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FreedomCAR and Vehicle Technologies Program

Multi-Year Research and Development Plan

Planned program activities
for 2004-2008

ORNL 03-03362/lmh

Less dependence on foreign oil, and eventual transition to an emissions-free, petroleum-free vehicle

FreedomCAR

21ST CENTURY TRUCK
PARTNERSHIP

U.S. Department of Energy
Energy Efficiency
and Renewable Energy

FreedomCAR and Vehicle Technologies Program

Multi-Year Research and Development Plan

November 2003

U.S. Department of Energy
Energy Efficiency
and Renewable Energy

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Acronyms and Abbreviations

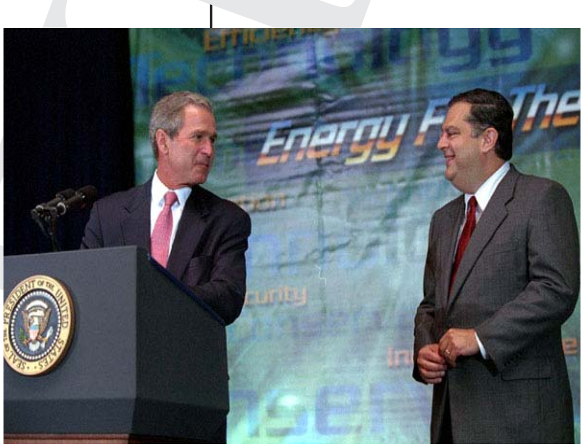
21st CTP	21st Century Truck Partnership
42V	42-Volt system
ACC	Automotive Composites Consortium
ACEM	aberration-corrected electron microscope
ADVISOR	Advanced Vehicle Simulator
AEMD	automotive electric motor drive
AFM	atomic force microscopy
AHHPS	Advanced Heavy Hybrid Propulsion Systems
AIPM	automotive integrated power module
ALM	automotive lightweighting materials
APBF	advanced petroleum-based fuels
APM	automotive propulsion materials
APRF	Advanced Powertrain Research Facility
APU	auxiliary power unit
ASTM	American Society for Testing and Materials
ATRIS	attenuated total reflectance infrared spectroscopy
CEO	chief executive officer
CFD	computational fluid dynamics
CHAIN	a computer modeling tool
CIDI	combustion-ignition direct-injection
COP	coefficient of performance
CSAFM	current-sensing atomic force microscopy
Cu	copper
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EGR	exhaust gas recirculation
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPAct	Energy Policy Act
EPS	essential power systems
EV	electric vehicle
FCVT	FreedomCAR and Vehicle Technologies Program
FTIR	Fourier Transform infrared spectroscopy

GATE	Graduate Automotive Technology Education
GHG	greenhouse gas
GREET	Greenhouse Gas, Regulated Emissions, and Energy use in Transportation model
HCCI	homogeneous-charge combustion-ignition
HEV	hybrid electric vehicle
HFCIT	Hydrogen, Fuel Cells, and Infrastructure Technologies
HIL	hardware-in-the-loop
HSWR	high-strength weight reduction
HTML	High Temperature Materials Laboratory
HVPM	heavy vehicle propulsion materials
ICE	internal combustion engine
ISO	International Standards Organization
LDV	light-duty vehicle
Li	lithium
Li/S	lithium/sulfur
Li-ion	lithium ion
LTC	low-temperature combustion
Mg	magnesium
MMC	metal-matrix composite
MTBE	methyl tert-butyl ether
NiMH	nickel metal hydride
NMR	nuclear magnetic resonance
NO_x	nitrogen oxides
NPBF	non-petroleum-based fuels
NVH	noise, vibration, and harshness
OFCVT	Office of FreedomCAR and Vehicle Technologies
OHFCIT	Office of Hydrogen, Fuel Cells, and Infrastructure Technologies
PM	particulate matter
PNGV	Partnership for a New Generation of Vehicles
PP	polypropylene
PSAT	Powertrain Systems Analysis Toolkit
PSAT-PRO	PSAT Prototyping software
PTW	pump to wheel

R&D	research and development
ReFUEL	Renewable Fuels and Lubricants Facility
RFI	radio-frequency interference
Sb	antimony
SBIR	Small Business Innovative Research
Si	silicon
SI	spark-ignited
SiC	silicon carbide
SUV	sport-utility vehicle
USABC	U.S. Advanced Battery Consortium
USCAR	U.S. Council for Automotive Research
VISION	a computer modeling tool
WTP	well to pump
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction

Executive Summary

America's energy security is largely dependent on the efficiency and fuel choices made for its transportation system. The transportation sector, in turn, has a significant influence on the nation's economic and environmental well-being. Our highway vehicles use more petroleum products than our country produces domestically, and as transportation energy use continues to grow, the situation will only worsen. Domestic oil production has been steadily declining for over two decades, and oil imports are expected to reach 70% by 2025. Oil imports have been a growing problem because petroleum resources are distant from most of the world's consumers, unevenly distributed globally, and concentrated in regions with political or environmental sensitivities. Not only is the U.S. demand for oil growing, but the global demand in both industrialized and developing countries is increasing rapidly—especially in countries such as China and India where the growth in motor vehicles is far outpacing that of the U.S.



President George W. Bush and Energy Secretary Spencer Abraham.

The President's FreedomCAR and Hydrogen Fuel Initiative is designed to reverse America's growing dependence on foreign oil by developing the technology for hydrogen-powered fuel cell vehicles by the middle of the next decade. Secretary of Energy Spencer Abraham has designated the Office of FreedomCAR and Vehicle Technologies (OFCVT) to lead the Department's vehicle partnerships with the U.S. automotive industry. Secretary Abraham has also assigned the responsibility for the development of fuel cells, on the government side, to the Office of Hydrogen, Fuel Cells, and Infrastructure Technologies (OHFCIT), in which a separate research and development (R&D) plan has been formulated.

America's energy security is largely dependent on the efficiency and fuel choices made for its transportation system. The President's FreedomCAR and Hydrogen Fuel Initiative is designed to reverse America's growing dependence on foreign oil by developing the technology for hydrogen-powered fuel cell vehicles by the middle of the next decade.

Industry Partners

Before fuel cell vehicles become a commercial reality and a hydrogen infrastructure is in place, vehicle efficiency improvements are needed for the transition from current internal combustion engines (ICEs) to fuel cell vehicles.

The OFCVT, in conjunction with its industry partner, the U.S. Council for Automotive Research (USCAR), is leading the effort, through the FreedomCAR Partnership, to develop the technologies that improve vehicle efficiency in the interim and simultaneously facilitate the transition ultimately to hydrogen-powered fuel cell vehicles. Both OFCVT and OHFCIT are program offices that support this partnership within the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE). FCVT and this multi-year plan are also supportive of another important industry partnership, the 21st Century Truck Partnership. By developing commercially viable technologies in heavy-duty vehicles, the nation can further reduce its dependence on imported oil and improve air quality. The federal government, led by DOE, and the trucking industry are working together to develop these new technologies and develop prototype production heavy-duty trucks and buses with improved fuel efficiency, reduced emissions, enhanced safety and performance, and lower operating costs.

Developed to their full potential, fuel cells could reduce our demand for oil by 11 million barrels of oil per day by 2040. By 2025, the savings could be from 4.5 to nearly 6 million barrels per day.

Program Benefits

Advanced technologies for cars and trucks developed under these two government–industry partnerships will result in significant benefits for the nation.

- **Energy security.** The President anticipates that if fuel cells are developed to their full potential, we could reduce our demand for oil by 11 million barrels of oil per day by 2040. FCVT includes research on advanced automotive and truck technologies (e.g., hybrid powertrains, power electronics, energy storage, lightweight materials) that will provide the transition to hydrogen-powered fuel cell vehicles. FCVT technologies will also enable fuel savings during the transition before fuel cells are ready to be commercialized in the transportation sector. By 2025, the oil savings potential for FCVT-supported technologies could be in the range of 4.5 to nearly 6 million barrels per day depending on the timing and success of fuel cell vehicles. Should there be a delay in fuel cell vehicle commercialization, the fuel savings potential for FCVT technologies would continue to grow, as those technologies would already be in the marketplace.

Hybrid electric vehicles can reduce greenhouse gas emissions by nearly 50% over conventional vehicles, during the transition to fuel cell vehicles operating on hydrogen. Efficiency improvements in heavy-duty vehicles will bring additional greenhouse gas reductions.

- **Improved environment.** On a per-vehicle basis and in terms of the total energy cycle, hybrid vehicles can reduce greenhouse gas emissions by nearly 50% compared with conventional vehicles, providing additional environmental benefits during the transition to the ultimate goal—fuel cell vehicles operating on hydrogen. In addition, the fuel economy improvements achieved by heavy-duty vehicles will contribute to a reduction in greenhouse gas emissions, as carbon emissions are directly related to fuel economy for petroleum fuel.
- **Economic competitiveness.** The global automotive and truck markets are extremely competitive because of the economic benefits of high-wage manufacturing jobs. FCVT activities in advanced technology development are conducted jointly with USCAR, a consortium of U.S. car makers. An even more diverse consortium, the heavy-duty truck industry, is another research partner with FCVT. One of the direct benefits of FCVT research will be to enable U.S. companies to be more competitive with lower-wage countries by leading in the development of advanced technologies. In addition, the reduction of petroleum use in transportation will reduce the nation's dependence on oil imports from unstable regions of the world, lessening the opportunities for oil price shocks and the attendant economic consequences.

FCVT R&D will enable U.S. auto companies to be more competitive. In addition, the petroleum savings would make oil price shocks less likely.

For heavy trucks, near-term improvements will focus on improving combustion and reducing parasitic losses to increase efficiency and reduce emissions.

THE TRANSITION TO HYDROGEN FUEL CELL VEHICLES

Technology Development for the Future

Many technical and economic barriers currently exist for affordable, mass-produced hydrogen fuel cell automobiles. Although R&D is under way, with DOE working closely with industry, the research on fuel cell vehicles is not expected to be completed for another 10 to 12 years; then a business case must be made for this shift to a new fuel and new propulsion system. In the interim, FCVT will support the development of advanced technologies that will be more energy-efficient in the near term and, at the same time, provide some of the technology base for the eventual commercialization of fuel cell vehicles. Because of the more demanding requirements for heavy-truck applications, near-term improvements will focus primarily on improved combustion and reduced parasitic losses to increase efficiency and reduce emissions.

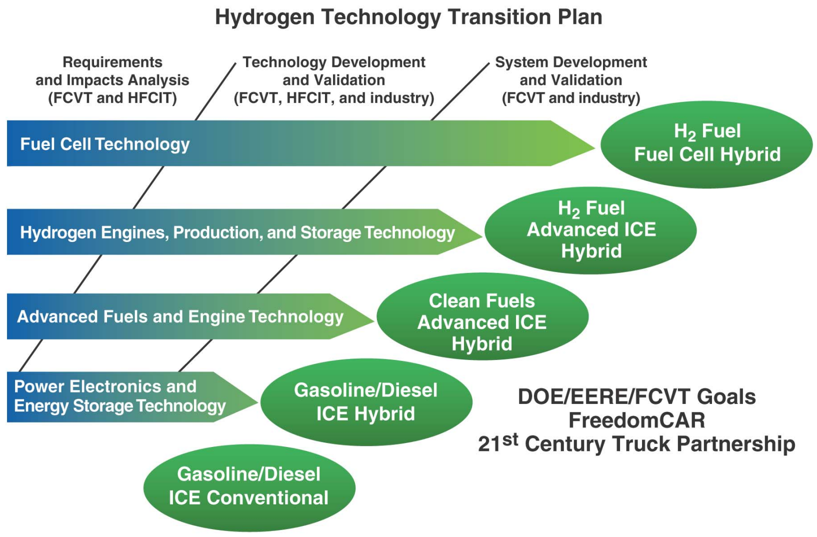


Figure ES.1. Paths to use of hydrogen fuel cell vehicles.

One possible path to a hydrogen future for transportation is illustrated in Figure ES.1, which also shows how FCVT-supported technologies can become commercialized in the process. The first stage in the transition, as shown in this illustration, is hybridization. FCVT and its predecessor organizations in DOE have supported the development of hybrid vehicle technology for many years, and hybrid vehicles are now being introduced in the U.S. market in limited numbers. Further improvements are expected with advanced combustion techniques and cleaner fuels.

Improvements in energy storage and power electronics technologies will continue to make hybrid vehicles, and eventually fuel cells, more affordable. Hydrogen ICEs can provide a major assist in the transition to a hydrogen transportation system. Auto companies can continue to use existing engine plants, while the hydrogen ICE will encourage hydrogen production and distribution, as well as advances in hydrogen storage. With a hydrogen infrastructure in place and a public that has become comfortable with hydrogen as a fuel for personal vehicles, fuel cell vehicles can be introduced in the mass market.

These technologies may be commercialized in a different order; and other technologies, such as lightweight materials, may be introduced at any time during the process, as they are not limited to any particular propulsion system. Many different paths exist to a future that provides personal and transport mobility with hydrogen fuel cell vehicles, and the path and timing will vary for the different types of vehicles. Long-haul trucks, for example, that use the high energy content of diesel fuel to minimize refueling times, may adopt fuel cell technology later. The common thread is the research that is needed on the many different aspects of the vehicle system to make that future a reality.

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THE RESEARCH AND DEVELOPMENT PROCESS

FCVT Mission

DOE is a large department with several missions, the first being "to foster a secure and reliable energy system that is environmentally and economically sustainable." EERE contributes to that mission by (1) enhancing energy efficiency and productivity and (2) bringing clean, reliable, and affordable energy production and delivery technologies to the marketplace. The FCVT effort, within those missions, is to support the development of technologies that will achieve transportation energy security through a U.S. highway vehicle fleet consisting of affordable, full-function cars and trucks that are free from petroleum dependence and harmful emissions without sacrificing mobility, safety, and vehicle choice.

Although FCVT does not build cars and trucks, it does support the R&D that results in technologies that improve efficiency, use non-petroleum fuels, and reduce emissions. Figure ES.2 illustrates how each of the FCVT key activities focuses on developing advanced technology products that are validated at the vehicle systems level to meet the goals of both the FreedomCAR Partnership and the 21st Century Truck Partnership. FCVT addresses the goals of the partnerships established among the industry and government partners. Priority FCVT goals have been established and performance measures defined to allow continual assessment of progress.

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Establishing Technical Targets

The key to successful development of advanced vehicle component technologies that enable the attainment of fuel efficiency goals is defining the technical goals, requirements, and targets for those components. The targets guide the technology development and, when the R&D is completed, provide the opportunity to

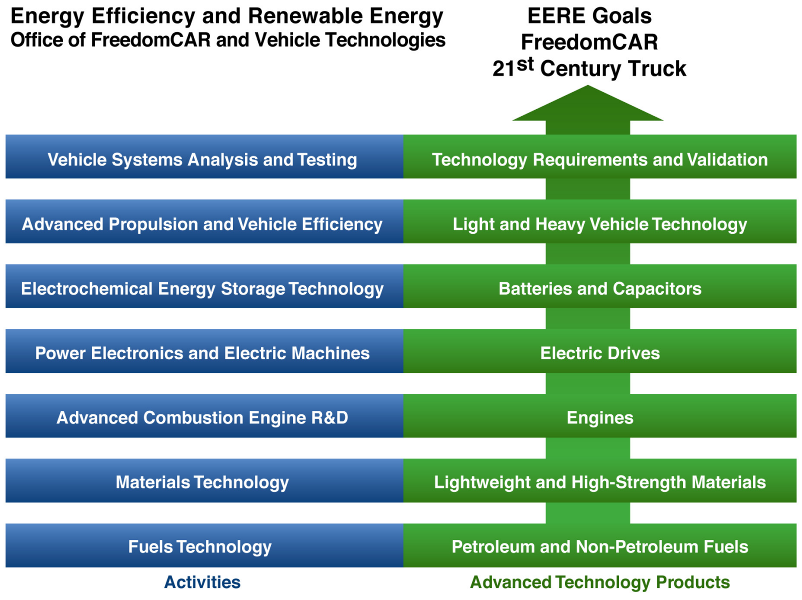
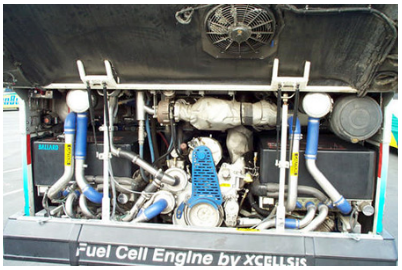


Figure ES.2. FCVT R&D areas and resulting advanced technologies.

validate the component technologies in a vehicle systems context. The industry partners can then incorporate the technologies into their own vehicle designs. As shown in Figure ES.2, each of the activities in FCVT has specific outputs that lead directly to advanced technologies needed to meet the goals of the FreedomCAR Partnership or the 21st Century Truck Partnership. In the case of Vehicle Systems Analysis and Testing, this activity provides the technology requirements for each of the other activities and, at the end, provides validation that the R&D has been successfully completed.

Identifying the Technology Barriers

The relatively low price of gasoline and diesel fuel is an impediment to the development of more fuel-efficient vehicle technologies. In addition, a number of technical barriers limit the performance of the more advanced vehicle technologies. The combination of performance and economic barriers results in an inadequate incentive for industry to develop new technologies when low fuel prices do not encourage a market for fuel-efficient vehicles. Because of these barriers, FCVT works in partnership with industry to develop the technologies that can improve our energy security with the attendant benefits of an improved environment and a better economy. Specific barriers have been identified for each technology area.



FCVT works in partnership with industry to develop technologies that can improve our energy security, our environment, and our economy.

The Research Agenda

Each FCVT activity has goals designed to meet the overall FCVT goal of developing fuel-efficiency technologies for automotive and truck applications. The research agenda for each of the activities is summarized.

Vehicle systems analysis and testing. Vehicle systems activity provides an overarching vehicle systems perspective to the technology R&D activities of DOE's FCVT and HFCIT Programs. This activity uses analytical and empirical tools to model and simulate potential vehicle systems, validate component performance in a systems context, benchmark emerging technology, and validate computer models. For this activity to be successful, extensive collaboration with the technology development activities in FCVT and HFCIT is required in both analysis and testing. The analytical results of this activity are used to estimate national benefits and/or impacts of DOE-sponsored technology development. The section of this summary titled "Managing the Research" presents more information on this activity.

Advanced propulsion and vehicle efficiency improvements. Two principal research areas are applicable to both light-duty and heavy-duty vehicle applications: hybridization and parasitic loss reduction. Hybridization is being developed for both light and heavy vehicles, with particular emphasis on hydrogen ICEs and fuel cells for light-duty applications. Parasitic loss reduction will be especially important in the truck applications; here, research is focused on auxiliary load electrification, aerodynamic and rolling resistance, friction and wear reduction, underhood thermal management, and efficient climate control. A priority FCVT goal is to develop technologies that reduce parasitic energy losses, including losses from aerodynamic drag, from 39% of total engine output in 1998 to 24% in 2006.

Two principal research areas are applicable to both light-duty and heavy-duty vehicle applications: hybridization and parasitic loss reduction. Hybridization is being developed for both light and heavy vehicles, with particular emphasis on hydrogen internal combustion engines and fuel cells for light-duty applications. Parasitic loss reduction will be especially important for trucks.

Energy storage technologies. Energy storage is critical for near-term hybrid vehicle improvements as well as the long-term goal of fuel cell vehicles. There are three closely-related research areas. First, full battery system development is under way with R&D on lithium-sulfur batteries for electric vehicles and lithium-ion batteries for both high power density for electric vehicles and high energy density for hybrid vehicles. Second, applied battery research is conducted on lithium-ion chemistry cost, battery life, and abuse tolerance. Third, long-term exploratory battery research is focused on the fundamental problem of chemical instabilities that impeded the development of advanced batteries. A priority FCVT goal is to reduce the production cost of a high-power 22-kW battery for use in light-duty vehicles from $3000 in 1998 to $200 in 2010; an intermediate goal of $720 in 2006 would enable cost-effective entry of hybrid vehicles (at a production level of 100,000 batteries per year).

Energy storage is critical for near-term hybrid vehicles as well as long-term fuel cell vehicles. There are three closely-related research areas: full battery system development, applied battery research, and long-term exploratory battery research.

Advanced power electronics and electric machines. The electric drive system is the technology foundation for both hybrid electric and fuel cell vehicles. The research in power electronics includes fundamental R&D; development of an integrated chip controller (without external circuitry) to reduce cost; development of a bi-functional dc/dc converter to interconnect the fuel cell's high-voltage bus to the low-voltage bus for auxiliary loads; development of a lightweight, low-cost inverter to convert dc power from a fuel cell or battery to ac power for the electric motor; and research on capacitors as alternatives to inverters. Concurrently, R&D is being conducted on high-performance, low-cost materials and thermal management systems for electric motors and generator, with special emphasis on permanent magnet motors. Researchers are also investigating advanced component modeling and fabrication and manufacturing techniques to integrate motor and power control technologies and thereby reduce the size and cost of power management systems. A priority FreedomCAR Partnership goal is to develop an electric propulsion system with a 15-year life that is capable of delivering at least 55 kW for 18 seconds and 30 kW continuously at a system cost of $12/kW peak.

Advanced combustion engine R&D. Combustion and emissions control applies to both current light-duty and heavy-duty vehicles. This research will focus on three areas concurrently: (1) in-cylinder combustion and emissions control, (2) exhaust aftertreatment, and (3) fuel formulation with the objective of finding the most cost-effective approach to optimizing engine efficiency and performance while reducing emissions to meet future Environmental Protection Agency standards. In addition to fundamental combustion research and applied research in low-temperature combustion regimes—such as homogeneous-charge, compression-ignition (HCCI) engines—work will also be undertaken on hydrogen-fueled ICEs, since they will provide an interim hydrogen powertrain technology leading to the ultimate goal of hydrogen fuel cell vehicles. Waste heat recovery for heavy-duty vehicles will also be explored. New fuel formulations and advanced combustion techniques will be assessed to ensure that no adverse health impacts are associated with the new technologies. A priority FCVT goal is to improve the efficiency of ICEs from 30% to 42% by 2010 for light-duty and from 40% to 55% by 2012 for heavy-duty applications while meeting cost, durability, and emissions constraints.

David Garman, DOE Assistant Secretary for Energy Efficiency and Renewable Energy with the Test Machine for Automotive Crashworthiness, a new tool for testing composites and other automotive lightweight materials.

Materials technologies. Weight reduction not only contributes to greater vehicle fuel efficiency but also can offset the weight increases that may result from some advanced powertrain systems. Research in this area is divided into four functional areas: automotive lightweight materials, automotive propulsion materials, high-strength weight-reduction materials, and heavy-vehicle propulsion materials. This research also includes the contributions of the High Temperature Materials Laboratory, which works with numerous industries, universities, and government laboratories on a wide range of applications of high-temperature materials. Research in automotive lightweight materials is focused on dramatic weight reductions for body and chassis components without compromising vehicle cost, performance, safety, or recyclability.

Automotive propulsion materials research is focused on materials for emissions reduction, thermal management, electrode performance, and fuel cell stack performance. The high-strength weight reduction materials research concentrates on reducing parasitic energy losses due to the weight of heavy vehicles; areas of focus are the cab, chassis, and drivetrain, and the relevant materials are advanced engineered materials such as metal matrix composites and ultralight materials such as laminates and foams. Heavy-vehicle propulsion materials research includes fuel systems materials and exhaust aftertreatment materials. Priority FCVT goals are to reduce the production cost of carbon fiber from $12 per pound in 1998 to $3 per pound in 2006 and to reduce the weight of an unloaded tractor-trailer combination from the current 23,000 pounds to 18,000 pounds by 2010, a weight reduction of 22%.

Fuels technology. Advanced fuels technologies will enable current engines to be more efficient and will foster the transition to hydrogen by maximizing the production of hydrogen when it is reformed on-board hydrogen ICEs and fuel cell vehicles or at the refueling facility. The Advanced Petroleum Based Fuels component of this effort consists of R&D of highly refined petroleum fuels produced from crude oil, and possibly of blends of petroleum fuels with performance-enhancing non-petroleum components derived from renewable resources such as biomass or from fossil resources such as natural gas or coal. The other major component, Non-Petroleum-Based Fuels, consists of R&D of fuels or fuel blending components derived primarily from non-petroleum sources such as agricultural products, biomass, natural gas, or coal. A wide variety of fuels will be tested and evaluated to develop a better understanding of the relationships among fuel properties, engine emissions, and efficiency, as well as to identify compatible lubricants for use with the newly developed fuels. Close collaboration with the Advanced Combustion Engine R&D activity will be necessary. Further, to assess the impacts of advanced fuel formulations that may eventually replace petroleum, a New Fuels Technology Impact effort will seek to identify, analyze, quantify, and therefore avoid potentially deleterious ecosystem impacts of new fuels, specifically

A wide variety of fuels will be tested and evaluated to develop a better understanding of the relationships among fuel properties, engine emissions, and efficiency and to identify compatible lubricants for use with the newly developed fuels.

fuels that are envisioned to replace petroleum fuels. A priority FCVT goal is to develop a specification by 2007 for a fuel formulation that incorporates the use of a non-petroleum-based blending agent enabling a 2% diesel fuel replacement in 2010.

Managing the Research

OFCVT has established four technical teams to plan, coordinate, and manage the technology development needed to meet the technical targets set jointly by FCVT and its industry partners. They are the Vehicle Systems Team (which includes any field testing), the Advanced Materials Team, the Fuels Team (which also addresses lubricants, as well as meeting the requirements of the Energy Policy Act), and the Engine and Emissions Control Team.

Figure ES.3 illustrates the process by which these four teams are able to meet the goal of the Office: developing vehicle technologies that can be successfully commercialized and improve the nation’s energy security by dramatically reducing our dependence on petroleum. As shown in the bottom portion of the chart, the R&D process begins by developing technology requirements and setting technical targets. The ADVISOR model is used to quickly estimate the fuel-saving potential of any new vehicle propulsion system and develop technical targets. The PSAT model then uses dynamic analysis of vehicle performance and efficiency to support detailed component design and hardware development. At this point, each of the FCVT technology teams, plus the HFCIT teams for hydrogen and fuel cell R&D, has the technical direction to conduct the appropriate technology development that will lead to components that are expected to perform in a vehicle systems context so that the energy efficiency targets can be met. The

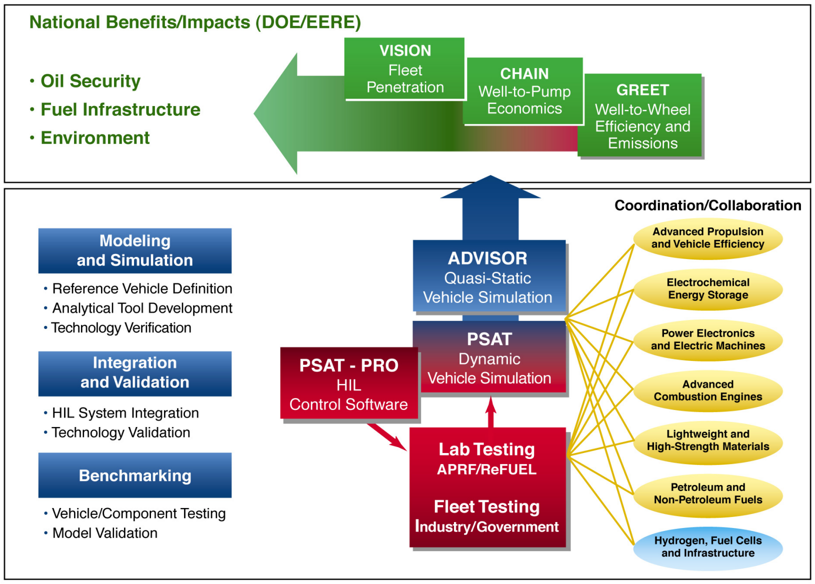


Figure ES.3. Process by which the four technical teams meet the goals of the Office of FreedomCAR and Vehicle Technologies.

