21ST CENTURY TRUCK PARTNERSHIP

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Roadmap and Technical White Papers

...safely and cost-effectively move larger volumes of freight and greater numbers of passengers

...dramatically reducing dependency on foreign oil

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

21st CENTURY TRUCK PARTNERSHIP

ACKNOWLEDGEMENTS

The 21st Century Truck Partnership would like to acknowledge the time and resource investment that all our partners have made in developing this roadmap and technical white paper document, and in remaining committed to the goals and objectives outlined herein. We would also like to extend our appreciation to the industry and government teams that produced the individual technical white papers, and the leaders of those teams who are listed below.

Engines: Ron Graves (Oak Ridge National Laboratory) with Dennis Siebers (Sandia National Laboratories)
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Parasitic Losses: Jud Virden (Pacific Northwest National Laboratory)
Idle Reduction: Glenn Keller (Argonne National Laboratory)
Safety: Bill Knee (Oak Ridge National Laboratory)

Table of Contents

21st Century Truck Partnership
"Unprecedented Collaboration for Unparalleled Results"
An Agreement between the Federal Government and the Heavy Duty Vehicle Industry

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
1. Transportation in America supports the growth of our nation's economy both nationally and globally.
2. Our nation's transportation system supports the country's goal of energy security.
3. Transportation in our country is clean, safe, secure, and sustainable.
4. America's military has an agile, well-equipped, efficient force capable of rapid deployment and sustainment anywhere in the world.
5. 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.

- Promote research for engine, combustion, exhaust aftertreatment, fuels, and advanced materials to achieve both significantly higher efficiency and lower emissions.

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

- Promote research to reduce parasitic losses to achieve significantly reduced energy consumption.

- Promote the development of technologies to improve truck safety, resulting in the reduction of fatalities and injuries in truck-involved crashes.

- Promote the development and deployment of technologies that substantially reduce energy consumption and exhaust emissions during idling.

- Promote the validation, demonstration, and deployment of advanced truck and bus technologies, and grow their reliability sufficient for adoption in the commercial marketplace.

This is an "agreement to agree" between Government and Industry. 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.

Specific technology goals have been defined in five 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 improves the engine system fuel efficiency by 20% (from approximately 42% thermal efficiency today to 50%) by 2010.

- Research and develop technologies which will achieve a stretch thermal efficiency goal of 55% in prototype engine systems by 2013, leading to a corresponding 10% gain in over-the-road fuel economy over the 2010 goal.

- By 2010, identify and validate fuel formulations optimized for use in advanced combustion engines exhibiting high efficiency and very low emissions, and facilitating at least 5% replacement of petroleum fuels.

Heavy-Duty Hybrids

A heavy-duty hybrid (>8,500 lb GVW) implies a hybrid-electric propulsion 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 2012 technology goals are:

- Develop a new generation of drive unit systems that have higher specific power, lower cost, and durability matching the service life of the vehicle. Develop a drive unit that has 15 years design life and costs no more than $50/kW by 2012.

- Develop an energy storage system with 15 years of design life that prioritizes high power rather than high energy, and costs no more than $25/kW peak electric power rating by 2012.

- Develop and demonstrate a heavy hybrid propulsion technology that achieves a 60% improvement in fuel economy, on a representative urban driving cycle, while meeting regulated emissions levels for 2007 and thereafter.

Parasitic Losses

Aerodynamic drag resistance, rolling resistance, drivetrain losses, and auxiliary load losses account for 40% of the total fuel energy used to move a heavy-duty vehicle. Specific 2012 technology goals are:

- Develop and demonstrate advanced technology concepts that reduce the aerodynamic drag of a Class 8 highway tractor-trailer combination by 20% (from a current average drag coefficient of 0.625 to 0.5).

- Develop and demonstrate technologies that reduce essential auxiliary loads by 50% (from current 20 horsepower to 10 horsepower) for Class 8 tractor-trailers.

- Develop and demonstrate lightweight material and manufacturing processes that lead to a 15% to 20% reduction in tare weight (for example, a 5000-lb weight reduction for Class 8 tractor-trailer combinations).

Idle Reduction

Class 7 and 8 trucks alone consume over a billion gallons of diesel fuel per year when idling. Achieving specific technology goals will reduce fuel usage and emissions from idling heavy vehicles by more than 85%. These goals are:

- Establish an industry/government collaboration to promote the research, development, and deployment of cost-effective technologies for reducing fuel use and emissions due to idling of heavy-duty diesel engines.
- Establish an educational program for truck and bus owners and operators to implement enabling technologies and operational procedures to eliminate unnecessary idling.
- Develop 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.
- Facilitate the development of consistent electrical codes and standards that apply to both on-board and stationary electrification technologies.
- Develop and demonstrate add-on idling-reduction 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, by 2009.
- Produce a truck with a fully-integrated idling-reduction system to reduce component duplication, weight, and cost, by 2012.
- 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.

Safety

- Crash Avoidance: develop and implement technologies for braking, rollover protection and visibility enhancement:
  - Braking: Advanced braking technologies will be sought with the research goal of achieving a reduction of stopping distances by 30% from operational speeds in appropriate platforms. Improvement in retention of braking ability during grade descents is desired.
  - Roll-Over: Reduce the incidences of heavy vehicle roll-over through the application of advanced technology brake control systems and other complementing technologies.
  - Vehicle Position: Develop and implement driver aid systems that promote safe following distance and in-lane tracking.
  - Visibility: Develop and implement systems that provide the operator with 360 degree visibility (direct and indirect) in day and night conditions.
  - Work with tire manufacturers to improve truck tire performance and reduce tire debris. Incorporate tire advancements with improved braking technologies to achieve substantial vehicle handling improvements.
- Determine the feasibility of enhanced occupant survivability in collisions (offset, frontal, and angle/sideswipe) at differential speeds up to 35 mph between heavy vehicles and passenger vehicles weighing approximately 4,000 pounds. Also, improvements will be sought in truck occupant seat belt use rates by harmonizing restraint systems requirements to enhance comfort and, therefore, driver acceptability.

I.1. Partnership History

The 21st Century Truck Partnership was initially announced 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 half-decade, it became apparent that the participants could best achieve common interests by establishing goals more specific to industry sectors. For that reason, the document you are currently reading was developed to pursue detailed goals for engine systems, heavy-duty hybrids, parasitic losses, idle reduction, and safety. Although the specific goals may have changed since 2000, a common thread among the first roadmap, this current roadmap/white paper document, and all other Partnership discussions is 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 unique in that it 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. This was the case in 2006, when the NTSB brought the issue of truck aggressivity (mismatch of truck structure to car structure in crash situations that causes more severe damage to the smaller vehicle) to the entire group, allowing NTSB to discuss the issue with the industry and government partners at one time.

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. This has been done with the Validation Working Group (2006) that gathered a subset of truck manufacturers, government representatives, and hybrid team members to establish a path forward for the Partnership to move technologies developed under Partnership guidance from the laboratory to on-road vehicle testing, and ultimately to widespread usage. As of this writing, the group has held a number of productive meetings to outline the methodology, and plans to complete a white paper that clearly presents the group's ideas to the Partnership. Another sub-group that resulted from 21CTP discussions was a group of hybrid team members, truck manufacturers, and electrical suppliers to come 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 U.S. 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.

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 I-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.

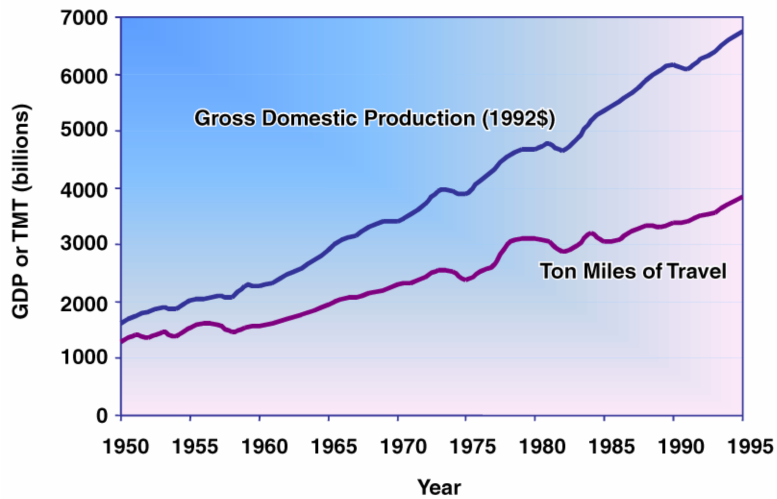


Figure I-1. The nation's economy is linked to truck transport.
Source: Argonne National Laboratory.

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 2002 Vehicle Inventory and Use Survey (Department of Commerce, 2005) reports that there are 79 million light trucks [Class 1 and 2 trucks up to 10,000 lb (4,535 kg) in GVW], 2.8 million medium trucks [Class 3–6 trucks between 10,001 and 26,000 lb (11,791 kg) GVW], and about 2.3 million heavy trucks [Class 7–8 trucks between 26,001 and 130,000 lb (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 per year, according to the Federal Highway Administration: combination trucks

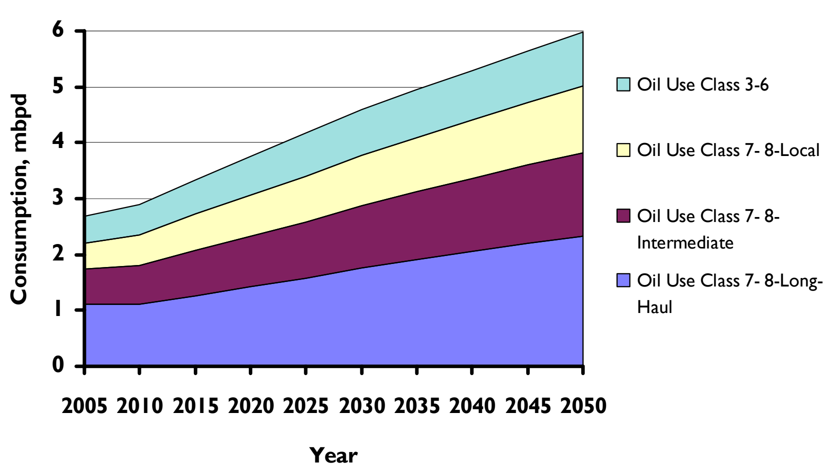


Figure 1-2. Projected Fuel Use for Heavy Trucks through 2050. *Source:* GPRA 06 FCVT Heavy Vehicle Benefits, Preliminary Results, TA Engineering

(trucks with one or more trailers) use about 26.8 billion gallons of fuel per year. As the graph in Figure I-2 shows, fuel use for heavy trucks is projected to increase significantly in the next several decades if we do not make any significant changes to current truck efficiency measures. Figure I-3 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.

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 program 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.

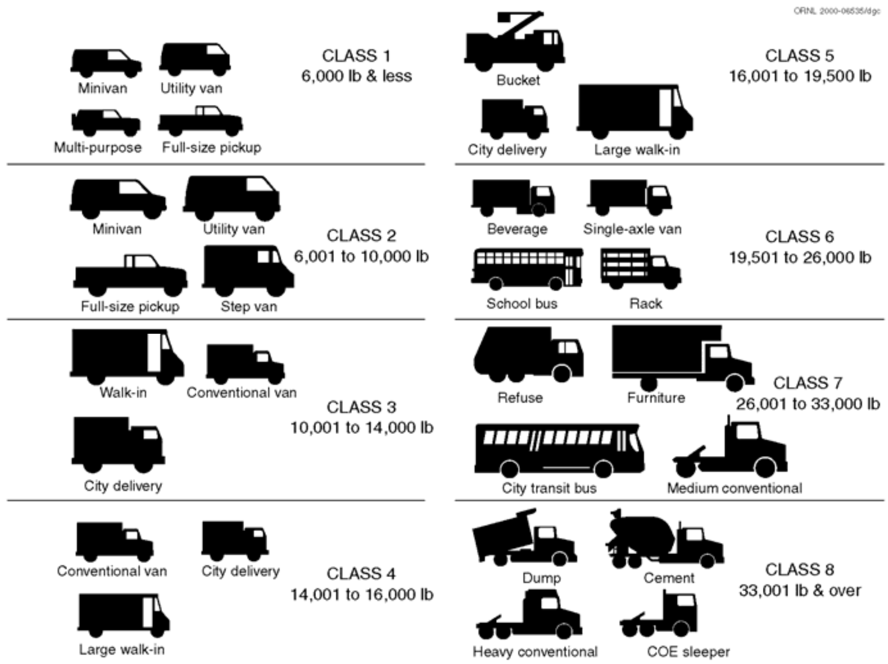


Figure I-3. Truck types by gross vehicle weight (GVW). *Source: Commercial Carrier Journal* (http:\\www.ccjmagazine.com).

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 FreedomCAR and Vehicle Technologies Program (and 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 to this program its mission-oriented intelligent transportation systems and highway transportation safety programs. 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 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 trucking 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 is committed to reducing truck-related fatalities by 50% by 2010. It is expected that the technology developed through the 21st Century Truck Program will contribute significantly to meeting this goal.

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.

I.4. Vehicle Energy Balance

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.

The nature of heavy truck energy use can be better appreciated if it is summarized in an energy audit. Figure I-4 shows the energy audit for a typical Class 8 tractor-semitrailer combination vehicle traveling on a level road at a constant speed of 65 mph and a GVW of 80,000 pounds.

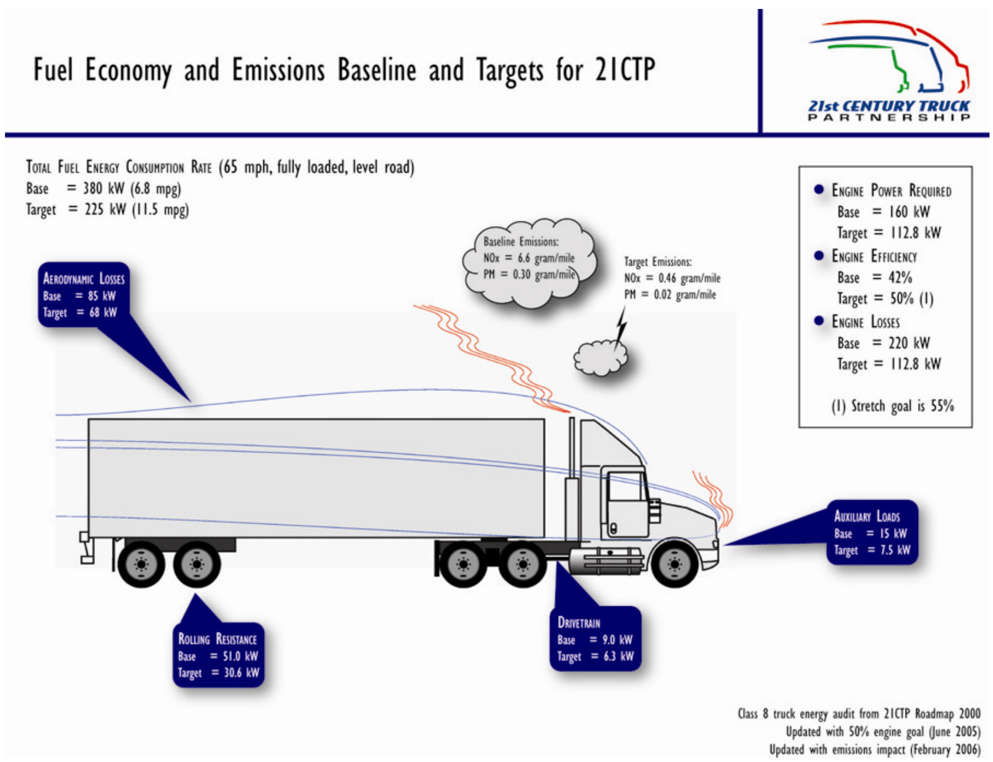


Figure 1-4. Energy Audit for Class 8 Heavy Truck.

Engine losses, aerodynamic losses, and tire-rolling resistance account for approximately 94% of the energy used to sustain vehicle speed at 65 mph. Because these factors are all dependent on vehicle speed, terrain, traffic conditions, etc., the expected benefits to fuel economy will be highly dependent on zone of operation. Driveline friction and engine-based accessories, such as compressors and alternators, account for the remaining 6%. It follows, therefore, that improvements in engine efficiency, aerodynamic drag, and tire-rolling resistance will have a significant impact on fuel efficiency; improvements in driveline and accessory efficiency will have a small influence on fuel efficiency. Nevertheless, any improvement in efficiency should be actively pursued if the cost-benefit relationship is favorable.

I.5. 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, as illustrated in the text box to the right. 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 a series of five white papers to outline their collaborative research efforts. These papers represent a collaborative 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 White Papers provide 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.

