types of trucks in use will allow much more accurate estimates of the fuel savings that are possible with specific technologies, and understanding the variations in drive cycles will allow an accurate assessment of how robust a technology will be in actual use.

In addition to drive cycles, specific information about the efficiency of individual technologies or devices is lacking. It is recommended that individual products should be thoroughly tested in the laboratory and/or in actual use when they become available in order to quantify the effectiveness of new technologies. Thorough characterizations of the performance of real products under different operating conditions will allow modeling of the technologies to be used for making evaluations in a broader range of uses. Using real products provides a means by which realistic performance can be assessed as opposed to purely theoretical projections. Any such testing should be conducted by organizations that operate independently from the trucking industry in order to prevent any possible conflicts of interest, and care should be taken to present data in a way that does not bias the perception of results. Developing an approach that will allow testing to be performed so that fuel savings are clearly understood and relevant to different vehicles will not be easy, and many decisions are needed as to how such testing could be most efficiently performed.

Component testing of heavy duty truck technologies is currently being performed in Canada under the EnergoTest campaign,[42] and experience from this testing could be used as guidance for similar testing in the United States.

Driver behavior is known to affect the efficiency of trucks, and the impact can be very significant in some cases. The frequency of braking and acceleration and the rates of acceleration are indicators of how aggressive a driver is. It is recommended that methods be developed to quantify driver behavior and the impact that it has on fuel consumption. The impact of driver aggressiveness should then be evaluated using modeling for any technologies that are proposed for use in particular applications, and the expected benefits of a technology can be assessed in light of the real variations of driver behavior that exist in the real world. Variations in driver behavior and its effect on fuel economy can be studied by measuring driver accelerator control inputs from different drivers when they drive over the same segments of roadway at the same time or at least during similar conditions. A combined measurement and modeling approach to evaluate drive cycle and control input effects on fuel consumption can then be pursued to assess how much fuel economy can change if different drivers use advanced technologies that are intended to provide reductions in fuel consumption.

This type of driver behavior research will result in a selection of technologies that are more robust with respect to variations in driver behavior, and will likely also cause technology developers to develop solutions that can reduce the sensitivity of fuel economy to individual driver behavior. It is expected that advanced computer controls and automated driver supervisory systems can be developed to mitigate the deleterious effect that driver behavior can have on fuel consumption performance, but to do so requires a better understanding of how sensitive the fuel consumption is to variations in how different individuals drive. Statistical evaluations based on differences in real driver behavior are necessary to perform such an assessment. Research in this domain should be focused on identifying key parameters of driver behavior that affect fuel consumption, measuring and understanding the full range of variations that exist among different drivers, and developing methods to accurately quantify how fuel consumption is affected, on average, when efficiency technologies are used by different drivers.

6.4 Other Research Needs

6.4.1. Increased Freight Capacity of Heavy Duty Vehicles

The amount of freight carried by trucks has a direct impact on the overall efficiency of transport. Even though the fuel economy of a truck, expressed in miles per gallon, generally decreases as the load that is hauled increases, it is clearly not effective to operate without any payload. Since the objective in freight transport is to haul the greatest quantity of goods over the distances required using the least amount of fuel, an appropriate metric for freight efficiency is either ton-miles/gallon or cubic foot-miles/gallon, depending on whether, for the freight being hauled, a truck reaches it maximum load (regulatory weight limit) or maximum volume (based on the physical size of the trailer). For today's class 8 trucks, the freight efficiency continues to increase as load increases up to the maximum load capacity, which means that the

---

[42] C. McCormick, "Proof Positive," *Motortruck*, September-October 2009.

best situation is to operate trucks at their maximum capacity. A more complete discussion of freight efficiency is provided in a recent paper by Anthony Greszler.[43]

A large number of trucks operate at loads well below the maximum legal weight limit of 80,000 pounds for a number of reasons. In many cases, trucks haul low density freight that results in the available volume being filled before the truck reaches its maximum weight limit. When trucks drop the load they are carrying at their final destination, there may be no additional freight available for carrying another load from a nearby location. This fact results in about 10-25% of trailers running empty as they travel to pick up their next load from another location. There are also many LTL carriers that pick up relatively small loads from multiple customers, and the trucks are infrequently, if ever, loaded to their full capacity due to the nature of the operation. These types of low-load operations may be difficult to improve upon significantly, although continuing to improve supply chain logistics can impact the average loads carried by various carriers. Typical loads are not well known across the trucking fleet today, and a better understanding of the present situation may be helpful in developing ways to increase the loads carried by trucks. There may be opportunities for policies or regulations that could reduce the number of trucks operating with partial loads, and allowing different truck configurations may allow shippers to develop approaches that can reduce the number of trucks by carrying the same freight in fewer trucks. Research is needed in this area to develop an understanding of load distributions among different types of carriers.