PSAT-PRO model enables these components to be tested and validated in a hardware-in-the-loop environment. The hardware that is developed can be validated in the laboratory or in field tests; after successful performance testing, it will be ready to be "harvested" by industry and commercialized. At any step along the way, a series of macro-models (GREET, CHAIN, and VISION) can provide national-level impact analysis of the total energy cycle, infrastructure requirements, and emissions and oil consumption, ensuring that the benefits of the research exceeds the taxpayer investment in these advanced vehicle technologies.

The pursuit of cleaner, more-efficient vehicles today and emissions-free, petroleum-free vehicles tomorrow is a national goal important to the nation's energy, environmental, and economic future.

To assess progress toward achievement of the goals, intermediate milestones and performance measures have been established. Technologies developed by FCVT are evaluated to validate that the component/subsystem technologies developed by FCVT meet the technical targets assigned to them.

Outlook for the Future

The FCVT goal meets a national need: reducing our dependence on imported oil.

The FCVT goal meets a national need: reducing our dependence on imported oil. Government and industry are partnering to develop advanced vehicle technologies. The barriers, both performance and economic, have been identified and goals and technical targets established. The R&D process to manage the technology development uses established approaches to increase the probability of success. However, because the government is not involved in commercialization of the technologies and does not conduct research on near-term applications, which are the purview of industry, the government R&D is concentrated on high-risk, long-term technology development. Nevertheless, the pursuit of cleaner, more-efficient vehicles today and emissions-free, petroleum-free vehicles tomorrow is a national goal set by President Bush and is important to the nation's energy, environmental, and economic future. The research agenda in this plan leads to this vision of the future.

1. Introduction

The purpose of this FreedomCAR and Vehicle Technologies (FCVT) *Multi-Year Program Plan* is to describe how the FCVT Program will conduct future transportation-related technology research and development (R&D) to reduce the nation's dependence upon imported petroleum.

The mission of the FCVT Program is to develop more energy-efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum. To accomplish this mission, the FCVT Program promotes the development of fuel-efficient motor vehicles and trucks, researches options for using cleaner fuels, and implements efforts to improve energy efficiency. In collaboration with industry, national laboratories, universities, state governments, and other federal agencies, the FCVT Program supports R&D on advanced vehicle technologies and fuels that could dramatically reduce and eventually eliminate the demand for petroleum, decrease emissions of criteria air pollutants and greenhouse gases, and enable the U.S. transportation industry to sustain a strong, competitive position in domestic and world markets.

Mission: Develop more energy-efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum.

Research, development and validation activities are focused on technologies to reduce oil use by highway vehicles such as cars, light trucks, and heavy vehicles (composed of medium and heavy trucks and buses). Off-highway vehicles (such as vehicles used in construction, mining, and agriculture) and locomotives may benefit from this research because they use engines that are similar to those in heavy-duty trucks.

The FCVT Program's approach to implementing R&D activities emphasizes jointly funded partnerships with academia and industry to develop and validate technologies. This approach ensures that (1) the nation's best resources are applied to R&D activities, (2) maximum technology transfer will take place, and (3) government resources will be leveraged by those of industry.

FreedomCAR Partnership goal: Enable the full spectrum of light-duty passenger vehicles to operate without using petroleum or producing harmful emissions while sustaining freedom of mobility and vehicle choice.

In January 2002, the Secretary of Energy and executives of the U.S. automobile industry announced a new cooperative automotive research partnership between the U.S. Department of Energy (DOE) and the auto industry's U.S. Council for Automotive Research (USCAR). This government-industry partnership, designated "FreedomCAR" (in which *CAR* stands for "Cooperative Automotive Research") supersedes and builds upon the successes of the previous Partnership for a New Generation of Vehicles (PNGV). The FreedomCAR Partnership departs from the family sedan "vehicle" focus of PNGV to address the development of advanced technologies suitable for all light-duty passenger vehicles (i.e., cars, SUVs, pickups, minivans). Additionally, compared with PNGV, the government's role in the FreedomCAR Partnership has shifted to more fundamental, longer-range, higher-risk technology research. The long-term goal of the FreedomCAR Partnership is to enable the full spectrum of light-duty passenger vehicle classes to operate completely free of petroleum and free of harmful emissions while sustaining the driving public's freedom of mobility and freedom of vehicle choice.

21st Century Truck Partnership goal: Dramatically improve the energy efficiency and safety of trucks and buses while maintaining a dedicated concern for the environment.

In November 2002, the Secretary of Energy announced the rejuvenation of the government–industry 21st Century Truck Partnership to address the R&D needs of commercial vehicles. The ultimate goal of this partnership is to dramatically improve the energy efficiency and safety of trucks and buses while maintaining a dedicated concern for the environment. The 21st Century Truck Partnership is a partnership between the U.S. truck and bus industry and its supporting industries and the federal government. This partnership is for R&D on commercially viable technologies that will dramatically cut the fuel use and emissions of commercial trucks and buses while enhancing their safety and affordability and maintaining or enhancing performance.

In February 2003, President Bush announced the FreedomCAR and Hydrogen Fuel Initiative to develop technologies for (1) fuel-efficient motor vehicles and light trucks, (2) producing cleaner fuels, (3) improving energy efficiency, and (4) hydrogen production and the nationwide distribution infrastructure needed for vehicle and stationary power plants, to fuel both internal combustion engines (ICEs) and fuel cells.

Within DOE's Office of Energy Efficiency and Renewable Energy (EERE), the FCVT Program and the Hydrogen, Fuel Cells, and Infrastructure Technologies (HFCIT) Program have been assigned the responsibility for implementing the FreedomCAR and Hydrogen Fuel parts of the initiative, respectively. The FCVT and the HFCIT Programs are working together closely to implement the initiative, and the interdependency of the two programs is depicted in Figure 1. The FCVT Program also has responsibility for the 21st Century Truck Partnership. The HFCIT Program efforts in support of the initiative are provided under separate cover in the HFCIT *Multi-Year Research, Development, and Demonstration Plan*.

The FCVT *Multi-Year Program Plan* describes how the FCVT Program will carry out its mission. The plan focuses on R&D during

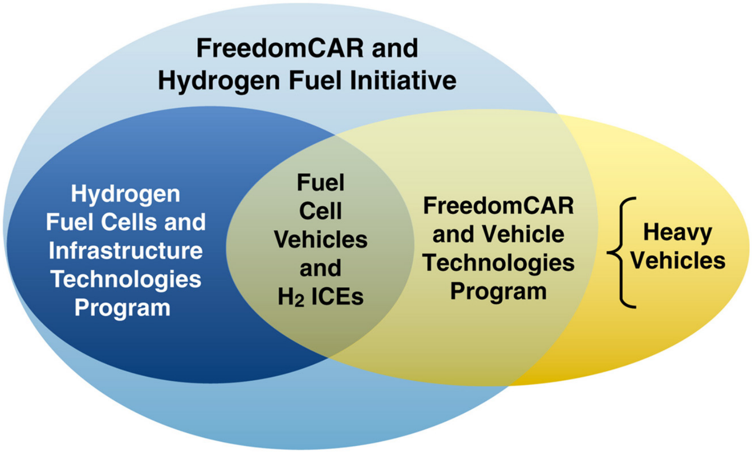


Figure 1. Interdependency of the HFCIT and FCVT.

the 2004–2008 time frame, the first five years of the FreedomCAR and Hydrogen Fuel Initiative. One possible pathway for how the FCVT Program's R&D efforts will contribute to the initiative is provided in Figure 2.

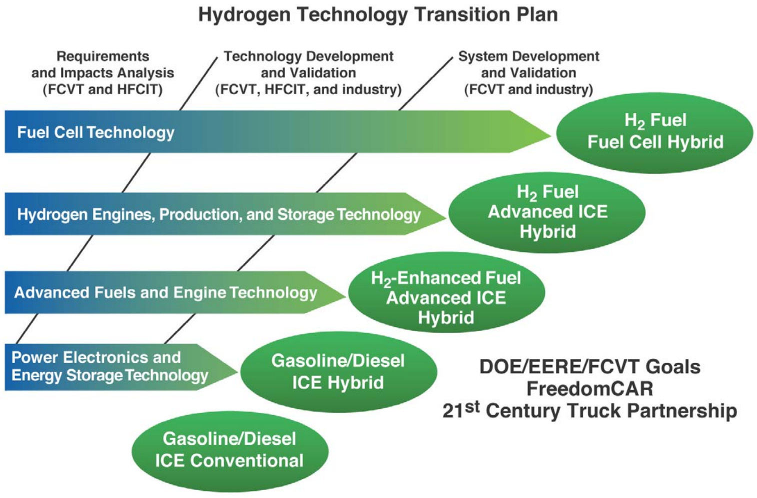


Figure 2. One pathway to the introduction of EERE-supported technologies into commercial products after the FCVT Program has validated the components.

FreedomCAR Partnership. The FCVT Program plays a prominent role in the FreedomCAR Partnership by conducting R&D to achieve the near- to mid-term goals of the partnership through continued development of advanced technologies that will dramatically reduce the fuel consumption and emissions of all petroleum-fueled, light-duty personal vehicle classes, as reflected in Figure 2. Achieving these near- to mid-term goals is paramount to providing the necessary technologies for fuel cell hybrid-electric vehicles.

Figure 3 identifies the organizational structure for the FreedomCAR Partnership. The role of the FCVT Program in R&D for specific technologies ends once a technology has been validated and a viable technology development pathway has been identified to meet the needs for commercialization. Further discussion of the terms *validated* and *validation* are provided in Section 4.1. Other parts of EERE and DOE, or other federal agencies, may work with industry in fostering the commercialization of the technologies; however, those efforts are not within the scope of this plan.

21st Century Truck Partnership. Commercial vehicles provide an important contribution to U.S. economic activity. Historically, the rise in gross domestic product (GDP), a measure of economic activity, has been directly linked to the increase in vehicle-miles of commercial transport. There are large efficiency gains to be realized with commercial vehicles, especially heavy-duty transport vehicles, which are more dependent on high-energy-density petroleum-based fuels because of the long distances they travel, their heavier

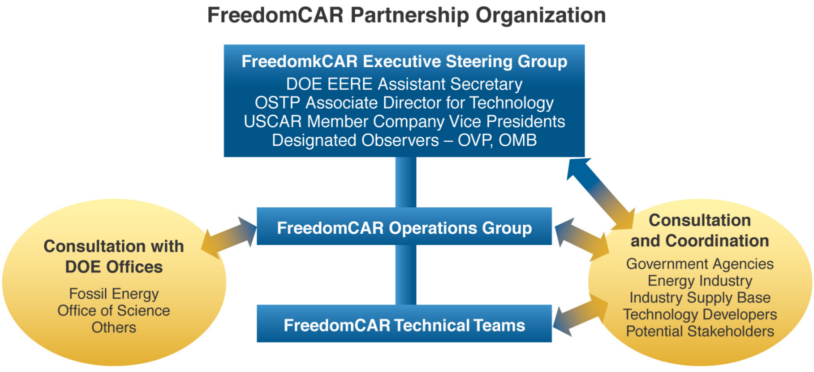


Figure 3. Major groups participating in the FreedomCAR Partnership, where OSTP implies Office of Science and Technology Policy, OVP implies Office of the Vice President, and OMB implies Office of Management and Budget.

payloads, and more demanding duty cycles. Therefore, in addition to working on technologies for light-duty passenger vehicles, the FCVT Program addresses R&D technologies for commercial vehicles. This is accomplished through the 21st Century Truck Partnership. The FCVT Program has the responsibility for management of the government's participation in this partnership and for conducting and supporting the R&D necessary to meet the partnership's goals. Major participants in the 21st Century Truck Partnership are identified in Figure 4.

21st Century Truck Partnership Participants

- Partnership is centered in DOE's FreedomCAR and Vehicle Technologies program
- Team with Departments of Transportation and Defense and EPA
- The 15 industry partners include heavy-duty engine manufacturers, truck and bus original equipment manufacturers, and hybrid powertrain suppliers

Figure 4. Major groups participating in the 21st Century Truck Partnership.

In addition to these two partnerships, achieving the goals expressed in this *Multi-Year Program Plan* is furthered through the use of laws and regulations relating to intellectual property. Patent and copyright protection of intellectual property associated with the new technologies developed under this plan encourages exploitation of the new technologies by enhancing the competitive position of FCVT Program industrial partners. The degree of intellectual property ownership provided to the industrial partner for new technologies arising under this *Multi-Year Program Plan* is determined on a case-by-case basis and is commensurate with cost-sharing amounts.

The FCVT *Multi-Year Program Plan* is organized in the following manner. Section 2 presents the national benefits that will be derived as a result of the conduct of the R&D described herein. Section 3 defines the goals of the FCVT Program and places them in the context of the national need, the National Energy Policy, and the missions of DOE and EERE. Section 4 presents the technical plan for carrying out each of the activities. For each activity, this section describes the goals, targets, technical barriers, approaches to be taken to address barriers, and critical tasks and milestones for technology development and validation. Section 5 outlines the management plan for implementing the FCVT Program.

Finally, the FCVT *Multi-Year Program Plan* is considered to be a living document and, as such, will be updated as required.

2. Program Benefits

"...Hydrogen can be produced from domestic sources—initially, natural gas; eventually, biomass, ethanol, clean coal, or nuclear energy. One of the greatest results of using hydrogen power, of course, will be energy independence for this nation.... If we develop hydrogen power to its full potential, we can reduce our demand for oil by over 11 million barrels per day by the year 2040. That would be a fantastic legacy to leave for future generations of Americans."

President George W. Bush
The National Building Museum
February 6, 2003

"Now, there's a lot of obstacles that must be overcome in order to make fuel cells economically viable. And, therefore, we're promoting more research and development. In January, Secretary Abraham announced a $150 million FreedomCAR plan. ..."

President George W. Bush
The South Lawn
February 25, 2003

The President's FreedomCAR and Hydrogen Fuel Initiative is designed to reverse America's growing dependence on foreign oil by developing the technologies that lead to hydrogen-powered fuel cell vehicles. This initiative was chosen primarily because of the energy security benefits associated with a transportation fuel that can be produced domestically from a diversity of feedstocks. Of the $150 million in funding for FreedomCAR announced by Secretary Abraham, approximately half is for fuel cell and hydrogen research; the other half is for nearer-term automotive technologies within the FreedomCAR and Vehicle Technologies (FCVT) Program that improve energy efficiency and provide the transition to fuel cells and hydrogen. The R&D conducted by FCVT serves the objectives of the Initiative in three ways:

1. Reducing petroleum dependence in the near term by improving hybrid vehicle technology [with gasoline or diesel internal combustion engines (ICEs)] and clean fuels while fuel cell technology is still being developed.
2. Developing additional technologies, such as power electronics, energy storage, and lightweight materials, that will eventually be needed for fuel cell vehicles.
3. Stimulating the development of a hydrogen infrastructure through the near-term use of hydrogen-enhanced fuels and hydrogen for use in ICEs.

The *Multi-Year Research, Development and Demonstration Plan* for EERE's Hydrogen, Fuel Cells, and Infrastructure Technologies (HFCIT) Program Office presents the rationale and potential national benefits for pursuing technologies that provide an increase in energy security through reduced petroleum dependence and a reduction in both criteria pollutants and greenhouse gas emissions in transportation. The factors that provide the rationale for a government role in R&D in vehicle energy use can be summarized as follows:

U.S. crude oil production can provide for some of the nation's petroleum needs; however,

- Crude oil production peaked in 1970.
  - It has declined steadily since the mid-1980s, even with the addition of oil from Alaska's North Slope.
- Oil imports are a growing national concern.
  - The United States imports more than half its oil (compared with a third during the 1973 oil crisis).
  - Oil imports are expected to exceed 70% by 2025.
- Three trillion barrels of recoverable oil exist worldwide—a finite resource (U.S. Geological Survey).
  - One fourth of the oil has already been produced and consumed.
  - One-fourth of the oil has been discovered and "booked as reserves."
  - One-half is either reserve growth or probable, but undiscovered, resources.
  - Oil is relatively abundant, but it
    - is distant from most major consumers,
    - has an uneven geographic distribution, and
    - is concentrated in regions that have either political or environmental sensitivities.
- Global transportation trends in petroleum consumption will increase oil demand.
  - Continued growth in transportation oil use in industrialized countries.
  - Growth in transportation oil consumption in developing countries will accelerate as their economies modernize: for example, in terms of vehicles per person, China is where the United States was in 1913, but it is growing at twice the current U.S. rate.

In addition, carbon emissions, which are directly proportional to the carbon in the fuel, result in greenhouse gases, such as carbon dioxide and methane, that are considered to have a detrimental effect on the global climate. The conclusion from the energy and environmental trends is that the world cannot remain forever dependent on petroleum fuels; therefore, a transition will be necessary at some point. The earlier the transition is begun, the smoother the process is likely to be (i.e., there will be fewer economic shocks due to fuel price spikes). The FreedomCAR and Hydrogen Fuel Initiative provides for such a transition. Hydrogen and fuel cell vehicles provide the eventual shift to a new transportation fuel using new powertrains for the vehicles. The FCVT Program provides a number of enabling technologies for that transition, as well as near-term relief from excessive dependence on imported petroleum.

ENERGY SECURITY BENEFITS

The Presidential FreedomCAR and Hydrogen Fuel Initiative identifies the potential for reducing the nation's demand for oil by over 11 million barrels per day by the year 2040. This reduction in petroleum demand is due to the displacement in fuel consumption provided by hydrogen vehicles and fuel cell vehicles. Fuel cell vehicle research is anticipated to be completed by 2015. Meeting both the performance and economic goals would allow business decisions to be made and provide the basis for significant market penetration beginning three years later.

Fuel cell vehicles will benefit significantly from reducing the weight of the vehicle and from the widespread adoption of hybrid electric vehicle (HEV) propulsion systems, including improved energy storage systems that allow start-up with a battery or other energy storage device and the ability to capture energy via regenerative braking. These technologies will have petroleum savings benefits of their own well before the introduction of fuel cell vehicles. The petroleum reduction benefits of hybrids are smaller than those of fuel cells because fuel cells are projected to be more efficient and in this analysis are assumed to use non-petroleum feedstocks for hydrogen. Nevertheless, oil savings from HEVs (gasoline or diesels) in the near term can be significant and occur sooner than savings from fuel cell vehicles.

OIL SAVINGS IN LIGHT-DUTY VEHICLES

The oil savings benefit of successful market penetration of HEVs (gasoline or diesel HEVs) was evaluated with the VISION model.[1] This analysis did not estimate the total benefits of all the technologies supported by FCVT, which include hybridization, energy storage, lightweight materials, advanced combustion and emissions controls, and non-petroleum based fuels. To calculate potential oil savings, only the fuel economy benefits of hybridization were used. The benefits of the other technologies would then be incremental. Conversely, if the reader considers the market penetration rate in this analysis to be too optimistic, then the absence of these additional benefits could be seen as compensating.

Two cases were analyzed. In one case, the HEV market penetration escalates from its current level of about 0.4% of new light-duty vehicle sales to 10% in five years, accounts for a third of new vehicle sales in ten years, and levels off at just over 50% of sales in 2018 when fuel cell vehicles are introduced. Thereafter, HEV sales decline as fuel cell vehicle sales increase. In this case, called the Early

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[1] VISION: a spreadsheet energy use model developed by Argonne National Laboratory for the U.S. Department of Energy.

Transition Case, fuel cell vehicles eventually achieve complete market penetration as identified in the HFCIT *Multi-Year Program Plan* developed for the President's FreedomCAR and Hydrogen Fuel Initiative. The market penetration rates of both HEV technology and fuel cell technology are illustrated in Figure 5.

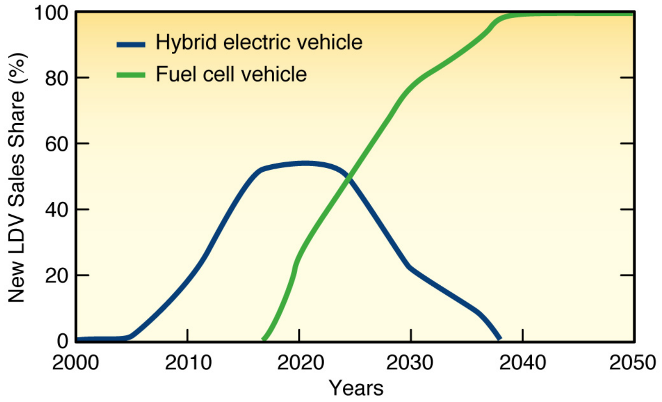

Figure 5. Hybrid-electric and fuel cell vehicle sales in the Early Transition Case.

In the second case, called the Extended Transition Case, an auto industry scenario is simulated. Ford Motor Company CEO Bill Ford recently envisioned that HEV and fuel cell vehicle sales in 25 years "might be 75/25 at that point."[2] This would presume that fuel cell vehicles would still be successful, but the market penetration would not be as early as anticipated. Nevertheless, under this scenario, HEVs (gasoline and diesel ICEs), hydrogen ICEs, and fuel cell vehicles would displace the conventional powertrain in new vehicles in 25 years. The market penetration rates for this case are shown in Figure 6. In each of the two cases, the fuel economy of the HEVs is assumed to be 25% greater than that of the conventional vehicles they are replacing and to gradually improve until 2025, when HEVs have doubled the fuel economy of conventional vehicles.[3] However, HEVs will still have a lower fuel economy than the fuel cell vehicles that are beginning to be introduced at that time.

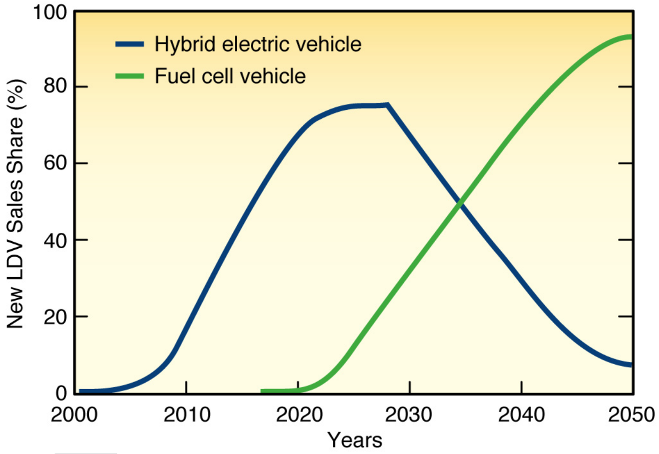

Figure 6. Hybrid-electric and fuel cell vehicle sales in the Extended Transition Case.

Oil savings from both the Early Transition Case and the Extended Transition Case are shown in Figure 7. While the focus of the Presidential FreedomCAR and Hydrogen Fuel Initiative is the 11 million barrels of oil per day saved in the year 2040, the Early Transition Case illustrates that by 2025, nearly 5 million barrels of oil could be saved daily, with almost 3 million barrels due to the hybrid vehicle technologies being supported by the FCVT Program in partnership with the auto

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[2] *Automotive News*, May 26, 2003.

[3] The report *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, R. Graham, Electric Power Research Institute Final Report 1000349, Palo Alto, California, July 2001, estimates the fuel economy improvement of current HEVs to be 70% compared with current conventional vehicles. Future fuel economy benefits will depend on the relative improvements between hybrid and conventional powertrains.

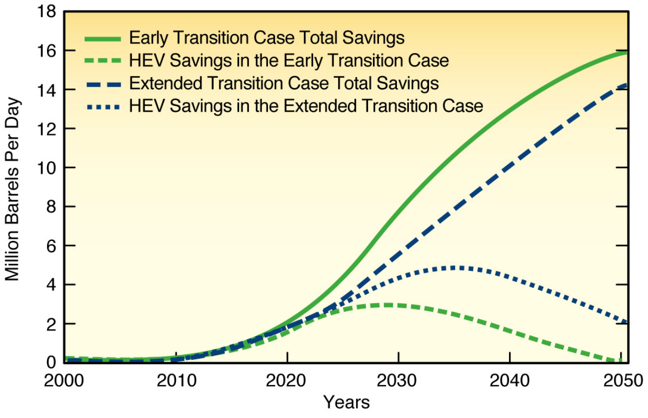

Figure 7. Light-duty vehicle oil savings with hybrid-electric and fuel cell vehicles.

industry. The Extended Transition Case, in which the introduction of fuel cell vehicles is delayed, still results in savings of 3.5 million barrels of oil per day by 2025. In both cases, petroleum savings continue to increase over time and illustrate how the technologies supported by the FCVT and HFCIT Programs for the light-duty vehicle sector work together to achieve national benefits.