21st Century Truck Partners

Industry

Allison Transmission	BAE SYSTEMS
Caterpillar, Inc.	Cummins, Inc.
DaimlerChrysler Corporation	Detroit Diesel Corporation
Eaton Corporation	Freightliner LLC
General Motors Corporation	Honeywell, Inc.
International Truck & Engine Corporation	Mack Trucks, Inc.
NovaBUS	Oshkosh Truck Corporation
PACCAR, Inc.	Volvo Trucks North America, Inc.

Government

U.S. Department of Defense (represented by the U.S. Army)
U.S. Department of Energy
U.S. Department of Transportation
U.S. Environmental Protection Agency

Engine Systems: Within the Engine Systems area, the main industry partners will be the engine manufacturers (Caterpillar, Cummins, Detroit Diesel, 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, FreedomCAR and Vehicle Technologies Program, 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.

Heavy-Duty Hybrids: In heavy-duty hybrid research, the industry role will be represented by the heavy-hybrid team members (chiefly Allison Transmission, BAE Systems, and Eaton Corporation, although Oshkosh Truck is also playing a role in hybrid research). The Department of Energy is pursuing heavy hybrid research through the FreedomCAR and Vehicle Technologies Program. The DOE Hydrogen, Fuel Cells, and Infrastructure Technologies Program is also interested in heavy hybrid technologies as a bridge to the hydrogen fuel cell vehicle of the future. 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.

Parasitic Losses: The industry participation in parasitic loss reduction research will be through the truck original equipment manufacturers (DaimlerChrysler/Freightliner, International Truck & Engine Company, 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 FreedomCAR and Vehicle Technologies Program 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.

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 Hydrogen, Fuel Cells, and Infrastructure Technologies office at DOE). The Department of Defense is researching idle reduction technologies to ensure reliable power sources and silent operation when needed in combat situations.

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 dramatically lower emissions.

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 ~40% of the fuel energy is converted to mechanical work, resulting in ~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 improves the engine system fuel efficiency by 20% (from approximately 42% thermal efficiency today to 50%) by 2010.

- Research and develop technologies which will achieve a stretch thermal efficiency goal of 55% in prototype engine systems by 2013, leading to a corresponding 10% gain in over-the-road fuel economy over the 2010 goal.

- By 2010, identify and validate fuel formulations optimized for use in advanced combustion engines exhibiting high efficiency and very low emissions, and facilitating at least 5% replacement of petroleum fuels.

1.3 State of Technology

Efficiency: Diesel engines derive their high efficiency by both emulating 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 reduces 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 emissions challenge for traditional diesel combustion has given rise to re-consideration of alternative powerplants such as heavy-duty spark-ignition engines in some technical venues, but a market shift to this or other technologies would likely increase petroleum use and does not appear likely for the foreseeable future.

Modern highway truck diesel 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 may be increased to 50% within the next few years in research designs, but may not be sufficiently developed nor cost effective (depends upon fuel price, etc.) as a commercial product. To improve thermal efficiency while reducing emissions by over 90% from current levels (per regulations) is a much more complex challenge that will be discussed further in the next section. As shown in Figure 1.1 and 1.2, efficiency gains have moderated in recent years at a time while emissions have been reduced by an order of magnitude. The expected outcome of a well-supported government industry program is continued advancement in engine technology. Most further advances in thermal efficiency will be achieved with improvements in 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.

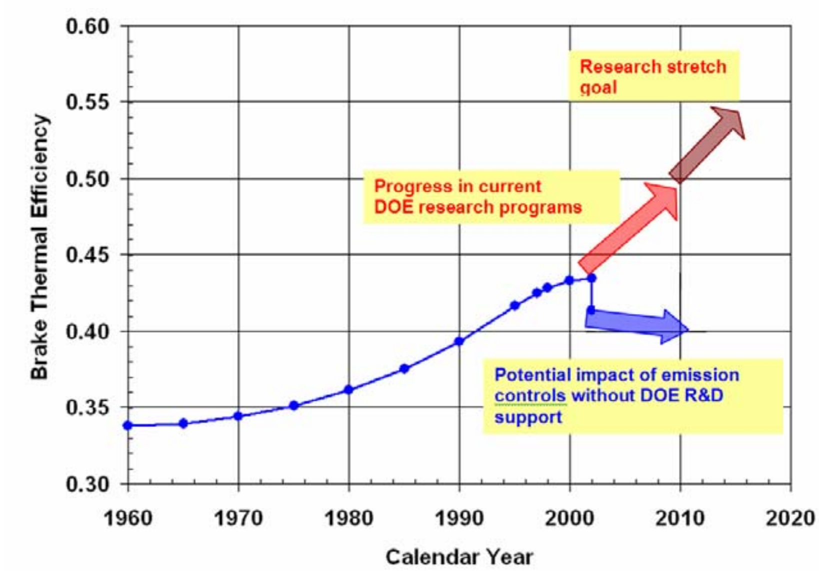


Figure 1.1. Historical progress in heavy-duty engine efficiency and the challenge of simultaneous emissions reduction, illustrating positive impact from 21CTP R&D support. Adapted from DEER 2006 presentation, courtesy of Detroit Diesel Corporation.

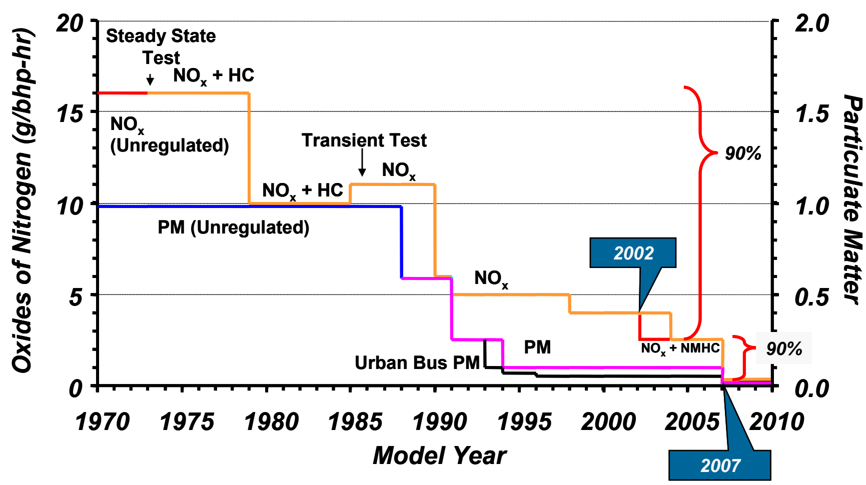


Figure 1.2. Historical Trend in Emissions from New Diesel Engines

Exhaust Emissions: Over the past 20 years, diesel-engine manufacturers have achieved remarkable reductions in NOx (85%) and PM (95%) emissions by modifying their engines. Through 2006 heavy-duty diesel engines are 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 allow a phase in sales average NOx at ~1.2 g/bhp-h and PM at 0.01 g/bhp-h, and most manufacturers have announced that NOx aftertreatment will not be required for 2007. Progress in integrating fuel injection, combustion enhancements, improved air handling, and introduction of exhaust gas recirculation have led to these significant reductions in emissions. R&D efforts today are focused on meeting the emissions regulations to be phased in between 2007-2010, where in 2010 emissions must be lowered another 83% to 0.20 g/hp-h NOx+HC and 0.01 g/hp-h PM. Approaches available to address these challenges include minimizing engine-out emissions and integrating with highly effective exhaust aftertreatment. As research has progressed it has become clear that achieving the goals will require a system development approach involving both of these strategies. More than ever, an effective on-board control system will be required to monitor and coordinate multiple subsystems.

Engine-out emissions can be further reduced through better understanding and coordination of combustion and emission formation processes, improved fuel injection strategies and technologies, and utilization of new combustion modes such as low-temperature combustion (LTC) to control NOx emissions and PM.

Exhaust aftertreatment has not been required nor utilized to meet emissions standards for heavy-duty diesels to date 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 have progressed in recent years and beginning in 2007 all truck heavy duty diesel engines are likely to be equipped with diesel particle filters (DPF). Catalyst-based DPFs used with ultra-low-sulfur diesel fuel (<15 ppm) can achieve PM reductions well in excess of 90%. In October 2006, ultra-low sulfur diesel fuel became the mandatory 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 outstanding issues with the DPF technology, including initial cost, operating cost, fuel economy penalty due to backpressure, thermal management and regeneration requirements. These barriers to 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 with advanced combustion, exhaust gas recirculation, and air-handling technology have negated the need for NOx aftertreatment for 2007 engines. For 2010 NOx regulations two aftertreatment technologies have emerged, after much R&D, that have substantial potential:

- Lean NOx traps (LNT) also known as NOx adsorber catalysts, and
- Selective catalytic reduction (SCR) systems using urea.

These two approaches, in full scale laboratory prototype experiments, have yielded NOx reductions sufficient to suggest that meeting the future regulations is possible, but substantial challenges remain in cost, fuel penalty, and durability. The foremost remaining challenge for NOx adsorbers is maintaining effectiveness over a long lifetime during which numerous high-temperature desulfation events must occur. Desulfation is required even with low sulfur fuel, and each event consumes fuel and potentially permanently degrades the catalyst. The fuel penalty incurred with each NOx regeneration event, required every few minutes of operation, is a further disadvantage of LNTs. Although there are a few performance issues with SCR, such as low-temperature effectiveness, the principal challenge is the urea supply infrastructure and technology to assure that urea is actually on the vehicle and is being used. At present, the engine and vehicle industry appears committed to the SCR path. It is already in use in Europe. Combinations of LNT and SCR devices have recently been announced and are under development and consideration.

Limited research continues on hydrocarbon SCR for its advantages of being relatively simple and needing no new infrastructure. Hydrocarbon SCR has marginal NOx control effectiveness for known catalysts unless specific hydrocarbons are supplied as the reductant. Use of a reformer may aid both HC-SCR as well as LNTs.

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 (ex: fuel injection delivery and timing). The beachhead for future controls requirements in the heavy duty diesel engine environment was realized with the recent introduction of EGR and the ongoing implementation of more sophisticated fuel injection systems. With the anticipated 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 minimum required capability of heavy-duty control system hardware and software will increase several orders of magnitude. Advanced control system technologies must be developed and implemented to address these massively complex control system integration and calibration challenges.

Fuels: 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. In December 2000, regulations were finalized that require much lower sulfur content in diesel fuel (a maximum of 15 ppm) to be available in 2006. Low sulfur fuel will enable the use of a broader range of effective catalytic NOx aftertreatment devices as well as aiding PM control. 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 and the relation between fuel properties and low-temperature combustion modes is largely unexplored. Tighter 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, tar (oil) sands, coal, etc. The production of diesel fuel from these sources is being expanded, and the production of biodiesel is growing rapidly as is the use of oil sands syncrudes from Canada. 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. Imported F-T liquids have been used as blending material in California diesel fuels since 1993. F-T diesel and biodiesel have a lower energy density than conventional diesel fuel. Uniformity and quality of these new fuels need to be defined and improved to allow for engine system to take advantage of them.

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.

Materials: Current heavy duty diesel engines are extremely durable, in most cases performing reliably for more than 1-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 temperatures and compression and expansion ratios. Higher compression ratios will result in higher cylinder pressures and temperatures to levels exceeding the current mechanical property limitations of many engine components, 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. Finally, lowering the rotating mass in valve-trains and 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 valve-train and air handling components.

1.4. Research Progress in the 21st Century Truck Partnership

Progress by diesel engine manufacturers in reducing emissions has been evident in demonstrations of production-ready engines in trucks reaching the 2007 emissions requirements of ~1.2 g/hp-h NOx+HC, 0.01 g/bhp-h PM with minimal fuel use penalty.

Engine manufacturers in co-sponsored research with DOE achieved 45% thermal efficiency with the ability to meet 2007 and 2010 regulations and have established technical feasibility of reaching 50%.

Diesel engine manufacturers continued participation with DOE laboratories, catalyst suppliers, and universities in an aggressive effort to improve computational simulations of diesel emission control systems 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.

The 21CT Partnership formed a Materials Team in 2001 and published a Research and Development Plan for Materials in December, 2001 (21CT-002). Members of the partnership are ongoing participants in DOE's Heavy Vehicle Propulsion Materials Program, and have helped developed successful materials solutions to the problems of durability, manufacturability, and cost associated with EGR in the engines introduced in October 2002.

The DOE's Heavy Vehicle Propulsion Materials Team has also been helpful in identifying commercial materials solutions being introduced in 2007 engines. A number of these materials have been identified as enablers of higher efficiency engines that are being developed for future engine technology. The Heavy Vehicle Propulsion Materials program has been instrumental in developing materials technologies for future engine technologies.
The Advanced Petroleum Based Fuels-Diesel Emission Control (APBF-DEC) Project completed comprehensive studies with full engine + aftertreatment systems to determine effects of fuel and lube constituents on emission control systems, focused on sulfur initially. The project was guided by an industry/government steering committee. A new DOE-industry project on fuels for advanced combustion engines (FACE) was initiated 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.

Research on advanced Low-Temperature Combustion (LTC) strategies, such as homogeneous charge compression ignition (HCCI), is being conducted under the advanced engine combustion Memorandum of Understanding (MOU) between industry and national labs. In addition, LTC research complementary to MOU research is being conducted in two university consortia. LTC offers the potential for dramatic reductions of NOx and PM emissions from high-efficiency, heavy-duty engines. Industry partners involved in the MOU include ten engine producers (Caterpillar, Cummins, Detroit Diesel, International, John Deere, Mack/Volvo, General Electric, General Motors, Ford, and DaimlerChrysler). In late 2006, five energy companies also joined the MOU (Chevron, ConocoPhillips, Shell, ExxonMobil and British Petroleum) bringing a strong research focus on fuel effects on advanced LTC strategies. The research-to-date has led to significant advances in the understanding of various strategies for achieving LTC and in the simulation capabilities for LTC. Research and proto-type engine development employing LTC strategies under the name "High-Efficiency Clean Combustion," (HECC) was also initiated by DOE in a solicitation that resulted in numerous contracted projects involving engine companies, energy companies, and national labs. In addition, new research projects on waste heat recovery were initiated.

On-road demonstrations of clean diesel technologies were conducted, including clean fuels combined with diesel particle filters, and urea SCR systems. The potential for near-zero PM emissions was evident. An analysis of the infrastructure for urea supply was completed, and a technology for simultaneous urea and diesel "co-fueling" was demonstrated. The auto and engine industry initiated a multi-faceted program to enable urea SCR as the NOx control system of choice for 2010.

1.5. Goals

The overarching technology goals are restated here to introduce the discussion of key barriers:

- Develop and demonstrate an emissions compliant engine system for Class 7-8 highway trucks that improves the engine system fuel efficiency by 20% (from approximately 42% thermal efficiency today to 50%) by 2010.

- Research and develop technologies which will achieve a stretch thermal efficiency goal of 55% in prototype engine systems by 2013, leading to a corresponding 10% gain in over-the-road fuel economy over the 2010 goal.

- By 2010, identify and validate fuel formulations optimized for use in advanced combustion engines exhibiting high efficiency and very low emissions, and facilitating at least 5% replacement of petroleum fuels.

For year 2010, a goal of 50% thermal efficiency is targeted over the most widely used operating points for class 7-8 highway trucks, which are the greatest fuel-consuming classes of all trucks. Considering that a fuel economy penalty is expected from additional emission controls, this represents close to a 20% improvement over 2002 technology. The technology improvements achieved for the large highway truck engines are expected to be mostly transferable to other truck classes for similar proportional gains. For 2013, an even more aggressive goal of 55% is planned for prototype engines in a dynamometer lab environment at the 2010 emissions levels.

In the original version of this whitepaper, an intermediate goal was set to meet the EPA emissions regulations to be phased in between 2007 and 2010 while still improving engine efficiency. More specifically, we wanted to demonstrate at least 45 percent peak thermal efficiency for heavy-duty diesel engines while meeting 2007 Federal (EPA) emissions levels [1.18 g/bhp-hr NOx (fleet average) and 0.01 g/bhp-hr PM]. This intermediate goal has been met. The challenge for 2010 will then be meeting the NOx+HC standard of 0.20 g/hp-hr and the particulate matter (PM) standard of 0.01 g/hp-hr. Carbon monoxide (CO) and hydrocarbons (HC) are also regulated, but they pose no significant challenge for the conventional diesel combustion process. 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.

The partnership also supports retrofit of emission control devices to in-use engines and the R&D necessary to develop and certify them. With the relatively slow turnover of trucks and engines, the retrofit programs have significant potential for impact on air quality. Quantitative goals here cannot yet be determined because of the wide range of applications in the existing vehicle fleet and general lack of control over implementing retrofit systems.

Goals for fuels (and lubricants) satisfy two major objectives; they are enabling technologies, integral with combustion and aftertreatment, to meet the emissions and efficiency goals, and (2) in a longer-range strategy, expanded use of non-petroleum fuels is a goal in itself. A major goal for the fuels area was completed in 2005 through the documentation of sulfur levels that would enhance the ability of engines to meet 2007-2010 emissions goals (requiring a systems approach) while maintaining or improving efficiency. (completed with the conclusion of APBF-DEC). In 2006, the fuel industry complied with the EPA 2001 sulfur rule, which was based in part on DOE-generated data.