For vehicles that normally operate at full load capacities, as described above, freight efficiency can be improved by increasing the load limits and/or by allowing larger volumes to be hauled, so that fewer trucks will be needed to carry the same amount of freight. Current federal regulations limit the maximum weight of trucks to 80,000 pounds, but it has been argued that increased load limits could provide improved efficiency without jeopardizing safety or deteriorating the nation’s roadways if trucks are upgraded to include a sixth axle to carry the additional load, and if braking capacity is increased. The most recent transportation reauthorization bill debated in Congress included provisions for an increased federal truck weight limit of 97,000 pounds for vehicles with six axles. Similar increases to truck load limits have been proposed in the past but have been rejected, largely over concerns related to safety, bridge load capacity and pavement damage issues. Many studies have been performed over the years to address these issues. DOT’s Comprehensive Truck Size and Weight Study,[44] completed in 2000, included an analysis of the impact of a broad range of proposed changes to size and weight regulations, and results from studies regarding the safety and infrastructure implications of truck loads are reviewed in the final report.

Recently, Maine and Vermont allowed temporary increases in truck maximum loads as a one-year pilot project to evaluate the impact of higher loads on safety, road wear and freight efficiency on interstate highways. The Maine exemption was for 100,000-pound 6-axle tractor trailer combinations, while the Vermont load limit was increased to 99,000 pounds. The results of this short-term study could provide very important data that has the potential to influence the future direction of truck load limits across the United

---

[43] A. Greszler, “Technologies and Policies for Improving Truck Fuel Efficiency& Reducing CO_2,” in *Transportation and Climate Solutions: Findings from the 2009 Asilomar Conference on Transportation and Energy Policy*, Edited by D. Sperling and J.S. Cannon, Institute of Transportation Studies, Davis, CA, 2010.

[44] U.S. Department of Transportation, *Comprehensive Truck Size and Weight Study*. Publication Number: FHWA-PL-00-029. August 2000. http://www.fhwa.dot.gov/policy/otps/truck/finalreport.htm. Accessed 2/10/11.

States. Thorough analysis of safety, road damage and freight efficiency data during this pilot project should be conducted to understand the real world implications of the higher load limits. Studies are needed to clearly quantify the benefits for fuel consumption, and accident rates should be statistically analyzed to evaluate the significance of the higher loads with respect to highway accidents. For the question of freight efficiency, there have been questions raised as to how effective increased loads can be for reducing fuel consumption with existing truck designs. Some have suggested that current designs that were developed based on the 80,000 pound national limit may limit the fuel saving potential that a higher load limit could provide, and more powerful engines might be needed to achieve the maximum benefits in freight efficiency. It would be worthwhile to empirically quantify the freight efficiency of several different truck configurations so that the benefits of operating at the higher loads are well documented. As new truck efficiency technologies are developed, it would also be worthwhile to evaluate their effectiveness not only at current load limits of 80,000 pounds, but also at load limits that are under consideration for the near-term future of up to 100,000 pounds.

Given that many trucks reach volume limits before load limits, another approach that will improve freight efficiency is by allowing greater trailer volume capacity with triple trailer configurations and longer double trailers. Federal regulations restrict double trailers to 28 feet per trailer, but longer trailer combinations are legal in rural areas of many western states, as are triple trailers. There is a corridor through Indiana and Ohio in which triple trailers are permitted to operate on the interstate highways, and collection and analysis of data from triple trailer operations through this corridor will allow a better understanding of the safety, road damage and fuel efficiency issues. For the Ohio/Indiana corridor, the load limits are greater than the normal 80,000 pound federal limit, but even without increasing the load limit there may be significant efficiency benefits for triple trailer operations since many low-density freight applications may be able to carry additional freight if additional trailers are allowed. One of the primary concerns for triples and other long trailer combinations is the fact that they can exhibit a serpentine swaying behavior, with oscillatory lateral movements of one foot or more for the last trailer in the triple trailer combination. Little research has been conducted to evaluate the stability characteristics of triple trailers, yet with advanced stability control systems, it may be possible to limit this swaying behavior with small corrective differential braking or through simple design modifications to the trailer design. Research into the stability of double and triple trailers is needed to better understand their stability characteristics and to identify if there are means that can be applied to make them operate without the oscillations that can be unnerving to other drivers. Positive results of this research could support the wider acceptance of the use of multiple-trailer units leading to improved freight fuel efficiency.

7. Issue in Focus - Natural Gas for Medium-Duty and Heavy-Duty Trucks

7.1. Background

Natural gas has been in use as a vehicle fuel for nearly one hundred years, with varying levels of success. Interest in natural gas vehicles has risen and fallen as the availability and cost of natural gas has increased or decreased, and as natural gas vehicle availability has changed. Recent developments in economic recovery of natural gas from shale formations in the United States has greatly expanded the availability of natural gas and decreased its cost, resulting in heightened interest in this fuel for fleet applications. The graph in Figure 25 shows the projections for natural gas supply and consumption over the next several decades, and illustrates that the United States could become a net exporter of natural gas sometime in the next decade. This has implications for potential expanded use of natural gas as a vehicle fuel in the future, which are already being noted by medium-duty and heavy-duty vehicle customers.