OIL SAVINGS IN HEAVY-DUTY VEHICLES

Heavy trucks account for about one-fourth of the energy consumed in highway vehicles. Much of the nation's high-value freight is shipped by trucks, and the propulsion system for over-the-road trucks (Class 8) is dominated by relatively efficient diesel engines. Nevertheless, there is room for energy efficiency improvements. The FCVT Program supports technology development to improve medium- and heavy-duty truck fuel economy. This research, conducted with industry in the 21st Century Truck Partnership, is focused on advanced combustion, improved aerodynamics and rolling resistance, heavy hybrid technology, and essential power systems. The oil savings potential of fuel economy improvements in heavy-duty vehicles was also evaluated with the VISION model. FCVT research activities have a goal of 20% improvement in engine efficiency by 2010 and additional improvements in parasitic losses. These fuel economy improvements were assumed to be introduced in 2010, with a 15% improvement in miles per gallon, and reach a 50% improvement by 2025. This improvement in fuel economy assumes that by 2025, technologies being developed by FCVT are fully mature and ready for the market. These will include improvement in engine efficiency while meeting emissions standards, reductions in parasitic loads (aerodynamic, rolling, and auxiliary), and recapture of or reduction in wasted energy (such as hybridization for braking energy recovery and idling reduction technologies). The baseline fuel economy is 8.2 mpg for medium-duty trucks and 5.5 mpg for heavy-duty trucks. By 2025, these fuel economy improvements could keep truck fuel use relatively flat for more than a decade and reduce oil use by 1 million barrels of oil per day, as shown in Figure 8. Petroleum savings in the

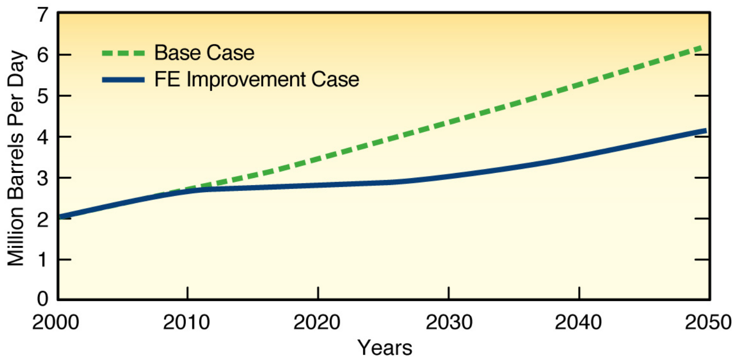

Figure 8. Heavy-duty vehicle oil use.

heavy-duty truck sector would continue to grow, reaching two million barrels per day by 2060.

COMBINED OIL SAVINGS

The combined oil saving potential for light-duty and heavy-duty vehicle technologies being developed by FCVT could range from 4.5 to 5.8 million barrels per day by 2025, depending on whether the transition of conventional HEV technologies to fuel cell vehicles begins early or later.

GREENHOUSE GAS EMISSIONS

Upstream emissions (well-to–pump, or WTP) that occur in the production and distribution of fuels may be as important as vehicle emissions (pump-to–wheel). Gasoline and diesel HEVs may have considerable greenhouse gas (GHG) benefits, as illustrated in Figure 9. On a per-vehicle basis, and examining the total energy cycle using the GREET (Greenhouse gas, Regulated Emissions, and Energy use in Transportation) model, hybridization can reduce GHG emissions by nearly 50% compared with conventional vehicles, providing environmental benefits prior to a transition to fuel cell vehicles operating on hydrogen.[4] Fuel cell vehicles operating on hydrogen have no GHG emissions from the vehicle, but the upstream (WTP) emissions vary considerably by pathway. The fuel economy improvements achieved by heavy-duty vehicles will also contribute to a reduction in GHG emissions, as carbon emissions are directly related to fuel economy for petroleum fuels.

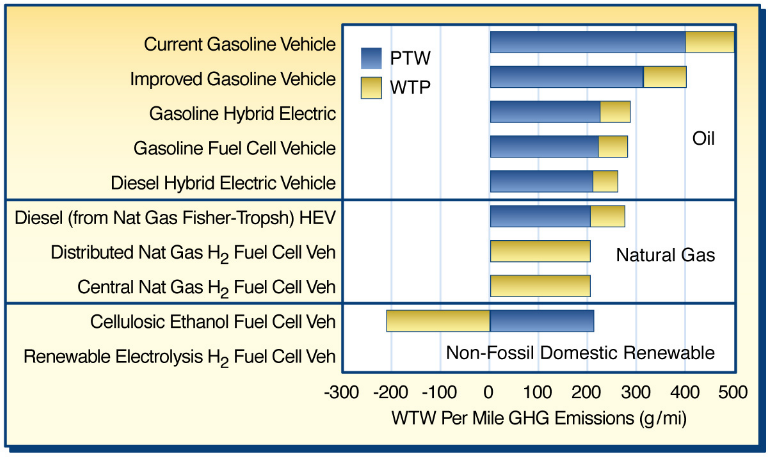

Figure 9. Comparative vehicle technologies: Well-to-wheel greenhouse gas emissions.

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[4] Wang, M. Q., *Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies*, ANL/ESD/TM-163, Argonne National Laboratory, June 2001.

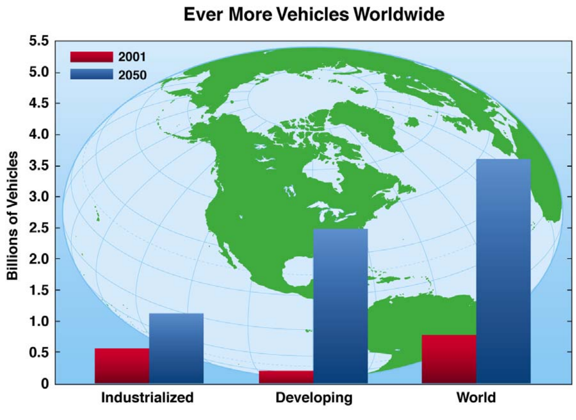
3. Goals

The mission, vision, and goals of the FreedomCAR and Vehicle Technologies (FCVT) Program, covered in this section, are consistent with the National Energy Policy, the DOE Annual Performance Plan, and the Energy Efficiency and Renewable Energy Strategic Plan. This section also provides an examination of the energy, environmental, and economic drivers for the Office of FCVT portfolio of technology R&D activities and a discussion of the Office of FCVT implementation strategy.

NATIONAL ENERGY, ENVIRONMENTAL, AND ECONOMIC DRIVERS

The United States faces major challenges in meeting the ever-increasing demand for transportation goods and services while striving also to minimize adverse energy, environmental, and economic impacts. More than 97% of the fuel consumed by the U.S. transportation sector is petroleum-based, and this usage accounts for two-thirds of the nation's total oil consumption. Specific vehicle fuel efficiencies have improved steadily since the 1970s, but increases in population and per capita miles driven, as well as the increased use of sport utility vehicles over cars, have more than offset these gains. The outcome has been an overall increase in consumption of petroleum for transportation. With the demand for petroleum products growing at more than 1.6% per year, and domestic crude oil production declining by about 0.4% per year, the Energy Information Administration (EIA) predicts that the share of petroleum consumption met by net imports will rise to 73% by the year 2025. The EIA also forecasts that by 2010, one-third of the oil traded on the international market will come from the Persian Gulf, a region characterized by continued political instability.

In addition to a growing demand for petroleum in the United States, worldwide demand for petroleum has grown steadily during the 1900s. Globally, petroleum demand for 2025 is expected to reach 123 million barrels per day, compared with 77 million barrels per day in 2000, an annualized growth rate of about 2% per year. Rapid growth among developing nations means global competition for the world's petroleum. The potential for economic and environmental instability associated with petroleum consumption continues to grow, as indicated by the projected growth of worldwide vehicle registrations. In 2000, total motor vehicle registrations worldwide numbered 701 million. Between 2000 and 2050, motor vehicle registrations could easily grow from 700 million to 3 or 4 billion (Figure 10). Industrialized countries could experience a



Source: EE Analytic Team

Figure 10. Motor vehicle registration growth.

doubling of vehicle registrations, but most future growth in the vehicle market will come in developing countries.

The implication of rapid growth in petroleum demand coupled with declining oil resources is that we need to begin introducing more-efficient vehicles soon, if not now, to avoid consequences similar to the economic impacts of the oil shortages of the 1970s and subsequent price shocks generated by the actions of the Organization of Petroleum-Exporting Countries. Every major oil price shock of the last 30 years was followed by a recession, and every major recession was preceded by an oil shock. The total cost of our oil dependence since 1970 is estimated at $7 trillion (in 1998 dollars). In addition to the economic costs, oil dependence imposes military costs (estimated by the General Accounting Office at $33 billion per year) and political costs, because the need to have access to oil potentially involves conflicts with other national objectives.

About 90 million Americans live in areas with poor air quality, according to the Environmental Protection Agency. The American Lung Association estimates that health problems due to air pollution cost Americans more than $50 billion annually. Automobile emissions are a key contributor to air pollution.

There is also continuing concern about poor air quality and levels of greenhouse gases. In October 1999, the U.S. Environmental Protection Agency reported that about 90 million Americans live in areas that do not meet the National Ambient Air Quality Standards. The American Lung Association estimated in 1988 that Americans spent $50 billion annually on health care to treat problems resulting from air pollution. (The Association is currently updating this estimate and has indicated that the cost today is considerably higher, not only because of rising health care costs but also because of dramatically improved understanding of the impacts particulate emissions have on the human body.) The concentration of carbon dioxide in the air is 25% higher than it was before industrialization, an increase that is directly related to increased energy use. Increases in atmospheric concentrations of greenhouse gases are likely to alter the earth's climate, although scientists do not agree on the timing and nature of potential climate changes or on the scope and severity of the problems associated with a changing climate.

Another issue is the increasing global market competition in the transportation sector. Other countries with automobile industries (most notably Japan and the European nations) have committed substantial public funds to support advanced automotive research in partnership with their domestic manufacturers. All indicators suggest a long-term commitment by these governments to the development and production of advanced vehicles for both the domestic and the export markets. The emerging economies of Asia, Latin America, and Eastern

Europe, where much of the future growth in the automotive market is expected, are becoming a competitive battleground for the global automotive industry. These markets are expected to be particularly receptive to cost-competitive advanced vehicles with high fuel economy and low emissions.

NATIONAL ENERGY POLICY

The DOE and EERE support the basic principles set forth by the National Energy Policy, more specifically, the second principle of three, which is stated as follows:

> *The Policy will advance new, environmentally friendly technologies to increase energy supplies and encourage cleaner, more efficient energy use.*

DOE MISSION

The DOE mission includes several elements; most notably for the EERE and FCVT efforts, the mission includes this element:

> *Foster a secure and reliable energy system that is environmentally and economically sustainable.*

EERE MISSION, VISION, AND STRATEGIC GOALS

In support of the DOE mission, and as stated in the EERE Strategic Plan, the EERE mission is to

> *Strengthen America's energy security, environmental quality, and economic vitality through public-private partnerships that*

- Enhance energy efficiency and productivity;
- Bring clean, reliable, and affordable energy production and delivery technologies to the marketplace; and
- Make a difference in the everyday lives of Americans by enhancing their energy choices and their quality of life.

The EERE Vision, as stated in the EERE Strategic Plan, is

> *A prosperous future where energy is clean, abundant, reliable, and affordable.*

And, it continues, specifically applicable to the FCVT Program, an energy future where

> *... Our cars and trucks will be more efficient and will be powered by a variety of clean domestic fuels and technologies that free the U.S. from dependence on foreign supplies of energy.*

The FCVT Program most directly supports the general goal to "enhance energy security by developing technologies that foster a diverse supply of affordable and environmentally sound energy, improving energy efficiency, providing for reliable delivery of energy, exploring advanced technologies that make a fundamental change in our mix of energy options, and guarding against energy emergencies."

Goal 1 of the nine EERE strategic goals delineated in the EERE Strategic Plan provides the basis for the FCVT Program.

> *Goal 1. Dramatically Reduce, or Even End, Dependence on Foreign Oil.*

FCVT VISION

The vision for the FCVT Program is that, ultimately:

> *Transportation energy security will be achieved through a U.S. highway vehicle fleet of affordable, full-function cars and trucks that are free from petroleum dependence and harmful emissions without sacrificing mobility, safety, and vehicle choice*

FCVT MISSION AND GOALS

As set forth in the EERE Strategic Plan, the mission of the FCVT Program is to

> *Develop more energy-efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum.*

With this mission, the general FCVT Program goal is to

> *Develop technologies that enable cars and trucks to become highly efficient, through improved power technologies and cleaner domestic fuels, and to be cost and performance competitive. Manufacturers and consumers will then use these technologies to help the nation reduce both energy use and greenhouse gas emissions, thus improving energy security by dramatically reducing dependence on foreign oil.*

The long-term aim is to develop "leapfrog" technologies that will provide Americans with greater freedom of mobility and energy security, with lower costs and lower impacts on the environment. To accomplish the mission, the FCVT Program includes promoting the development of fuel-efficient motor vehicles and trucks, researching options for using cleaner fuels, and implementing programs to improve energy efficiency. In collaboration with industry, research entities, universities, state governments, and other federal agencies, the FCVT Program supports R&D of advanced vehicle technologies and fuels that could dramatically reduce, and eventually eliminate, the demand for petroleum, decrease emission of criteria air pollutants and greenhouse gases, and enable the U.S. transportation industry to sustain a strong, competitive position in domestic and world markets. These collaborations facilitate the coordination of activities and attract cost sharing to provide leveraged benefits for the American taxpayer. The program focuses its technology development investments specifically on areas that would not be pursued by industry alone because of high risks and uncertain or long-term outcomes.

Program implementation includes research, development, demonstration, testing, technology validation, technology transfer, and education. Work is aimed at developing technologies that could achieve (1) significant improvements in vehicle fuel efficiency and (2) displacement of oil by other fuels that ultimately can be domestically produced in a clean and cost-competitive manner. It is focused on technologies to reduce oil use by highway vehicles such as cars, light trucks, and heavy vehicles (comprising medium and heavy trucks, and buses). Off-highway vehicles (such as vehicles used in construction, mining, and agriculture) and locomotives may benefit from this research because they use engines that are similar to those in heavy-duty trucks. As detailed in the Introduction to this plan, the FCVT supports, and works through, three major partnerships with the following goals:

> *The long-term goal of the FreedomCAR Partnership is to enable the full spectrum of light-duty passenger vehicle classes to operate completely free of petroleum and free of harmful emissions while sustaining the driving public's freedom of mobility and freedom of vehicle choice.*
>
> *To address the R&D needs of commercial vehicles, the ultimate goal of the 21st Century Truck Partnership is to dramatically improve the energy efficiency and safety of trucks and buses, while maintaining a dedicated concern for the environment. The vision of the Partnership is for our nation's truck and buses to safely and cost-effectively move larger volumes of freight and greater numbers of passengers while emitting little or no pollution and dramatically reducing the dependence on foreign oil.*
>
> *The Presidential FreedomCAR and Hydrogen Fuel Initiative is to develop technologies for (1) fuel-efficient motor vehicles and trucks, (2) producing cleaner fuels, (3) implementing programs to improve energy efficiency, and (4) a hydrogen production and distribution infrastructure needed to power fuel cell vehicles and stationary fuel cells.*

The FCVT Program plays a prominent role in the FreedomCAR Partnership by conducting R&D to achieve the nearer-term goals of the Partnership through continued development of advanced technologies that will dramatically reduce the fuel consumption and emissions of all petroleum-fueled, light-duty personal vehicle classes. Achieving these goals is paramount to providing the necessary technologies for fuel cell hybrid-electric vehicles and achievement of the long-term goal. The FreedomCAR partners have identified nine challenging high-level technical goals for government and industry R&D efforts. The FCVT Program has exclusive responsibility for four of these goals and shares one with the Hydrogen, Fuel Cells, and Infrastructure Technologies Program:

- Electric Propulsion Systems with a 15-year life capable of delivering at least 55 kW for 18 seconds and 30 kW continuous at a system cost of $12/kW peak.
- Internal Combustion Engine Powertrain Systems costing $30/kW, having a peak brake engine efficiency of 45%, that meet or exceed emissions standards.
- Electric Drivetrain Energy Storage with 15-year life at 300 Wh with discharge power of 25 kW for 18 seconds and $20/kW.
- Material and Manufacturing Technologies for high-volume production vehicles that enable/support the simultaneous attainment of a 50% reduction in the

weight of vehicle structure and subsystems, affordability, and increased use of recyclable/renewable materials.

- Internal Combustion Engine Powertrain Systems operating on hydrogen with a cost target of $45/kW by 2010 and $30/kW in 2015, having a peak brake engine efficiency of 45%, that meet or exceed emissions standards (shared responsibility).

Development of technologies to achieve these goals applies to purposes 1, 2, and 3 of the Presidential FreedomCAR and Hydrogen Fuel Initiative.

In addition to working on technologies for light-duty passenger vehicles, the FCVT Program addresses R&D of technologies for commercial vehicles through the 21st Century Truck Partnership. The FCVT Program has the responsibility for 21st Century Truck Partnership management and for conducting and supporting the R&D necessary to meet the Partnership goals. Specific technology goals have been defined in five critical areas that will reduce fuel usage and emissions while increasing heavy vehicle safety. The Partnership supports research, development and demonstration to enable achieving these goals with commercially viable products and systems.

Engine Systems

- 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 that will achieve a stretch thermal efficiency goal of 55% in prototype engine systems in 2012.
- Develop new diesel fuel formulation specifications, which include the use of renewables and other non-petroleum based blending agents, that enable achieving high-efficiency and low-emission goals while displacing petroleum fuels by 5% by 2010.

Heavy-Duty Hybrids

Specific 2012 technology goals are

- Develop a drive unit that has 15 years of characteristic life and costs no more than $50/kW peak electric power rating.
- Develop an energy storage system with 15 years of characteristic life that costs no more than $25/kW peak electric power rating.
- 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

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

- Develop and demonstrate a 5-kW, $200/kW, diesel-fueled internal combustion engine auxiliary power unit (APU) by 2007.
- Develop and demonstrate a fuel cell APU system in the 5 to 30-kW range, capable of operating on diesel fuel, at a delivered cost of $400/kW by 2012.
- Develop consistent electrical codes and standards that apply to both truck (on-board) and truck stop (stationary) electrification technologies, to enable the introduction of new idle reduction technologies.

Safety

- Contribute to reducing truck related fatalities by 50% and truck-related injuries by 20% by 2012, relative to 1996, through the development and implementation of technologies in crashworthiness and crash protection.
- Achieve occupant survivability for vehicle collisions at the front, rear, and sides for differential speeds of up to 35 mph between heavy vehicles and other typical light mid-size vehicles (weight <4000 lb).
- Develop and implement advanced technologies for braking, rollover protection, visibility enhancement, and safety of tires needed to achieve the following performance for crash avoidance:

  Braking: One-third reduction in stopping distances at operational speeds.

  Roll-over: Maintain vehicle stability without exceeding static roll-over thresholds.

  Visibility: Full operator visibility (360°) with no blind spots anytime, anywhere, and on any side of the heavy vehicle for the operator, and increased on-road recognition of trucks by other vehicles.

The FCVT Program supports the development and validation of technologies to achieve all of the goals. The following six priority goals have been determined through discussion with partners and through internal government deliberation (for example, between DOE and the Office of Management and Budget):

Heavy Vehicle Systems

Develop technologies that reduce parasitic energy losses, including losses from aerodynamic drag and ancillary systems, from 39% of total engine output in 1998 to 24% in 2006.

Materials Technologies

Reduce the weight of an unloaded tractor-trailer combination from 23,000 pounds in 2003 to 18,000 pounds in 2010, a reduction in weight of 22%, thereby increasing heavy truck fuel efficiency.

Hybrid Electric Propulsion

Reduce the production cost of a high-power 25-kW battery for use in light-duty vehicles from $3000 in 1998 to $500 in 2010, with an intermediate goal of $750 in 2006 that would enable cost-effective entry of hybrid vehicles. (This will be measured as the cost per 25-kW battery system, estimated for a production level of 100,000 battery systems per year.)

Advanced Combustion Engine R&D

Improve the efficiency of internal combustion engines from 30% (2002 baseline) to 45% by 2010 for light–duty applications and from 40% (2002 baseline) to 55% by 2012 for heavy-duty applications while meeting cost, durability, and emissions constraints, and while using an advanced fuel formulation that incorporates a non–petroleum-based blending agent to reduce petroleum dependence and enhance combustion efficiency.

Materials Technologies

Reduce the production cost of carbon fiber from $12 per pound in 1998 to $3 per pound in 2006.

Fuels Technologies

Develop a specification by 2007 for a fuel formulation that incorporates the use of a non–petroleum-based blending agent enabling a 5% diesel fuel replacement in 2010.

These have been used to formulate performance measures to allow continual assessment of progress as delineated in Section 5, which covers management of this program. The FCVT Program is divided into key activities and sub-activities to parallel technology areas, as shown in Section 4; and each activity section gives a further breakout of technology-specific goals and technical targets necessary to achieve the goals, along with the necessary tasks and important milestones.

4. Technical Plan

The FreedomCAR and Vehicle Technologies (FCVT) Program develops technology for near- and vs. automotive and truck fuel economy improvements and emissions reduction while aiding the transition to a hydrogen-based transportation system with advanced vehicle and propulsion technology. The *FCVT Multi-Year Program Plan* describes the activities of the Office of FCVT and the products that contribute to the goals of DOE, as well as the joint government-industry research efforts. Figure 11 lists the sections of the plan, which correspond to activities in FCVT, and the advanced technology products targeting the goals of DOE/EERE/FCVT, FreedomCAR, and the 21st Century Truck Partnership.

The plan identifies the goals of each of the activities; the status and approach, including targets versus current status; barriers that must be overcome to meet the targets; associated research task descriptions; and milestones to signify progress. Critical decision points are identified for the activities in the plan, i.e., whether research should be continued, refocused, or discontinued based on technical achievements to that point in time. Various risk analysis tools are being analyzed to assist with these critical decision points.

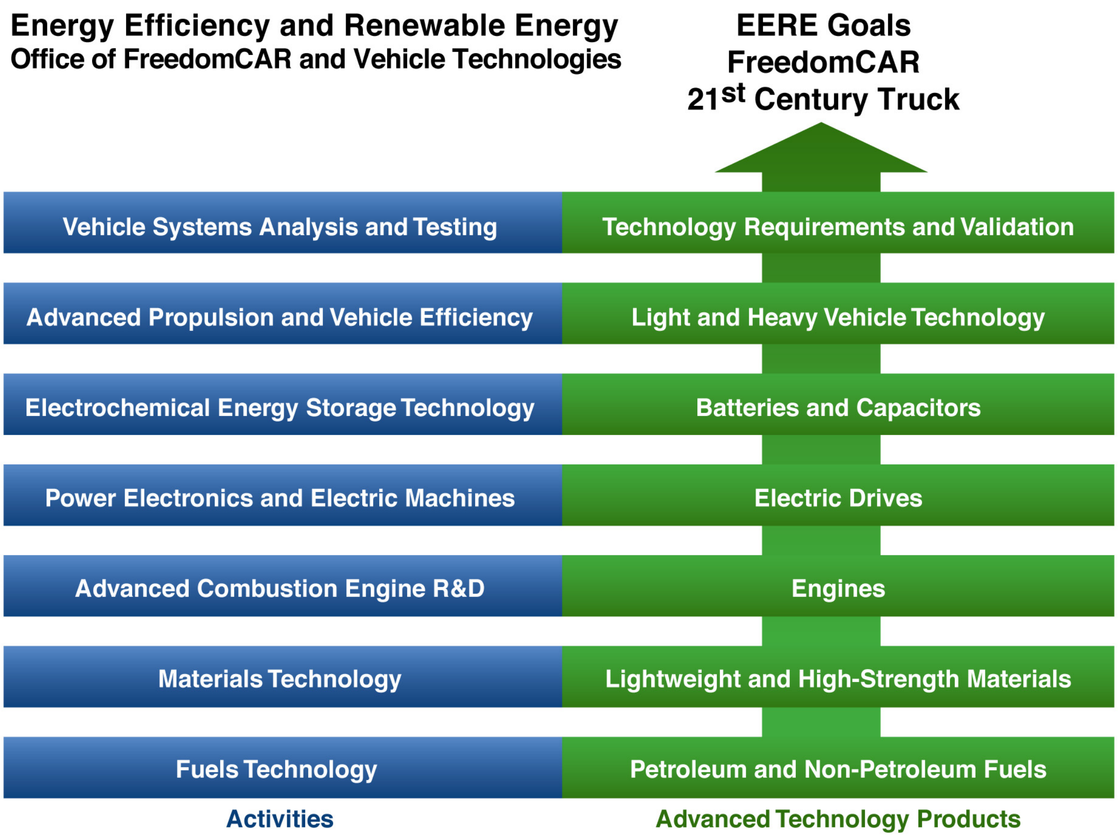


Figure 11. Sections of the plan, corresponding to FCVT activities and advanced technology products.

Since the long-term success of the FCVT Program depends on the success of the transportation-related technology development activities of the Hydrogen, Fuel Cells, and Infrastructure Technologies Program (HFCIT), collaborative activities are identified to ensure successful propulsion system/vehicle integration and validation.

4.1 VEHICLE SYSTEMS ANALYSIS AND TESTING

The role of this activity is to provide an overarching vehicle systems perspective to the technology R&D activities of DOE's FCVT and HFCIT Programs. As depicted in Figure 12, this activity uses analytical and empirical tools to model and simulate potential vehicle systems, validate component performance in a systems context, benchmark emerging technology, and validate computer models. Extensive collaboration with the technology development activities in FCVT, as well as HFCIT, is required in both analysis and testing for this activity to be successful. The analytical results of this activity are used to estimate the national benefits and/or impacts of DOE-sponsored technology development.

Goals

Use an integrated systems approach to develop, maintain, and employ analytical tools, techniques, and test facilities to benchmark emerging

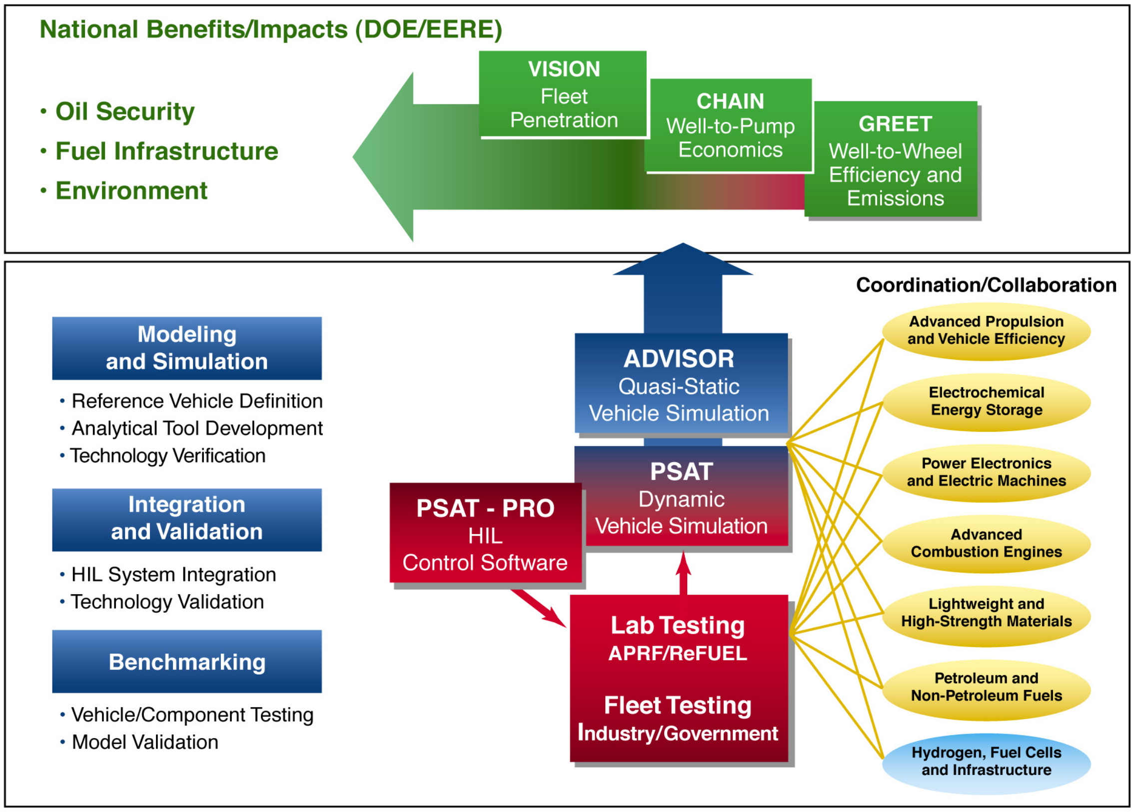


Figure 12. Analytical and empirical tools used to model and validate vehicle components and systems and benchmark emerging technology.

technologies and support the development and validation of DOE-sponsored technologies in a vehicle systems context.