Intermediate goals and additional milestones are stated as follows:

- By 2010 identify and exploit fuel properties that could increase efficiency and reduce overall tailpipe emissions through (1) lower engine-out emissions, including new low-temperature combustion regimes, and (2) enhancement of aftertreatment performance for 2010 emissions regulations.

- By 2013, identify non-petroleum fuel formulations (e.g., renewables, synthetics, hydrogen- carriers) for advanced engines and new combustion regimes for the post-2010 time frame that enable further fuel economy benefits and petroleum displacements while lowering emissions levels to near-zero, thus adding incentive for using non-petroleum fuels.

1.6. 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.

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 typically reduced by measures to reduce NOx emissions either in-cylinder or by aftertreatment;
- Lack of adequate combustion understanding and simulation capability, especially for new combustion regimes such as HCCI, LTC;
- Poor cost-effectiveness of known exhaust-heat-utilization systems;
- Cost of advanced materials and their processing;
- Material limits (temperature capability and strength);
- Limitations of coolants;
- Tribological limits of current materials and lubricants;
- Lack of cost-effective controller management and calibration techniques;
- Inadequate integrated controls of engine and aftertreatment system;
- 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;
- Relatively large thermodynamic losses in traditional combustion processes
- Apparent lack of cost-effective and innovative advanced engine concepts.

In-cylinder NOx reduction methods in conventional diesels limit efficiency by limiting peak in-cylinder temperatures and the time spent at peak temperatures. Aftertreatment systems have energy penalties that reduce the overall engine/aftertreatment system energy efficiency. Current commercially viable materials and lubricants limit engine efficiency by limiting peak temperatures and pressures at which critical engine components can operate.

Barriers to Achieving Emissions Requirements: The following are three categories of key barriers to achieving the technical targets for emissions reduction from diesel engines for trucks. 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.

1. NO_x/PM trade-off during combustion—that is, maintaining efficiency and low NO_x 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;

- inadequate understanding of in-cylinder combustion and emission formation processes and inadequate simulation capabilities; and
- limited effectiveness of cost-effective fuel additives and reformulation.

2. Aftertreatment system limitations for NOx and PM control
   - 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;
   - inadequate methods for introducing reductants;
   - 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
   - undeveloped infrastructure for urea SCR;
   - regeneration of DPFs subjected to extended low-temperature operation;
   - possible generation of unregulated toxic emissions;
   - inadequate sensors for process control or diagnostics;
   - deficiencies in the fundamental understanding and modeling capabilities needed for designing effective catalysts through means other than trial-and-error;
   - inadequate test methods for rapid-age testing and screening catalyst materials;
   - impact of DPF regeneration temperature on down-stream NOx catalyst;
   - back pressure from aftertreatment and the negative impact on engine efficiency; and
   - packaging constraints on the vehicle, including need to preserve efficient aerodynamic features.

3. 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.
   - Limited simulation capability for these types of systems.

Barriers to broader use of non-petroleum fuels: Barriers to wider use of renewable fuels such as biodiesel, and synthetic fuels such as Fischer-Tropsch liquids 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.

- Need industry-accepted specifications, assurance 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

1.7. Approach to Reaching Goals

The 21st Century Truck Partnership presents an opportunity to address key barriers to cleaner, 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. The facilities and expertise found in the government laboratories and universities are well suited to participation in collaborative projects with industry.

Efficiency: Approaches to improve engine efficiency are effectively built upon understanding the losses of energy and exergy. The combustion process, mechanical friction, heat transfer, air handling, parasitics, and exhaust losses all are key in 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.
- 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 NOx, NH_3, and PM sensors.
- 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 lower reciprocating mass and greater wear resistance
    - *Major Engine Components*. Cost-effective materials with higher strength and fatigue resistance for engine blocks and cylinder heads: 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.
    - *Improved exhaust manifold materials and sealing methods to handle increased exhaust pressure and heavier turbochargers*

Emissions: Meeting the 21CTP goals will require a three-pronged diesel engine emissions control strategy involving the research, development and effective integration of three major areas: (1) the engine/combustion process, (2) aftertreatment, and (3) fuels. 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, especially for aftertreatment systems due to their current poor state of development, is a high priority need. Major elements of the technical strategy to meet emissions targets additionally include:

- 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.
- Improve methods for generating and introducing NOx reductants to catalysts.
- 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.
- 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 (ex: NOx) is 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.

Fuels as Enablers: Fuel properties, in particular sulfur content, are pivotal in whether NOx adsorber catalysts will be successful. Since 1999, effects of sulfur on aftertreatment devices have been thoroughly studied in government-industry programs with major funding support from DOE. Other aspects of fuels as efficiency and emissions enablers can be brought forward by the following R&D activities. 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.

- Determine the impacts of fuel and lubricant constituents, other than sulfur, on emission controls devices. These include additives that form deposits, which can degrade emission control performance though at a much lower rate than sulfur.
- Determine effects of fuel composition, including non-petroleum fuels, on degradation of EGR system performance.
- Identify and exploit fuel properties that enable expanded application of new low-temperature combustion regimes for higher efficiency and lower emissions. Include blending materials and additives.
- Develop a first principles understanding of the property effects of potential alternative liquid fuels on combustion and emissions processes needed for optimizing engine and aftertreatment systems, and/or specify the optimum fuel characteristics for liquid fuels generated from gas-to-liquid or biological processes.
- Determine fuel properties or strategies that enhance aftertreatment system performance (such as through NOx reducing agents).

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 the 21CTP. However, the partnership can take steps to ensure that technology is at least compatible and preferably enhanced by non-petroleum fuels.

- In developing improved engine technology and emissions controls, take measures to ensure that the technology will be compatible with fuels that can be produced from renewable and synthetic feedstocks.
- Determine renewable and synthetic fuel formulations that can improve engine efficiency and reduce emissions to near-zero levels for the post 2010 time frame, such as by enabling new combustion regimes or advanced emission controls, thus adding incentive to the use of non-petroleum fuels.

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.

Table 1.1. Schedule of Major Activities and Milestones

	01	02	03	04	05	06	07	08	09	10	11	12
Engine Efficiency*												
1. Achieve 2002 emissions levels with engine efficiency maintained at approximately 42%. Improve efficiency to 45% by 2007 in compliance with 2007 standards. See Emission Reduction section, below.		⬥					⬥					
2. Develop and apply advanced fuel injection, engine control strategies, new combustion regimes, exhaust recovery strategies, air-handling, and mechanical designs, for their potential efficiency gains, with modeling and simulation as an integral component of the system design strategy.	○											◇
3. Demonstrate engine efficiency of 50% with 2010 emissions compliance through integration of advanced fuel injection, new combustion regimes, exhaust-heat recovery, aftertreatment, advanced controls, low-friction features, air handling, thermal management, and advanced materials										◆		
4. Research and develop technologies which will achieve a stretch thermal efficiency goal of 55% in prototype engine systems in 2013.												◆
Emission Reduction*												
1. Improve performance and durability of NOx_x control technology through improved combustion and aftertreatment processes, sulfur management, reductant strategies, and improved materials	○				⬥							
2. Develop and apply advanced fuel injection, engine control strategies, new combustion regimes, air-handling, and aftertreatment for emissions reduction, with modeling, simulation and controls integrated in the approach.	○											◇
3. Develop and implement cost effective retrofit emission control technologies	○								⬥			
4. Determine the best configuration and controls for NO_x and PM reduction through engine/aftertreatment integration	○						⬥					
5. Achieve production-feasible, life-cyle effective, emission control system(s) that will meet NOx and PM regulations phasing in starting 2007, also with reductions of unregulated “toxic” emissions					⬥							
6. Research pathways to emissions post 2010 regulations for emissions TBD, such as toxics and carbon dioxide.								○				◇
Fuels*												
1. Establish the influence of fuel and lubricant sulfur on emission-control technologies	○				◆							
2. Identify and exploit fuel properties that reduce overall tailpipe emissions through lower engine-out emissions, including new low-temperature combustion regimes and enhancement of aftertreatment performance.		○					⬥					
3.By 2010, identify and validate fuel formulations optimized for use in advanced combustion engines exhibiting high efficiency and very low emissions, and facilitating at least 5% replacement of petroleum fuels										◆		
4. By 2013, identify non-petroleum fuel formulations (e.g., renewables, synthetics, hydrogen- carriers) for advanced engines and new combustion regimes for the post-2010 time frame that enable further fuel economy benefits and petroleum displacements while lowering emissions levels to near-zero, thus adding incentive for using non-petroleum fuels.					○							◆

○ 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 U.S. Department of Energy's 21st Century Truck Partnership (21CTP) 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 defined as Class 2b through Class 8. This definition includes a diverse set of vehicles ranging from approximately 8,500 lb GVW to 100,000+ lb GVW.

Hybrid electric vehicle (HEV) technology is a key enabling technology that will help 21CTP achieve its goals. It enables truck and bus manufacturers to simultaneously improve fuel economy, emissions, and performance. In addition, HEV technology provides a technological and commercial bridge from today's conventional powertrains to future fuel cell powertrains. No other technology can support such aggressive claims. For the purposes of this section, 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 (Toyota Prius and Honda Insight/Civic), heavy-hybrid technology for commercial trucks and buses needs significant research and development (R&D) before it will be ready for widespread commercialization.

This paper seeks to highlight the benefits of this technology for heavy-hybrid vehicles. It also describes key research priorities where industry and government need collaborative investments. It is one of a series of papers, each of which discusses a specific technology goal that will reduce fuel use and emissions and increase heavy vehicle safety.

The top priority HEV R&D areas that require government funding to meet 21CTP's goals include:
- Drive unit reliability;
- Drive unit cost;
- Energy storage system reliability;
- Energy storage system cost;
- Demonstrated ability to meet 2007 HD engine emissions requirements; and
- 60% improvement in fuel economy (compared to today's conventional, non-hybridized heavy-duty vehicles).

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 lb 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 deploying these technologies.

- Establish confidence in HD hybrid technologies by testing and evaluating 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:

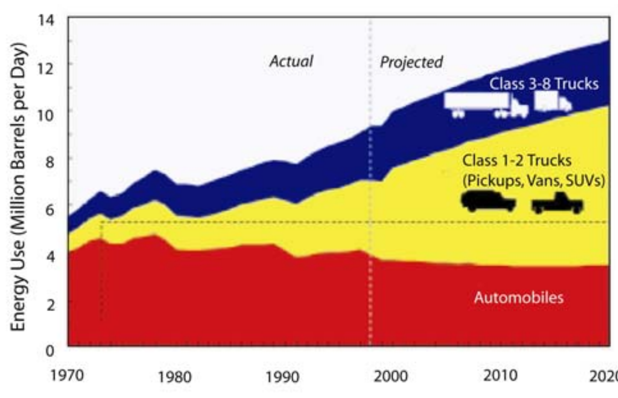
- It is a key technology that enables truck and bus emissions, performance, and fuel efficiency goals to be met simultaneously (without sacrificing one for the other).
- Hybrid electric technology is well aligned with the DOE FreedomCAR light-duty program and DOE's long-range technology roadmap for passenger cars and heavy vehicles.
- Hybrid electric architecture is an integral part of the technology roadmap for fuel cell-powered 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

The Challenges Facing Heavy-Duty Trucks

Since the 1973 oil embargo ALL the increase in U.S. highway fuel consumption has been due to trucks. Approximately 70% of the diesel fuel is burned by HD line haul trucks. Other HD vehicles, including vocational vehicles, pickup and delivery vehicles, and buses consume the remaining 30%. These trucks often operate in nonattainment zones.

HD trucks are unpopular, but America cannot economically survive without them and Americans cannot live without them. The average American does not think about the importance of HD trucks. On the contrary, the prevailing attitude toward HD trucks ranges from indifference to outright hostility. They are perceived as dirty, noisy, and smelly, and many of them aren't pretty. American drivers have to share the roads with trucks that may be intimidating, cause accidents, clog traffic, and ruin the roads. No wonder finding public policy support for HD trucks is difficult. A reality is that 72% of the dollar value of goods shipped in the nation move by truck. Thus, the trucking industry is vital to the United States.



Sources: EIA. 1999. *EIA Annual Energy Outlook 2000*, DOE/EIA-0383 (2000) December 1999. Davis, Stacy C. 1999. *Transportation Energy Data Book: Edition 19*, DOE ORNL 6958, September 1999

Figure 2.1. Trucks account for increasing highway transportation energy use

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 FreedomCAR 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 lb 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 2.1 compares some differentiating characteristics of LD and HD vehicles in North American markets. Key differences include:

Table 2.1: Comparison of Heavy-Duty and Light-Duty Vehicle Characteristics

Characteristic	Heavy Duty (HD) Vehicles	LD Trucks & Passenger Cars
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	18,000,000
Number of configuration variants	Millions	A few thousand
Fuel of choice	Diesel	Gasoline
Fuel consumption	5 to 15 MPG	14 to 40 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

- 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. An HD truck buyer prioritizes reliability and low cost of ownership; a car buyer prioritizes styling and performance.
- An HD truck weighs 2–10 times more, has 2–10 times the horsepower, and burns 3–4 times more fuel per mile driven, than a car.
- The payload of an HD vehicle is designed to exceed vehicle curb weight; 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 FreedomCAR 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 2004 emission regulations (in 2002 for companies that are party to the consent decree). HD engine company representatives have stated that EGR can reduce fuel economy by as much as 5%. Considering the trucking industry's razor thin margins, the cost increase driven by a 5% reduction in fuel economy could be devastating to both the trucking industry and the nation's economy.

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 fuel cell-powered and all-electric HD trucks and buses. Fuel cells have the potential of becoming the prime power source for future vehicles. Fuel cell technology is currently estimated to be a decade away from commercialization. Although the FreedomCAR initiative was conceived to accelerate this transition for passenger cars, a complementary initiative is needed for HD vehicles. This gap can be filled with an HD hybrid technology development initiative.

This approach works because a fuel cell produces the electric power needed for propulsion; however, the components from an HD hybrid system such as power electronics, electric drive units, and possibly energy storage will still be needed in a fuel cell system. HD hybrid systems make the electric drive technology that a fuel cell needs to become a propulsion system a reality.

Foreign competition is moving out 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 first to commercialize fuel-efficient, clean-running hybrid trucks, leaving U.S. manufacturers scrambling to compete. Will Toyota-backed Hino beat domestic trucking mainstays Freightliner, PACCAR, Volvo/Mack and International to market with fuel efficient, environmentally friendly HD hybrid product offerings? It has happened before. Government support for the U.S. HD hybrid industry can level the playing field against government-funded global competitors to keep it from happening again. Will the Government address this issue proactively, or wait until a crisis (like the largest blackout in U.S. history) 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 $500 million to $1 billion per company and take as long as 10 years. DOE has budgeted approximately $4 million per year since FY 2000 for this technology. Thus, 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 Office of FreedomCAR and Vehicle Technologies has initiated a cost-shared R&D program for advanced next-generation heavy hybrid propulsion systems and hybrid vehicle systems. The Advanced Heavy Hybrid Propulsion System (AHHPS) Program will focus on improving the fuel efficiency of heavy trucks (Classes 3–8) and buses by as much as 100%, while maintaining the U.S. Environmental Protection Agency's (EPA) 2007 emissions standards. DOE is funding approximately $4 million per fiscal year of cost-shared projects with the heavy hybrid industry (approximately 50/50 cost share) on the AHHPS Program. Three subcontract awards have been made to AHHPS participants. This program is a step in the right direction, but it is underfunded and does not include all of the major HD hybrid manufacturers.

Department of Transportation (DOT): DOT has taken leadership in the area of HD hybrids for public transit. Under the Advanced Technology Transit Bus (ATTB) program, DOT drove toward the goal of taking a third of the weight out of the bus through composite structures technology and dramatically reducing fuel consumption and emissions through hybrid electric propulsion. DOT invested over $50 million in this program that showed the industry what could be done. North American Bus Industries (NABI) picked up on the composite structures idea and introduced in their new lightweight CompoBus. After ATTB, DOT invested in the Demonstration of Universal Efficient Transportation Systems (DUETS) program where a conventional 40-foot transit bus was retrofitted with hybrid electric propulsion, more efficient electrically driven accessories, an advanced active suspension system and a high speed vehicle data network. This bus was successfully demonstrated in New York City under actual city transit operating conditions. Finally, DOT sponsored a fuel cell bus program with Georgetown University and the US Army National Automotive Center (NAC) under which three 30-foot and two 40-foot transit buses were designed, built and tested with liquid methanol powered fuel cells. A number of these buses are still in demonstration service today. DOT continues to fund the purchase of transit buses, some of which are advanced hybrid electric powered, through their various capital procurement accounts. During the 2003-2004 reauthorization process for legislation governing transportation projects, the SAFETEA bill will be developed to shape DOT spending for the next 6 years. It will be crucial that hybrid electric buses retain their eligibility for funding as a clean fuel bus under this legislation regardless of fuel type.