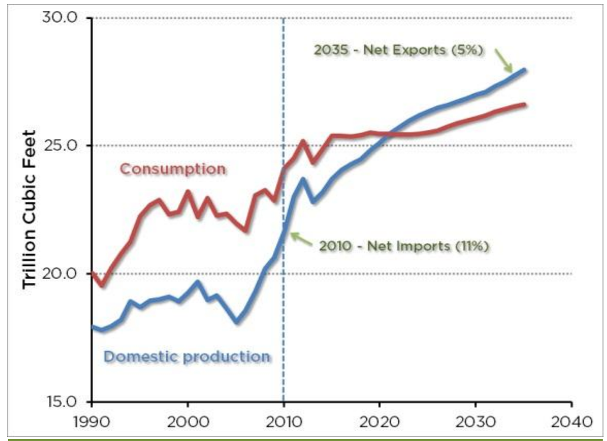

Figure 25. Projections for Natural Gas Consumption and Domestic Production through 2035 (EIA Annual Outlook 2012)

Because of the increased interest in natural gas among fleet customers, 21CTP has explored the potential role for collaborative research and development in this area through a natural gas information/discussion workshop that was held at the Argonne National Laboratory in June 2012. The goal of the workshop was to educate the Partnership's members on the current state-of-the-art in natural gas technology for vehicles and infrastructure and to discuss potential future research and development needs to improve natural gas usage for commercial trucks and buses. The information presented below is the result of this consensus discussion among the 21CTP partners.

At present, no decisions about future research directions have been made, so 21CTP is not including any specific Partnership goals in this technical roadmap related to natural gas as a result of these discussions. The information is being included in the technical roadmap to highlight the need for such research, and to outline the Partnership's collective assessment of the necessary topics.

7.2. Engine Development

7.2.1. Introduction

Research and development is needed to overcome critical barriers to the highest efficiency, emission compliant, durable and cost-effective use of natural gas (NG) in internal combustion engines (ICEs). R&D requirements include the need for developing high efficiency enabling NG combustion strategies, the need for more robust ignition and gaseous fuel injection technologies, and the need for a science-based understanding of the fundamentals of NG fuel introduction and ensuing combustion processes. Specifically, these needs include R&D on:

- Advanced high-efficiency enabling Compression-Ignition (CI) and Spark-Ignition (SI) combustion strategies such as:
    - Diesel micro pilot-NG CI <2% diesel
    - Advanced pre-treatment strategies for air and/or fuel streams
    - Incorporate proven stationary engine concepts in transportation engines
    - Reactivity Controlled CI (RCCI) of diesel and NG
    - Lean and dilute premixed-charge, direct-injection SI
    - Stratified-charge, direct-injection SI
    - Boosted operation with advanced combustion approaches
    - Waste heat utilization for efficiency improvements
- Ignition systems/strategies for spark ignition
    - Extend durability and reliability
    - Extend lean limits of ignition
    - Extend the exhaust gas recirculation (EGR) fraction (currently limited to 22%)
    - Accelerate rate of flame growth
    - < 5% Coefficient of Variation (COV) of Indicated Mean Effective Pressure (IMEP) under high (>15 bar) Brake Mean Effective Pressure (BMEP) conditions
    - Advanced ignition approaches
- Durable/reliable NG fuel injection technologies for the high-efficiency options
- Engine combustion system computational fluid dynamics (CFD) design tools validated for NG
- Supporting fundamental research to provide the knowledge-base for designing engines with high-efficiency combustion strategies and developing/validating CFD design tools for NG use
    - Fuel injection processes
    - A CFD fuel injection model suitable for gaseous fuel
    - In-cylinder fuel-air mixing, ignition, combustion and pollutant formation processes for advanced NG combustion strategies
    - Combustion instability sources and control
    - Tribology/lubrication for NG use (engine and fuel injectors)
- Engine combustion tolerance for fuel quality variations (methane number of 50)

7.2.2. Specific Research Concepts from Workshop

The bullets below list the concepts related to engine combustion that were developed as part of the workshop as potential areas of research for future consideration. At present, these concepts are not listed in any priority order.

- ***A-1:*** Spark plug durability and other ignition system technologies
- ***A-2:*** High-pressure direct-injection (HPDI) injector life and reliability
- ***A-3:*** Combustion stability/engine response in CNG SI stoichiometric engines (transmission response)
- ***A-4:*** Fundamental combustion studies for advanced strategies for high efficiency

- ***A-5:*** Tribology, wear, lubrication – is there a need for improvement?

7.2.3. Additional Concepts from NREL Presentation to DOE

In addition to the information collected as part of the 21CTP natural gas workshop, DOE provided the Partnership with some additional research topics from the National Renewable Energy Laboratory to supplement the workshop discussions. Where appropriate, topics from NREL that relate to those from the 21CTP workshop are cross-referenced. As with the results shown above, these are reported in no particular order.