Programmatic Status

A unique set of tools has been developed and maintained by the Vehicle Systems Analysis and Testing activity to support the FCVT Program. The tools depicted in Figure 12 are described in the following paragraphs. VISION, CHAIN, and GREET are used to forecast national-level energy and environmental parameters including oil use, infrastructure economics, and greenhouse gas contributions of new technologies, based on FCVT vehicle-level simulations that predict fuel economy and emissions using ADVISOR or PSAT. Dynamic simulation models (i.e., PSAT) are combined with DOE's specialized equipment and facilities to validate DOE-sponsored technologies in a vehicle context (i.e., PSAT-PRO control code and real components in a virtual vehicle test environment). The Advanced Powertrain Research Facility (APRF) and the Renewable Fuels and Lubricants Facility (ReFUEL) are used to test light-/medium- and heavy-duty vehicles (operating on a variety of liquid and gaseous fuels), propulsion systems, and components in controlled environments to acquire scientific data. Fleet tests are used to assess the functionality of technology in the less-predictable real-world environment. Modeling and testing tasks are closely coordinated to enhance and validate models as well as ensure that test procedures and protocols comprehend the needs of coming technologies.

ADVISOR (ADvanced Vehicle SimulatOR) is used to understand trends and preliminary vehicle design through quasi-static analysis of component performance and efficiency characteristics to estimate fuel economy. Vehicle power demand on the road is used to calculate the demand on propulsion system components and their resulting characteristics each second (using static component map data); these values are summed to produce overall results for a driving cycle (commonly referred to as "backward-facing" simulation). This architecture is suitable for quick evaluation of multiple scenarios due to fast runs. Capabilities include component selection and sizing (conventional, hybrid, and fuel cell vehicles), energy management strategies, optimization, and target development.

PSAT (Powertrain Systems Analysis Toolkit) allows dynamic analysis of vehicle performance and efficiency to support detailed design, hardware development, and validation. A driver model attempts to follow a driving cycle, sending a power demand to the vehicle controller which, in turn, sends a demand to the propulsion components (commonly referred to as "forward-facing" simulation). Dynamic component models react to the demand (using transient equation-based models) and feed back their status to the controller, and the process iterates on a sub-second basis to achieve the desired result (similar to the operation of a real vehicle). The forward architecture is suitable for detailed analysis of vehicles/propulsion systems and the realistic command-control-feedback capability is directly translatable to PSAT-PRO control software for testing in the laboratory. Capabilities include transient performance, efficiency and emissions (conventional, hybrid, and fuel cell vehicles), optimization of control strategies, and identification of transient control requirements.

PSAT-PRO (PSAT rapid control PROtotyping software) allows dynamic control of components and subsystems in hardware-in-the-loop (HIL) testing. Real components are controlled in an emulated vehicle environment (i.e., a controlled dynamometer and driveline components) according to the control strategy, control signals, and feedback of the components and vehicle as determined using PSAT. The combination of PSAT-PRO and HIL is suitable for propulsion system integration and control system development as well as rigorous validation of control strategies, components, or subsystems in a vehicle context (without building a vehicle). Capabilities include transient component, subsystem, and dynamometer control with hardware operational safeguards compatible with standard control systems.

Laboratory testing applies state-of-the-art facilities to support the development of detailed technology integration requirements, validate DOE-sponsored technologies, and measure, within a vehicle systems context, progress toward FCVT technical targets. In addition, lab tests benchmark components and vehicles to validate models, supports technical target setting, and provides data to help guide technology development tasks. Descriptions of the heavy-duty ReFUEL and the light-/medium-duty APRF are in Appendixes B and E, respectively.

Operational and fleet testing evaluates vehicles in real-world applications to measure progress toward FCVT technical targets and disseminate accurate, unbiased information to potential vehicle users, DOE, industry technology developers and vehicle modeling tasks. The scope includes vehicles that use DOE-sponsored technology or technologies of particular interest to FCVT (i.e., hybrids and internal combustion engine vehicles fueled with hydrogen and other gaseous/liquid fuels), as well as the related fueling infrastructure. Capabilities include measuring performance, costs, fuel consumption, in-use maintenance requirements, and operational characteristics. The execution of these tasks occurs under cost-shared agreements with industrial partners such as electric utilities and automotive companies. Test sites may include utility or government locations where fleet vehicles are used and maintained. National laboratories provide data acquisition, analysis, reporting, and management support.

Approach

Vehicle Systems Analysis and Testing will develop, maintain, and use advanced analytical tools, techniques, and test facilities to (1) provide guidance to the technology development activities and (2) validate the performance of DOE-sponsored technologies in the context of complete vehicle systems.

Task Descriptions

The sub-activities and associated tasks are described in the following paragraphs. Each sub-activity will involve extensive coordination and/or collaboration with the FCVT Program technology development activities and those HFCIT Program activities that address transportation technology.

Modeling and Simulation

Reference vehicle definition—Develop attributes and specifications for a portfolio of hypothetical “reference vehicles” that represent the spectrum of vehicles addressed by the FCVT and HFCIT programs.

Analytical tool development—Develop and maintain computer models and analytical tools that will enable simulation of the component technologies and reference vehicles. The tools will comprehend the technology development direction, as well as the needs of the industry partners, of both FCVT and HFCIT.

Technology verification—Incorporate component and subsystem models in the reference vehicles and conduct vehicle simulations to ensure compatibility with potential propulsion/vehicle configurations.

Integration and Validation

HIL system integration—Integrate and test DOE-sponsored experimental component/subsystem hardware in an emulated vehicle environment with realistic control system interfaces and interactions. PSAT-PRO will be used to optimize propulsion system control, leading to refined performance and control requirements to feed back to DOE technology developers and industry partners.

Technology validation—Validate, within a vehicle systems context, that the technologies developed by the FCVT and HFCIT programs meet their technical targets and are suitable for vehicle applications.

Benchmarking

Vehicle/component testing—Test and analyze emerging technologies obtained from worldwide sources other than the FCVT and HFCIT programs, using laboratory facilities and field testing. The results will be distributed to DOE and industry partners to support (re)assessment of the content and targets of R&D activities.

Model validation—Use test data to validate the accuracy of the vehicle and component computer models, including overall measures (e.g., fuel economy and state-of-charge of energy storage devices over a driving cycle) as well as transient component behavior (e.g., fuel rate and torque).

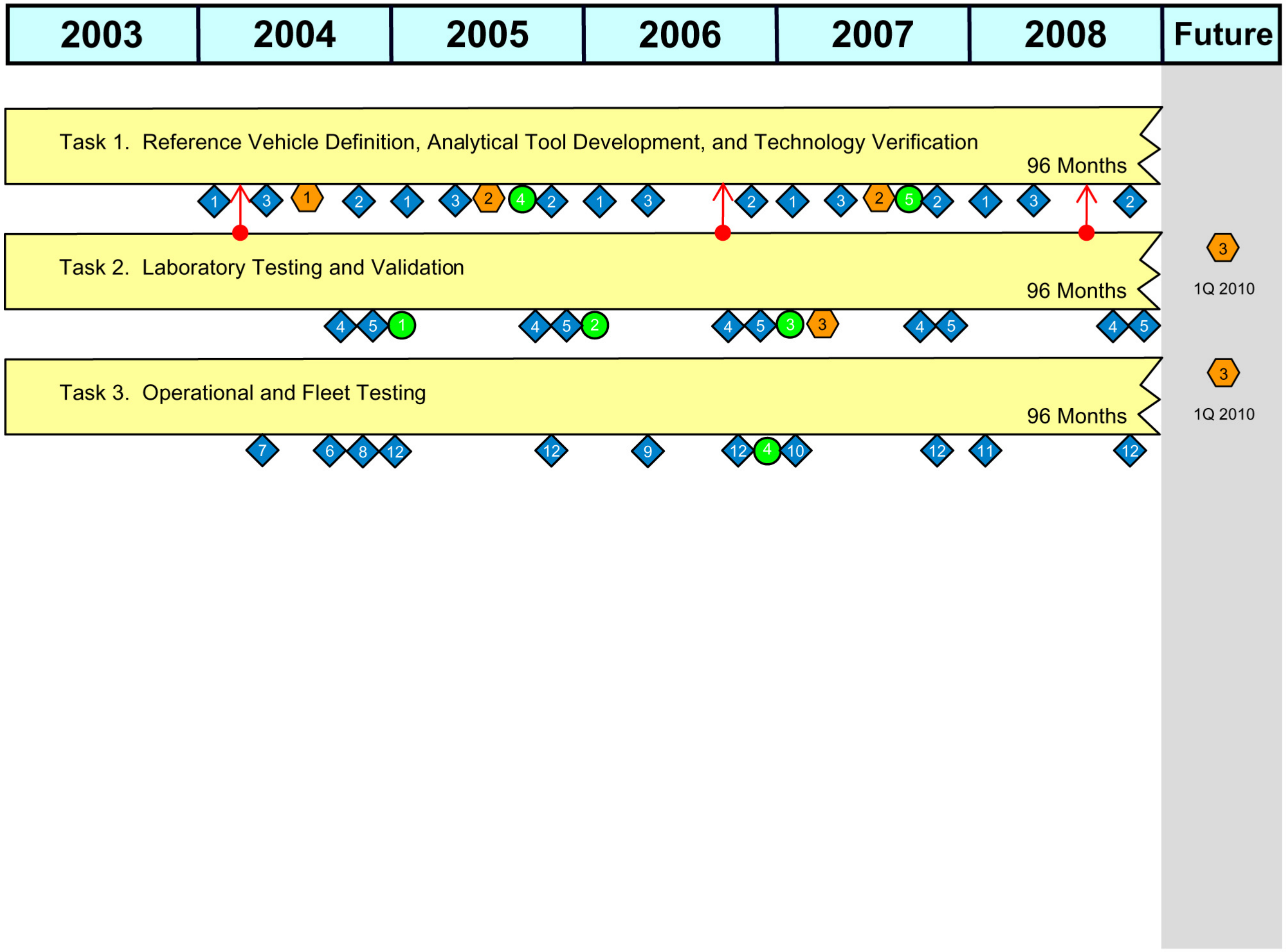
Vehicle Systems Analysis and Testing is a support activity conducted on a continuous basis, with software and hardware tasks refined annually, as shown in Table 1.

Table 1. Vehicle Systems Analysis and Testing tasks

Task	Title	Duration
1a	Reference Vehicle Definition	1 month (per annum)
1b	Analytical Tool Development	96 months (with annual updates)
1c	Technology Verification	As required (i.e., new initiatives or technology introductions)
2a	HIL System Integration	96 months (revised annually)
2b	Technology Validation	96 months (revised annually)
3a	Vehicle/Component Testing	96 months (revised annually)
3b	Model Validation	96 months (revised annually)

Milestones

Milestones cannot be precisely defined because this activity is dependent on the availability of data/models and experimental hardware from other FCVT and HFCIT technology development activities, as well as the availability of technologies from worldwide sources. Therefore, the milestone schedule reflects annual updates and is subject to annual revision. Milestones for Vehicle Systems Analysis and Testing are shown in the following network chart.



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Milestone

1. Specification of representative vehicle platforms
2. Simulation software release
3. Verification of DOE-sponsored technologies
4. HIL system integration and hardware studies
5. DOE-sponsored component validation
6. MY04 Toyota Prius benchmarking
7. Hydrogen/highly compressed natural gas vehicle testing
8. Orion compressed natural gas/electric hybrid bus testing
9. Technical and economic evaluation of advanced propulsion system Hydrogen Fueling Pilot Plant
10. Hybrid electric transit bus testing
11. Hydrogen fuel cell vehicle testing
12. Model validation

Technology Program Output

1. Technical targets for advanced technology components and subsystems
2. Revised targets for advanced technology components and subsystems
3. Validated technologies to industry

Supporting Input

1. Light Vehicle propulsion subsystem components for vehicle—level integration and testing using HIL
2. Semiconductor motor-controller for validation
3. 42V/12V DC-DC converter for validation
4. Fuel cell subsystem for integration and testing in 5 kW APU
5. Engine + aftertreatment R&D results from Combustion and Emission Control R&D

4.2 ADVANCED PROPULSION AND VEHICLE EFFICIENCY IMPROVEMENTS

The Advanced Propulsion and Vehicle Efficiency Improvements activity has the vision of improving vehicle fuel economy while meeting future emissions regulations. Figure 13 shows the light-duty and heavy-duty vehicle sub-activities and technology outputs for this activity and the collaboration between this activity and others. Development technologies for both light and heavy vehicles focus on increasing propulsion system efficiency, improving vehicle energy management and utilization, and decreasing parasitic losses. However, vehicle usage patterns, technical requirements, and commercial markets differ substantially; and the technologies have different industry partners. Hence light- and heavy-duty technology development are presented separately. A common thread running through all light- and heavy-duty technology development is the requirement to view and design for the overall vehicle system to capture the system efficiency and energy management gains possible.

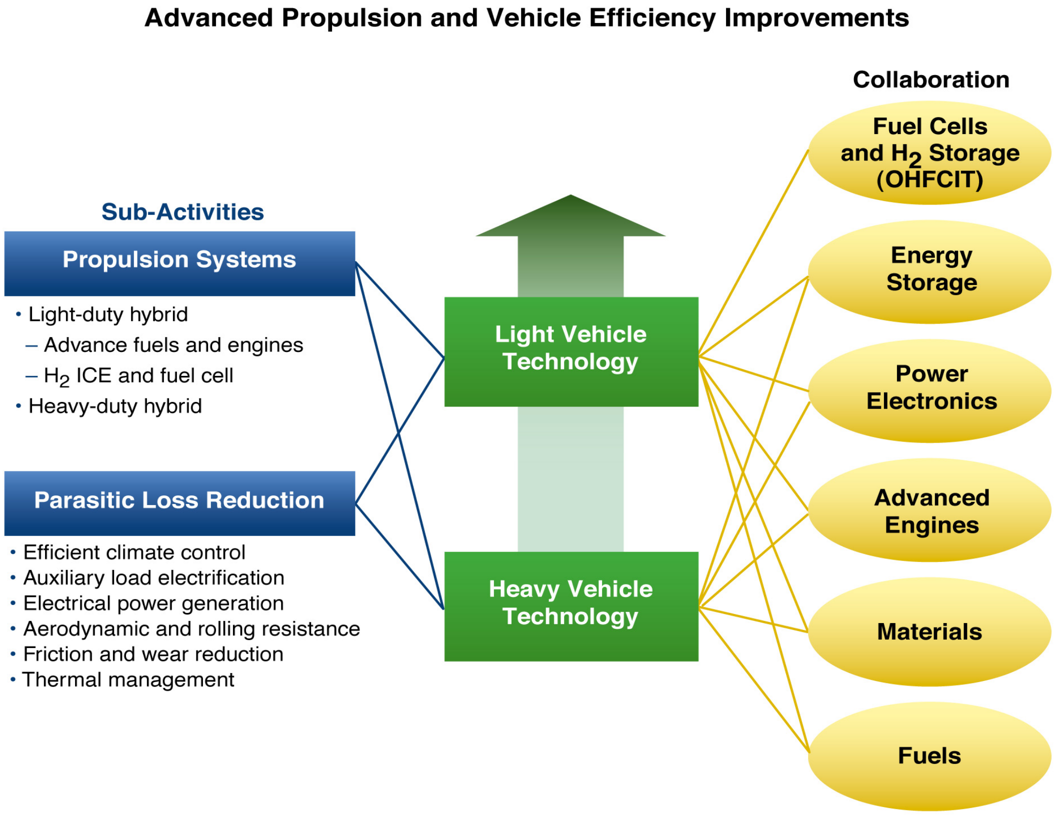


Figure 13. Light-duty and heavy-duty vehicle sub-activities and technology outputs and collaboration between this and other activities.

4.2.1 Light Hybrid Propulsion Systems

Goals

Integrate and develop propulsion system technology developed by DOE and industry partners to achieve the technical targets of the FreedomCAR Program and support the transition to hydrogen technology.

Programmatic Status

Advanced propulsion system development in FCVT has focused on hybrid technology and conventional fuels. The demonstrated fuel economy improvements and the experience gained in this sub-activity were factors in decisions by DOE's automotive industry partners to introduce production hybrid vehicles by 2004. DOE's analytical and testing capabilities at the national laboratories have evolved substantially as well. Candidate technologies can now be analyzed and tested using hardware-in-the-loop (HIL) techniques in virtual vehicle environments (i.e., without building vehicles). This capability is currently being used to understand the relationship between fuel economy, emissions, and control strategy in hybrid propulsion systems to minimize the fuel economy penalty of emissions control.

Targets

- By 2010, develop an internal combustion engine (ICE) powertrain system with peak brake efficiency of 45% that is estimated to cost $30/kW.
- By 2010 and 2015, develop hydrogen ICE powertrain systems with peak brake efficiency of 45% that are estimated to cost $45/kW and $30/kW, respectively.

Integrate and test the fuel and propulsion system combinations in the FCVT hydrogen technology transition concept (as the technology becomes available) to quantify the potential contributions to DOE/EERE goals:

- Diesel fuel, ICE hybrid with advanced power electronics and energy storage
- Hydrogen-enhanced fuel, advanced ICE hybrid
- Hydrogen fuel, advanced ICE hybrid
- Hydrogen fuel, fuel cell hybrid

As Figure 14 implies, achieving targets for an integrated system depends on receiving subsystems from FCVT technology development areas (represented by the diagrams and detailed in Sections 4.2–4.7) and, sometime in the future, receiving fuel cell-and hydrogen-related subsystems from HFCIT or DOE subcontractors.

Barriers

Technical barriers for components/subsystems are listed in the appropriate sections. The barriers presented here are system-level issues that cannot be addressed solely by analysis.

A. Powertrain system emissions due to engine warm-up and transient demands.
B. Determination of fuel cell system interface, hydrogen fueling, and storage requirements without fuel cell system components.
C. Undefined research protocols and standards for advanced propulsion systems/fuels.

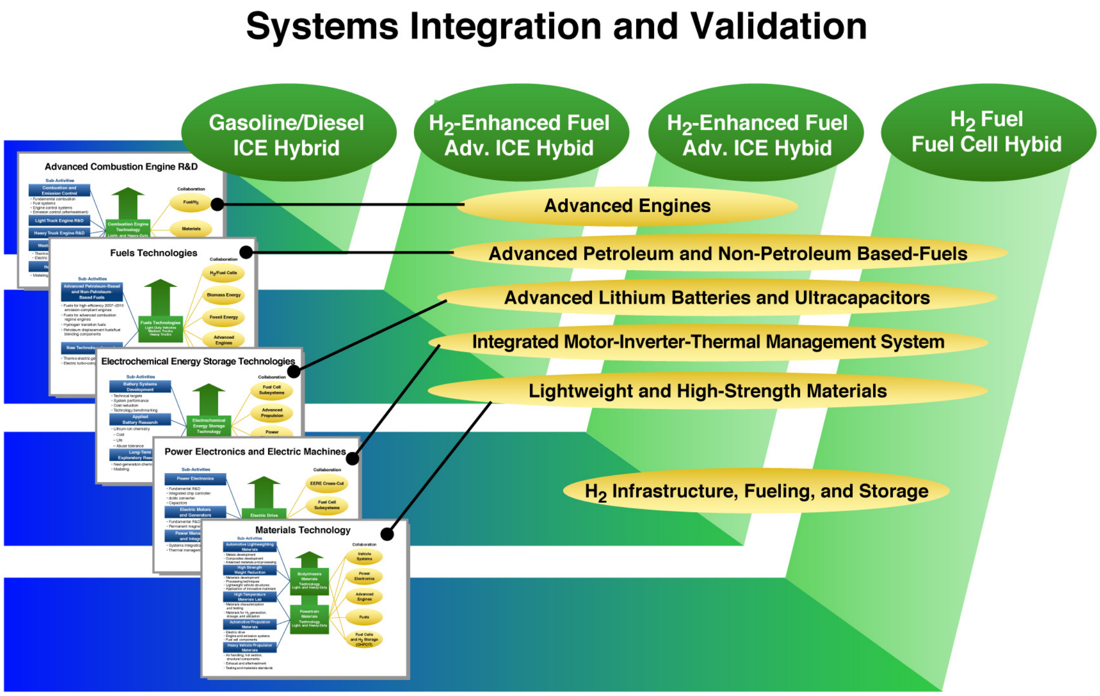


Figure 14. Reaching targets for an integrated system depends on receiving subsystems from FCVT development areas and HFCIT and from subcontractors.

Approach

The transition to hydrogen vehicle technology requires development of the vehicle components, subsystems, and support systems, as well as the infrastructure. The transition concept described previously suggests combinations of fuels and propulsion systems be explored to get the most out of hybrid propulsion systems and gain experience with hydrogen technology while fuel cells are being developed (briefly described in the following paragraphs). Analysis and testing capabilities and procedures at the national laboratories will be enhanced to comprehend these fuels and powertrains, including simulation tools, component/subsystem integration, and HIL testing, as well as vehicle-level validation of DOE-sponsored hardware development.

Gasoline/diesel fuel, ICE hybrid—Apply DOE-sponsored advancements in power electronics, energy storage, aftertreatment, and control to improve efficiency and minimize the emissions control penalty.

Hydrogen-enhanced fuel, advanced ICE hybrid—Find fuel formulations to increase hydrogen content and find advanced combustion technology to improve hybrid system efficiency and meet emissions requirements.

Hydrogen fuel, advanced ICE hybrid—Assess hydrogen hybrid propulsion potential and support planning/development/implementation of fueling and storage for vehicle applications (with HFCIT).

Hydrogen fuel, fuel cell hybrid—Develop fuel cell hybrid benefits from previous developments in energy storage and electric drive technologies, as well as hydrogen infrastructure planning/development (with HFCIT).

Task Descriptions

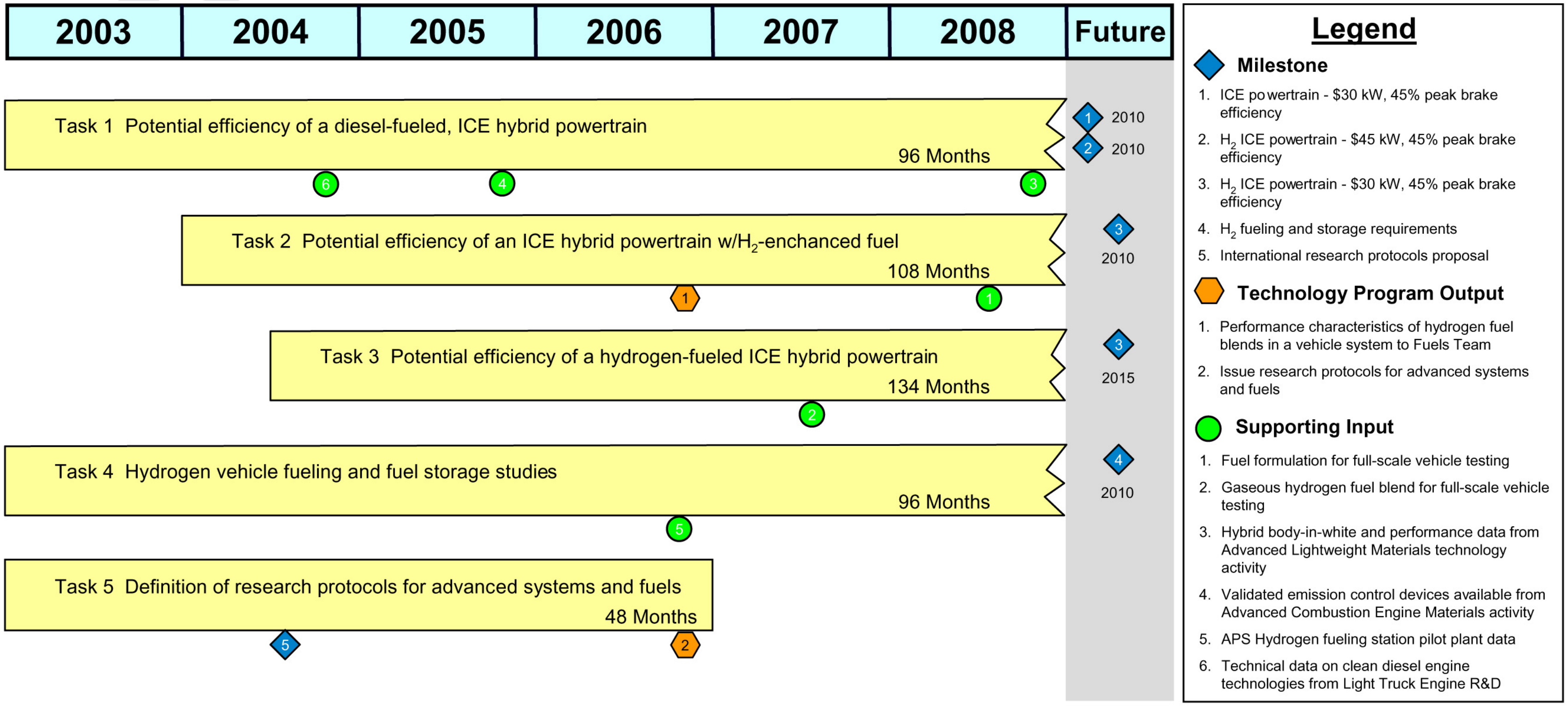
A description of the task, along with the estimated duration and barriers associated with the task, is provided in Table 2.

Table 2. Tasks for Light Hybrid Propulsion Systems

Task	Title	Duration/ barriers
1	Potential efficiency of a diesel-fueled, ICE hybrid powertrain	96 months Barrier A
2	Potential efficiency of an ICE hybrid powertrain w/H_2-enhanced fuel	108 months Barrier A
3	Potential efficiency of a hydrogen-fueled ICE hybrid powertrain	134 months Barrier A
4	Hydrogen vehicle fueling and fuel storage studies	96 months Barrier B
5	Definition of research protocols for advanced systems and fuels	48 months Barrier C

Milestones

The network chart shows milestones for Light Hybrid Propulsion Systems.