Department of Defense (DOD): To date, DOD has probably spent more on HD hybrids than all of the other agencies combined. DOD has taken leadership in the area of HD hybrid for combat vehicles and heavy trucks. The US Army, acting through AMC's Tank-Automotive Research, Development and Engineering Center (TARDEC) and its subordinate organization, the National Automotive Center (NAC), DOD has sponsored numerous HD hybrid programs. Some of these are:

- Hybrid Electric Power System (HEPS);
- Combat Hybrid Power System (CHPS);
- Advanced Hybrid Electric Demonstrator (AHED);
- Recon, Surveillance, Targeting Vehicle (RST-V);
- Future Combat System (FCS);
- Various hybrid electric truck and combat vehicle demonstration programs that include both electric and hydraulic HD hybrid systems;
- Unmanned Ground Combat Vehicle (UGCV); and
- Future Tactical Truck System (FTTS).

The Air Force (USAF) has also sponsored several small HD Hybrid demonstration programs through Warner Robins Air Force Base (WRAFB).

Environmental Protection Agency (EPA): EPA has sponsored a program to develop and demonstrate hydraulic hybrid propulsion technology, an alternative, hydro-mechanical approach to HD hybrid electric propulsion. 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 to 5,000 PSI 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. This HD hybrid approach has been demonstrated successfully, producing good results on a number of commercial and military trucks.

2.7. Status and Plans

Energy conversion technology status

Drive unit (electric traction, motor, transmission, generator, inverter, controller and cooling devices): 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.

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 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.

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.

Energy storage status

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 do not require high-energy electrical storage systems. HEVs need high-power storage systems because they only use the energy storage system 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 three major electrical energy storage systems that are being considered for hybrid electric propulsion systems are electrochemical batteries, ultracapacitors, and electric flywheels. 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.

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.

Power plant and control system optimization status

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. Torque is provided by electric machines either directly or through a parallel drive unit. This allows use of a lighter duty, lower torque, more fuel efficient internal combustion engine to perform the job of a larger, heavier engine. 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 differ substantially 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. Many series, parallel, and power-split hybrid propulsion system configurations are possible. Other alternative system configuration options, including hybrid hydraulic systems, could meet some specific or niche vehicle system, customer, or market requirements. 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.

Powertrain modeling tools to enhance development efficiencies

There have been many synergistic opportunities for the US National Laboratories to collaborate with industry in the area of modeling and simulation. Because of the large number of possible advanced vehicle architectures, it is impossible to manually build every single powertrain configuration due to time and cost constraints. One analysis tool, the Powertrain Systems Analysis Toolkit (PSAT) is a state-of-the-art flexible and reusable simulation package, developed by Argonne National Laboratory and sponsored by the U.S. Department of Energy (DOE). PSAT was designed to be a single tool that can be used to meet the requirements of automotive engineering throughout the development process, from modeling to control.

In addition to applications of the PSAT 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.

Electrical energy generation status

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:

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.

Small auxiliary power units (APUs): APUs can electrify auxiliary loads, and power dedicated mechanisms and hotel loads in heavy hybrid vehicles. Small APUs (5 kW) are currently available in limited quantities, which limits their performance, durability, reliability, and cost effectiveness. Available APU types are small diesel generators, fuel cells, and advanced thermoelectric units that have been demonstrated at the single HD vehicle prototype-level. Little attention has been made to optimizing such systems for HD vehicles. For some HEV architectures, an APU could actually provide power for a limp-home capability in the event of main engine failure.

Waste heat recovery systems: These systems could be integrated with small APUs to provide a secondary (backup) source of electrical generation for emergency and safety reasons, auxiliary load powering, and generally as an additional source of electrical generation and efficiency. Waste heat recovery systems available are electro turbo compounding units and advanced thermo electrics.

Auxiliary load electrification status

Significant energy can be saved while a truck is moving if pumps, fans, compressors, and other accessories were electrified. Current design concepts for trucks have the pumps, fans, and compressors driven with belts or gears connected to the drive shaft. Thus, the speed and power consumption of those accessories are roughly proportional to engine speed and independent of the actual requirements. If pumps and fans were electric driven, their speeds would be adjusted and optimized independent of engine speed, saving a significant amount of energy. Other benefits of auxiliary load electrification include emissions and cooling loads reduction, and more design flexibility.

System safety status

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

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.

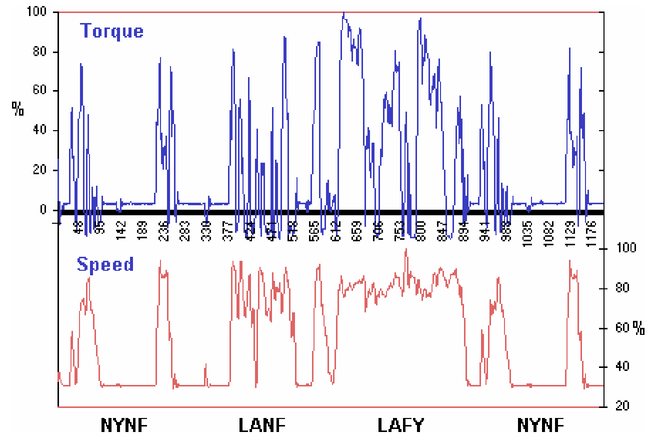


Figure 2.2. Heavy-Duty Federal Test Procedure Cycle

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 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.

2.8. Technical Barriers

This section addresses the barriers to widespread acceptance of technologies associated with the strategic approach outlined in Section 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 progress in HD hybrid product development; and

- High emissions and low fuel economy of today's trucks translating into a significant opportunity for societal benefit.

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

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

2.9. Component-specific barriers

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 500,000-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, and 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 are no domestic suppliers for high-power switch devices. This must be corrected.

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

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.

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.

Electrical Energy Generation Barriers

<u>Regenerative braking systems.</u> These are too inefficient and slow to capture available kinetic energy from the vehicle.

<u>Small auxiliary power units (APUs)</u>. These have high cost, performance, reliability, durability and system integration issues.

<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.

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.

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.)

Test and Evaluation/Certification Barriers

Currently, there is no hybrid testing protocol development 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

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.

Technical goals for HD hybrids

Drive unit (electric traction motor, transmission, generator, inverter, controller and cooling devices). Develop a new generation of drive unit systems that have higher specific power, lower cost, and durability matching the service life of the vehicle. Develop a drive unit that has 15 years design life and costs no more than $50/kW by 2012.

Energy Storage. Develop an energy storage system with 15 years of design life, that prioritizes high power rather than high energy, and costs no more than $25/kW peak electric power rating by 2012.

Heavy hybrid propulsion technology. Develop and demonstrate a heavy hybrid propulsion technology that achieves a 60% improvement in fuel economy, on a representative urban driving cycle, while meeting regulated emissions levels for 2007 and thereafter.

2.11. Methodologies and Schedule

This section shows the research approaches that will be used to achieve the technical milestones outlined in the technical milestone section and a schedule for completing these milestones. The research areas, presented along with proposed budget allocations, are shown below. The research areas address the challenges described in the technical challenges section.

Table 2.1. Schedule of Major Activities and Milestones

Hybrid Electric Propulsion	01	02	03	04	05	06	07	08	09	10
1. Develop a new generation of drive unit systems that have higher specific power, lower cost, and durability matching the service life of the vehicle. Develop a drive unit that has 15 years design life and costs no more than $50/kW by 2012.										
2. Develop an energy storage system with 15 year design life, that prioritizes high power rather than high energy, and costs no more than $25/kW peak electric power rating by 2012.								◆		
3. Develop high temperature power electronics that can be cooled directly from the ICE cooling loop by 2007.										
4. Develop and demonstrate a heavy hybrid propulsion technology that achieves a 60% improvement in fuel economy, on a representative urban driving cycle, while meeting regulated emissions levels for 2007 and thereafter.										
5. Determine "best practices" for HEV electrical safety, disseminate safety information, and promote safety awareness	○									◆
6. Design and test a brake-by-wire regenerative braking system on a prototype vehicle that is capable of capturing more than 50% of the wheel braking energy over the CBD cycle										
7. Develop application-specific power plants and customizable system-controller interfaces for commercial and military hybrid electric vehicles										

○ Begin activity ◆ Major milestone ◆ Key intermediate milestone

3. PARASITIC ENERGY LOSS REDUCTION

Promote research to reduce parasitic losses to achieve significantly reduced energy consumption.

3.1. Introduction and Background

Table 3.1 represents 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. The energy to move a heavy vehicle down the road includes energy losses associated with aerodynamic and rolling resistance, drivetrain and auxiliary loads. Collectively, these losses represent 40% (or 160 kWh) of the total energy. Improvements in aerodynamic drag and tire-rolling resistance 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.

Table 3.1. Energy audit and potential fuel efficiency improvements for line-haul trucks[a]

(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

[a]Fully loaded on level road at 65 mph for 1 hour.
[b]10% net engine efficiency improvement after losses in efficiency due to emissions requirements.
[c]Due to reduced power needs.

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. At highway speeds, approximately half of the fuel used to move the truck down the road (i.e., the energy to overcome aerodynamic and rolling resistance, drivetrain and auxiliary loads) is used to overcome aerodynamic resistance. A 20% reduction in aerodynamic drag results in savings in fuel consumption for steady highway travel in the range of 10 to 15%.

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.

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. 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.

3.2. Goals and Objectives

Parasitic losses due to aerodynamic resistance, accessory loads, overall vehicle weight, under hood thermal loads, friction, and wear collectively and significantly reduce the overall efficiency of heavy vehicles. Three 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 current average drag coefficient of 0.625 to 0.500).

- Technology Goal 2: Develop and demonstrate technologies that reduce essential auxiliary loads by 50% (from current 20 horsepower to 10 horsepower) for Class 8 tractor-trailers.

- Technology Goal 3: Develop and demonstrate lightweight material and manufacturing processes that lead to a 15% to 20% reduction in tare weight (for example, a 5000-lb weight reduction for Class 8 tractor-trailer combinations).

The 21 Century Truck Partnership has identified two other technology goals in the technical areas of 1) thermal management and friction and wear, and 2) rolling resistance. Initial goals were established in both of these areas as described below.

- Technology Goal 4: Thermal Management & Friction and Wear. 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% thereby improving Class 8 fuel efficiencies by 6 to 8%.

- Technology Goal 5: Rolling resistance technology goal: 10% reduction in tire-rolling resistance values relative to existing best-in-class standards without compromising cost or performance. **(An initial goal on rolling resistance was initially defined by the partnership but has not been an active area of investigation and will not be discussed further in this document)**

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 parasitic energy losses. The partnership will utilize a vehicle system approach to continually track overall benefits of individual technologies on overall vehicle efficiency and performance.

3.3. 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.

The Appendix to this roadmap document contains several reference documents related to aerodynamics. These include:

1. 2006 DOE overview presentation by Rose McCallen, Lawrence Livermore National Laboratory.
2. 2006 Truck Manufacturers Association overview presentation by Robert Clarke, TMA.
3. 2006 Annual Progress Report: Heavy Vehicle Systems Optimization Merit Review and Peer Evaluation.

Technology Goal 1: Develop and demonstrate advanced technology concepts that reduce the aerodynamic drag of a Class 8 highway tractor-trailer combination by 30% with general acceptance of the concepts by at least one large trucking fleet in the US and consideration of commercialization and implementation by at least one tractor and trailer manufacturer.

Background

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). 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.

Current add-on devices can achieve a 25% reduction 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.

Barriers

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.

Approach

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 considering 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.

3.4. Auxiliary Load

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.

The Appendix to this roadmap document contains several reference documents related to auxiliary loads. These include:

1) Electrification of heavy vehicle components “More Electric Truck”
   a. Summary of More Electric Truck
2) Fuel cell auxiliary power
   a. DOE Fuel Cell Technical Plan
   b. Industry Fuel Cell APU Project #1
   c. Industry Fuel Cell APU Project #2
   d. Solid State Energy Alliance Overview
3) Waste heat recovery
   a. FCVT Multiyear Program Plan, Waste Heat Recovery Section 3.3.4.
   b. DOE 2006 presentation on Thermoelectrics Program
   c. Summary of Thermoelectrics Program

Technology Goal 2: Develop and demonstrate technologies that reduce essential auxiliary loads by 50% (from current 20 horsepower to 10 horsepower) for Class 8 tractor-trailers.

Background

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.

In 2001 and 2002 the Partnership contributed to defining auxiliary power needs as part of both a workshop and multiyear technology plan focused on essential power systems for heavy vehicles. These activities defined research and technology needs to reduce the electrical and mechanical power requirements on heavy vehicles. These activities resulted in a fiscal year 2002 request for proposals in the area of essential power systems. Specific Industry partners are involved in a variety of individual projects with DOE and DOD ranging from component development to electrifying heavy vehicles.

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 Hydrogen, Fuel Cells, and Infrastructure 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 project was awarded by the DOE EERE Hydrogen, Fuel Cells and Infrastructure Program to develop solid oxide fuel cells for heavy vehicle auxiliary power applications. Project funding was limited in FY06 due to budget constraints.

Barriers

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.

Approach

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.

Fuel Cell for Auxiliary Power and Truck Electrification
- 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 year 2010 technology targets.

3.5. 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.

The Appendix to this roadmap document contains several reference documents related to lightweight materials. These include:

1. A short summary of the structure of the DOE HSWR Materials Program and projects.
2. A link to the full 2005 DOE Merit Review and Peer Evaluation Report for Heavy Vehicle Materials Program.
3. A link to the FY2005 Progress Report for High Strength Weight Reduction Materials.

Technology Goal 3: Develop and demonstrate lightweight material and manufacturing processes that lead to a 15% to 20% reduction in tare weight (for example, a 5000-lb weight reduction for Class 8 tractor-trailer combinations).

Background

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. 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 parasitic 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 15–20% weight reduction has been chosen for Class 8 tractor-trailer combinations. This is consistent with the 5,000-lb reduction established as a goal by the American Trucking Associations. 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, the HSWR Materials Program has had 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.

Barriers

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 for 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.

Approach

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 2003 to present 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. 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.

The Appendix to this roadmap document contains reference documents related to thermal management. These include:

1. 2006 Annual Progress Report: Heavy Vehicle Systems Optimization Merit Review and Peer Evaluation

Technology Goal 4: Develop and demonstrate technologies that reduce powertrain and driveline losses by 50% thereby improving Class 8 fuel efficiencies by 6 to 8%. 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% thereby improving Class 8 fuel efficiencies by 6 to 8%.

Background

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 virtually every approach for reducing energy consumption and emissions. Improved friction and piston/ring lubrication is an important component for increasing overall engine efficiency. Improved lubricants, coatings and lubricant formulations will be important to addressing engine exhaust soot, sulfur and phosphorus and the impact on advanced aftertreatment technologies. Advanced coating and lubricants will be needed to minimize friction losses. These advancements in lubrication and friction can also help reduce the losses in the drive line components (transmission, axles etc.)

The long-term objective is the development of tools and technology to reduce parasitic friction losses in engine, 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 3.1 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. Reducing boundary friction between engine components enables the use of low-viscosity grade lubricants to achieve significant fuel savings

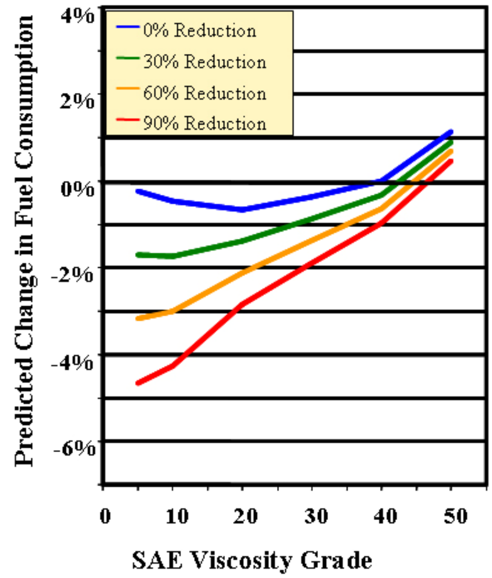


Figure 3.1: Reduction in Fuel Consumption as Function of Boundary Friction Reduction and Oil Grade

Thermal Management: 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 is expected to 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.

Barriers

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 the most probable near-term strategy for reducing NOx emissions, is expected to 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.

Friction and Wear: Several barriers/challenges in friction and wear include: improving fuel efficiency without sacrificing durability and reliability, development of low-ash additive engine and fuel additives, and cost-effective technologies to reduce friction and wear

- Reducing the viscosity of engine and 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.