- ***A-N1:*** Develop accurate kinetic models to employ high performance computing (HPC) simulation (mechanisms, flame speeds) for NG engine development
- ***A-N2:*** Develop on-board gas composition sensor for engine control input
- ***A-N3:*** Develop other technologies for advanced NG engines: CNG direct injection and advanced ignition systems *(similar to A-1 above)*
- ***A-N4:*** Sponsor engine development program for high-efficiency, low emissions NG engines; <10% fuel economy penalty from diesel, 0.00X g/hp-hr NOx, and low NH_3 (NOx and NH_3 are critical for long-term adoption in California)
- ***A-N5:*** Sponsor development of 2010-emissions compliant engine/vehicle retrofits to maximize sustainable NG adoption in response to end-user market demand
- ***A-N6:*** Sponsor high-horsepower engine development
- ***A-N7:*** Sponsor 2010 emissions-compliant engine/vehicle development for Class 6-7
- ***A-N8:*** Sponsor reliability improvements for key NG engine systems: injectors, ignition, and LNG fuel conditioning *(similar to A-1 and A-2 above)*

7.3. Emissions and Aftertreatment

7.3.1. Introduction

Natural gas powered vehicles employ internal combustion engines that operate either in stoichiometric or lean-burn mode. Engines operating in stoichiometric mode utilize three-way catalytic converters (TWC) that are, in principle, quite similar to standard catalysts found in commercial gasoline powered vehicles. As with commercial gasoline technology they are controlled via an oxygen sensor feedback loop and are very efficient at the control of the criteria pollutants. However, most natural gas vehicles have substantial quantities of methane in the exhaust, which poses an additional unique challenge. Oxidation of methane is problematic at all but the highest exhaust temperatures normally experienced during standard operation. For lean-burn NG engines the challenges with methane oxidation are even more pronounced due to the typically lower exhaust temperatures. In addition, stringent new NOx regulations will require the use of some form of selective catalytic reduction (SCR) or NOx storage/reduction device. Depending upon the service location of these vehicles, methane emissions may be regulated directly, not at all, or indirectly through a greenhouse gas equivalency. Other significant challenges include catalyst durability (degradation through chemical and/or thermal mechanisms) and the formation of unwanted products such as ammonia. R&D topics of particular relevance include:

- Methane oxidation

- Byproduct formation (e.g. ammonia)
- Thermal and/or chemical deactivation
- Particulate number control
- Real-world drive cycle simulations, life cycle analysis, and benefits studies

7.3.2 Specific Concepts from Workshop

The bullets below list the concepts related to emissions and aftertreatment that were developed as part of the workshop as potential areas of research for future consideration. At present, these concepts are not listed in any priority order.

- ***B-1:*** Methane, ammonia, other TWC issues
- ***B-2:*** HPDI with TWC (eliminate DPF and SCR)
- ***B-3:*** Aftertreatment issues – control of methane emissions and/or utilization of the methane as a reductant for advanced combustion strategies
- ***B-4:*** Validate the advantages in emissions in transient operating conditions that emulate real duty-cycles including powertrain, SI vs. CI and CNG vs. LNG variants

7.3.3. Additional Concepts from NREL Presentation to DOE

The NREL topics list did not include any that were specific to this technology area.

7.4. Natural Gas Pathways for Transportation Fuels

7.4.1. Introduction

A well-to-wheels (WTW) analysis can assess the energy use and emission impacts of alternative transportation fuels. In addition, this type of analysis can also address other important factors such as cost (fuel, infrastructure, etc.) and vehicle performance/adaptability to new fuels. Natural gas based fuels for heavy-duty vehicle applications are of importance to the 21CTP. Several recent U.S. studies have examined the impacts of shale gas and conventional NG production, so any effort to examine these fuels should build on this work. Similarly, past U.S. and European studies have examined the production of NG based fuels, however updating this work to include the most recent information would be helpful. With much of the WTW analyses focusing on light-duty vehicles, there are some opportunities to focus on key issues for heavy-duty vehicles, such as vehicle/engine efficiency for different duty cycles, impacts of tailpipe emission standards, and methane venting during refueling and operation.

7.4.2. Specific Concepts from Workshop

The bullets below list the concepts related to natural gas pathways that were developed as part of the workshop as potential areas of research for future consideration. At present, these concepts are not listed in any priority order.

- ***C-1:*** Well-to-wheels study of CNG, LNG, and gas-to-liquids fuels (to include diesel, propane, DME, and methanol)

7.4.3. Additional Concepts (NREL)

- ***C-N1:*** Host NG workshop to integrate NREL, INL, and BNL efforts for overall NG use from processing to stationary power to transportation.