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Milestone

1. ICE powertrain - $30 kW, 45% peak brake efficiency
2. H_2 ICE powertrain - $45 kW, 45% peak brake efficiency
3. H_2 ICE powertrain - $30 kW, 45% peak brake efficiency
4. H_2 fueling and storage requirements
5. International research protocols proposal

Technology Program Output

1. Performance characteristics of hydrogen fuel blends in a vehicle system to Fuels Team
2. Issue research protocols for advanced systems and fuels

Supporting Input

1. Fuel formulation for full-scale vehicle testing
2. Gaseous hydrogen fuel blend for full-scale vehicle testing
3. Hybrid body-in-white and performance data from Advanced Lightweight Materials technology activity
4. Validated emission control devices available from Advanced Combustion Engine Materials activity
5. APS Hydrogen fueling station pilot plant data
6. Technical data on clean diesel engine technologies from Light Truck Engine R&D

4.2.2 Heavy Hybrid Propulsion Systems

Goals

Develop and validate heavy hybrid propulsion technologies to support the goals of the 21st CTP.

> 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. Corollary to this is the 2012 technology goal to develop a drive unit that has 15 years of characteristic life and costs no more than $50/kW peak electric power rating.

The following is a goal with intermediate timing:

> Develop cost-effective heavy hybrid components and systems that could contribute to fuel economy improvements of up to 100% by 2008, for multiple vehicle applications, while meeting year 2007 EPA emissions standards.

Full achievement of the goals is critically dependent upon the achievement of goals in other sections of this plan, such as in Section 4.3, to advance the energy storage technology.

Programmatic Status

DOE has awarded three Phase I Advanced Heavy Hybrid Propulsion Systems (AHHPS) subcontracts for R&D on advanced heavy hybrid propulsion components and systems for a range of vehicle applications (Class 3 through 8 trucks and buses).

Hybrid electric propulsion components and systems are highly developed for light-duty vehicles, but the technology requires further development for heavy hybrid vehicle applications. Components for heavy vehicles either do not exist or cost too much because of precision manufacturing and/or low production volumes. In addition, component durability must be substantially improved to meet the typical 10–15 year, 1,000,000-mile lifetime requirement of the heavy vehicle industry.

Modeling, simulation, and optimization for Class 3–8 hybrid vehicles have been limited when compared with efforts for light-duty hybrid vehicles. Component and system-level technical targets are being analyzed and established as part of the AHHPS sub-activity. System-level modeling and optimization tools will require some adaptation to accommodate heavy vehicle components in order to configure propulsion systems and identify control strategies with the potential to meet the heavy vehicle fuel savings goal.

Targets

Preliminary technical targets, shown in Table 3, have been identified by the industry development teams, but they are expected to be modified as detailed analyses are completed and AHHPS developments mature.

Barriers

The technical barriers to achieving AHHPS goals are as follows:

A. **Initial and life-cycle component costs are too high.** Substantial reductions are required to make costs competitive for vehicle commercial viability.

B. **Component and system performance is too low.** Lower component volumes and weight, plus higher component and system efficiency, reliability, and durability are required to produce marketplace-acceptable performance levels that create clear technical and economic benefits.

C. **Heavy hybrid test procedures are not available.** Current protocols and certification procedures rely on engine testing alone and do not adequately address heavy hybrid vehicle propulsion system operation. New heavy hybrid test protocols and procedures are required to validate heavy hybridization technology.

Approach

The three AHHPS industry teams are analyzing a range of heavy hybrid vehicles, including Class 3–8 trucks and buses, to define system architecture, optimize control strategy, and quantify component requirements. Engine subsystems, energy storage, power electronics, controls, and auxiliary power units (APUs) will subsequently be developed to meet the requirements. The teams will also design, integrate, and validate complete vehicle systems using heavy hybrid test procedures and protocols developed within the time frame of the tasks. AHHPS preliminary technology development targets are identified in Table 3, and relevant FCVT targets for R&D coordination are identified in the following text.

Engine technology developed by the Advanced Combustion Engine R&D activity will be leveraged where possible. Particular attention will focus on the interface requirements for hybrid system components (i.e., electric motors and/or generators, energy storage, electric auxiliaries, and control systems). In addition, the need for advanced aftertreatment technology will be determined based on the propulsion system, duty cycle, and 2007 U.S. Environmental Protection Agency (EPA) emissions standards.

The Electrochemical Energy Storage activity conducts R&D for light-duty vehicles that forms the basis for AHHPS targets for improvements in battery life, capacity, power, weight, volume, and cost.

The Advanced Power Electronics and Electric Machines activity for light-duty vehicles provides the technology baseline for AHHPS targets for reductions in component size, weight, and cost, along with increases in power density, system voltage, and reliability. Power electronics control devices with faster semiconductors, advanced dc-to-dc conversion, higher power density, and power dissipation will be required, necessitating advanced thermal management solutions. Improved electric machines (e.g., permanent magnet motors) could enable lighter, more cost-effective systems with higher efficiency and power density compared with induction motors.

Table 3. Advanced Heavy Hybrid Propulsion Systems targets[a]

	Vehicle system	2003	2006	2010
Propulsion				
	Peak specific power (kW/kg)	0.6	0.8	0.8
	Weight (kg/kW)	1.67	1.25	1.25
	Volume (m^3/W)	0.375	0.3	0.3
	Cost ($/kW)	25	20	20
	Engine			
	Power (kW)	135–400	127–225	TBD
	Brake thermal efficiency	42%	45%	50%
	Specific power (kW/kg)	TBD	TBD	TBD
Energy Storage				
	Discharge power (kW)	25–75	50–150	50–150
	Weight (kg/kW)	1.5	1.0	1.0
	Volume (m^3/kW)	0.00175	0.00175	0.00175
	Cost ($)	2500	1000	1000
	Specific power (W/kg)	650	1000	1000
	Specific energy (W-h/kg)	30	40	40
Power Electronics				
	Operating voltage (V)	200–600	200–600	200–600
	Power (W)	50–150	50–150	50–150
	Lifetime (years)	<5	15	15
	Cost ($/kW)	35	7	7
	Specific power (kW/kg)	5	TBD	TBD
	Efficiency	97–98	97–98	TBD
Regenerative Braking				
	Efficiency	30%	30%	50%
Auxiliary Electric Power				
	Average/peak power (kW)	3–5/8–10	5–10/10–30	5–10/10–30

[a] Preliminary estimates by industry teams are subject to change. TBDs will be filled in as AHHPS tasks mature in FY 2004.

The system architectures envisioned require high-grade electrical power to charge energy storage systems and to run electric auxiliary components. An integrated approach to supply this power will be considered, including regenerative braking, APUs, and waste heat recovery systems.

A systematic approach to component and system requirements necessitates modeling and optimization. ADVISOR integrated modeling and optimization techniques will be provided for the vehicle, powertrain, energy storage and management, power electronics, auxiliary loads, and regenerative braking. In addition, industry teams will use proprietary models as well as PSAT for detailed design and control analysis. The AHHPS sub-activity is using vehicle systems technical target tools developed in vehicle systems analysis tasks to establish AHHPS technical targets. The AHHPS sub-activity is also integrating relevant task results and coordinating appropriate cross-linked R&D tasks in Sections 4.1, 4.3, 4.4, and 4.5.

Heavy hybrid vehicle testing is expected to begin in FY 2005 and will use national laboratory facilities. Hybrid vehicle testing results will validate heavy hybrid technologies to ensure they are ready for technical and economic commercialization, as well as validate AHHPS and industry vehicle models.

Task Descriptions

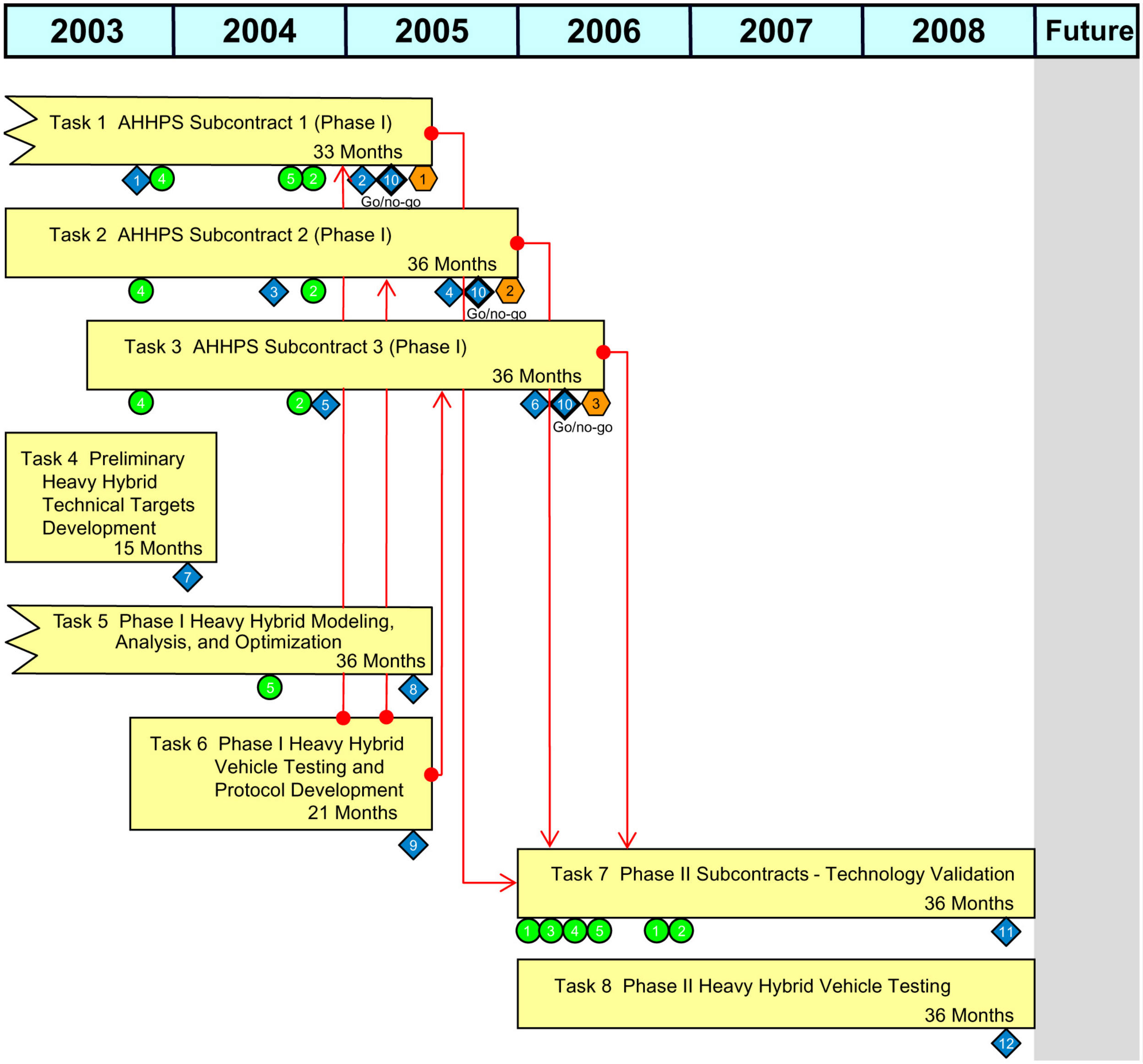
A description of the tasks, along with the estimated duration and barriers associated with the tasks, is provided in Table 4.

Table 4. Task for Heavy Hybrid Propulsion Systems

Task	Title	Duration/ barriers
1	AHHPS Subcontract 1 (Phase I) • Advanced Parallel Hybrid Propulsion System • Class 4–6 Heavy Hybrid Vehicle	33 months Barriers A, B, C
2	AHHPS Subcontract 2 (Phase I) • Advanced Series Hybrid Propulsion System • Class 7–8 Heavy Hybrid Vehicle	36 months Barriers A, B, C
3	AHHPS Subcontract 3 (Phase I) • Advanced Parallel Hybrid Propulsion System • Class 7 Heavy Hybrid Bus	36 months Barriers A, B, C
4	Preliminary Heavy Hybrid Technical Targets Development	15 months Barriers A, B
5	Phase I Heavy Hybrid Modeling, Analysis, and Optimization	36 months Barrier B
6	Phase I Heavy Hybrid Vehicle Testing and Protocol Development	21 months Barrier C
7	Phase II Subcontracts—Technology Validation	36 months Barriers A, B, C
8	Phase II Heavy Hybrid Vehicle Testing	36 months Barriers A, B, C

Milestones

Heavy Hybrid Propulsion System sub-activity milestones are provided in the following network chart.



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🔷 Milestone

1. AHHPS SC 1 – Phase I PTDR, Complete Model Validation Vehicle (Class 4-6)
2. AHHPS SC 1 – Complete Critical System Validation Vehicle (Class 4-6) – Phase I Final Report
3. AHHPS SC 2 – Phase I PTDR
4. AHHPS SC 2 – Complete Component and System Validation Vehicle (Class 7-8) – Phase I Final Report
5. AHHPS SC 3 - Phase I PTDR
6. AHHPS SC 3 – Complete Component and System Validation (Hybrid Bus System) – Phase I Final Report
7. Deliver Preliminary Heavy Hybrid Technical Targets Report and Presentation
8. Complete Phase I Heavy Hybrid Modeling, Analysis, and System Optimization – Final Phase I Report
9. Complete Phase I Heavy Hybrid Vehicle Testing and Test Protocol Development
10. **Go/no-go**. Phase II Subcontract Continuation
11. Complete Phase II Subcontracts
12. Complete Phase II Heavy Hybrid Vehicle Testing

⬢ Technology Program Output

1. AHHPS Class 4-6 Prototype Critical Systems Validation Truck
2. AHHPS Class 7-8 Critical Technologies Validation
3. AHHPS Advanced, Next Generation Hybrid Transit Bus Propulsion Validation

● Supporting Input

1. Advanced Heavy Vehicle Engine Performance from Advance Heavy Vehicle Engine Sub-Program
2. Advanced Energy Storage Characteristics and Behavior from Energy Storage Sub-Program
3. Heavy Vehicle Aerodynamic Performance from Heavy Vehicle Parasitic Loss Reduction Sub-Program
4. Lightweight Materials Characteristics and Behavior from Materials Technologies Sub-Program
5. Technical data for thermoelectric generators and electric turbocompound systems from Waste Heat Recovery R&D

4.2.3 Light Vehicle Ancillary Systems

Goals

The overall goal of this sub-activity is to reduce the fuel used by light-duty vehicle ancillary systems by 5 billion gallons by 2010.

Programmatic Status

Ancillary systems impose additional loads on the power source [ICE, hybrid electric vehicle (HEV) powertrain, or fuel cell vehicle stack] that affect performance, fuel economy, and emissions. The largest ancillary load is the air-conditioning system, which can result in a 4-kW load on the power source. About 7 billion gallons of fuel, equivalent to about 9.5% of our imported crude oil, are used to cool light-duty vehicle cabins. Current air-conditioning systems are not optimized to reduce fuel use or use the waste heat energy being rejected from the engine. More than half of the fuel used in vehicles is rejected as low-grade waste heat, a potential significant energy source for air-conditioning systems.

Targets

- By 2005 and 2010, demonstrate air-conditioning systems that reduce energy consumption by 50% and 75%, respectively, relative to current technology.
- By 2012, demonstrate a waste heat cooling system capable of achieving a COP of 0.5.
- By 2012, demonstrate a reduced-energy-use ancillary load system in a concept car.

Barriers

A. Higher cost of low-energy climate control systems.
B. Developing cabin-cooling technologies from waste heat: relatively low and variable temperatures, particularly in fuel cell vehicle applications; weight; volume; corrosion; and engine backpressure and pumping requirements.
C. Lack of a measurement tool to assess human comfort.

Approach

With industry cooperation, develop and test ancillary load solutions to reduce fuel use while maintaining occupant comfort. The focus is on complete system integrated modeling, use of advanced measurement and assessment tools, and development of a waste heat cabin cooling system. Reducing the energy usage for heating as well as cooling will be considered. Turning low-grade heat energy into useful energy is a priority. An experimental thermal comfort tool is being developed and will be validated to measure and predict human response to cabin thermal conditions. This tool will have realistic physical dimensions and weight as well as the ability to control surface heat output, control its sweating rate, and breathe warm, humid air. The approach to the integrated modeling is to simulate all the climate control and ancillary systems to determine their impact on vehicle fuel economy, tailpipe emissions, and the occupants' response to the thermal environment

Task Descriptions

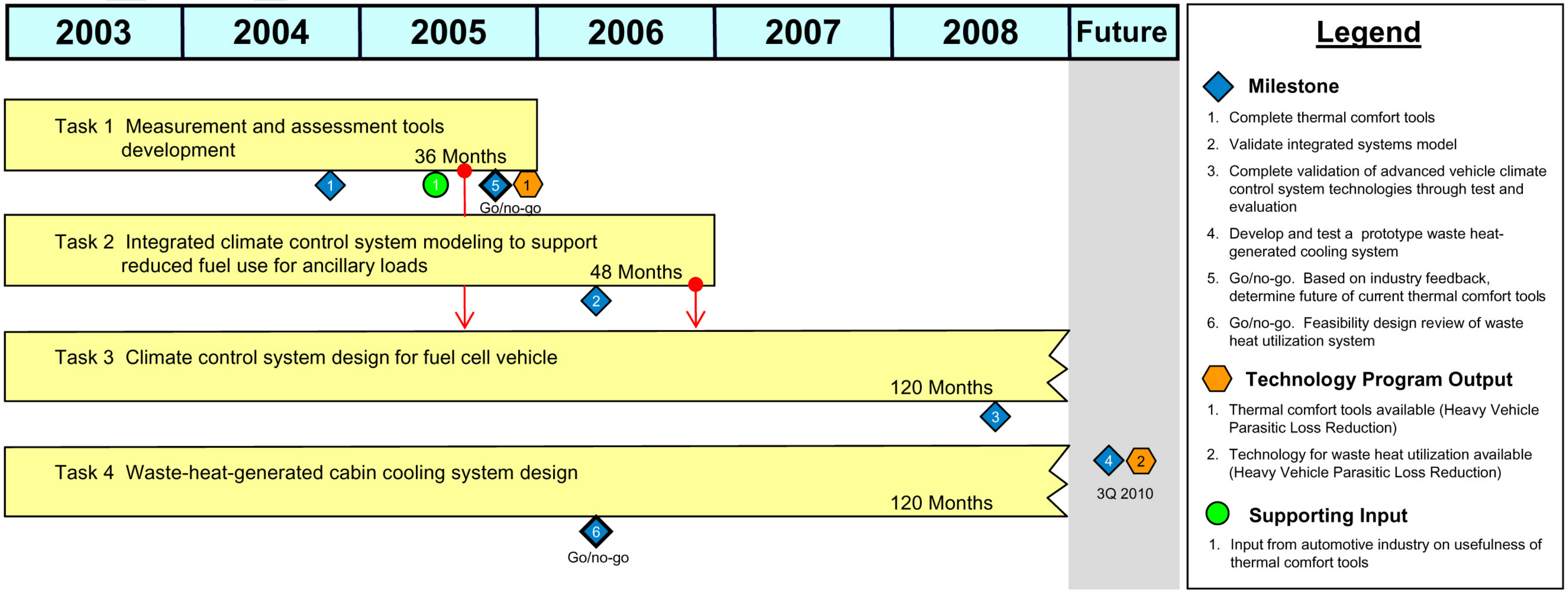
A description of the tasks, along with the estimated duration and barriers associated with the tasks, is provided in Table 5.

Table 5. Tasks for Light Vehicle Ancillary Systems

Task	Title	Duration/ barriers
1	Measurement and assessment tools development	36 months Barrier C
2	Integrated climate control system modeling to support reduced fuel use for ancillary loads	48 months Barrier A
3	Climate control system design for fuel cell vehicle	120 months Barrier A
4	Waste-heat-generated cabin cooling system design	120 months Barrier B

Milestones

Light Vehicle Ancillary Systems sub-activity milestones are provided in the following network chart.



Legend

◆ **Milestone**

1. Complete thermal comfort tools
2. Validate integrated systems model
3. Complete validation of advanced vehicle climate control system technologies through test and evaluation
4. Develop and test a prototype waste heat-generated cooling system
5. Go/no-go. Based on industry feedback, determine future of current thermal comfort tools
6. Go/no-go. Feasibility design review of waste heat utilization system

⬢ **Technology Program Output**

1. Thermal comfort tools available (Heavy Vehicle Parasitic Loss Reduction)
2. Technology for waste heat utilization available (Heavy Vehicle Parasitic Loss Reduction)

● **Supporting Input**

1. Input from automotive industry on usefulness of thermal comfort tools

4.2.4 Heavy Vehicle Parasitic Loss Reduction

The purpose of this sub-activity is heavy vehicle optimization to identify and develop technologies and components that reduce the parasitic energy losses of heavy vehicles. When parasitic energy losses are reduced, less energy is required to operate a heavy vehicle performing the same amount of useful work, translating into greater energy efficiency for the vehicle and thus the entire truck fleet. All parasitic energy losses except those due to the vehicle weight are addressed in this sub-activity, including aerodynamic drag, rolling resistance, friction and wear, thermal loads, and idling losses. The energy losses due to weight are addressed in the High–Strength Weight Reduction Materials activity.

Goals

In general, the goal is to reduce parasitic energy losses from non-engine components of heavy vehicles. Specifically, the goal is to

> Develop technologies that reduce parasitic energy losses, including losses from aerodynamic drag and ancillary systems, from 39% of total engine output in 1998 to 24% in 2006. (This is a priority FCVT goal identified in Section 3.)

Specific 2012 technology goals defined by government and industry for the 21st CTP supported by this sub-activity are these:

> 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 the 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).
>
> Develop and demonstrate a 5-kW, $200/kW diesel-fueled ICE APU by 2007.
>
> Develop and demonstrate a fuel cell APU system in the 5–30 kW range, capable of operating on diesel fuel, at a delivered cost of $400/kW by 2012.
>
> Develop consistent electrical codes and standards that apply to both truck (on-board) and truck stop (stationary) electrification technologies to enable the introduction of new idle-reduction technologies.

Programmatic Status

A series of seven technology-specific DOE-sponsored workshops were held from 1996 to 2002 in which enabling technologies were identified. As a result, technology plans and technology roadmaps were developed in collaboration with industry, academia, government, and consultant representatives. The plans assess the status of the various technologies for heavy vehicles, develop goals, identify barriers, develop an approach to overcoming the barriers, prioritize projected R&D tasks, and estimate task time frames and financial resource requirements. This approach facilitated the development of a national agenda for a coordinated R&D effort to achieve the stated goals that is industry-relevant and simultaneously responsive to the broader needs of the nation. A final plan in each technical area was published and broadly circulated to the technical community, especially within the heavy vehicle industry. In conjunction with the research tasks undertaken, computational models and simulation programs are being developed simultaneously and being used to predict the fuel economy implications of applying the candidate technologies.

Targets

- By 2004, demonstrate an 8% increase in fuel economy from electrification of accessory components.
- By 2005, produce a 5% reduction in aerodynamic drag coefficient.
- By 2008, develop a 12-kW diesel APU of less than 20 kg and 20 liters.
- By 2010, reduce aerodynamic drag by 15% using active devices and tire and mirror modifications.
- By 2010, reduce cooling system size for a Class 7-8 truck by 8% while meeting all cooling specifications.
- By 2015, develop system improvements and control strategies to improve the efficiency of railroad locomotives by 8%.

Barriers

Barriers common to all technology development tasks:

A. **Cost.** The cost of a new technology used in a vehicular component, even if cost-effective from a life-cycle perspective, continues to represent a major barrier to the timely implementation of the technology in the heavy-duty industry.

B. **Current market conditions.** The industry is being driven by the need to meet much tighter engine emission regulations, to such an extent that other innovations for improved energy efficiencies are not generally considered high priorities at this time.

C. **Safety, durability, and reliability.** Improvements in the safety, durability, and reliability of new technology are being demanded by industry and required by other government agencies.

D. **Computation models, design and simulation methodologies.** Codes for optimizing future designs, and for accurately predicting the fuel economies of advanced heavy vehicles on which the technologies are to be applied, are either not fully developed or not currently available.

E. **Higher vehicular operational demands.** Trends toward higher-horsepower engines, along with new technologies for reducing emissions, are substantially increasing heat-rejection requirements, while the industry requires maintaining or reducing component space requirements and costs.

Approach

To accomplish the goals of this technology development sub-activity, the methodologies identified to achieve the reductions in energy losses must be developed and tested in the laboratory. They must then be prototyped and tested on board a heavy vehicle. Subsequent to technology validation, on-road data must be accumulated to determine the durability, reliability, and life-cycle cost data of the developmental component and/or design strategy. It is axiomatic in the heavy vehicle industry that only real-world, real-time performance data from actual use in revenue-bearing service are considered sufficiently cogent to deem a technology development mature enough that introduction to the market place can be considered. Concomitant benchmarked computer modeling and simulation code formulation can then be employed for innovative design approaches and technical and cost optimization methodologies. This procedure of validating performance, component robustness, operational reliability, and cost-competitiveness—conducted in conjunction with prominent participants in the heavy vehicle industry through cost-shared R&D with DOE—is the process most likely to provide a basis for timely introduction of a technology into the marketplace and acceptance by industry. Ultimately, it is the broad application of the technology within the trucking industry that determines the actual level of success of the R&D effort.

DOE–industry cost-shared R&D tasks develop enabling technologies for reduction of parasitic energy losses, supported by national laboratories and universities, as described in the following paragraphs.

Aerodynamic drag reduction. The long-term goal is 25% improvement in fuel economy at 65 mph. The relationship between aerodynamic drag and vehicular efficiency is very close to two to one; that is, a 50% reduction in drag will result in a 25% increase in energy efficiency. Research sponsored by DOE has identified both active and passive methodologies that are capable of producing very large changes in the pertinent parameters and thus achieving significant fuel savings and concomitant emissions reductions cost-effectively. The primary issues that must be addressed are the durability, reliability, life-cycle cost benefits, and actual performance parameters for the various candidate methodologies. A flagship aerodynamic phenomenon known as the Cowanda effect has led to breakthrough concepts in the effort to render heavy-duty long-haul Class 7 and 8 trucks substantially more energy- and cost-efficient.

Computational fluid dynamics (CFD) tools and simulation models are being developed and used to assess various drag reduction techniques. The models will be compared with data derived from fractional-scale and full-scale vehicles in wind-tunnel tests simulating on-road wind and air flow conditions at various vehicular speeds, with varying geometries and yaw angles. These results will be used to help efficiently direct truck modification approaches and systems changes that can more rapidly achieve market introduction and acceptance of the technologies.

Prototypical aerodynamic drag reduction devices will be validated in fleet demonstrations in actual on-road, revenue-bearing service; and data will be accumulated on efficiency, durability, reliability, maintenance, and service data.