- The current levels of phosphorous-based additives (e.g. ZDDP) used in engine lubricants are too high and will rapidly degrade the performance of emission-control devices. Reducing the level of phosphorous (and other metal-containing additives) will accelerate the wear of critical engine components and degrade engine durability and reliability.
- 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.

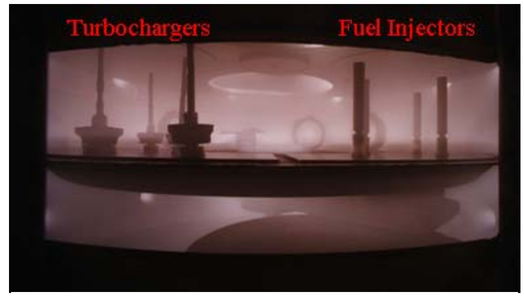


Figure 3.2: Plasma deposition of low-friction coatings on truck components

Approach

Thermal Management. 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
    - Thermal management related to use of higher electrical bus voltage
    - Variable speed pumps and fans
    - Variable shrouding
    - Integration of thermal management components into vehicle structure
- Advanced heat exchangers and heat-transfer fluids
    - Innovative, enhanced airside heat-rejection concepts
    - New materials, such as carbon foams, for cooling-system components
    - Nanofluid technologies for improving heat transfer properties of coolants and engine oils
    - Fundamental understanding of fouling mechanisms and mitigation
- Advanced thermal management concept development
    - Heat pipes
    - Cooling by controlled nucleate-boiling
    - Waste-heat recovery technologies (e.g., thermo-electric generators)
- Simulation-code development
    - Comprehensive CFD module for airflow and temperatures to include power train, under hood aerodynamics and airflow, lubricant cooling, vehicle-load predictions, cooling systems, and control systems
    - Experimental data base
- Thermal signature management
    - Masking technologies to mask overall signature
    - Masking technologies to mask specific cargoes

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 and meeting emission regulations :

- Integration of mechanistic friction and wear models into codes to predict and mitigate parasitic energy losses in engine, driveline, and auxiliary components
    - Code development & integration
    - Code validation
    - Engine and system tests
- Advanced materials and coating technologies that lower friction, reduce wear,

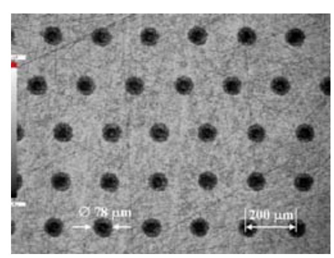


Figure 3.3: Laser microdimpled surfaces that reduce boundary and mixed lubrication

and improve reliability
- Lightweight materials – develop tribological systems for use on lightweight engine materials
- Coatings – develop low friction and wear-resistant coatings for engine components (rings, pistons, pins, valvetrains, bearings, gears, and fuel systems)

- Engineered surfaces – modeling, development, and testing of textured surfaces to improve friction and lubrication properties
  - Laser and mechanical texturing
  - Coated & textured surfaces
- Lubricant additives – development and testing of advanced additives
  - Low-friction – fuel economy improvements
  - Replacements for high-phosphorous additives
  - EGR-tolerant lubricants
- Boundary Layer Lubrication – fundamental studies of phenomena that control friction, durability and reliability of engine, driveline, fuel systems, and auxiliary system components
  - Development of protective surface films by additives
  - Development of scuffing and fatigue failure models to predict durability and reliability based on fundamental material and lubricant properties

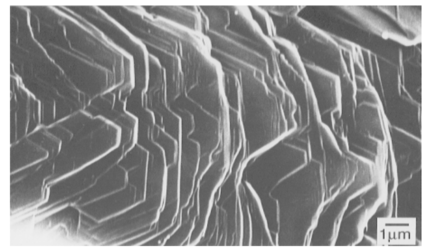


Figure 3.4: Formation of low-friction trobfilms from lubricant additives

4. IDLE REDUCTION

Promote the research, development, and deployment of technologies that substantially reduce energy consumption and exhaust emissions due to idling.

4.1. Introduction and Background

Justification of Inclusion of Idle Reduction in the 21st Century Truck Partnership

Long-haul trucks idle a significant portion of the time. A typical long-haul truck idles an estimated 1,800-2,400 hours per year when parked overnight at truck stops and other rest areas (e.g., borders, ports, 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[1]. 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 spend a significant amount of their engine on-time idling to provide power to their hotel loads, communication, and weapons usually as part of a stealthy silent watch operation.

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[2], 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. 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.[3] 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. California's Air Resources Board has adopted a rule that not only limits idling to 5 minutes, but also requires automatic shut-off devices beginning in 2007.

Extended idling by commercial trucks costs truck owners about three billion dollars annually and wastes over 1% of our petroleum resources. 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

[1] L. Gaines, A. Vyas, and J. L. Anderson, ESTIMATION OF FUEL USE BY IDLING TRUCKS, Transportation Review Board Annual Meeting, January 2006.
[2] 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.
[3] American Transportation Research Institute, COMPENDIUM OF IDLING REGULATIONS, 2006. http://www.atri-online.org/research/idling/818738_September2006IdlingCompendium.pdf.

extremely unpredictable. Truck owners have started installing idling reduction devices, and the 21st Century Truck Partners are working to accelerate achievement of the potential energy savings and emission reductions.

4.2. Goals and Objectives

The goal of this strategic element of the 21st Century Truck Partnership is to reduce fuel use and emissions produced by idling engines. The first four objectives that will enable achievement of the goal have been grouped together because they are inter-related. The objectives are to:

- Establish an industry/government collaboration to promote the research, development, and deployment of cost-effective technologies for reducing fuel use and emissions due to idling of heavy-duty diesel engines.
- Establish an educational program for truck and bus owners and operators to implement the most cost-effective enabling technologies and operational procedures to eliminate unnecessary idling.
- Develop 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 while at rest.
- Facilitate the development of consistent electrical codes and standards that apply to both on-board and stationary electrification technologies.
- Develop and demonstrate add-on idling-reduction 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, by 2009.
- Develop a truck with a fully-integrated idling-reduction system to reduce component duplication, weight, and cost, by 2012.
- Develop and demonstrate a viable fuel cell APU system for on-road and off-road transportation applications, in the 5-30 kW range, capable of operating on hydrogen directly, or using a carbon-based fuel with a reformer.

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 idle-reduction (IR) technologies, but market acceptance will depend primarily on the perceived economic benefit of the technology. The cost of integrating idling-reduction 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 the any new technology. 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 to reduce cost and weight. Note that equipment installed o new trucks is subject to the Federal Excise Tax, and this raises the cost of OEM-installed units.
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. Research and development 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 have not yet recognized the added value IR equipment represents.
3) **IR technology to address workday idling fuel usage.** Heavy-duty 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, or other device to enable vehicles to operate in creep mode with the main engine off, would be useful in addressing the workday idling fuel usage problem. A lower cost version of a heavy-hybrid powertrain would be one way to accomplish this.
4) **Consistent regulations.** 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 US 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. 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.

5) **Public awareness and truck fleet education programs.** Increasing industry publicity and education of end-users such as truck drivers, as exemplified by the U.S. Army SunLine fuel cell APU demonstration program, would help generate the public and fleet-owner awareness of idle-reduction technologies. In addition, dissemination of information on the comparative benefits of competing technologies would reduce buyer confusion about the plethora of available technologies (see Figure 4.1 at the end of this section).

6) **Increased financial incentives.** Even if rapid payback is assured, many heavy vehicle owners do not have the capital to invest upfront. The early adoption of idling reduction 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 idle reduction technologies mentioned here. Many incentive programs are only available for trucks that remain within a specific geographical area, but most long-haul trucks travel widely. Therefore, more programs need to be regional or national in scope. In addition, better enforcement of existing regulations would provide an increased disincentive for idling.

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 idling reduction. DOE analyzes technology needs and performs the appropriate R&D with industry 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 idle-reduction technology. EPA and DOT have been named to lead the effort in implementation. The established resources of the 21st Century Truck Partnership's Idling Reduction Task Force are at their disposal. 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. The 21st Century Truck industrial partners and their suppliers need to work together to make idle-reduction 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 idling reduction 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 cooperatives to address diesel engine emissions, with idling reduction as a major component of their efforts.

DOE activities: DOE was established by P.L. 95-91, the Department of Energy Organization Act of 1977, which gives it the role to perform "*energy conservation functions, including the development of comprehensive energy conservation strategies for the Nation, the planning and implementation of major research and demonstration programs for the development of technologies and processes to reduce total energy consumption, the administration of voluntary and mandatory energy conservation programs, and the dissemination to the public of all available information on energy conservation programs and measures.*"

DOE provided support for the initial development of idling reduction equipment and convened manufacturers to discuss options in 1996. DOE compiled data on performance, energy use, emissions, and cost for a variety of approaches, and published a landmark report on truck idling in 2000. This report, widely distributed and publicized in the trade press, is also available on the web, along with a recent worksheet to enable users to calculate their potential savings. DOE has provided information to truck drivers and owners via its booth at major truck shows, as well as by making presentations along with other Partners at conferences, state and local agency meetings, and to the Technology and Maintenance Council. The Clean Cities Program disseminates information to local agencies and other stakeholders, and provides funding for demonstrations, in over 80 coalition areas all around the US. DOE also examined locomotive idling reduction and funded a demonstration of IR equipment on 70 locomotives. DOE continues to identify and scope out opportunities for energy conservation and emissions reduction through reducing heavy vehicle idling. DOE sponsored work showed the importance of upstream fuel processing in the impacts from idling and its alternatives, identified and estimated the importance of workday idling, and compared the economics of the different options for supplying cab comfort to truck drivers.

In addition, DOE held an industry-government workshop in 2001 on Essential Power Systems to efficiently manage truck electrical and thermal requirements, via a transition from belts and gears to all electrically-driven auxiliaries that can be operated on demand to reduce parasitic loads. The DOE-supported research on the MorElectric™ Technology concept employs many of these approaches. The concept was demonstrated with on-highway trucks that used an auxiliary power unit (APU), a fully electronic modular HVAC unit, a high-efficiency scroll compressor, and an on-engine generator in place of the alternator in an effort to reduce overall fuel consumption. The resulting system provided on-road fuel savings as well as fuel savings from reduced idle time. The trucks showed a reduction of over 4% in fuel usage during the demonstration, and continue to operate.[4] DOE also funded several other demonstration projects in which trucking fleets installed after-market on-board idle-reduction 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 industrial partner demonstrated OEM installation: the partner is offering OEM-installed APUs as an option on its new trucks. Additional research was aimed at development of solid-oxide fuel cell technology to supply clean and quiet power for APUs.

DOE organized the National Idling Reduction Planning Conference, held in May, 2004, in Albany, NY, to develop comprehensive, nationwide solutions for heavy-vehicle idling reduction. The planning committee and sponsors included EPA, DOT, DOD, NYSERDA, and 21CT industrial partners, as well as IR equipment manufacturers and other industry stakeholders. Over 200 people attended from a broad range of government agencies at all levels, industries including users, truck stop operators, and manufacturers, and research institutions. Working groups were formed for technology and research, legislation and regulation, and energy, environmental impacts, economics, and outreach, and later formulated draft action plans, from which many suggested actions have been implemented. In addition, the National Idling Reduction Network News was created to continue the communication established by the national conference. It is e-mailed monthly to over 1500 recipients (and further distributed by many of them) to help them develop and identify consistent, workable solutions to heavy vehicle idling.

EPA Activities: In 2001, the National Energy Policy Development Group issued the National Energy Policy report to the President, which included this mandate for the EPA and DOT: "*The NEPD Group recommends that the President direct the EPA and DOT to develop ways to reduce demand for petroleum transportation fuels by working with the trucking industry to establish a program to reduce emissions and fuel consumption from long-haul trucks at truck stops by implementing alternatives to idling, such as electrification and auxiliary power units at truck stops along interstate highways. EPA and DOT will develop partnership agreements with trucking fleets, truck stops, and manufacturers of idle-reducing technologies (e.g., portable auxiliary packs, electrification) to install and use low-emission-idling technologies.*"

Since 2001, EPA has undertaken the following steps to respond to the President's mandate:

1. EPA conducted comprehensive testing in May 2001 and June 2002 on idling emissions from a representative sampling of trucks built from 1980-2002. The tests, partially funded by DOE and performed at a DOD facility, involved different engine speeds (600 rpm – 1200 rpm), different loads (AC, heat, no auxiliaries), and different temperatures (0-65-90 degrees F). The results represent Agency-approved emissions factors for use in modeling and air quality emission reduction credit programs. The final report is available at: http://www.epa.gov/smartway/idle-testing.htm.
2. EPA updated its mobile emissions model with extended idling emission factors for state air quality emission reduction credits. The current model contains an indirect emission factor for extended idling, as well as a

[4] Personal communication to L. Gaines, ANL with Clyde Dennis, Caterpillar, Inc., July 2006

direct emission factor for short duration idling; EPA will re-evaluate the extended idling emissions factors for the next mobile model.

3. In 2004, EPA issued guidance to states for quantifying and using truck extended idling emissions reductions in state implementation plans and transportation conformity to create incentives for reducing truck idling. The guidance can be found at: http://www.epa.gov/smartway/idle-guid.htm.
4. EPA demonstrated the effectiveness of mobile and stationary idle reduction technologies in reducing idling emissions and conserving fuel through over $6 million in grants, including several electrified parking space projects. EPA awarded the Electric Power Research Institute a grant to implement idle-reduction 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.
5. EPA, with the cooperation of other agencies and 21CT partners, hosted several workshops and conferences to educate the trucking industry and states about the need to reduce idling emissions from trucks and locomotives, conserve fuel, and reduce our nation's reliance on foreign oil imports. Starting in May 2001, EPA and DOT held a series of TSE workshops with States, truck OEMs, truck drivers, and trucking companies, and in 2003, they convened State DOTs and Metropolitan Planning Organizations, truck stop operators, and energy suppliers to create an investment team to support TSE at strategic points along the interstates. Presentation materials can be found at: http://www.epa.gov/smartway/idle-educ.htm.
6. EPA funded a study to measure the harmful contaminants entering a truck cab under extended idling conditions, and educated truck drivers about these findings. The measurements were performed at a large truck stop in Knoxville, TN by Oak Ridge National Laboratory (through an interagency agreement with DOE) and the University of Tennessee. The November, 2005, final report confirmed elevated pollutant levels inside an idling truck (http://www.epa.gov/smartway/idle-testing.htm). This raised interest within the trucking industry, and DOT agreed to fund a follow-on study to trace the location of the leaks.
7. EPA has coordinated with industry since 2004 to create consistent codes and electrical standards for stationary electrified parking spaces and on-board equipment, so ground and truck equipment are compatible. EPA hosted several meetings with partners, including trade associations and industrial stakeholders.
8. EPA, with cooperation from other agencies and industrial partners, led an effort to achieve greater consistency and practicality of state/local idle restriction laws by holding a series of workshops with truck owners and drivers and air-quality officials to (1) achieve greater understanding of each other's needs, and (2) agree on a common set of restrictions for engine idling. The meeting summaries and the final model for a state/local idling law can be found at: http://www.epa.gov/smartway/idle-state.htm.
9. EPA conducted a field observation of inner-city tour bus idling emissions and rates of idling around tourist attractions in Washington, D.C., during the peak tourist summer season of 2005. The results of this study are posted at: http://www.epa.gov/smartway/idle-demo.htm.
10. EPA, working with the Department of Transportation, states, and private lenders, is developing innovative, market-based and sustainable funding opportunities, such as low interest loans, to replace traditional grants to allow the truck and rail industries to purchase and use idle reduction technologies.

DOT Activities: DOT's role emphasizes infrastructure requirements and the development and implementation of operational guidelines to ensure the public safety. DOT is also able to provide considerable funding for IR implementation.

DOT's Congestion Mitigation Air Quality Improvement (CMAQ) program has funded numerous idle-reduction projects around the country through the State DOTs and Metropolitan Planning Organizations (MPOs). The CMAQ Program has funded electrified parking spot projects across the country totaling approximately $30 million. Also, the most recent transportation reauthorization bill (Section 1808 of SAFETEA-LU) includes a provision that makes the purchase of diesel engine retrofits for both on-road and off-road vehicles located in non-attainment/maintenance areas for ozone, PM10, or PM2.5 eligible for funding under the CMAQ Program (see Section 149(b) of Title 23 and Section 216 of the Clean Air Act (42 U.S.C. 7550)). Projects in CO non-attainment/maintenance areas are also eligible for CMAQ funding. Section 1808 also includes a provision making idle-reduction technologies (i.e. auxiliary power units and truck stop electrification systems) eligible for CMAQ funding.

To promote the expanded deployment of auxiliary power units (APUs), the Energy Act of 2005 authorized States to allow an incremental 400 pound gross vehicle weight tolerance for commercial motor vehicles equipped with on-board auxiliary power units (APUs) such that the operators will not be penalized for the weight increase that an APU installation would impart to their vehicle.