7.5. Natural Gas Fuel Quality and Standardization Considerations

7.5.1. Introduction

CNG with lower methane content (i.e., higher levels of ethane, propane, or butane) has resulted in some adverse effects on heavy-duty NG engine performance (e.g., misfire, stumble and underrated operation, engine knock, and overheating). Engine knock or pre-ignition problems can potentially result from the presence of higher non-methane hydrocarbons in NG. Examples include higher levels of ethane, propane, butanes, and heavier hydrocarbons. These types of gases are often referred to as "rich gases" and can be found in various parts of the world, including the United States, frequently in California. In particular, certain instate producers in the Central Valley region and off-shore producers have been identified as supplying NG with methane levels in the range of 80-90 percent, with relatively high levels of ethane and propane when compared to the national or state average. However, today's lean-burn closed-loop NG engines are better able to tolerate and compensate for variations through the applications of improved sensors, knock detection, and wider range fuel capability. The potential for engine knock increases with:

- Higher compression ratios
- Higher levels of non-methane hydrocarbon gases
- Higher engine loads
- Hotter ambient temperatures

Compression ratio, BMEP, and horsepower are terms often used to categorize or characterize a reciprocating engine. As a first-order estimate, an SI naturally-aspirated reciprocating engine will be more prone to engine knock as the compression ratio increases. The BMEP ratings associated with heavy-duty (diesel derivative) turbocharged NG engines are much higher when compared to light-duty (gasoline derivative) naturally aspirated NG engines. The average light-duty NG engine BMEP rating is 123 pounds per square inch (psi) while heavy-duty NG engines average 193 psi (or 60% higher specific performance from these heavy-duty NG engines). This can be of original equipment manufacturer (OEM) concern should heavy-duty engines be exposed to variances in NG heating values.

It has been shown that ship transport or storage will increase the heating value (HV) of the LNG. Many factors will affect ageing (the increasing of the HV) during travel or a period of prolonged storage. Factors like: type of LNG ship, age of LNG ship, distance to travel and time of year or sea conditions will affect the actual increase in HV. Most of the base load LNG plants are located at a distance from the market that can be reached with approximately 10 days of travel. A similar situation exists for LNG transport by rail tanker car across country. For simplicity, we have assumed 10 BTU/SCF increase in gross calorific value (GCV) to compensate for ageing. This is based on a 10 day travel time using 0.2% per day in boiloff rate. For a significant portion of the transported LNG, the loaded HV is 1127 or more. This group can never be marketable as a motor fuel without further processing or blending with other sources. Moreover, the GCV is too high for only blending with nitrogen or other non-combustible components.

7.5.2. Specific Concepts from Workshop

The bullets below list the concepts related to fuel quality that were developed as part of the workshop as potential areas of research for future consideration. At present, these concepts are not listed in any priority order.

- ***D-1:*** LNG boil-off fuel use for auxiliary power unit (APU) or trailer refrigeration unit (TRU) power?
- ***D-2:*** LNG storage, and boil-off issues when using LNG (on vehicle and during fuel transfer to the vehicle and at infrastructure transfer points). GHG issues due to venting
- ***D-3:*** Establish an NG fuel standard for transportation fuel (like propane HD-5 standard)

7.5.3. Additional Concepts (NREL)

- ***D-N1:*** Characterize NG properties in engine-relevant terms to consider future fuel quality standards (HV and methane number are not comprehensive) *(see D-3 above)*

7.6. Dimethyl Ether as a Transportation Fuel

7.6.1. Introduction

Dimethyl ether (DME) represents a practical alternative to CNG and LNG as a NG-derived transportation fuel. In contrast to CNG, which requires on-board storage at high pressures (3600 psi), and LNG, which requires -162^{o}C temperature, DME is a propane-like (low-pressure) fuel which is liquid at ambient temperatures and moderate pressures and well-suited for use in diesel applications such as trucks, buses, and construction equipment. DME is a naturally clean burning CI fuel that can achieve the unparalleled brake thermal efficiency of diesel fuel without significant modifications to the engine. DME is also non-toxic, and is not a GHG. DME has lower energy density (18.9 MJ/liter), however, than diesel (37.3 MJ/liter). Combustion studies and engine demonstrations of DME as a CI fuel were performed throughout the 1990's, but further activity halted when the price of NG went up nearly tenfold in 2000. Three important developments since 2000 make DME worthy of continued research: the discovery of large domestic supplies of NG and subsequent price stabilization; recent developments in advanced combustion regimes for engines; and process developments to convert NG to DME in retail outlet quantities. By making and dispensing DME on site, distribution through the existing NG infrastructure will increase the overall efficiency. Advanced combustion regimes, which use high dilution with EGR for NOx control, are ideal for DME since DME doesn't make particulate matter (PM) or have a semi-volatile hydrocarbon fraction like diesel. Thus, DME can lower the requirements of the aftertreatment system considerably. Barriers that need to be addressed with research include fuel lubricity and corrosivity, conversion efficiency from NG, lube oil compatibility, and potentially undesirable exhaust species formed during low temperature combustion. In addition, there is a need to fully optimize DME engines for emissions and fuel efficiency and to demonstrate the benefits of DME or CNG for given on-road or off-road duty cycles.