Development of innovative concepts will continue, including formulation of codes based on vorticity rather than conventional grid elements. An acoustic spoiler and a pneumatic drag reduction device, which can also increase tractor-trailer stability and improve braking, will be characterized.

An air disk brake system is under development to compensate for the expected increase in brake loads that result from reduction in aerodynamic drag. This system will use Si/SiC rotors and a composite material for the brake pads and is expected to improve overall braking effectiveness, reduce stopping distances substantially, and reduce brake fade in high-heat conditions.

Friction and wear reduction. Significant parasitic energy losses arise from the multiple surface interactions that occur in heavy vehicle systems. Examples of such interactions occur between numerous moving engine components, shafts and impellers in various pumps for fluid circulation, axles, rotors, and the like. A number of promising surface modification technologies have been identified that may be used to significantly alter and control surface interactions and the friction forces and wear that occur at those areas. Moreover, techniques are now available that allow near-atomic-level observation of both the surface-to-surface interaction mechanisms and the lubricant-surface interactions. The latter is expected to lead to methodologies to improve the formulations of both lubricants and their additive packages. This will substantially improve the performance of lubricated surfaces and their special lubricants, contributing to the reduction of the parasitic losses for which they are currently responsible.

To systematically characterize such surface and lubricant interactions, experiments have been undertaken to develop a fundamental understanding of the boundary-layer lubrication and surface-failure mechanisms of critical components in engines and vehicle subsystems that are oil-lubricated. Candidate coating and lubrication technologies, in addition to surface modification techniques to reduce friction/wear, will then be evaluated. Subsequently, prototype systems are expected to be constructed and subjected to simulation of operating conditions to provide performance data for further scale-up to on-road utilization and systems characterization prior to commercialization efforts.

Essential power systems (EPS). EPS are a crosscutting technology that addresses the efficient management of electrical and thermal systems and the distribution and control of energy on board the heavy vehicle. EPS are part of a systems approach to using on-board energy efficiently. Within the EPS approach, concepts to reduce energy losses will include diesel APUs; lightweight, efficient heating and air-conditioning systems; and electrification of various vehicle components. The latter is promising because significant amounts of energy are consumed by belts and gears in oil, water, and air pumps. Electric motors are substantially more efficient than belt drives and gears. Moreover, the decoupling of the components from the engine drive shaft permits greater opportunities to optimize the locations of accessory components and better usage of available volume. In addition, the ability to operate the electrified components on-demand, instead of the current practice of using them at maximum or near-maximum output, will contribute to attaining 8% greater energy efficiency. Further, this systematic approach to energy management enables an effective way of reducing the need to idle the heavy-duty tractor engine to heat or cool the cab/sleeper or heat the engine block, fuel, and oil (in winter) during idling hours. This could save up to 1.5 % of the total fuel use in the surface transport sector.

Regenerative shocks. A regenerative shock-absorbing device consisting of a permanent magnet and a copper coil will be used to recover a substantial fraction of energy otherwise dissipated in conventional shock absorbers. Theoretical calculations will be compared with results from tests on a simple experimental system. A decision to proceed to additional scale-up and system complexity will be based on the comparative results from these tests. It is likely that these devices will also be applicable to railroad rolling stock, where electrification of brake actuating systems is being examined by the U.S. Department of Transportation and the rail industry.

Predictive cruise control. It has been estimated that using modern computer control of the engine to help the driver determine the optimum vehicle speed could improve fuel efficiency in long-haul, heavy vehicles by up to 5%. Modeling and simulation of this control scheme confirm these estimates. On-road equipment has been designed and installed in a vehicle that will be tested under experimental conditions to determine the magnitude of the energy savings that are actually achievable.

Idle reduction. DOE has identified reducing heavy-duty truck engine idling as an effective means of conserving fuel, reducing undesirable emissions, and mitigating high noise levels in stationary idling locations. Products have been available to heat the cab/sleeper, but few are addressed to cooling it. These products, plus the EPS and truck electrification technologies that DOE and industry are developing, enable nearly complete idling elimination. Only about 1% of U.S. trucks are outfitted with the idle-reduction devices, while the equipment is carried by 70% of trucks in Germany. To combat the inertia in the U.S. trucking industry and better inform truck drivers, individual owner-operators, and fleet operators, DOE has prepared informational brochures and informative sample calculations demonstrating the potential cost savings for fuel based on the actual engine operating conditions used by an individual driver. This industry-specific literature is distributed directly to truckers at truck shows and meetings at a DOE/FCVT booth. It is estimated that full penetration of idling-reduction devices in the long-haul truck fleet could save up to 1.5 % of the total fuel used in the surface transport sector.

Locomotive systems. The railroads are coming under increasing pressure from the state of California and the EPA to substantially reduce the emissions produced by diesel locomotives. In addition, the rail companies have an increasing need to reduce their operating costs. DOE has entered into two cooperative agreements with locomotive companies to develop strategies, hardware, and operational equipment to reduce emissions and increase fuel efficiency. These will address the recovery of energy dissipated during dynamic braking, the use and development of affordable electrical energy storage devices, and the application of variable-frequency power conversion devices.

Off-highway systems. Off-highway heavy vehicles are faced with energy efficiency and emissions issues similar to those of on-road vehicles. However, they have unique challenges: limited heat rejection capabilities because of the lack of "ram air"; high noise levels that are subject to legislated restrictions (now in Europe, perhaps soon in the United States); and severely restricted under-hood volume for the addition of fuel-efficiency, emissions-reduction, or noise-abatement devices. A DOE/industry collaborative task has been initiated to develop a highly efficient radial fan to substantially increase cooling capacity for off-road vehicles; it will enable the use of advanced technologies to reduce emissions and increase the energy efficiency of off-highway vehicles despite increased levels of heat to be rejected.

Diesel reformer development. The reformation of diesel fuel could provide a ready supply of carbon monoxide and hydrogen for use directly in the combustion process or in catalyst regeneration. However, because of its higher carbon content, trouble-free reformation of diesel fuel has remained largely elusive and "coking" has been a constant problem with the various technical approaches. An innovative concept will be developed and tested for an autothermal diesel reformer that has high yield and can potentially avoid the coking phenomenon. The ability of the device to produce desirable hydrogen gas from conventional diesel fuel will be determined, and preliminary reliability and durability will be assessed. Hydrogen gas production will be compared with the amounts needed for catalyst regeneration, direct injection into the cylinder to facilitate cold starting, and, possibly, use in fuel cell operation. Based on the results of bench tests, a prototype will be constructed and integrated with an engine system.

Thermal management. The need to use exhaust gas recirculation (EGR) in heavy-duty engines to meet EPA emissions requirements will impose severe operating conditions on conventional cooling systems. It has been estimated that an increase of up to 40% in heat load will result from the EGR approach, and the industry consensus is that radically new approaches to heat rejection will be needed to prevent decreased energy efficiencies in the system, higher power requirements that increase parasitic energy losses, and potentially a need to redesign the nose of the tractor, which would lead to less aerodynamic vehicles that increase parasitic energy loss. Basic research on improving the performance of vehicle thermal management systems through the examination of critical heat flux measurements will be conducted to determine if this approach is practical and controllable enough to address the issues. The development of nanofluids for cooling systems will be pursued, based on experimental results that indicate at least a four-fold increase in their thermal capacity over conventional coolants. Phase-change heat transfer through evaporative cooling and the use of high-temperature coolants in advanced engine cooling strategies will also be explored. Experimental data will be provided to a national laboratory for benchmarking the newly developed 3D CFD code describing under-hood thermal distributions. It has been estimated that the use of one or more of these technologies could reduce the parasitic energy loss by more than 10%, despite the increased heat rejection requirements due to the EGR approach.

Task Descriptions

A description of the tasks, along with the associated estimated durations and barriers, is provided in Table 6.

Table 6. R&D tasks for Heavy Vehicle Parasitic Energy Loss Reduction

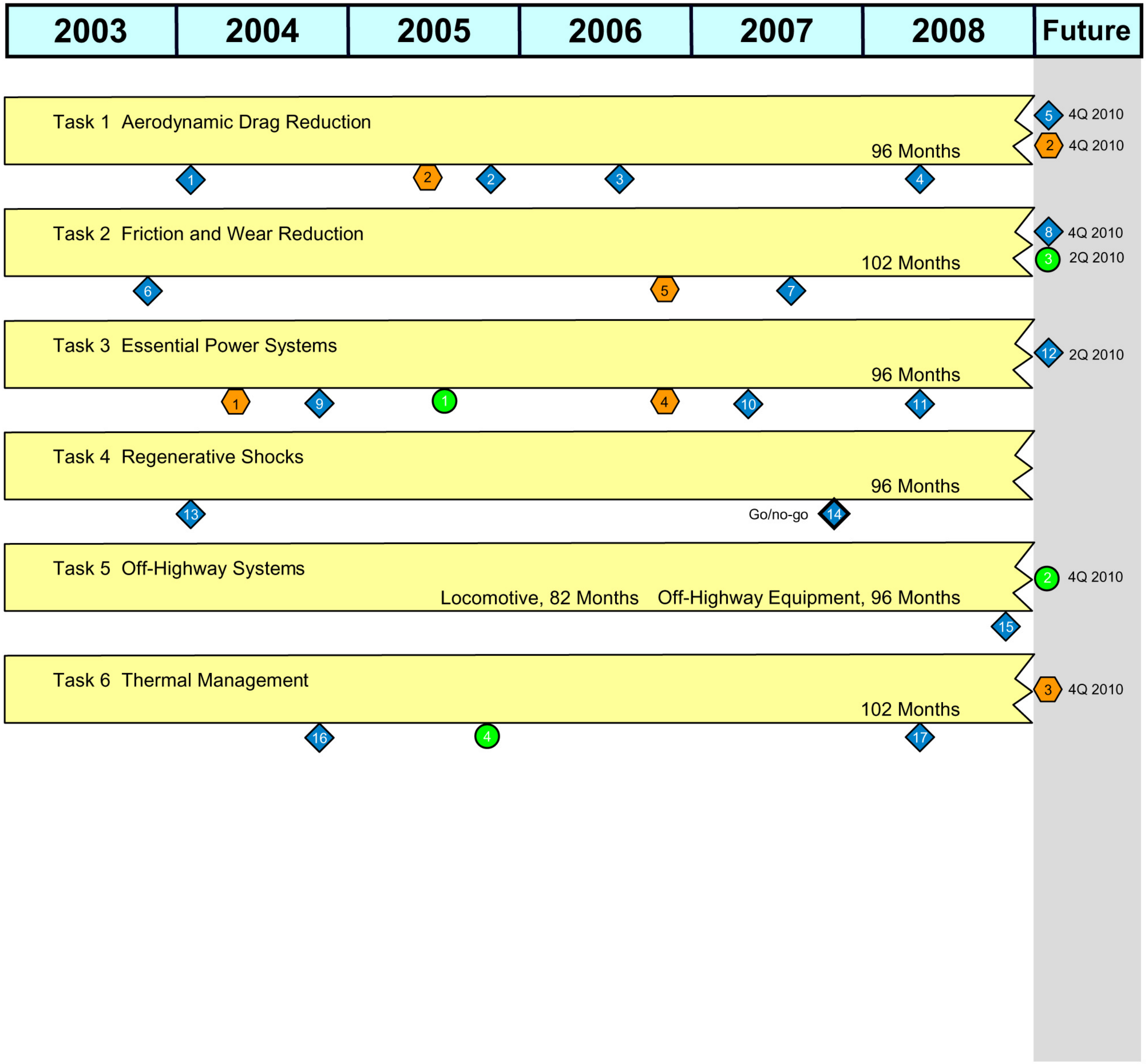
Task	Title	Duration/ barriers
1	Aerodynamic Drag Reduction—Phase 1 • Investigate the applicability of CFD to a complete tractor/trailer system • Validate CFD codes using wind tunnel tests • Instrument a tractor/trailer and conduct full-scale on-road testing	60 months Barriers A, C, D, E
	Aerodynamic Drag Reduction—Phase 2 • Explore near-term commercial aerodynamic drag devices • Conduct on-road testing with commercial fleets	36 months Barriers A, B, C, E
	Aerodynamic Drag Reduction—Phase 3 • Apply CFD to innovative drag reduction technologies for heavy-vehicle applications • Perform wind-tunnel testing for validation • Conduct on-road testing	60 months Barriers A, B (begin 3Q 2005)
	Aerodynamic Drag Reduction—Phase 4 • Use CFD to assess the benefits of aero improvements on safety, stability, and braking • Conduct wind-tunnel testing • Perform full-scale tests on instrumented, fully loaded tractor/trailer	52 months Barriers C, D, E
2	Friction and Wear Reduction—Phase 1 • Identify failure mechanisms in boundary-layer lubrication regime • Characterize the conditions under which the failure occurs by in-situ experiments • Evaluate candidate methodologies to mitigate the failure	48 months Barriers A, C, D, E
	Friction—Phase 2 • Identify mechanisms responsible for scuffing, galling, and scoring in the mixed-lubrication regime • Develop and apply computation and simulation techniques to predict failure modes • Systematically explore surface modification technologies and lubricant-surface interactions to enhance the durability and reliability of moving parts	72 months Barriers A, B, C, D, E
3	Essential Power Systems—Phase 1 • Develop the methodology to efficiently manage thermal and electrical systems and the distribution and control of energy on board the heavy vehicle • Design and assemble and bench test • Assemble a prototype vehicle • Test and validate the projected energy efficiency of a prototypic vehicle under realistic conditions on a test track	48 months Barriers A, B, C, E
	EPS—Phase 2 • Extend EPS technologies to medium-duty, light–duty, and other vehicles • Encourage the development of efficient, lightweight auxiliary power units to interface with EPS to reduce idling of heavy vehicles	48 months Barriers A, B, C, E

Table 6 (continued)

Task	Title	Duration/ barriers
4	Regenerative Shocks—Phase 1 • Using actual highway profiles, calculate potential energy recovery • Construct a prototype device • Bench-test a prototype device • Optimize the design of the prototype	60 months Barriers A, D, E
	Regenerative Shocks—Phase 2 • Assemble the prototype light test vehicle • Conduct road tests to determine recoverable energy • Determine the feasibility of transferring the technology to heavy vehicles	44 months Barriers A, D, E
5	Off-Highway Systems: Locomotive—Phase 1 • Identify and simulate promising energy-efficiency technologies and emission-reduction strategies • Select candidate technologies • Design and develop bench-test systems • Bench-test technologies • Build and test a prototype vehicle	70 months Barriers A, C, D, E
	Locomotive—Phase 2 • Test on locomotive in various conditions	12 months Barriers A, C, D, E
	Off-Highway Equipment—Phase 1 • Identify and simulate promising energy-efficiency technologies and emission-reduction strategies • Select candidate technologies • Design and develop bench-test systems • Bench-test technologies • Build and test a prototype vehicle	70 months Barriers A, C, D, E
	Off-Highway—Phase 2 • Test on off-highway vehicle under various operating conditions	12 months Barriers A, C, D, E
6	Thermal Management—Phase 1 • Define operational conditions and demands on the cooling system of a heavy vehicle using EGR to achieve EPA 2007 and 2010 emission requirements • Identify candidate technologies to address the cooling requirements	24 months Barriers A, C, D, E
	Thermal Management—Phase 2 • Apply simulation and modeling to optimize candidate systems • Design and assemble bench prototypes • Test bench prototypes • Optimize components and packaging	42 months Barriers A, C, D, E
	Thermal—Phase 3 • Install components on full-scale test vehicle • Perform instrumented tests under typical road conditions • Validate models based on instrumented test data • Optimize components using validated codes	24 months Barriers A, C, D, E
	Thermal—Phase 4 • Conduct fleet demonstration in revenue-bearing service	12 months Barriers A, C, D, E

Milestones

Milestones for the Advanced Propulsion and Vehicle Efficiency Improvements activity are shown in the network chart.



Legend

🔷 Milestone

1. Road test available aerodynamic drag reduction devices
2. 5% reduction in aerodynamic drag coefficient
3. Transfer data to computational fluid dynamics team
4. Demonstrate prediction capability with industry partners
5. 15% reduction in aerodynamic drag using active devices
6. Initiate boundary layer lubrication experiments
7. Identify candidate methods to mitigate failures
8. Select surface modification technologies and optimized lubricant-surface interactions
9. Electrify accessory components in class 8
10. Electrification complete for classes 3-6
11. Complete diesel APU development
12. Class 7/8 truck cooling system
13. Fabricate and test generation 3 regenerative shocks
14. Optimize design of regenerative shock absorbers for heavy vehicles (**Go/no-go**)
15. Build and test prototype locomotive
16. Identify component technologies to address cooling requirements
17. Bench-test prototype thermal management system

⬢ Technology Program Output

1. Fuel formulation constraints for APUs to Fuels
2. Drag reduction technology to AHHPS subcontracts and to industry
3. Thermal management technology to industry
4. Deliver APU for testing and verification
5. Technical data on surface modification technology to reduce friction to Heavy Truck Engine R&D

● Supporting Input

1. Receive fuel formulation for APU reformer
2. Efficiency confirmation of selected engines of various sizes
3. Lubricants optimized for use with specific surface modification methods to increase engine efficiency and reduce friction and wear
4. Accurate measurements of increased thermal loading on cooling systems as a result of increased EGR to meet emissions requirements

4.3 ENERGY STORAGE TECHNOLOGIES

Energy storage technologies, especially batteries, have been identified as critical enabling technologies for the successful development of advanced, fuel-efficient, light- and heavy-duty vehicles. The energy storage R&D effort of the FCVT Program is responsible for advancing the state of the art and facilitating the adoption of innovative batteries for a wide range of vehicle applications, including HEVs, battery electric vehicles (EVs), 42-V vehicular systems (42V), and fuel cell vehicles. The office is working in close partnership with the automotive industry, represented by the United States Advanced Battery Consortium (USABC). The USABC has responsibility for the FreedomCAR Electrochemical Energy Storage technical team.

Development activities are chosen to address energy storage needs identified through interaction between the Electrochemical Energy Storage technical team and the four functional collaboration areas listed in Figure 15. Target development begins by resolving system power needs reported from the technical teams responsible for defining global vehicle systems, specifically the advanced propulsion sub-systems and their components (fuel cells, power electronics, electric motors, and combustion engines). Models and verification efforts aid in resolving system interface conflicts, resulting in component-level technical targets compatible with system expectations.

The vision of energy storage technologies is to enable and support the development of durable and affordable advanced batteries covering the full range of applications from “start/stop” (denoting a vehicle whose ICE is off when the

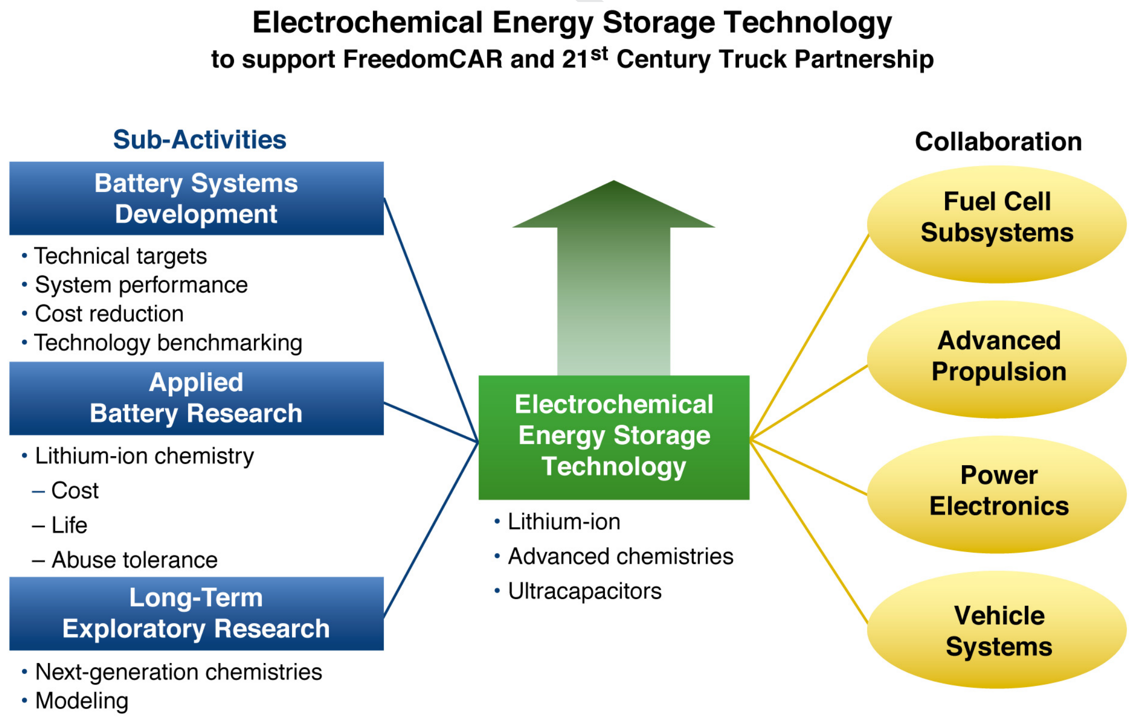


Figure 15. Interaction among the Electrochemical Energy Storage technical team and the collaboration areas.

vehicle is stopped) to full HEVs, EVs, and fuel cell vehicles. In addition, these development efforts will deliver technology that is directly applicable to heavy hybrid vehicle energy storage requirements. These efforts leverage all available resources, including those of automobile manufacturers, battery developers, small businesses, national laboratories, and universities, to address the technical barriers preventing the introduction of battery systems to the marketplace.

Goals

- By 2010, develop electric drive train energy storage with a 15-year life at 300 Wh with a discharge power of 25 kW for 18 seconds and $20/kW cost (a FreedomCAR Partnership Goal).

  By 2012, develop an energy storage system with a 15-year life and cost ≤$25/kW peak electric power rating (21st CTP Partnership Goal).
- Reduce the production cost of a high-power 25-kW battery (light vehicle) from $3000 to $750 in 2006 and to $500 in 2010 (Priority FCVT Goal defined in Section 3).
- Establish and continuously reaffirm performance and cost targets for batteries covering the full range of applications, including 42V systems and hybrid, electric, and fuel cell vehicles.
- Develop hardware for specific applications that can be tested against respective performance targets and used for subsystem benchmarking.

Programmatic Status

The energy storage effort has supported battery research for automotive applications for more than 25 years. For most of the early years, its work was primarily focused on validation tasks and on exploratory research, examining and evaluating a wide spectrum of electrochemical couples that showed some promise in electric vehicle applications. Upon the formation of the USABC in 1991, followed by the establishment of PNGV in 1993, efforts began to focus on the most promising technologies for EV and HEV applications, respectively, with a much heavier emphasis on development.

Battery modules (including LiAl/FeS_2, NiMH, Li-ion, and Li/polymer) have been built and tested against EV and HEV targets. Even after significant development, none of these systems was able to meet the most demanding PNGV requirements, especially cost, although modules designed for higher-power applications (for HEVs) came closer to meeting or exceeding their performance targets than systems built for higher-energy applications (for EVs).

In 1997, it was recognized that developers were facing a set of closely related challenges in developing Li-ion batteries. In response, FCVT consolidated resources and initiated an applied battery research sub-activity. This sub-activity consists of five national laboratories working together with the flexibility to quickly change focus as current obstacles are overcome and new challenges are identified.

In 2000, a long-term exploratory research sub-activity was organized around specific baseline systems. Teams of scientists were organized to address six research areas (cell development, anodes, cathodes, electrolytes, diagnostics, and modeling) with resources focused on identifying, understanding, and addressing long-term technical barriers.

Near-term barriers identified during development become subjects for applied research; longer-term barriers are addressed in long-term technology research. The following sections provide highlights of the status of the development, applied research, and long-term exploratory research activities.

Battery Development

Battery development is one of the primary activities of the energy storage effort. It is subdivided into three closely related sets of activities: full system development, technology assessment, and benchmark testing.

Full System Development

- NiMH battery development for EVs was successfully completed in FY 2000. The current task is focused on development and evaluation of a cost-optimized liquid-cooled monoblock HEV module.
- The development of an advanced lithium/sulfur (Li/S) system has been initiated. This technology has the potential of meeting all of the EV performance targets; however, it faces several significant technical barriers, including dendrite growth on the lithium, irreversible losses of both lithium and sulfur with aging, and isolation of sulfur in the form of Li_2S as a result of over-discharging.
- Recent work in Li-ion technology for EV applications has focused on addressing the gas buildup in cells, which reduces their useful life, especially at higher temperatures and states of charge. Another focus has been reducing the cost of a full HEV module. The developer delivered complete packs that met all of the FreedomCAR HEV performance targets except cost. Tables 7 and 8 present the current performance status of high-power (for HEV) and high-energy (for EV) Li-ion batteries against technical targets.

Technology assessment—Before entering into agreements to develop full systems (which can span several years and entail a significant cost), technology assessments are often conducted. These limited, 12-month tasks assess a developer's current

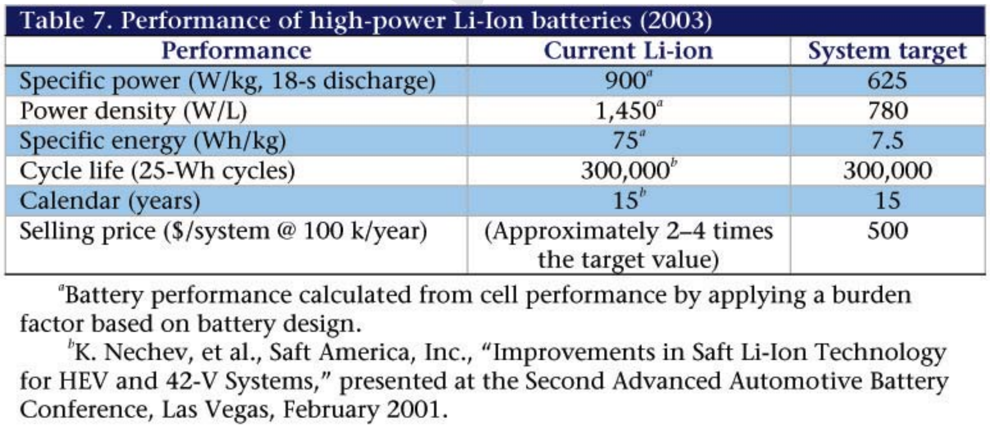


Table 7. Performance of high-power Li-Ion batteries (2003)

Performance	Current Li-ion	System target
Specific power (W/kg, 18-s discharge)	900[a]	625
Power density (W/L)	1,450[a]	780
Specific energy (Wh/kg)	75[a]	7.5
Cycle life (25-Wh cycles)	300,000[b]	300,000
Calendar (years)	15[b]	15
Selling price ($/system @ 100 k/year)	(Approximately 2–4 times the target value)	500

[a] Battery performance calculated from cell performance by applying a burden factor based on battery design.