In addition, advanced truck stop electrification systems (single-system electrified parking spaces) are eligible for funding under Section 1113(a)(1) of SAFETEA-LU, which amends Section 133(b) of Title 23. Advanced truck stop electrification system is defined (under Section 1122(b) of SAFETEA-LU) as "a system that delivers heat, air conditioning, electricity, or communications to a heavy-duty vehicle." On-board systems are also included. Finally, STP funding is eligible (under Section 133 of Title 23) for Transportation Control Measures (TCMs) (listed in Section 108(f)(1)(A) of the Clean Air Act). One of these measures is "programs to control extended idling of vehicles."

DOT, along with DOE, has supported EPA's public outreach efforts on idle-reduction 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 brochure entitled "CMAQ and Idle-Reduction Projects" as a public outreach tool in order to promote the use of CMAQ funds for cost-effective projects such as idle-reduction.

DOD Activities: The military specifically needs an auxiliary power unit (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, vibrate less, and have a smaller thermal signature than idling the primary engines, making the vehicles less detectable. Reducing fuel use is a key consideration since 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.

4.5 Next Steps

Cooperative action on the part of the 21CT partners will bring cost-effective idling reduction 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 idling reduction 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).

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.

Table 4.1. Schedule of Major Activities and Milestones

FY	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
EPA															
1. Implement idle reduction demonstrations			Spring												
2. Formulate appropriate incentives for idle reduction				Fall											
3. Report on results from idle reduction demonstrations					Spring										
4. Develop consistent electrical codes standards that apply to on-board and stationary truck stop electrification technologies					Fall										
5. Formulate national model law for idle reduction					start	publish									
DOE/INDUSTRY															
1. Perform in-use demo of heater and thermal storage air conditioner			start		end demo	report									
2. Perform in-use demo of MorElectric Truck			start			interim report	end demo	report							
3. Perform demo of heater and battery air conditioner				start		end demo	report								
4. Perform demo of factory APU installation					start		end demo	report							
5. Perform evaluation of the life-cycle tradeoffs among emissions, energy, and costs for current and promising technologies (DOE only)					start	emis-sions	costs								
6. Near-term 5 kW fuel cell APU			award		test	validat									
7. Near-term 10 – 30 kW fuel cell APU			award		test	validat e									
Industry															
1. Identify cost-effective idle reduction technologies for near-term production applications															
2. Participate in developing advanced Idle Reduction technologies								Ongoing							
3. Integrate idle reduction technologies into vehicle designs. Eliminate redundant systems.															
4. Validate IR system that meet cab comfort needs, has <2 yr payback, and produces lower emissions of PM & NOx than 2010 MY stds.															
DoD (U.S. Army TACOM /NAC)															
1. In-service evaluation of Sunline truck (diesel ICE + gaseous hydrogen PEM APU)			July	Jan.											
2. On-road Freightliner truck testing (Diesel ICE + methanol-reformed SOFC APU)			July												
3. Ballard synthetic diesel reformer testing using Syntroleum S-5			Apr - Sep												
4. Have on-site fuel cell testing capability			Jan												
5. Test Hydrogenics regenerative fuel cell			Jan												
6. Develop in-house FC APU integration modeling								Ongoing							
7. Formulation of interchangeable synthetic fuels								Ongoing							

Begin activity Major milestone Key intermediate milestone

Figure 4.1. 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 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. US 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.

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. 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.

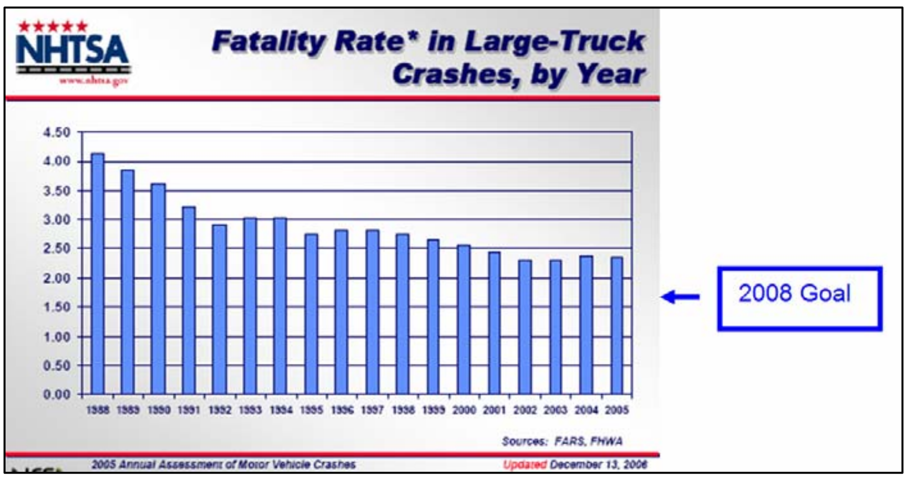
5. VEHICLE SAFETY

Promote the development of technologies to improve truck safety, resulting in the reduction of fatalities and injuries in truck-involved crashes.

5.1. Introduction and Background

The Truck and Bus Manufacturers and Federal Agencies that participate in the 21st Century Truck Research Partnership (21CTP) are working collectively toward achieving measurable improvements in heavy vehicle safety. One of the desired outcomes of the Partnership is to reduce truck and bus related fatalities through the development and implementation of technologies in areas such as crash avoidance and crashworthiness. Implementation of these technologies is expected to help substantially in reducing fatalities and injuries through the 2012 time frame.

Because transportation safety is the primary mission of the Department of Transportation (DOT), much of the 21CTP heavy vehicle safety interests/needs will be carried out with leadership from the DOT. Largely in parallel, but independent to the formation of 21CTP, DOT established some specific goals for highway safety involving trucks: (1) reducing US commercial truck-related fatalities by 50% and to reduce the number of persons injured in large-truck crashes by 20%, by the year 2010, and (2) reducing, by 2008, the fatality rate by 41%, based on the 1996 fatality rate. This will result in a rate of 1.65 fatalities in truck crashes per 100 million miles of truck travel. The new rate goal represents an additional 14,232 lives saved between 2002 and 2008. Because the goals of the 21CTP pertain primarily to vehicle-based technologies, the 21CTP facilitates progress toward the DOT safety goals but does not encompass all the paths to reduced fatalities and injuries.



For heavy vehicle safety, a two-fold approach will be taken. First, through this initiative, the Partnership will conceive, develop and contribute to the deployment of future transportation technologies that will simultaneously contribute to enhanced safety, fuel efficiency, and productivity, while sustaining the economic viability of the trucking industry and respecting the environment in which it must operate. Secondly, because safety is a crosscutting goal of the 21CTP, and because of the potential for conflict between the high-level goals (e.g. truck aerodynamics vs. regulated size/shape, decreases in aerodynamic drag and rolling resistance vs. stopping performance) of this initiative, a systems approach to safety is being supported to assure a balance in achieving all initiative goals.

5.2. Technology Goals

The 21CTP will work collaboratively in DOT-led research programs to enhance crash avoidance and crashworthiness, as outlined below.

<u>Crash Avoidance.</u> Develop and implement technologies for braking, rollover protection and visibility enhancement:

- Braking: Advanced braking technologies will be sought with the research goal of achieving a reduction of stopping distances by 30% from operational speeds in appropriate platforms. Improvement in retention of braking ability during grade descents is desired.
- Roll-Over: Reduce the incidences of heavy vehicle roll-over through the application of advanced technology brake control systems and other complementing technologies.
- Vehicle Position: Develop and implement driver aid systems that promote safe following distance and in-lane tracking.
- Visibility: Develop and implement systems that provide the operator with 360 degree visibility (direct and indirect) in day and night conditions.
- Work with tire manufacturers to improve truck tire performance and reduce tire debris. Incorporate tire advancements with improved braking technologies to achieve substantial vehicle handling improvements.

Potential examples of crash avoidance subsystem and component technologies that can contribute to reaching these goals may include, but are not limited to the following:

- Advanced brake materials, methods and systems
- Video-based visibility systems
- Electronic braking systems with automated stability control system software
- Active stability controls and counter measure systems
- Collision avoidance and lane-tracking systems
- Integrated vehicle-based safety systems (IVBSS)

<u>Crashworthiness.</u> Determine the feasibility of enhanced occupant survivability in collisions (offset, frontal, and angle/sideswipe) at differential speeds up to 35 mph between heavy vehicles and passenger vehicles weighing approximately 4,000 pounds. Also, improvements will be sought in truck occupant seat belt use rates by harmonizing restraint systems requirements to enhance comfort and, therefore, driver acceptability.

Potential examples of crashworthiness subsystem and component technologies for achieving these goals may include, but are not limited to the following:

- Intelligent and integrated seat belt technologies, with a focus on quarter-and-a-half turn truck roll-overs
- Advances in crash energy attenuation materials technologies
- Crash energy management technologies
- Reduction in vehicle mass for reducing differential impact in mixed traffic
- Vehicle structural system design and under-run barriers

5.3. Justification for Inclusion of Safety in 21CTP

Safety is a central element in the 21CTP vision. The OEMs 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 fatigue, truck aggressivity, and risks associated with exposure to heavy trucks. According to DOT (3), preliminary estimates involving large truck crashes and fatalities declined slightly and steadily from 1997 through 2002, but increased slightly in 2003. Annette Sandberg, FMCSA Administrator said (on July 9, 2004): "In 2003 we lost more than 43,000 people on our nation's highways. Of that 43,000, nearly 5,000 deaths were related to commercial motor vehicles. We were very encouraged by a steady decrease in truck-related fatalities from 1997 to 2002. However, the preliminary 2003 highway crash statistics showed a slight rise in these fatalities." This increase was among the smallest of highway users, however.

Although secondary in significance to fatalities, crashes involving such vehicles also impose a variety of costs on the vehicle and its driver, and other drivers either directly or indirectly involved in the crash.

Based on a study by the Pacific Institute (see http://ai.volpe.dot.gov/CarrierReserchResults/PDFs/Truck_Crash_Costs_2002_Final.pdf), the estimated cost of police-reported crashes involving trucks with a gross weight rating of more than 10,000 pounds averaged $59,153 (in 2000 dollars). The costs per crash with injuries averaged $164,730 for large truck crashes and $77,043 for bus crashes.

The average annual cost of large truck crashes in 1997-99 exceeded $19.6 billion. That total included $6.6 billion in productivity losses, $3.4 billion in resource costs, and quality of life losses valued at $9.6 billion.

Table 5.1. Average Annual Crash Costs, by Crash Type: 1997-99 (in millions of 2000 dollars)

Truck/bus crash type	Total
Straight truck, no trailer	4,966
Straight truck with trailer	1,259
Straight truck, unknown if with trailer	0
Bobtail	201
Truck-tractor, 1 trailer	12,564
Truck-tractor, 2 or 3 trailers	557
Truck-tractor, with unknown # of trailers	16
Medium/heavy truck, unknown if with trailer	66
All large trucks	19,630
Bus, transit/intercity	719

In developing programs to improve vehicle safety, it is essential to consider the multiple factors contributing to the cause of, or enabling truck crashes. These include:

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

Of this list, the factors being addressed in 21CTP are focussed vehicle design, performance and condition, whereas the other factors are being addressed in many other DOT programs. Nevertheless, safety is one of the strategic elements of the 21CTP, and improvements in vehicle design can yield significant crash prevention/mitigation improvements. Most of the technology changes that are being addressed by the 21CTP in pursuit of fuel economy, low emissions, and cost effectiveness can be inherently linked to the safety of the trucks operating on our nation's highways. The 21CTP will address the safety implications of all technological changes that are needed to meet the goals in the other facets of the Partnership.

Conversely, technologies that contribute to enhancing the safety of heavy vehicles can also contribute to enhanced fuel efficiencies, lower emissions, and enhanced productivity. For example, the ability to avoid congestion, work zones, and inclement weather, all have great safety benefits, and can also avoid needless idling, and inefficient low-speed operation of heavy trucks. Collision warning systems help to minimize incidents/accidents that could result in hours of congestion and increased idling times of vehicles attempting to navigate the incident area.

5.4. State of Technology

Truck Safety Characteristics. Medium/heavy trucks account for approximately 3% of vehicles in use on the nation's highways and accumulate 7% of all the vehicle miles traveled, while being involved in 8% of all fatal crashes and 3% of all crashes. The relative proportional involvement of medium/heavy trucks in fatal crashes has decreased over the past 8-to-10 years; they typically accounted for 10-to-12% of the total about 10 years ago.

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. Nearly half of 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.

Compared to the number for Class 8 heavy-duty trucks, 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 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 this platform differ from that of the tractor-trailer platform, the crash avoidance safety issues are similar. The primary focus should be on braking, rollover, and visibility. This sector of the market is usually not large enough to support the development of separate safety technologies; however, the improvements made in light vehicles and heavy trucks will also benefit medium-duty trucks.

The greatest improvement in vehicle safety for Class 2b vehicles will result from vehicle design that, where practical, incorporates all safety features required of passenger cars and light-duty vehicles. Passenger car safety technology is expected to cover the major issues in Class 2b and thus will not receive substantial emphasis in 21CTP.

Overview of Crash Avoidance Issues and Technology. Among the many factors leading to truck crashes, vehicle design and performance characteristics play an important role, and can be addressed within the scope of the 21CTP. These attributes, if they do not directly cause a crash to occur, make it more difficult for a truck driver to recover from an error or avoid an unforeseen conflict. (This is not to say that faulty vehicle design is the cause of most accidents and as previously mentioned, this is not the case. The scope of the 21CTP addresses principally the vehicle, however). Once a crash occurs, the way trucks are designed can affect the severity of trauma sustained by the occupants of all the vehicles involved.

It is widely recognized that other factors, principally the roadway type on which the truck is operated and the behavior/performance of both truck drivers and other vehicle drivers, have a large influence on crash causation. Nevertheless, vehicle design and performance attributes are important concerns that, if optimized, can enhance large truck safety and help reduce truck crash-related fatalities. However, it is important to balance optimization efforts. For example, design enhancements that reduce aerodynamic drag may adversely affect braking capability. On the other hand, such design enhancements might be used to reduce the severity of car-truck impacts.

Several high-technology tractor-trailer demonstrators have already been built that have shown a reduction on the order of 30% in stopping distance compared with current production designs. This has been accomplished by a combination of air disc brakes throughout the tractor-trailer combination, much more powerful front axle brakes, and electronic control. Electronic control of braking offers better brake control and balance because the braking action can be modulated at each individual wheel of the combination. It also offers reduced application times, which is especially important in multiple-trailer combinations. Recognizing that stopping distances are affected by the large variation of heavy truck vehicle configurations, contribution to a performance target of a 30% reduction in stopping distances (for certain vehicle platforms or types) is reasonable as an element of the safety goals for 21CTP. To achieve this goal, the frictional characteristics of tires will also have to be improved from current production designs. Such characteristics may have a significant impact on the ability to reduce rolling resistance for tires because increasing braking traction typically also increases rolling resistance.

The use of disc brakes on both tractors and trailers will also improve the thermal capacity (fade resistance) for new Class 8 foundation brake systems. The biggest challenge will be to provide disc brake designs that are economically feasible and not at odds with energy-saving goals. Current disc brake designs are much heavier and much more expensive than drum brakes. The size of currently available disc brakes inhibits their adoption in

North America. New, lightweight friction materials will have to be developed for both rotors and brake pads. In order to obtain sufficient stopping power with smaller-diameter wheels, designs employing multiple discs will be necessary. Incompatibility of brakes between old trailers and new tractors, or vice-versa, will present a major problem during phase-in, which may be, at best, addressed through the use of electronically controlled brake systems.

Engine braking can also be a significant additional factor. Today, with the use of variable-geometry turbochargers, the power absorption capability of engine brakes may exceed its power rating.

Vehicle stability characteristics such as static roll stability and load transfer ratio can be improved by reducing the center-of-mass height of the vehicle and by such vehicle design improvements as increasing the tractor to 102 inches in overall vehicle width. Advanced technology collision avoidance systems are also areas of activity where improvements can be expected.

Class 5-6 trucks use mostly hydraulic brakes, but some of the heavier ones use air or air-over-hydraulic brakes. Most hydraulic braked trucks have already begun using disc brakes. These trucks operate predominantly in urban areas at slower speeds than tractor-trailers, so aerodynamic braking would be only minimally beneficial. However, electric and hybrid power plants will allow regenerative braking to decrease the burden on the foundation brakes.

Overview of Crash Protection. Work to improve crash protection for truck occupants has been under way within the truck manufacturing industry for approximately the last ten years. That work includes improvements to occupant restraint systems, rollover protection, and cab structural integrity. Progress in that area can be incorporated and expanded upon in 21CTP's safety goals.