7.6.2. Specific Concepts from Workshop

The bullets below list the concepts related to DME that were developed as part of the workshop as potential areas of research for future consideration. At present, these concepts are not listed in any priority order.

- ***E-1:*** Support for DME research as a CI fuel (NG feedstock)
- ***E-2:*** DME study as an alternative NG usage scenario
- ***E-3:*** Fuel injection system compatibility of DME

7.6.3. Additional Concepts from NREL Presentation to DOE

The NREL topics list did not include any that were specific to this technology area.

7.7. Natural Gas Storage Tank Improvements

7.7.1. Introduction

Thirty years of practical experience with compressed natural gas (CNG) vehicles has proven that the development of codes & standards and regulations alone cannot ensure the safe initial deployment of vehicles or the safety of those vehicles over their intended lifespan. The safe deployment of natural gas vehicle requires a multi-faceted strategy that encourages and motivates practical applications of smart and safe practices in the field. At present, there are no effective regulatory mechanisms to monitor and enforce compliance issues related to in-service vehicles, especially with cylinder tracking procedures, safety inspections and end of life notification protocol. Joint government-industry efforts can best support this process by working together on initiatives and action items like those listed below.

7.7.2. Specific Concepts from Workshop

The bullets below list the concepts related to storage tanks that were developed as part of the workshop as potential areas of research for future consideration. At present, these concepts are not listed in any priority order.

- ***F-1:*** CNG tank safety (DOT-NHTSA funded). Inspection period. Integrated warning system.
- ***F-2:*** Means to lower CNG and LNG tank cost and weight
- ***F-3:*** Renewed R&D on NG adsorber systems (800 psi)

7.7.3. Additional Concepts (NREL)

- ***F-N1:*** Develop high density on-board CNG storage (i.e., adsorption technologies) *(see F-3 above)*
- ***F- N2:*** CNG cylinder replacement program *(see F-1 above)*

7.8. Refueling Infrastructure Economics

7.8.1. Introduction

Natural gas is typically compressed or liquefied to increase its energy density and dispensed via time-fill or fast-fill, liquid or gaseous infrastructure. For compressed natural gas (CNG) vehicles that return to base each day, time-filling may be sufficient to meet fleet needs. Less expensive than fast-fill systems, time-fill systems compress pipeline-supplied natural gas over several hours (typically overnight) and are often owned by the fleet operator, thereby ensuring fuel availability but diverting resources to capital equipment that lies idle the rest of the day. Fast-fill CNG systems are more expensive and more likely to serve regional trucking fleets en route to a home base, private vehicles, or high mileage local fleets like taxis and delivery trucks. Fast-fill stations dispensing either CNG or liquefied natural gas (LNG) may be open to the public or limited to fleets that contract with a separate station operator. Often these anchor fleets improve station economics by providing a steady, predictable base load and associated cash flow. Fast-fill LNG systems, being developed at truck stops along major interstate corridors, typically serve long-haul fleets.

Whether by compression, liquefaction or some as-yet unknown technology, fuel conditioning is essential to improve the energy density of natural gas for use in internal combustion engines. With current technologies, it is also a major contributor to infrastructure cost. In order to ensure 24/7 reliability, redundancy is normally built into the cost of compressors which can account for 30% or more of station cost. Liquefaction costs can be comparable. On top of these, storage tanks – either for high pressure gases or cryogenic liquids – can cost hundreds of thousands of dollars. At $1 million or more, CNG or LNG stations reflect a developing but still immature industry in which station designs are only now becoming standardized, compression and storage technologies are not optimized to the volumes and needs of refueling stations, and infrastructure economics are not yet well understood. A better understanding is needed of such issues as daily and hourly demand patterns and how they affect dispensing and storage needs, the cost and performance of conventional and advanced technology conditioning storage equipment, and tradeoffs between supply, demand and storage capacity. Research and development is also needed on new methods and technologies for fuel conditioning and storage that can improve the reliability and reduce the cost of fueling infrastructure.

7.8.2. Specific Concepts from Workshop

The bullets below list the concepts related to infrastructure economics that were developed as part of the workshop as potential areas of research for future consideration. At present, these concepts are not listed in any priority order.

- ***G-1:*** LNG and CNG infrastructure in the United States
- ***G-2:*** Cost of refueling station. How big does an LNG station have to be?

7.8.3. Additional Concepts (NREL)

- ***G-N1:*** Continue technology and economic analysis (what attributes describe a good NG station?)
- ***G-N2:*** Conduct NG fueling infrastructure regional analysis. Where can big impacts be made?

7.9 Future Transportation Fuel Strategies (Natural Gas)

7.9.1. Introduction

Natural gas can be used as a transportation fuel either directly, in the form of compressed (CNG) or liquefied natural gas (LNG), or as a feedstock for producing other fuels. Each fuel option has its own set of benefits and disadvantages in terms of cost, complexity, energy efficiency, emissions, and the infrastructure development needed to enable using the fuel broadly in the current U.S. transportation system. As a result, there are a broad range of issues that must be considered to determine which fuel option is optimal, and what is best for one application may not be ideal for another. Given the costs and challenges in creating a new fuel production and distribution network to serve the U.S. transportation system, it is important that all options be evaluated carefully to ensure that the greatest long-term benefits will be realized.