[b] K. Nechev, et al., Saft America, Inc., "Improvements in Saft Li-Ion Technology for HEV and 42-V Systems," presented at the Second Advanced Automotive Battery Conference, Las Vegas, February 2001.

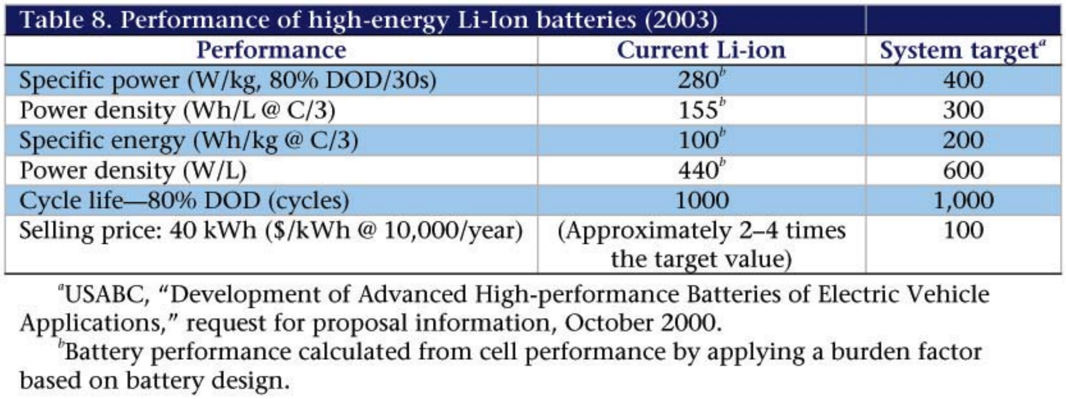


Table 8. Performance of high-energy Li-Ion batteries (2003)

Performance	Current Li-ion	System target[a]
Specific power (W/kg, 80% DOD/30s)	280[b]	400
Power density (Wh/L @ C/3)	155[b]	300
Specific energy (Wh/kg @ C/3)	100[b]	200
Power density (W/L)	440[b]	600
Cycle life—80% DOD (cycles)	1000	1,000
Selling price: 40 kWh ($/kWh @ 10,000/year)	(Approximately 2–4 times the target value)	100

[a] USABC, "Development of Advanced High-performance Batteries of Electric Vehicle Applications," request for proposal information, October 2000.

[b] Battery performance calculated from cell performance by applying a burden factor based on battery design.

capabilities and validate technical claims by independent testing. The purpose of these limited tasks is to assess the developer's current technology status as well as assess the developer's ability to conduct development research in order to deliver a full-scale, fully packaged battery. Current assessment tasks include cells based on Li-ion gel technology, a spinel-based chemistry, and a new $LiFePO_4$ cathode active material.

Benchmark testing—Benchmark testing of emerging technologies is important for remaining abreast of the latest industry developments. Working with the national laboratories, FCVT purchases and independently tests hardware against the manufacturer's specifications and the most applicable technical targets. Recently completed benchmark testing included Li-ion/manganese spinel chemistries against HEV and EV targets.

Other Development Activities

Low-cost separator task—Studies at the national laboratories have shown that, for high-power batteries, the cost of non-active material components (packaging, current collectors, and separator) can equal or exceed the cost of the active materials. The cost of the separator dominates the cost of the non-active materials. As a consequence, support is being provided to the development of a low-cost, polypropylene (PP)-based separator using a wet process, an established dry production process applied to PP-based separators, and a nylon-based high-strength low-cost separator. The goal of these tasks is to produce acceptable separators at a cost of $\$1/m^2$.

Ultracapacitors—Current ultracapacitors (symmetric carbon-carbon double layer ultracapacitors can attain only approximately 50% of the energy density requirements specified in the PNGV battery manual for HEVs in power-assist mode. In response to recently reported advances, FCVT continues to track this technology. Commercially available ultracapacitors are purchased and benchmarked against technical targets at DOE laboratories. Requirements and test procedures for ultracapacitors are currently being revised in collaboration with the technical team. Note that ultracapacitors may be particularly relevant for heavy-duty hybrid vehicles.

Applied Battery Research

Li-ion systems, currently closest to meeting all of the technical energy storage requirements for vehicle applications, face several cross-cutting barriers that are being addressed through applied battery research.

Five national laboratories participate in this sub-activity, and each brings its own expertise. The major focus areas are

- Battery system development and electrochemical diagnostics
- Battery testing and electrolyte development
- Spectroscopy and microscopy diagnostic, including X-ray diagnostics
- Abuse evaluation, accelerated life test protocol development, and statistical analysis

Long-term Exploratory Battery Research

Long-term exploratory research addresses fundamental problems of chemical instabilities that impede the development of advanced batteries. This research provides a better understanding of why systems fail, develops models to predict system failure and to optimize systems, and investigates new and promising materials. It presently concentrates on six research areas: cell development, anodes, electrolytes, cathodes, diagnostics, and modeling. It focuses on the improvement of three baseline systems and several exploratory systems that are direct extensions of the baselines. The baseline systems are reviewed every two or three years and updated if necessary. The present systems are shown in Table 9.

Table 9. Current baseline and exploratory systems

Systems	High energy	Moderate energy/power	High power
Baseline	Natural graphite/$LiPF_6$ in PC:EC:DMC/$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$	Natural graphite/$LiPF_6$ in PC:EC:DMC/$LiFePO_4$	Natural graphite/LiBOB in γBl:EA/$LiMn_2O_4$
Exploratory	Alloys/$LiPF_6$ in PC:EC:DMC/Layered oxides	Natural graphite/gel/phosphates	Natural graphite/gel/spinels
	Li/X/electrolyte/ layered oxides	—	—
	Li/X/gel/sulfur-based	—	—

In **cell development**, experimental cells incorporating novel materials are prepared and evaluated. For example, several sources of $LiFePO_4$, optimized for rate capability, have recently been acquired and are being evaluated.

Investigators working on **anodes** have developed Sn-based intermetallic alloys of Cu, Sb, and Mg. These materials suffer from capacity loss on cycling as a result of structural changes. The search continues for a material that would not exhibit structural changes.

Work on **electrolytes** has mostly focused on solid polymer electrolytes. Cells with a composite polymer electrolyte have been assembled and cycled. Dendrite formation continues to be a major challenge.

Work on **cathodes** has concentrated on two materials, $LiFePO_4$ and $LiNi_xM_yMn_{1-x-y}O_2$. $LiFePO_4$ is a low-cost, stable, and abuse-tolerant material. $LiNi_xM_yMn_{1-x-y}O_2$ is a high-voltage, high-capacity material.

Work in **diagnostics** has resulted in tools to help researchers better understand the processes occurring in actual cells. It has advanced the capabilities of Fourier Transform infrared spectroscopy (FTIR), attenuated total reflectance infrared spectroscopy (ATRIS), nuclear magnetic resonance spectroscopy (NMR), X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), Raman spectroscopy, atomic force microscopy (AFM), and current-sensing atomic-force spectroscopy (CSAFM).

Work in **modeling** has led to a better understanding of cell performance issues. Models of molecular interactions have led to the understanding of ion transport in an organic solvent and to the optimization of electrolytes. First-principles calculations have led to the understanding of cathode structure and the source for capacity fade. A model is being developed to understand the formation of dendrites at the lithium metal interface.

Other Research

Improved thermal designs for sample cells and modules have been produced and tested. The state-of-the-art design is currently an air-cooled system, but more efficient liquid-cooled battery systems have been analyzed. The latter systems will receive further development and validation.

Battery electrical models have been developed and validated for use in vehicle simulation and target analysis. These models have been used for optimization studies and for evaluation of combined energy storage devices, such as a battery combined with an ultracapacitor.

Finally, FCVT has monitored and managed several Small Business Innovative Research (SBIR) projects related to advanced electrode and electrolyte materials.

Targets

The technical targets established by the energy storage group in close cooperation with the technical teams are provided in Tables 10–12 for the 42-V systems (two types: M-HEV and P-HEV), HEV systems (two types: power-assist minimum and maximum), and EVs. Table 13 includes proposed targets for a fuel cell vehicle; these requirements are to be refined and adopted by 2005.

Although heavy vehicle energy storage targets have not been finalized, the Energy Storage effort is prepared to support the energy storage needs of these vehicles and to work with the appropriate technical teams to establish the technical targets.

The Heavy Hybrid Propulsion sub-activity also requires advanced energy storage systems to meet technology goals. The Energy Storage activity will support the Advanced Heavy Hybrid Propulsion sub-activity by assisting in the finalization of technical targets and by developing energy storage systems that meet the targets for these vehicles. This sub-activity interfaces with the appropriate 21st CTP and FreedomCAR technical teams when defining the technical targets.

Table 10. Energy Storage targets for 42-V systems: M-HEV and P-HEV

Characteristics	USABC M-HEV commercialization goals	USABC P-HEV commercialization goals
Discharge pulse power (kW)	13 (for 2 seconds)	18 (for 10 seconds)
Regenerative pulse power (kW)	8 (for 2 seconds)	18 (for 2 seconds)
Engine-off accessory load (kW)	3 for 5 minutes	3 for 5 minutes
Available energy (Wh @ 3 kW)	300	700
Recharge rate (kW)	2.6 kW	4.5 kW
Energy efficiency on load profile (%)	90	90
Cycle life, profiles (engine starts)	150 k (450 k)	150 k (450 k)
Cycle life and efficiency load profile	Partial power assist (PPA)	Full power assist (FPA)
Cold cranking power @ •30°C (kW)	8 (21 V minimum)	8 (21 V minimum)
Calendar life (years)	15	15
Maximum system weight (kg)	25	35
Maximum system volume (liters)	20	28
Self discharge (Wh/day)	<20	<20
Maximum operating voltage (Vdc)	48	48
Maximum open circuit voltage (Vdc)	48 (after 1 second)	48 (after 1 second)
Minimum operating voltage (Vdc)	27	27
Operating temperature range (°C)	•30 to 52	•30 to 52
Selling price ($/system @ 100-k units)	260	360

Table 11. Energy Storage targets for hybrid electric vehicles

FreedomCAR HEV goals Characteristics	Power-assist minimum	Power-assist maximum
Pulse discharge power (kW)	25 (for 10 seconds)	40 (for 10 seconds)
Maximum regenerating pulse (10 s; kW)	20 (50 Wh pulse)	35 (97 Wh pulse)
Total available energy (kWh)	0.3	0.5
Round trip efficiency (%)	>90–25 Wh cycle	>90–50 Wh cycle
Cycle life for specified SOC increments (cycles)	300-k 25-Wh cycle (7.5 MWh)	300-k 50-Wh cycle (15 MWh)
Cold-cranking power at •30°C (three 2-second pulses, 10-s rests between; kW)	5	7
Calendar life (years)	15	15
Maximum weight (kg)	40	60
Maximum volume (liters)	32	45
Production price @ 100K units/year ($)	500	800
Maximum operating voltage (Vdc)	<400 maximum	<400 maximum
Minimum operating voltage (Vdc)	>0.55 × V_{max}	>0.55 × V_{max}
Maximum self-discharge (Wh/d)	50	50
Operating temperature (°C)	•30 to +52	•30 to +52
Survival temperature (°C)	•46 to +66	•46 to +66

Barriers

Batteries can be designed to achieve either a high power-to-energy ratio, as in an HEV, or a moderate power-to-energy ratio, as in an EV. Today, batteries designed for high power-to-energy ratios can deliver 300,000 shallow discharge cycles in a lifetime, and they meet or exceed most of the performance targets. However, larger, energy-dense systems have difficulty meeting the requirement of 1000 deep discharge cycles over the life time. In addition, state-of-the-art batteries meeting some or most of the FreedomCAR performance targets fall short of the cost goals. Technical barriers can be characterized under one of four headings: cost,

Table 12. Energy Storage targets for electric vehicles: 40 kWh			
Characteristics	**Mid-term goal**	**Minimum goals for long-term commercialization**	**Long-term goal**
Power density (W/L)	250	460	600
Specific power—discharge, 80% DOD/10 second (W/kg)	150	300	400
Specific power—regeneration, 20% DOD/10 s (W/kg)	75	150	200
Energy density—C/3 discharge rate (Wh/L)	135	230	300
Specific energy—C/3 discharge rate (Wh/kg)	80	150	200
Power : energy ratio	2 : 1	2 : 1	2 : 1
Total energy (kWh)	40	40	40
Life (years)	5	10	10
Cycle life—80% DOD (cycles)	600	1000 to 80% DOD, 1600 to 50% DOD, 2670 to 30% DOD	1000
Power and capacity degradation (% of rated spec.)	20	20	20
Ultimate price—10,000 units @ 40 kWh ($/kWh)	150	<150 ($75/kWh desired)	100
Operating environment (°C)	–30 to 65	–40 to 50 20% performance loss (10% desired)	–40 to 85
Normal recharge time (hours)	6	6 (4 desired)	3 to 6
High rate charge	40–80% SOC in 15 minutes	20–70% SOC in <30 minutes @ 150 W/kg (<20 min.@ 270 W/kg desired)	40–80% SOC in 15 minutes
Continuous discharge in 1 hour—no failure (% of rated energy capacity)	75	75	75

Table 13. Proposed Energy Storage targets for fuel cell vehicles (FCVs)		
FreedomCAR FCV goals characteristics	**FCV battery minimum**	**FCV battery maximum**
Pulse discharge power (kW)	25 (for 18 second)	75 (for 18 second)
Maximum regeneration pulse (kW)	22 (for 10 second)	65 (for 10 second)
Total available energy (kWh)	1.5	5
Round trip efficiency (%)	>90	>90
Cycle life (cycles)	TBD (15 year life equivalent)	TBD (15 year life equivalent)
Cold-start at •30°C (TBD kW for TBD min.; kW)	5	5
Calendar life (years)	15	15
Maximum weight (kg)	40	100
Maximum volume (liters)	30	75
Production price @ 100K units/year ($)	500	1,500
Maximum operating voltage (Vdc)	≤440 maximum	≤440 maximum
Minimum operating voltage (Vdc)	≥0.5 × V_{max}	≥0.5 × V_{max}
Maximum self-discharge (Wh/d)	50	50
Operating temperature (°C)	•30 to +52	•30 to +52
Survival temperature (°C)	•46 to +66	•46 to +66

performance, life, and abuse tolerance. Of these, cost is the overriding factor, and the other three must be pursued with a continual consideration of their impact on battery cost. Each of these barriers has been developed in collaboration with the technical teams and battery manufacturers.

A. **Cost.** Batteries are typically designed for either high-power or high-energy applications. In the former case, the electrodes are constructed with very high surface area, minimizing the amount of active material in the cell and maximizing the amount of inactive material (such as separator and current collectors). For higher-energy systems, the reverse is true; electrodes are made as dense and thick as possible to maximize the energy density. Therefore, based on the type of technology, the relative costs of the components can vary widely. The major contributors to the cost barrier that will be addressed are the separator, the cathode, and the cost of processing the highly reactive components into a functioning Li-ion battery.

B. **Performance.** Systems optimized for different applications may need to meet different performance targets. Several general barriers are limiting performance and will continue to be addressed, including low-temperature performance, high-energy-system performance, and the energy density of ultracapacitors.

C. **Life.** Hybrid systems with conventional engines have a life target of 15 years. EVs are expected to achieve a life target of 10 years. Three technical barriers must be overcome to achieve these life goals: accurate life predictions are presently not available, a correlation of life to micro changes is lacking, and the continual introduction of new low-cost battery materials on the open market requires a rapid method of screening those that can meet the life requirements.

D. **Abuse tolerance.** It is critical that any new technology introduced in a vehicle be safe under normal and extreme operating conditions. The specific technical barriers that will be addressed include abuse tolerance during high-temperature exposure, overcharge conditions, and impact or crush situations.

Approach

The approach to overcoming the technical barriers must be tailored to the needs of the automobile industry. As mentioned, these needs are quite broad, ranging from relatively small 42V systems that would be adequate for a vehicle designed to operate in a minimum “start/stop” mode, to the moderate-size, high-power systems for use in HEVs and fuel cell vehicles, to the large batteries needed for EVs. These needs will not be met with a single battery, and they may not be met with a single battery chemistry.

In response to these needs, a range of tasks are implemented, from hardware development with industrial contractors to mid-term R&D and long-term research. The tasks begin with the establishment of technical requirements by FCVT in cooperation with industry. Next, batteries available in the marketplace are evaluated against these requirements. If the requirements cannot be met, additional R&D is undertaken, consisting of either short-term directed research (applied research), or more long-term exploratory research.

In all cases, the R&D is directed at overcoming specific technical problems so that the needs of the automotive industry are met. The R&D activities leverage the efforts of many parts of the electrochemical community, including universities, national laboratories, and small and large businesses.

General focus areas. The following are specific tasks that FCVT is currently focusing on and plans to continue developing over the next several years.

- Establish and reaffirm the Fuel Cell and Systems Analysis technical teams' performance targets for batteries for 42V and hybrid, fuel cell, and electric vehicle systems.
- Establish hardware development projects with qualified battery developers to develop batteries for validation testing against the technical targets.
- Perform independent validation testing of developer-supplied hardware.
- Manage an applied battery research sub-activity that focuses on immediate technical barriers that inhibit the attainment of established performance and cost targets for batteries.
- Manage a long-term battery research sub-activity that addresses fundamental problems impeding the development of advanced batteries, develops and evaluates novel battery materials, and broadens advanced diagnostic and modeling capabilities.

As part of FCVT's management of all of its activities, periodic reviews are conducted to ensure that work is appropriately focused. For example, merit reviews before an independent panel of battery and automotive experts are held to assess the quality and relevance of the work.

Task Descriptions

To implement this approach, specific tasks, described in Tables 14–17, have been identified under the development, applied battery research, long-term exploratory research, and other research activities.

Development

FCVT works closely with the car makers through the FreedomCAR Energy Storage technical team in carrying out all of the technical tasks, particularly in the development area. The tasks planned in development are shown in Table 14.

Applied Battery Research

This sub-activity addresses critical, cross-cutting barriers impeding the adoption of technologies that are close to being adopted by the marketplace. Specific task details are presented in Table 15.

Long-Term Exploratory Research

The long-term exploratory research sub-activity consists of research on new electrochemical systems that have the potential to meet the technical targets. The

Table 14. Task descriptions for the development area

Task	Title	Duration/ barriers
1	Establish Targets, Benchmark and Assess Technologies, and Assess Ultracapacitors • Establish and maintain technical targets for the 42V system, HEV, electric vehicle, fuel cell vehicle, and heavy-duty hybrid batteries. This is a critical step because it provides the R&D community clear goals for their work. The targets that have already been determined are presented earlier in this section • Pursue the continuous evaluation of available technology. Evaluate new technologies and commercial products as they become available, and combine data from these studies with similar data from other development contracts to identify areas for additional R&D • Assess technologies based on the results of current benchmark testing and a thorough review of other available data. If the assessment is positive, begin development with an established manufacturer, potentially to support application to heavy-duty hybrid vehicles	120 months Barriers A, B, C, D (begin 1Q 1999)
2	Develop 42V Battery, Issue Solicitation for FCV Battery Development, Develop Li-ion/ Gel Polymer Battery, and Develop Li/S Technology • Based on cost and the ability to meet performance targets, increase the emphasis of the Energy Storage technical team on the development of 42V systems and reduce the emphasis on high-voltage batteries for HEVs • Prepare and publicly advertise a solicitation to attract qualified battery developers to develop hardware for validation testing against fuel cell vehicle targets • Initiate plans with a qualified developer to further investigate the feasibility of an Li-ion/gel polymer system, a leading candidate for meeting all FreedomCAR targets, including safety. This task involves the go/no-go decision of determining if Li-ion polymer meets the life requirement by 12/31/04 • Because Li/S shows great promise as a high-energy battery couple, and its continued evaluation and development are critical to the success of high-energy storage systems, focus on addressing the lithium/sulfur isolation issue through the development of new processes to protect the lithium anode. Then evaluate these processes, with one developer being chosen to continue development of the most promising technology. Determine if Li/S meets the cycling requirement by 11/30/2006, a go/no-go decision point	84 months Barriers A, B, C, D (begin 1Q 2003)

emphasis is on understanding fundamental processes and limitations and using this knowledge to develop new and improved materials and components. This work requires a steady, focused, long-term commitment.

Baseline systems for exploratory research are defined to help maintain a level of cohesiveness and provide continuous focus to the investigators. Specific task details are shown in Table 16.

Other Research

Other activities carried out by FCVT that are not exclusive to one of the preceding sub-activities are presented in Table 17. These tasks include the modeling of thermal properties, development of both battery and full system models, and ongoing participation in SBIR.

Table 15. Task descriptions for applied battery research

Task	Title	Duration/ barriers
3	Screen Materials, Study Power Fade, Study Overcharge, Improve Abuse Tolerance, and Develop Advanced System • Rapidly screen and evaluate new materials being offered by vendors by using advanced diagnostic techniques to determine whether they meet performance and life targets. Disseminate results of the screening to the battery community through formal reports and quarterly reviews • Apply a range of diagnostic techniques to a group of cells aged to various degrees in order to determine the exact cause of power fade in cells designed for high-power applications • Expose cells designed specifically for high-power applications to overcharge and high-temperature conditions to increase understanding of the chemical processes occurring that may result in thermal runaway and cell failure • Evaluate additives, coatings, and new active materials designed specifically to mitigate the effects of exposure to overcharge and/or high temperatures • Pursue work under way to define an advanced electrochemical system with lower cost, higher stability, and improved low-temperature capability. This is being done through advanced electrolyte modeling, advanced anode screening and development, and electrochemical testing and diagnostics	132 months Barriers A, B, C, D (begin 1Q 1999)
4	Develop Accelerated Life Testing Protocols, and Evaluate Enhanced Quality Control • Validate and publish by the end of 2005 a robust Accelerated Life Testing protocol that will provide the battery industry with a statistically accurate prediction of cell life within a short time period. This protocol is to be user-friendly to encourage rapid adoption by battery developers • Undertake a diagnostic effort to address issues related to cell-to-cell reproducibility, material handling, and quality control procedures during electrode manufacturing. This diagnostic effort will lead to more cost-effective cell production and lower unit cost	120 months Barriers B, C (begin 1Q 1999)

Table 16. Task descriptions for long-term exploratory research

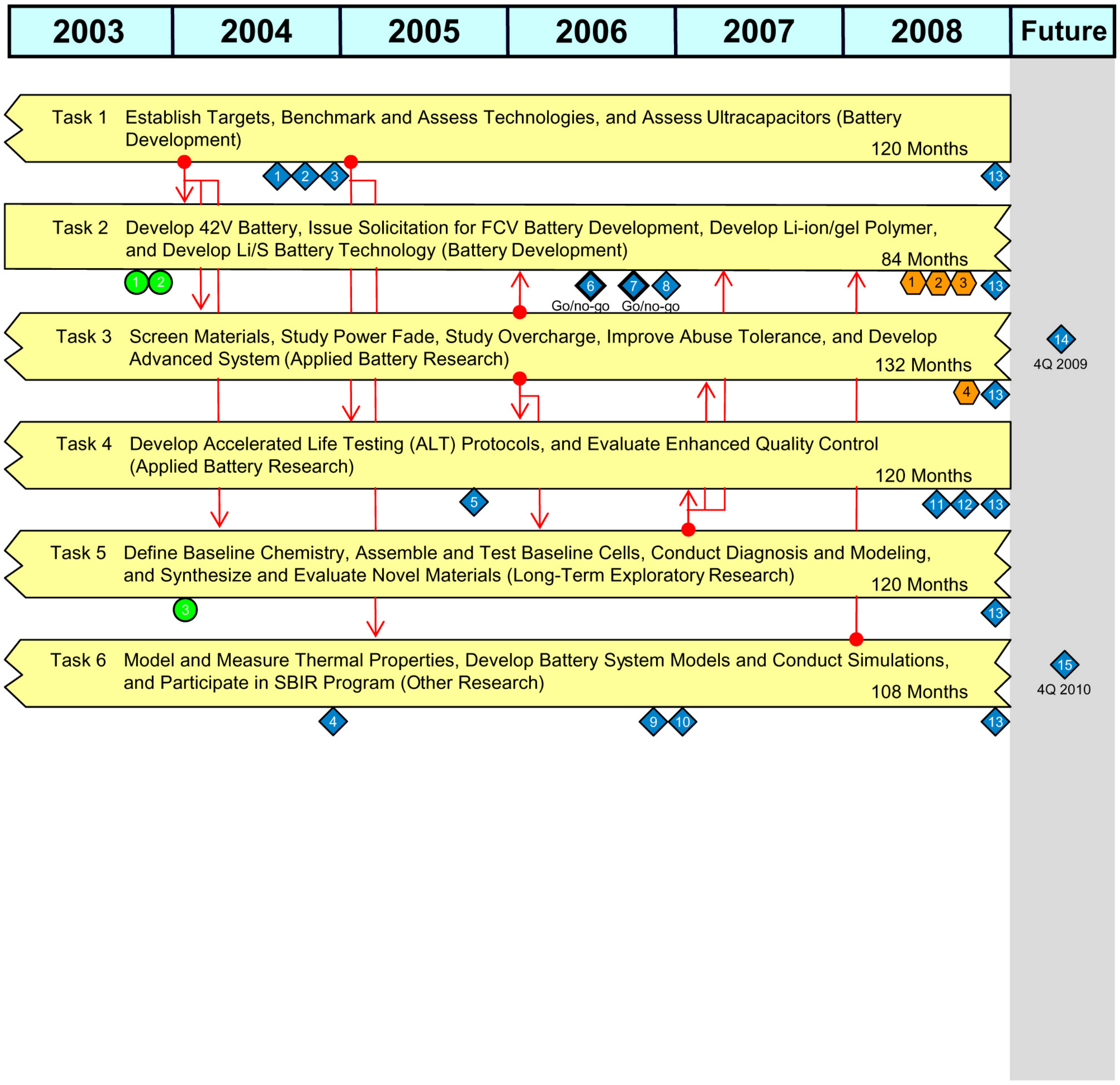
Task	Title	Duration/ barriers
5	Define Baseline Chemistry, Assemble and Test Baseline Cells, Conduct Diagnosis and Modeling, and Synthesize and Evaluate Novel Materials • Review the baseline and exploratory systems every 2 to 3 years and revise them as needed to provide direction and cohesiveness to investigators • Assemble materials acquired from the anodes, electrolytes, and cathodes areas or from outside sources into laboratory cells and test them (Cell Development group) • Examine virgin materials, as well as materials from uncycled and cycled cells, to determine failure mechanisms (Diagnostics group). Model the baseline systems and optimize the design of each system for applications where each system is more likely to meet performance targets. Model growth of the surface-electrolyte interface layer, structural changes during cycling, and ohmic losses due to poor particle-to-particle contact (Modeling group) • Synthesize novel materials offering the possibility for improved cell performance, life, or cost (anodes, electrolytes, and cathodes group). Research on polymers may shift to gels where significant cost savings can be achieved	120 months Barriers B, C, D (begin 1Q 2001)

Table 17. Task descriptions for other research

Task	Title	Duration/ barriers
6	Model and Measure Thermal Properties, Develop Battery System Models and Conduct Simulations, and Participate in the SBIR Program • Measure thermal characteristics of batteries. Model the thermal performance of batteries and use computer-aided design tools to develop configurations with improved thermal performance. Give special attention to 42-V batteries for three classes of HEVs and to fuel cell systems. The effectiveness of high-frequency ac to preheat batteries at very cold temperatures is under study • Task engineers to work with battery developers to improve and validate energy storage models for system simulations. Researchers will use these models in optimization studies and target analyses for different platforms and vehicle types • Prepare SBIR topics each year, focusing on innovative technologies that stand a reasonable chance of technical success and market penetration. Subject to the availability of SBIR funding, publish these topics, review proposals, and make grants to the best proposals. This is an extremely valuable method for DOE to fund small, low-cost, high-risk research that promises to revolutionize the battery industry	108 months Barriers B, C (begin 1Q 2002)

Milestones

The task-level milestones showing the Energy Storage Group's plans for the next several years are shown in the network chart. The formal milestones exclude those concerned with management tasks (e.g., holding merit reviews and changing the direction of work based on developer needs).