Until recently, activities to reduce the structural aggressivity of trucks in collisions with other vehicles have been limited to the rear structures of trailers. The incorporation of aerodynamic shapes/designs in tractor-trailers offers the possibility of making truck frontal and side structures complementary and compatible with the increasingly advanced crash protection features/capabilities of passenger cars, light trucks, and SUVs, thereby improving the likelihood that occupants of vehicles involved in collisions with trucks will survive.

5.5. Research Progress in Truck Safety

DOT's original support for 21CTP was reflected in the Technology Roadmap of the 21st Century Truck Program that was prepared in December 2000. This roadmap embodied DOT's efforts under the Intelligent Vehicle Initiative (IVI), a portion of its Intelligent Transportation Systems (ITS) Program. Since that time, the IVI has been concluded. In the reauthorization of DOT's Transportation Bill in FY05, the results of the IVI program will be built on to support a revolutionary new direction for ITS. This new direction/program is entitled the Vehicle-Infrastructure Integration (VII) Program. The vision for the VII Program is that every vehicle operating on our highways will be a sensor probe, with communication capabilities involving not only vehicle-to-infrastructure (VI), but also vehicle-to-vehicle (VV). Such real-time, wireless communication capabilities can provide enhanced traffic management, congestion/incident avoidance, active collision avoidance (e.g., prevention of intersection collisions), and an increased number of commercial vehicle safety inspections via wireless transfer of vehicle and driver data. Achievement of high-priority VII commercial-vehicle objectives will require active participation by truck OEMs in the program.

The following section will review the truck safety technologies from IVI's Commercial Vehicle efforts as well as other relevant truck safety-related programs across the various DOT agencies. It should be noted that because truck safety spans a number of DOT agencies, it involves interests related to regulation, enforcement, training/credentialing, education, highway design, ITS, crash avoidance, crash worthiness, etc. While all are important for safety, the elements that are most closely aligned to the interests of 21CTP are those involving crash avoidance, crash worthiness, and ITS. Furthermore, since 21CT also includes busses, some relevant transit research programs are also discussed. In addition to DOT, DOE is sponsoring R&D that has safety implications. For example, DOE has efforts underway on truck aerodynamics and brake materials both of which could affect truck safety.

Intelligent Vehicle Initiative (IVI) – Commercial Vehicle Platform

Field Operational Test of Rollover Prevention Technology – Freightliner Corp. This operational test involved the development, testing and evaluation of an in-cab advisory system that indicates to a truck driver what the rollover threshold of the combination tractor-trailer is, and how close to that threshold the driver is driving at any particular time. The primary systems evaluated were a Roll Stability Advisor and Roll Stability Controller (RA&C). The objective of the RA&C is to reduce the risk of rollover by improving driver performance through in-cab advisory messages (Roll Advisor) and, when necessary, by taking partial, momentary control, to slow the vehicle (Roll Controller). The field test was designed to determine whether or not the RA&C could improve driver performance in curves and turns, and whether or not such changes can reduce the risk of rollover crashes.

Results: Evaluation of the data collected during the test showed that the system appears to improve driver performance in turns, i.e. reduced rollover risk, especially in severe turns (small turn radius). In terms of crash reduction, it was estimated that the technology could reduce the number of rollover crashes caused by driving too fast in a turn by about 20-to-30%. In addition, the analysis estimated that the technology could reduce single vehicle roadway departure crashes (SVRD) caused by driving too fast in a turn, by about 30%. In terms of driver opinion, they see a potential benefit in the system and were generally accepting of the technology. Regarding technical performance, there were engineering improvements identified and these have been incorporated into the systems being sold today. A full evaluation report is available at: http://www.itsdocs.fhwa.dot.gov/JPODOCS/REPTS_TE/13871.pdf

Field Operational Test of In-Cab Messaging and Lane Departure Warning Technology: Mack Trucks, Inc. The primary focus of this operational test was on evaluating a lane departure warning system. In addition, a system was developed and tested which provides the driver with an in-vehicle warning when the vehicle approaches a location which historically experiences a significant number of heavy vehicle crashes.

Collision Avoidance and Advanced Braking Field Operational Test – Volvo Trucks North America. The operational test involved one hundred new Volvo tractors. Fifty of them were equipped with a set of bundled advanced safety systems, and the remaining 50 (control vehicles) were equipped with standard drum brakes, equipped with WABCO anti-lock brake controls, and the current generation Eaton-Vorad Collision Warning System. The equipped tractors were used with various trailers from the US Xpress fleet. Systems whose effectiveness were tested included an Electronically Controlled Brake System (EBS), Collision Warning System (CWS) and Adaptive Cruise Control (ACC). The advanced safety system bundle is expected to reduce the number and severity of tractor-trailer accidents specifically associated with rear-end collisions (forward crash) and lane change collisions. The EBS is also anticipated to improve the effectiveness of braking from high speeds through improved control of thermal degradation, and the ability to maintain stability during braking.

Partial Listing of Additional Commercial Vehicle-IVI Projects

Vehicle Stability (ECBS) Field Operational Test. Vehicle instability can often lead to rollover and roadway departure crashes for large trucks. This field operational test focuses on electronically controlled braking systems to improve vehicle stability.

Drowsy Driver Field Operational Test. A significant number of crashes each year are caused primarily by driver drowsiness or fatigue. This field operational test focuses on the effectiveness of state-of-the-art fatigue monitoring technology.

Driver Distraction. The research conducted under this project provided an important initial step in determining the need for and approach to developing guidelines or standards to limit the exposure of truck drivers to unsafe distractions. The objectives of the project were to: (a) provide greater clarification of the extent and nature of the truck driver distraction problem, through crash data analysis; (b) compare and contrast truck driver distraction with light vehicle distraction, through analysis of devices and through focus groups; (c) critically examine selected in-truck devices in terms of human factors requirements; and (d) identify needs for truck-specific research. The project is completed and a final report is available. The report will be posted electronically soon by US DOT and is available to any 21st Century Partnership member upon request (contact Mike Perel, NHTSA 202-366-5675).

5.6. Major Barriers To Achieving Safety Goals

It is important to reiterate that truck (vehicle) safety technology is only one of many factors that affect accidents and injuries. The barriers to achieving 21CTP safety goals are not only technical in nature, but additionally involve regulatory and institutional issues. Programs like the IVI made significant progress in improving the safety associated with the process of driving, and engaged in research that involved vehicle critical safety systems (e.g., electronic braking evaluation). Greater emphasis by the 21CTP, however, needs to be placed on studying and improving on-board critical safety systems.

Regulatory Issues. Many new and emerging safety and energy efficiency technologies are pushing the current regulatory envelope with regard to size, weight, etc. For example, a federal motor vehicle safety standard that took effect in January 1998 stipulates that certain types of tractor-trailer trucks must be outfitted with a bumper guard less than 22 inches above the road. Unfortunately, these lower bumpers have a negative impact on tractor-trailer aerodynamics. Another example involves the use of wide single tires. While significant fuel savings are postulated, they also carry safety concerns related to blowouts, rollover, etc. Regulations and standards should reflect more broadly a balance between safety and efficiency, and solutions should be sought that balance both. Other emerging technologies such as splash and spray preventers, hybrid-electric propulsion systems, alternative fuels (LNG, CNG, Hydrogen, etc.) and their associated fuel tanks, and the use of auxiliary power units (APUs), carry similar safety/efficiency balance concerns. Furthermore, such technologies must also not negatively impact the economic viability of fleets that utilize such technologies. Regulations and standards should be readdressed, and if necessary, changed to promote a balance between safety, efficiency and economic viability. Ideally, regulations and standards should support new safety technologies that enhance fuel efficiencies and can be easily adopted by industry. In reality, the major issues are very rarely so nicely aligned.

Lack of Coordination Between Safety and Energy Efficiency Research. There is an inadequate understanding of the link between safety technologies and energy efficiencies. Emerging energy efficiency technologies must be mindful of potential safety impacts just as new safety technologies must consider impacts on energy efficiencies. Very little research exists that quantify the fuel savings that are associated with IVI technologies. This has not been part of the mission of DOT. Conversely, impacts to critical safety systems due to lighter weighting, reduction of aerodynamic drag, etc., are also not well quantified. This has not been part of the mission of DOE. As a result, a disconnect exists that is a barrier to the 21CTP strategic approach to safety.

Vehicle Control. A lack of focus on vehicle control is a third general barrier. Because advanced control involves relatively subjective elements (e.g., the driver), it is viewed as relatively untenable, involves issues related to manufacturer's product liability, and impinges on sociological issues. Considered collectively, the evolution towards advanced control capabilities in the US has been very slow. With the dawn of the VII Program, new, advanced and active control will likely be addressed. Although a challenging area, emphasis on understanding the safety and economic benefits of implementing advanced control capabilities needs to be addressed. Failure to address this strategic area is seen as a barrier to achieving greater safety on our highways on a more timely basis.

Dispersed Pockets of Research. This organizational barrier concerns the distributed nature of much of the vehicle-based safety research in the US. Although larger programs such as the IVI focused efforts within a handful of OEMs, first-tier suppliers and fleets, much of the safety related research on heavy vehicles is accomplished across multiple agencies, with little coordination. For reasons of competitiveness, private industry also conducts research that is not coordinated with outside organizations. As a result, heavy vehicle safety research is being carried out in pockets of research, conducted by multiple organizations, with very little coordination. Such pocketed research is a barrier to achieving enhanced safety. What is needed is a focused, government-led research program involving multiple agencies and multiple industry participants conducting research that meets multiple goals. Such an effort could involve safety research associated with energy efficiency technologies and vice versa. The 21CTP provides an appropriate forum to stimulate improved safety/efficiency research coordination across its member organizations.

Affordability and Integration. A major barrier across all 21CTP goals is affordability. Although there is a general desirability of making the cost of safety systems less than $500 each, multiple safety systems can drive up the cost of safety very quickly. In addition, too many independent safety systems, operating simultaneously have the potential to decrease overall safety. Efforts need to be focused on: 1) integration of safety features to drive down the cost of such systems and to manage the critical information flow to drivers, and 2) achieving semi-autonomous driving capabilities (e.g., as suggested in the 21CT Technology Roadmap and a direction for the new VII program). Efforts need to be directed to assure that there is not a proliferation of multiple independent safety systems. A new program led by DOT entitled the Integrated Vehicle-Based Safety System (IVBSS) Program, initiated in FY05 may address research in this area.

Lack of Appropriate and Thorough Cost/Benefits Assessment. Numerous technologies in history have been stymied by commercial introduction of an underdeveloped product. Air disc brakes were developed in the early '80s, but were big, heavy, gained a reputation of being difficult to maintain, and were reported to have some operational problems. Wide single tires were reputed to cause accelerated road damage. Issues and claims such as these should be thoroughly reviewed for validity and a thorough cost/benefit assessment should be conducted. The results of this review and assessment should be disseminated via an educational process. Failure to conduct a thorough cost/benefits assessment is a barrier in the appropriate acceptance of new safety technologies by the industry.

Need for Additional 21CTP Research Partners. Many of the 21CTP safety goals involve issues that require interacting with organizations that are not currently partners in 21CTP. More specifically, manufacturers in the areas of tires, trailers, axles, and controllers are not partners. Without a 21CTP mechanism for allowing such manufacturers to provide input to 21CTP, a barrier exists for addressing safety issues associated with their products and the use of these products in advanced truck concepts.

5.7. Technical and Strategic Approach

Systems Approach. As research is conducted in support of the non-safety goals of the 21CTP, a systems approach to research is suggested that will focus on efforts to assure that the directions and results of the research do not negatively compromise heavy truck safety. In particular, research in the areas of aerodynamics, rolling resistance (including tire-road interfaces/traction), the use of light-weight materials, and propulsion technologies (including hybrid technologies) could have an affect on braking efficiencies, stopping distances, adverse deceleration limits, tractor-trailer braking compatibility, vehicle stability, crash worthiness, crash aggressivity, noise-vibration-harshness, and high voltage and fire hazards. A systems approach will assure that new and evolving non-safety-based technologies can be developed in harmony with the concerns for safety.

DOT, the VII, and Other DOT Activities. 21CTP safety research will be led by DOT, and it will address the significant safety-related problem areas that have previously been identified by DOT. Earlier in the 21CTP this effort was largely reflected within its IVI. Future efforts will involve the VII and the new IVBSS Program. The goal of the IVI was to accelerate the development and commercialization of vehicle-based driver assistance systems that would warn drivers of dangerous situations, recommend actions, and in the longer-term, to assume partial control of vehicles to avoid collisions. Much of the research conducted within the IVI provided information to the driver in order to support more informed decision-making regarding the driving task. Over the next eight years, through the VII Program, more active driver assistance features are expected to be introduced. Such features may include active braking, steering, and maneuverability assistance, and could include semi-autonomous driving capabilities. For buses, technologies to avoid bus-pedestrian interactions may also be addressed. The VII and IVBSS activities are described in more detail later in this paper.

Other DOT sponsored heavy vehicle research in areas such as braking materials, braking performance, rollover characterization, and the effects of super-single tires are being conducted by organizations such as the National Transportation Research Center (in particular, NTRC Inc.), and VRTC. Organizations such as these have been sensitive to the research needs of DOT, have provided environments for the easy conduct of multi-agency research, and have provided a demonstrated capability for partnering with industry to achieve research results based on leveraged funding. Such organizations have a strong propensity for understanding the safety/efficiency trade-off.

Importance of Operational Testing for Implementing Safety Products. In order to adequately achieve the 21CTP safety goals, the 21CTP safety R&D program should focus on the development and implementation of safety products through successive stages of technology verification, field operational tests and deployment planning. Program strategies should underscore the importance of operational testing after each safety product or systems component is technically proven and verified. Such real-world experiences will provide evidence of costs and benefits that will function to encourage early adoption of such technologies. In addition, planning for operational testing should be a major component for implementing 21CTP safety strategies. Appropriate planning will assure that these critical efforts are adequately funded and are not accomplished by cannibalizing other research efforts. Lastly, a national outreach plan on payoffs of safety system and components should be included in the planning of the 21CTP safety program. These efforts expose the industry to benefits of the technology, promote early adoption and implementation of safety technology and products, and improve the global competitiveness of safety products developed by 21CTP program for the international market. The FMCSA is testing a new concept entitled a Roadside Testing Laboratory (RTL) that will have the capability to test and evaluate the benefits of new commercial vehicle safety technologies in real-world environments. Laboratory-, bench-top-, simulator-, test-loop-, test-track-, and corridor-based testing may also be conducted.

Near-Term and Long-Term Product Implementation: Implementing available and proven technologies should be achieved within 3-4 years (near-term milestones). Developing new and emerging technologies for truck safety practice may take a longer-term (5-10 years). The milestones for achieving safety goals should reflect both near- and long-term product implementation.

5.8. Summary of Recommended Research Areas

21CTP safety goals are suggested in two major areas. They are the areas of: 1) Crash Avoidance, and 2) Crash Worthiness. The first deals with technologies that may allow a driver to avoid a crash. The second area involves technologies for surviving a crash. Both are important safety areas and are an inherent part of DOT's commercial vehicle safety strategy. Within these areas there are a number of technologies that can be addressed. Those discussed below are of high importance, and some were selected because of their tie to energy efficiency.

Crash Avoidance

Braking (Near-Term). Near-term focus should be placed on achieving performance improvements in the state-of-the-art of brake systems technologies currently available in the market. Identifying and quantifying the safety performance of these devices, including disc brakes and ECBS should be a priority. Additionally, the feasibility and value of on-board braking performance monitoring and diagnostics, and driver-alerting systems should be explored. Brake research sponsored by DOT and being conducted at the National Transportation Research Center (NTRC) under the Heavy Vehicle Safety Research Center (HVSRC) is appropriate in covering:

- Establishment of changes in material (frictional) properties of common brake materials for incorporation into an advanced brake behavior models.
- Determination of the most useful format and number of dimensions required for friction input to a brake behavior model.
- Development of data on friction-temperature-humidity behavior for conventional brake materials.
- Investigation of the effects of pad contact area on friction coefficient.
- Determination of the effects of environmental exposure on friction-induced films.
- Study of novel brake materials and severe condition performance.
- Comparison of premium vs. economy brake performance.
- Correlation of brake performance on a test-stand, at a test-track and during a field test.
- Brake calibration status assessment via a multi-plate performance-based brake tester.
- Testing of wireless brake diagnostics.

Braking (Long-Term). R&D for improving braking technology in the long-term should focus on innovative, lightweight and durable material technologies for weight reduction in disc brakes and development and deployment of lightweight friction materials including composite and carbon fiber materials. Driver assist devices such as integrated retarders and electrical brake activation should be operationally tested and deployed for improving brake system compatibility in heavy vehicles. Active brake system activation for advanced VII functions such as intersection collision avoidance, platooning, etc., should be addressed. Integration of electronic controlled braking with electronic steering is encouraged to enhance vehicle stability and improve vehicle handling.