A detailed assessment is needed to compare the infrastructure requirements, vehicle incremental costs, and overall energy efficiency and emissions between the fuel options. Infrastructure requirements and associated costs can vary considerably. For example, if natural gas is used as a feedstock to produce diesel using a gas-to-liquid process, the existing fuel distribution and filling station network could be used with very minimal changes, and the existing truck fleet could use the alternatively produced diesel fuel without modification. On the other hand, both on-vehicle systems and fueling stations will be more complex to handle either high pressure CNG or cryogenic LNG. For other fuel options such as dimethyl ether (DME), infrastructure development would be needed for the fuel production and distribution, but only relatively minor changes to the vehicle are expected to be necessary. It is important to consider not only the supply-side economics, but also to evaluate the expected economic benefits of the end user in order to verify that there will be sufficient demand for the alternative fuel. From the perspective of the user, the incremental cost of the vehicle (due to different powertrain, fuel storage and emissions control systems) relative to a conventional diesel- or gasoline-powered vehicle is critical, since the vehicle's incremental cost along with the fuel price and annual fuel use will determine the payback period that a user can achieve. To evaluate the efficiency and emissions impacts of different fuel options, a well-to-wheels analysis is needed in each case so that the efficiency of different engine types as well as the energy losses and emissions associated with the conversion of one fuel to another, or due to the compression/liquefaction of the pure natural gas, are properly accounted for. An accounting of the costs, energy usage, and emissions, along with other consequences of transitioning to a new fuel, is necessary to understand the true benefits over the long term for each alternative fuel.

7.9.2. Specific Concepts from Workshop

The bullets below list the concepts related to fuel strategies that were developed as part of the workshop as potential areas of research for future consideration. At present, these concepts are not listed in any priority order.

- ***H-1:*** Cost-effective methane to diesel conversion (Fischer-Tropsch)
- ***H-2:*** NG conversion to DME
- ***H-3:*** Low sulfur diesel fuel
- ***H-4:*** NG as CNG or LNG

7.9.3. Additional Concepts from NREL Presentation to DOE

The NREL topics list did not include any that were specific to this technology area.

7.10. Expand Natural Gas Vehicle Deployment Programs

7.10.1. Introduction

The U.S. Department of Energy's Clean Cities initiative advances the nation's economic, environmental, and energy security by supporting local actions to reduce petroleum consumption in transportation. Clean Cities accomplishes this work through the activities of nearly 100 local coalitions. These coalitions provide resources and technical assistance in the deployment of alternative and renewable fuels, idle-reduction measures, fuel economy improvements, and new transportation technologies, as they emerge.

Clean Cities was established in 1993 in response to the Energy Policy Act of 1992 and is housed within the U.S. Department of Energy's (DOE) Vehicle Technologies Office. Since its inception, Clean Cities has saved more than 3 billion gallons of petroleum. Clean Cities' overarching goal is to reduce U.S. petroleum use by 2.5 billion gallons per year by 2020.

Clean Cities works to reduce U.S. dependence on petroleum in a variety of ways, at the local, state, and national levels. Clean Cities activities include:

- Establishing local coalitions of public- and private-sector stakeholders
- Providing technical assistance to fleets deploying alternative fuels, advanced vehicles, and idle-reduction measures
- Identifying funding and financial opportunities to support Clean Cities projects
- Documenting, analyzing, and publishing data from industry partners and fleets
- Developing information resources about alternative fuels, advanced vehicles, and other measures to reduce petroleum use
- Working with industry partners and fleets to identify and address technology barriers to reducing petroleum use
- Developing online tools to help stakeholders reduce petroleum consumption.

7.10.2. Specific Concepts from Workshop

- Consider ways to support and expand natural gas vehicle deployment programs such as those conducted by Clean Cities

7.10.3. Additional Concepts (NREL)

- ***I-N1:*** Co-sponsor NG Vehicle Technology Forum (NGVTF) with California Energy Commission to leverage industry collaboration and growth
- ***I-N2:*** Develop an updated facility NG retrofit guide
- ***I-N3:*** Update maintenance and life-cycle cost information to educate market adopters like truck and bus fleets

8. Acronyms List

ABS	Anti-Lock Braking System
AC	Alternating Current
AEC MOU	Advanced Engine Combustion Memorandum of Understanding
APU	Auxiliary Power Unit
ARRA	American Recovery and Reinvestment Act
ASTM	American Society for Testing and Materials
ATRI	American Transportation Research Institute
BMEP	Brake Mean Effective Pressure
CAFEE	Center for Alternative Fuels, Engines, and Emissions
CARB	California Air Resources Board
CERDEC	Communications-Electronics Research, Development, and Engineering Center
CFD	Computational Fluid Dynamics
CI	Compression Ignition
CLEERS	Cross-Cut Lean Exhaust Emission Reduction Simulations
CMAQ	Congestion Mitigation and Air Quality
CNG	Compressed natural gas
CO	Carbon Monoxide
COV	Coefficient of Variance
CRC	Coordinating Research Council
DEF	Diesel Exhaust Fluid
DME	Dimethyl ether
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
DPF	Diesel Particulate Filter
DRIFTS	Diffuse Reflective Infrared Spectroscopy
DSRC	Dedicated Short Range Communications
ECBS	Electronically Controlled Braking Systems
EERE	Energy Efficiency and Renewable Energy
EGR	Exhaust Gas Recirculation
EISA	Energy Independence and Security Act of 2007
EMA	Engine Manufacturers Association
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EPS	Electrified Parking Space
ERS	Enhanced Rear Signaling Systems
ESC	Electronic Stability Control
EV	Electric Vehicle
FACE	Fuels for Advanced Combustion Engines
FCW	Forward Collision Warning

FE	Fossil Energy
FMCSA	Federal Motor Carrier Safety Administration
FTA	Federal Transit Administration
FTP	Federal Test Procedure
GDP	Gross Domestic Product
GHG	Greenhouse Gases
HC	Hydrocarbon
HCCI	Homogeneous Charge Compression Ignition
HD	Heavy Duty
HECC	High Efficiency Clean Combustion
HEMTT	Heavy Expanded Mobility Tactical Truck
HEV	Hybrid Electric Vehicle
HPC	High Performance Computing
HPDI	High Pressure Direct Injection
HSWR	High Strength Weight Reduction
HTUF	Hybrid Truck Users Forum
HV	Heating Value
HVAC	Heating, Ventilation, and Air Conditioning
ICE	Internal Combustion Engine
IGBT	Isolated Gate Bipolar Transistor
IMEP	Indicated Mean Effective Pressure
IR	Idle Reduction
ITS	Intelligent Transportation Systems
LCV	Long Combination Vehicle
LD	Light Duty
LDW	Lane Departure Warning
LNG	Liquefied natural gas
LNT	Lean NOx Trap
LTC	Low Temperature Combustion
LTL	Less Than Truck Load
MARAMA	Mid-Atlantic Region Air Management Association
MD	Medium Duty
METI	Ministry of Economy, Trade, and Industry
MPO	Metropolitan Planning Organization
NAS	National Academy of Science
NCFRP	National Cooperative Freight Research Program
NDA	Non-Disclosure Agreement
NFCBP	National Fuel Cell Bus Program
NG	Natural gas
NGVTF	Natural Gas Vehicle Technology Forum
NGWBS	New Generation Wide-Base Single (tires)
NHTSA	National Highway Traffic Safety Administration
NiMH	Nickel Metal-Hydride

NPRM	Notice of Proposed Rulemaking
NREL	National Renewable Energy Laboratory
OBD	On-board Diagnostics
OEM	Original Equipment Manufacturer
ORC	Organic Rankine Cycle
ORNL	Oak Ridge National Laboratory
PBBT	Performance Based Brake Testers
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PHEV	Plug-In Hybrid Electric Vehicle
PM	Particulate Matter
PSI	Pounds per Square Inch
RCCI	Reactivity Controlled Compression Ignition
RDECOM	Research, Development, and Engineering Command
RITA	Research and Innovative Technology Administration
RMS	Root Mean Square
RSC	Roll Stability Control
SAE	Society of Automobile Engineers
SAFETEA-LU	Safe Accountable Flexible Efficient Transportation Equity Act - a Legacy for Users
SCR	Selective Catalytic Reduction
SECA	State Energy Conversion Alliance
SI	Spark Ignition
SOFC	Solid Oxide Fuel Cell
STP	Surface Transportation Program
SUV	Sport Utility Vehicle
TADA	Technology Acceleration and Deployment Activity
TARDEC	Tank-Automotive Research, Development, and Engineering Center
TCM	Transportation Control Measure
TIGGER	Transit Investments for Greenhouse Gas and Energy Reduction
TMA	Truck Manufacturers Association
TRB	Transportation Research Board
TRU	Trailer Refrigeration Unit
TSE	Truck Stop Electrification
TTI	Texas Transport Institute
TWC	Three-way catalyst
ULSD	Ultra-Low Sulfur Diesel
VMT	Vehicle Miles Traveled
VT	Vehicle Technologies Office (DOE)
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
WHR	Waste Heat Recovery
WRI	Wireless Roadside Inspection
WTW	Well to wheels
WVU	West Virginia University

21CTP	21st Century Truck Partnership

21st CENTURY TRUCK PARTNERSHIP

Partnership Vision

Our nation's trucks and buses will safely and cost-effectively move larger volumes of freight and greater numbers of passengers while emitting little or no pollution and dramatically reducing the dependency on foreign oil.

February 2013