Roll Over (Near-Term). Emphasis should be given to the performance of statistically significant operational testing of available new technologies affecting heavy vehicle roll over. Such technologies include next generation single tires, trailers with lower center-of-gravity, tractors with wider wheel bases, and computer-based roll-over warning systems.

Roll Over (Long-Term). Long-term development and testing should focus on improvements in emerging stability control systems; active chassis systems, electronic steering and steer-by-wire systems, integration of electronic braking and steering, and development of a computer-based braking-assistant. Concepts and methods to increase torsional stiffness should be studied and integrated with the design of chassis systems to enhance roll stability.

Visibility (Near-Term). A range of technologies is currently available for improving driver visibility that is ready for operational testing and implementation in the near-term. These technologies include vision enhancement systems, video-based backing systems, and video devices to augment visibility. Most of these devices are effective at lower speeds. Several low-cost and easy to install products such as visibility enhancing luminous tapes are now available to improve the conspicuity of trucks and heavy vehicles in mixed traffic, and night-time traffic. A round-robin testing program should be initiated to measure the benefits of new-vision-based technologies.

Visibility (Long-Term). Focus in the long-term should be placed in developing and implementing emerging technology products and systems for improving dynamic visibility at higher speeds. Potential technologies include integrated visibility information systems, high-speed surround systems, advanced night-vision and blind-spot systems, head-up displays, and pulsed ultra-violet headlights. Major barriers for implementing these include initial cost of the products, human factor issues and approaches for presenting synthesized information for operator action with minimal distraction. The 21CTP safety efforts should emphasize human factors issues in implementing advanced safety systems.

Crash Worthiness

Compared with crash avoidance technologies, crash worthiness R&D typically has a relatively fewer number of products available for implementation. The 21CTP safety efforts should focus on increasing the range of available options and products to improve crashworthiness.

Seat Belt Systems (Near-Term). Increasing seat belt usage through human factors engineering and advanced restraint systems should be the number one priority in the crash worthiness area, not to diminish the value of education and enforcement, but which are outside the scope of 21CTP.

Seat Belt Systems (Long-Term). Development of intelligent and integrated seat belt technologies that ensure seat belt application, senses situational measures, and adjusts to improve safety in crashes and potential roll-overs, should be tested and implemented.

Crash Energy Attenuation and Management (Near-Term). Focus should be placed on steps for recognizing and reducing kinetic energy of vehicle crashes by reducing the aggressivity of front-end, eccentric and oblique collisions. This should be accomplished by incorporating crash absorbable material in crash critical structural elements and by designing and incorporating crash deflectors.

Crash Energy Attenuation and Management (Long-Term). Some of the crash energy management priorities for the longer- term should include the development of dynamic performance measurements for improving crash attenuation, incorporating crash resistant and crash absorbent material design, reducing vehicle mass disparity, and minimizing the geometric mismatch.

Structural Systems Design (Near- and Long-Term). Efforts should involve the development and incorporation of advanced materials in vehicle structural systems with specific consideration to develop crash worthy vehicle geometry and crash protected front- and rear-end designs and enhancing stiffness dispersion.

5.9. Details of New US DOT ITS Initiatives

Integrated Vehicle Based Safety Systems (IVBSS)

Goal. All new vehicles would be equipped with advanced driver assistance systems that would help drivers avoid the most common types of deadly crashes.

Background. About 2.6 million rear-end, road departure or lane change crashes occur each year. Of these, 27,500 crashes (about ¾ of the fatal crashes) result in one or more fatalities. A NHTSA analysis showed that widespread deployment of advanced driver assistance systems addressing rear-end, road departure and lane change collisions could reduce motor vehicle collisions by 17 percent. Integrated systems will be more effective and will provide better threat information from multiple sensors, enabling coordinated warnings to reduce driver distraction.

Approach. This initiative, in partnership with the automotive industry, will build on completed and ongoing IVI field operational tests as well as results from naturalistic-driving studies. It will involve projects and studies that include private passenger vehicles, freight-carrying trucks and transit buses. It will consolidate current information about available countermeasures; perform additional research into integration of the driver-vehicle interface (DVI); develop objective tests and criteria for performance of systems that simultaneously address these three types of crashes; and design appropriate data acquisition systems. There is an extensive body of knowledge on countermeasures for addressing each of these three types of crash unilaterally; this initiative will be the first attempt to fully integrate these individual solutions. This research will assimilate existing research results and state-of-the-art commercial products and product performance for all systems that are related to this problem.

Milestone. Integrated vehicle-based systems that address multiple crash types will be developed, tested and evaluated.

Vehicle Infrastructure Integration (VII):

Goal. The goal of VII is to achieve nationwide deployment of a communications infrastructure on the roadways and in all production vehicles, and to enable a number of key safety and operational services that would take advantage of this capability.

Background. VII builds on the availability of advanced vehicle safety systems developed under the IVI and the availability of radio spectrum at 5.9GHZ recently approved by the FCC for Dedicated Short Range Communications (DSRC). The VII would enable deployment of advanced vehicle-to-vehicle and vehicle-to-infrastructure communications that could keep vehicles from leaving the road and enhance their safe movement through intersections. These deadly roadway scenarios account for 32,000 of the 43,000 deaths annually on America's highways.

Approach. This initiative builds on the research and operational tests conducted under DOT's IVI. Vehicle manufacturers would install VII technology in all new vehicles, beginning at a particular model year, to achieve the safety and mobility benefits while at the same time, the federal/state/local transportation agencies would facilitate installation of the roadside communications infrastructure. Vehicles would serve as data collectors, transmitting traffic and road condition information from every major highway within the transportation network. Access to this information will allow transportation agencies to implement active strategies to relieve congestion. In addition to these direct benefits to the traveling public and the operators of the transportation network, the automotive companies view VII as an opportunity to develop new businesses to serve their customers. To determine the feasibility and an implementation strategy, a three-party consortium has been formed consisting of seven vehicle manufacturers, the American Association of State Highway and Transportation Officials (AASHTO), ten State Departments of Transportation and the USDOT.

Milestones. A decision to proceed with full deployment will be reached by 2008 and will be accompanied by a plan for deployment.

5.10. National Highway Traffic Safety Administration (NHTSA) Brake R&D

Research at the Oak Ridge National Laboratory (ORNL)

NHTSA has initiated several brake-related research activities at the Oak Ridge National Laboratory (ORNL). These include the following:

Development of a Standardized Rating System for Brake Friction Materials. This research will allow owners and operators to acquire brake components with a standard rating for friction performance and wear, and would facilitate acquiring replacement parts that provide the same braking behavior as the original parts.

Brake Performance Correlation. This research involves the study of the braking performance of Original Equipment (OE) brake materials and aftermarket brake material on vehicles tested at a test track and during a 12-month field test. The same materials will be tested on a small-scale brake tester in a laboratory. Class-8 and Class-7 dump trucks as well as a Class-8 refuse hauler will be run on the test track and during a field test. Performance correlations across the three tests are sought.

Research at the Vehicle Research Test Center (VRTC)

NHTSA has also conducted brake research at their Vehicle Research Test Center (VRTC) in East Liberty, Ohio. Research has included:

- Parking Brake Tests on Air-Braked Heavy Truck and Tractors.
- S-Cam Brake Effectiveness Comparison Using Two Fixtures and Two Lining Types on a Single Inertia Dynamometer.
- Single-Unit Truck and Bus ABS Braking-In-a-Curve Performance Testing.

5.11. Federal Highway Administration (FHWA) Heavy Vehicle Research at ORNL

FHWA Brake and Rollover R&D

FHWA has initiated two efforts at ORNL involving heavy vehicle braking and rollover. They are:

Enhancement of TruckSim Braking System Modeling. This effort conducted laboratory tests on braking materials for various temperatures, humidity and braking torques to develop correlations to improve the braking module of the TruckSim model.

Truck Rollover Characterization. This effort is examining the vehicle dynamics associated with a class-8 tractor-trailer engaged in various FMVSS-121-based maneuvers. Standard dual tires and next generation single tires are being studied for a comparison of their effects on heavy truck rollover.

5.12. DOE Research With Safety Benefits

The Effects of Ice Control on Braking Components. This study, conducted by Pacific Northwest National Laboratory (PNNL) involves an analysis of the corrosive effects of magnesium chloride on braking components and friction materials and concepts for mitigating its deleterious effects.

Heavy Vehicle Duty Cycles. This study will characterize long-haul duty cycles by collecting data from instrumented trucks traveling from Chicago, Illinois to Portland, Oregon. This study could be broadened to include the collection of long-haul naturalistic driving data and information.

Consortium on Heavy Vehicle Aerodynamic Drag. Through multiple experimental and computational projects, this consortium is developing an improved understanding and predictive capability for heavy vehicle aerodynamics. The subjects important to vehicle safety include splash and spray from tires, and brake cooling.

5.13. Transit Safety Research

Transit Collision Avoidance Systems. DOT's FTA is evaluating technology that helps drivers avoid the most prevalent types of transit crashes – rear and side collisions. In Pittsburgh, Pennsylvania, 100 transit buses are equipped with side-collision warning systems. In Michigan, the Ann Arbor Transportation Authority is evaluating a system that prevents other vehicles from crashing into the back of transit buses. This system will use radar to sense the imminent crash and attempt to warn the violating driver with a flashing warning. The Transit System in San Mateo, California (Samtrans), in partnership with the California Department of Transportation (Caltrans) and PATH, is evaluating a collision avoidance system that warns transit drivers of an impending collision with the vehicle ahead.

5.14. Schedule of Major Activities and Milestones

The following figures depict major activities and milestones.

Figure 5.1. IVBSS Schedule from DOT Program Plan, April 2004

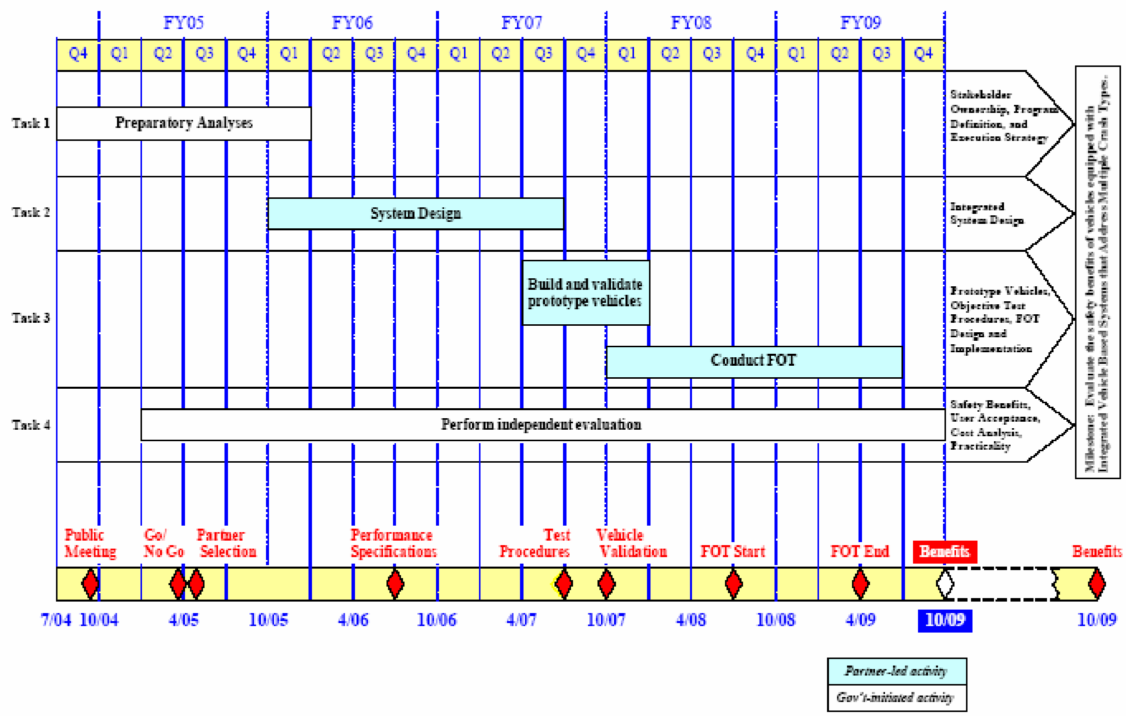


Figure 5.2. Milestone Schedule for Representative Safety Projects at DOE Laboratories

	FY04	FY05	FY06	FY07
Truck Rollover Characterization (ORNL)				
- Final Report		◇		
Brake Material Characterization (ORNL)				
- Instrument Vehicles		◇		
- Conduct Field Tests			◇	
- Conduct Track Tests			◇	
- Conduct La testing on SSBT			◇	
Brake thermal analysis and materials (PNNL)				
- Develop disk brake thermal model		◇		
Heavy Vehicle Duty Cycle (ORNL et al)				
- Instrument Truck		◇		
- Conduct Pilot Test Final Report		◇		
- Prepare Pilot Test Final Report		◇		
- Instrument Truck for Field Test			◇	
- Conduct Field Test				◇
Effects of Ice Control Chemicals (PNNL) -Develop understanding of effects of chemicals on heavy vehicle brake materials		◇		
Heavy Vehicle Aerodynamics Consortium (LLNL et al) -Establish predictive capability for splash & spray				◇

5.15. References

1. Web-page of the Federal Motor Carrier Safety Administration (FMCSA): http://www.fmcsa.dot.gov/safetyprogs/hm.htm

2. Web-page of the Intelligent Vehicle Initiative (IVI): http://www.its.dot.gov/ivi/ivi.htm

3. Pacific Institute for Research and Evaluation "Revised Costs of Large Truck- and Bus–Involved Crashes – Report to FMCSA", November 2002

The table below defines a number of the acronyms used in this roadmap discussion.

21CTP	21st Century Truck Partnership
AASHTO	American Association of State Highway and Transportation Officials
AHHPS	Advanced Heavy Hybrid Propulsion Systems Program
ANL	Argonne National Laboratory
APBF-DEC	Advanced Petroleum Based Fuels-Diesel Emission Control
APU	auxiliary power unit
ATTB	Advanced Technology Transit Bus Program
BMEP	brake mean effective pressure
CBD	Central Business District (vehicle test cycle)
CFD	computational fluid dynamics
CLEERS	Cross-cut Lean Exhaust Emission Reduction Simulations
CMAQ	Congestion Mitigation and Air Quality
CNG	compressed natural gas
CO	carbon monoxide
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
DPF	diesel particulate filters
ECBS	electronically controlled braking system
EERE	DOE Office of Energy Efficiency and Renewable Energy
EGR	exhaust gas recirculation
EPA	Environmental Protection Agency
EV	electric vehicle
FACE	Fuels for Advanced Combustion Engines
FE	DOE Office of Fossil Energy
FHWA	Federal Highway Administration (DOT)
FMCSA	Federal Motor Carrier Safety Administration (DOT)
FMVSS	Federal Motor Vehicle Safety Standards
F-T	Fischer-Tropsch (synthetic diesel fuel)
FTP	Federal Test Procedure
GDP	gross domestic product
GVW	gross vehicle weight
HC	hydrocarbons
HCCI	Homogeneous Charge Compression Ignition
HC-SCR	hydrocarbon selective catalytic reduction
HD	heavy-duty
HECC	High-Efficiency Clean Combustion
HEV	hybrid-electric vehicle
HSWR	high-strength weight reduction materials
HVAC	heating, ventilation, and air conditioning
HVSRC	Heavy Vehicle Safety Research Center
ICE	internal combustion engine
IR	idle reduction
ITS	Intelligent Transportation Systems
IVBSS	Integrated Vehicle-Based Safety System
IVI	Intelligent Vehicle Initiative
kW	kilowatt
LD	light-duty

LLNL	Lawrence Livermore National Laboratory
LNG	liquefied natural gas
LNT	lean-NOx traps
LTC	low temperature combustion
MOU	memorandum of understanding
MY	model year
NAC	National Automotive Center
NEPD	National Energy Policy Development
NHTSA	National Highway Traffic Safety Administration (DOT)
NOx	oxides of nitrogen
NTRC	National Transportation Research Center
NTSB	National Transportation Safety Board
NYSERDA	New York State Energy Research and Development Authority
OBD	on-board diagnostics
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PEMFC	Polymer electrolyte membrane fuel cell
PM	particulate matter
PNNL	Pacific Northwest National Laboratory
ppm	parts per million
PSAT	Powertrain Systems Analysis Toolkit
R&D	research and development
RD&D	research, development, and demonstration
SAFETEA	Safe, Accountable, Flexible and Efficient Transportation Equity Act
SCR	selective catalytic reduction
SECA	Solid-State Energy Conversion Alliance
SI	spark ignition
SOFC	Solid oxide fuel cell
TSE	truck stop electrification
VII	Vehicle-Infrastructure Integration
VRTC	Vehicle Research and Test Center (NHTSA)
ZDDP	Zinc dialkyl dithiophosphate

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