Legend

Milestone

1. Establish battery performance targets for 42V system
2. Establish technical targets for fuel cell vehicle batteries
3. Establish technical targets for heavy hybrid vehicle energy storage systems
4. Develop validated math-based integrated energy storage models
5. Validate Accelerated Life Test (ALT) protocol
6. Determine if Li-S battery meets cycling requirements **(Go/no-go)**
7. Determine if Li-ion polymer battery meets life requirements **(Go/no-go)**
8. Issue solicitation for fuel cell vehicle battery development
9. Validate improved battery thermal management system
10. Validate experimental hardware for battery preheating
11. Validate performance against requirements for fuel cell vehicle battery targets
12. Finalize evaluated hardware for ultracapacitor and battery combinations for hybrid and fuel cell vehicles
13. Reaffirm all technical targets with the FreedomCAR tech teams
14. Validate $20/kW for high-power batteries
15. Validate low-cost, energy-efficient thermal management system

Supporting Input

1. 42V battery-related technical information (from industry)
2. Fuel cell vehicle battery-related technical information (from joint team of Vehicle Systems and Office of Hydrogen, Fuel Cells, and Infrastructure Program)
3. New battery technologies related technical information (from industry)

Technology Area Output

1. Prototype 42V battery (to Vehicle Systems)
2. Prototype heavy hybrid vehicle battery (to Heavy Hybrid Vehicle Systems)
3. Prototype battery with improved battery management system (to Vehicle Systems)
4. Hardware for ultracapacitor battery combinations for hybrid and fuel cell batteries (to Vehicle Systems)

4.4 ADVANCED POWER ELECTRONICS AND ELECTRIC MACHINES

Achieving FreedomCAR goals will require the development of new technologies for power electronics and electric machinery. The new technologies must be compatible with high-volume manufacturing; must ensure high reliability, efficiency, and ruggedness; and must simultaneously reduce cost, weight, and volume. Key components for fuel cell vehicles and HEVs include motors, inverters/converters, sensors, control systems, and other interface electronics. Figure 16 shows the Power Electronics and Electric Machines sub-activities with the resulting outputs and the collaboration between this activity and others.

This section discusses the needs and barriers specific to light vehicles. Heavy vehicle technologies are discussed in Section 4.2, Advanced Propulsion and Vehicle Efficiency Improvements.

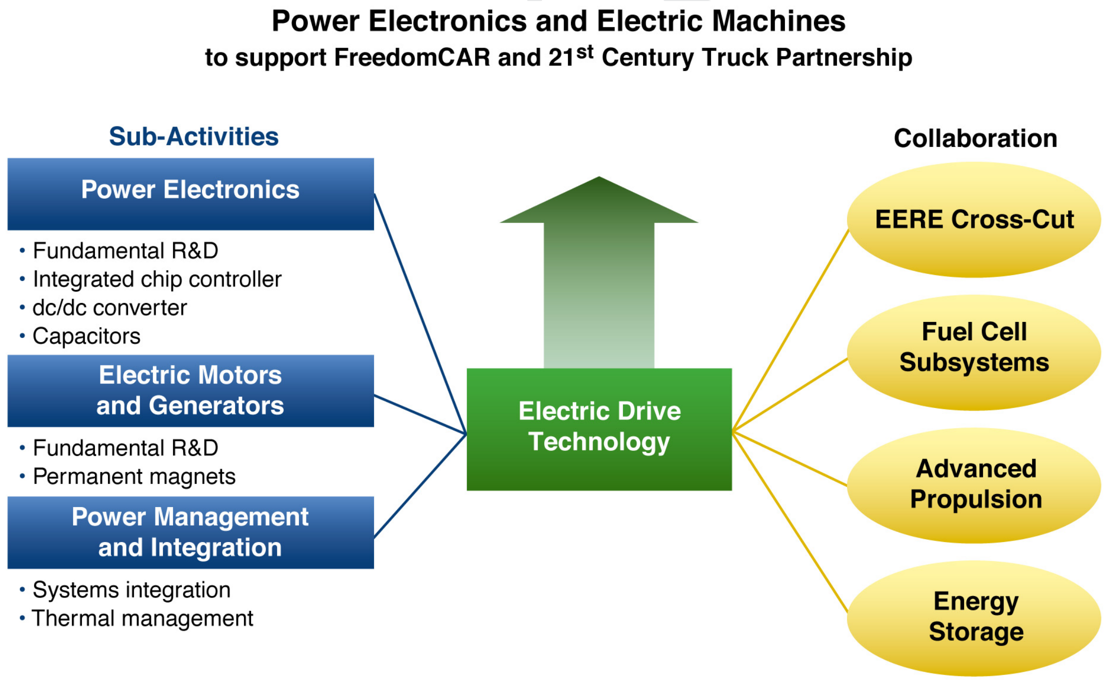


Figure 16. Power Electronics and Electric Machines sub-activities with the resulting outputs and the collaboration between this activity and others.

Goals

Develop by 2010 an integrated electronics system that costs no more than $12/kW peak and can deliver at least 55 kW of power for 18 seconds and 30 kW of continuous power. Additionally, the propulsion system will have an operational lifetime of 15 years (a FreedomCAR Partnership Goal).

Programmatic Status

The Advanced Power Electronics and Electric Machines Activity is divided into three sub-activities: (1) power electronics, (2) electric motors/generators, and (3) power management and integration.

Power Electronics

The power electronics sub-activity is focused on R&D for flexible, integrated, modular power inverters and electronics for power conditioning and control, including a power switch stage capable of running a variety of motors and loads.

An inverter is needed to convert dc power from a fuel cell or a battery to ac power for the motor. An automotive integrated power module (AIPM) has been developed that approaches the FreedomCAR targets for weight and cost, but only if the coolant temperature is lower than desired. Further research will focus on the use of (1) silicon carbide (SiC) semiconductors, which can be operated at much higher temperatures than current silicon (Si) semiconductors; (2) improved thermal management technologies; and (3) innovative topologies that have the potential for reducing the weight, volume, and cost of the system.

Capacitors account for a major fraction of the weight, volume, and cost of an inverter. Currently, electrolytic aluminum capacitors are used for applications below 450 V; but, in addition to being bulky, they cannot tolerate high temperatures; tolerate very little ripple current; have short lifetimes; and, when they fail, sometimes do so catastrophically. Two promising alternatives to electrolytic aluminum are polymer-film capacitors and ceramic capacitors. Polymer-film capacitors are used for voltages above 450 V and are less bulky, but they also cannot tolerate sufficiently high temperatures. Research to date has identified several candidate polymers with higher-temperature capabilities, and that research will continue with an emphasis on scale-up and manufacturing technologies. Research also will continue on ceramic capacitors, which have the greatest potential for volume reduction and the ability to tolerate very high temperatures. The emphasis for ceramic capacitors will be on ensuring a benign failure mode and lowering the cost.

Current motor controller technology revolves around digital signal processors, but external circuitry is still required to accomplish all of the functions necessary for efficient motor control. A new R&D effort is being initiated to develop a system on a chip that will provide the opportunity for considerable cost reduction.

Fuel-cell-powered vehicles will require a bi-directional dc/dc converter to interconnect the fuel cell power high-voltage bus and the low-voltage bus for vehicle auxiliary loads. A new R&D effort is being initiated to develop innovative designs and demonstrate commercial viability in high-volume production. Technical issues to be addressed include choice of topology, filtering requirements, switches, switching frequency, radio-frequency interference (RFI) considerations, thermal management, and types of magnetic components. Cost, reliability, weight, and volume are critical factors.

Electric Motors and Generators

Emphasis in this sub-activity is on advanced motor technologies, performance, low-cost materials, and thermal management systems that will yield higher power densities and cost-effective solutions.

Induction motors have the advantage of being the most widely manufactured and used, but they cannot meet the FreedomCAR requirements of cost, weight, volume, and efficiency; and the likelihood of achieving additional improvements is low because the technology is mature. A permanent magnet motor has the highest power density; but it does not have a sufficient constant power speed range, and its costs are too high. Switched reluctance motors are potentially the lowest-cost candidate but have serious problems in terms of high torque ripple, high noise, and low power factor.

The automotive electric motor drive (AEMD) task has developed an external permanent magnet motor that met the power requirements but fell considerably short of cost, weight, and volume goals for FreedomCAR. Future research will focus on alternate designs for a permanent magnet motor and on field weakening to increase the constant power speed range.

The unacceptably high cost of permanent magnet motors is due to the high cost of magnet materials, magnet manufacturing, and rotor fabrication. Research is being conducted on polymer-bonded particulate magnets with the objectives of increasing the useful operating temperature from 150 to 200ºC and decreasing the cost to about 25% of its current price of approximately $90/kg.

Power Management and Integration

This sub-activity emphasizes system issues such as the integration of motor and power control technologies. A primary research focus is the thermal management of inverters and motors with two phase-cooling technologies. Advanced component modeling, fabrication, and manufacturing techniques are being investigated. Work is under way on integrating emerging power electronic technologies in order to manage and control high-power components, which will provide rapid, bidirectional energy flow to improve performance and lower costs.

Targets

Technical targets for inverters and motors for a traction powertrain are presented in Table 18. The actual power rating (kW) and the cost ($) are highly dependent on a specific vehicle's electrical requirements. The greatest challenge is cost, which is intensified by the need to simultaneously increase performance and reduce size and weight. It is anticipated that efforts beyond 2006 will be focused on an integrated inverter/motor system. The trend toward an integrated system encompassing the motor, inverter, cooling system, and all interface connections is represented in the targets presented in Table 19.

Barriers

Barriers to achieving the technical targets include the following:

A. **Cost.** Materials, processing, and fabrication technologies for power electronics and electric machinery are too costly for automotive applications.

B. **Volume and thermal management.** Power electronics and electric machines are bulky and difficult to package for automotive applications. Current thermal management techniques are inadequate to dissipate heat in high-power-density

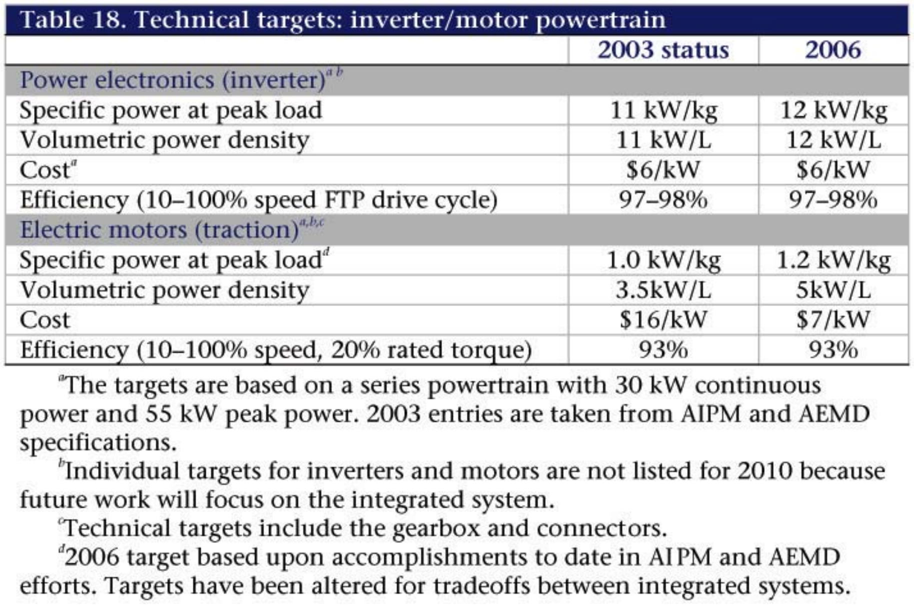


Table 18. Technical targets: inverter/motor powertrain

	2003 status	2006
Power electronics (inverter)[a b]		
Specific power at peak load	11 kW/kg	12 kW/kg
Volumetric power density	11 kW/L	12 kW/L
Cost[a]	$6/kW	$6/kW
Efficiency (10–100% speed FTP drive cycle)	97–98%	97–98%
Electric motors (traction)[a,b,c]		
Specific power at peak load[d]	1.0 kW/kg	1.2 kW/kg
Volumetric power density	3.5kW/L	5kW/L
Cost	$16/kW	$7/kW
Efficiency (10–100% speed, 20% rated torque)	93%	93%

[a] The targets are based on a series powertrain with 30 kW continuous power and 55 kW peak power. 2003 entries are taken from AIPM and AEMD specifications.

[b] Individual targets for inverters and motors are not listed for 2010 because future work will focus on the integrated system.

[c] Technical targets include the gearbox and connectors.

[d] 2006 target based upon accomplishments to date in AIPM and AEMD efforts. Targets have been altered for tradeoffs between integrated systems.

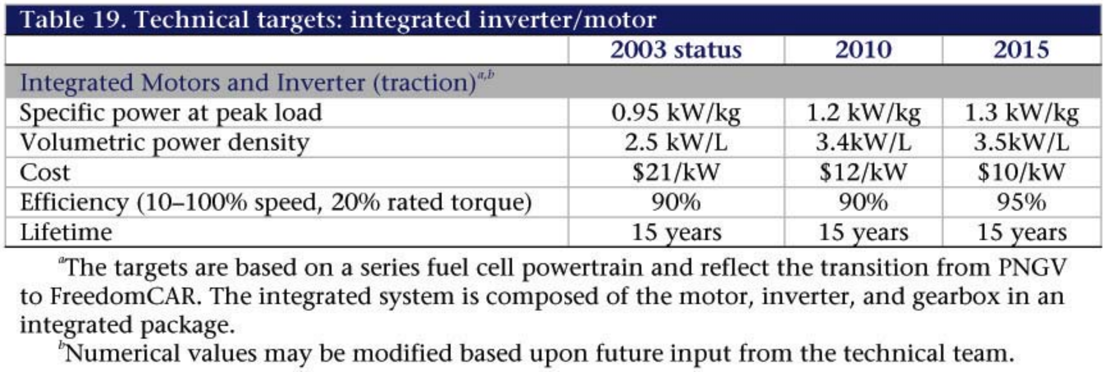


Table 19. Technical targets: integrated inverter/motor

	2003 status	2010	2015
Integrated Motors and Inverter (traction)[a,b]			
Specific power at peak load	0.95 kW/kg	1.2 kW/kg	1.3 kW/kg
Volumetric power density	2.5 kW/L	3.4kW/L	3.5kW/L
Cost	$21/kW	$12/kW	$10/kW
Efficiency (10–100% speed, 20% rated torque)	90%	90%	95%
Lifetime	15 years	15 years	15 years

[a] The targets are based on a series fuel cell powertrain and reflect the transition from PNGV to FreedomCAR. The integrated system is composed of the motor, inverter, and gearbox in an integrated package.

[b] Numerical values may be modified based upon future input from the technical team.

systems. Achieving cost and goals is difficult because the components must be packaged and cooled effectively.

C. **Weight.** Current electric machinery and power electronics controllers are too heavy and require additional structural weight for support.

D. **Reliability and ruggedness.** Power electronics modules and motors that meet the requirements for size and weight are not rugged or reliable enough to operate in harsh environments (e.g., extreme temperatures, humidity, dirt) for 150,000 miles or 15 years. Also, the operating and shelf life of energy storage (or buss) capacitors is only 5 years under moderate conditions.

These barriers must be considered together; one cannot be resolved at the expense of another. Performance must be improved, costs decreased, and size and weight reduced simultaneously.

Approach

The Power Electronics and Electric Machine effort focuses on R&D in key technologies that will enable achievement of the technical targets of the FreedomCAR Partnership. The FCVT Program partners with automobile component suppliers to develop advanced technologies suitable for introduction into the marketplace. This cooperation ensures that the technical attributes, automotive-scale manufacturing, and cost sensitivities are addressed in a timely fashion and that the resulting technologies reside with companies that are willing and able to supply derived products to the automobile companies. National laboratories, universities, and small businesses will focus high-risk enabling technology R&D on overcoming the critical technology barriers. This research will be coordinated with the electrical and electronics FreedomCAR technical team.

Current and Pending Elements

Current and pending elements of Advanced Power Electronics and Electric Machines R&D are listed in Table 20. Elements are being conducted by companies under cooperative agreements and by national laboratories and universities to support FVCT Program objectives. The Power Electronics elements related to a controller on a chip and a dc/dc converter are expected to start in FY 2004. Timing for the pending element on an integrated system will be determined in the near future.

Task Descriptions

A description of each technical task, along with the estimated duration and the technical barriers associated with the task, is provided in Table 21.

Table 20. Current and pending elements (pending elements are printed in *italics*)

Elements	Objective/target	Benefit achieved
Power Electronics (Task 1)		
AIPM	5 kW/kg, 12 kW/L, $7/kW, >97% efficiency	Increased specific power and efficiency Reduced cost, volume, and weight
Controller on a chip	*Integrate functions and include necessary external circuitry in single semiconductor device*	*Performance targets achieved* *Reduced cost, volume, and weight*
dc/dc converter	*Achieve high-voltage (400-V) to 12-V output with 42-V option*	*Increased specific power and efficiency* *Reduced cost, volume, and weight*
Z-Source converter	*Combine dc/dc converter with dc/ac inverter into single-stage power conversion circuit*	*Reduced cost, volume, and weight and increased constant power speed ratio*
Higher-temperature inverter	*Increase useful operating temperature of inverter*	*Performance targets achieved* *Reduced cost, volume, and weight*
Capacitors	Produce a polymer-film dielectric that can operate continuously at 110°C Develop high-dielectric-constant, thin-film capacitors	Increased reliability and robustness Reduced cost and volume
Power Electronics R&D	Fundamental R&D	Increased specific power, efficiency, and thermal performance Reduced cost, volume, and weight

Table 20 (continued)

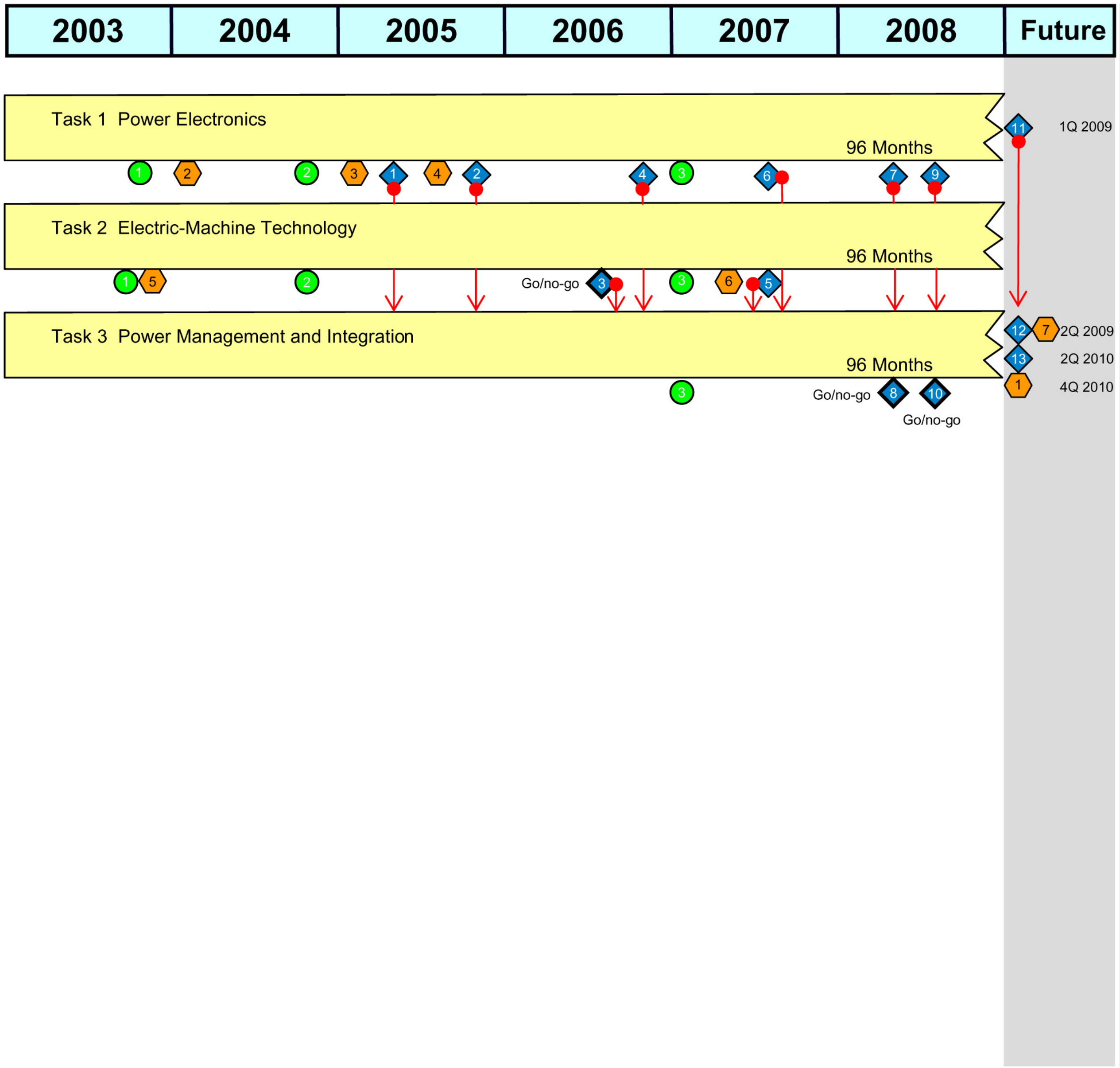
Elements	Objective/target	Benefit achieved
Electric Motors and Generators (Task 2)		
AEMD	1.6 kW/kg, 5 kW/L, $11/kW, >93% efficiency	Reduced cost, volume, and weight
New-configuration machine	*Develop interior permanent magnet motor that will meet FreedomCAR targets for series system*	*Performance targets achieved* *Reduced cost, volume, and weight*
Permanent magnets	Reduce cost, increase maximum operating temperature to 200°C Increase energy product of NdFeB permanent magnets by 25%	Reduced cost, volume, and weight
Electric Machinery R&D	Fundamental R&D	Increased efficiency, improved thermal characteristics Reduced cost, volume, and weight
Power Management and Integration (Task 3)		
Integrated system	*15-year lifetime, capable of 55 kW for 18 s and 30 kW continuous*	*Increased specific power and efficiency* *Reduced cost, volume, and weight*
Thermal management	Improve thermal characteristics of power electronics and motors with combination of high-temperature materials and advanced cooling strategies	Increased power density and reliability, lower cost

Table 21. Tasks for Power Electronics and Electric Machines

Task	Title	Duration/ barriers
1	Power Electronics • Develop improved inverter/converter architectures and topologies, including special buss bar designs, and less expensive transistors to allow faster switching and enhanced performance • Develop improved packaging concepts, focusing on component integration with improved thermal management • Develop improved low-cost dielectric materials and improved capacitors with high-temperature, high-current capabilities, low equivalent-series resistance, and long operating lifetimes • Develop efficient control algorithms and sensorless control techniques • Develop a system-on-a-chip semiconductor controller suitable for automotive use • Develop a dc/dc converter suitable for automotive fuel cell applications	96 months Barriers A, B, C, D
2	Electric Motors and Generators • Develop advanced motor materials and manufacturing processes to reduce costs • Develop lower-cost magnet materials without sacrificing performance • Develop improved technologies for candidate motors	96 months Barriers A, B, C, D
3	Power Management and Integration • Develop and fabricate integrated motor/inverter drive systems with emphasis on cost, density, reliability, and efficiency • Develop advanced thermal management techniques for the inverter, motor, and other vehicle systems • Develop steady-state and dynamic electric-drive-system computer models, including the capability to determine performance/cost trade-offs for drive systems	96 months Barriers A, B, C, D

Milestones

The milestones for this activity are listed in the network chart.



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Milestone

1. Build inverter with SiC components and evaluate thermal and performance improvements
2. Receive semiconductor motor controller deliverables
3. **Go/no-go.** Verify that developments in field-weakening techniques contribute to attaining technical targets for permanent magnet motors. If not, discontinue work on field-weakening techniques
4. Receive high-voltage to 42V/12V dc/dc converter deliverables for testing and evaluation
5. Validate contribution of developments in magnet materials to technical targets for motors
6. Validate improvements in inverter packaging methods
7. Receive improved capacitor for test and evaluation
8. **Go/no-go.** Evaluate progress toward development of integrated motor-controller and decide whether to continue, downselect, or terminate
9. Evaluate newly developed component technologies in an automotive inverter
10. **Go/no-go.** Validate improved thermal-management techniques resulting in size, weight, and cost reductions of at least 10% on components, or delay work on system-level electric-power management
11. Evaluate sensorless technology in an automotive application
12. Complete a common motor/inverter thermal-management system
13. Complete integrated motor/inverter system

Technology Program Output

1. Integrated inverter/motor to meet FreedomCAR goals to Vehicle Systems Analysis
2. Prototype AIPM to Vehicle Systems Analysis
3. Controller on a chip to Vehicle Systems Analysis
4. dcv/dc converter to Vehicle Systems Analysis
5. Prototype AEMD to Vehicle Systems Analysis
6. Prototype internal PM motor to Vehicle Systems Analysis
7. Thermal-management system to Vehicle Systems Analysis

Supporting Input

1. Requirements for power, weight, volume, and cost for power electronic components and electric machines from industry
2. Battery targets for fuel cell vehicles from Energy Storage
3. Fuel cell performance characteristics from HFCIT

4.5 ADVANCED COMBUSTION ENGINE R&D

Advanced Combustion Engine R&D activity efforts are focused on removing critical technical barriers to commercialization of higher-efficiency, advanced ICEs in light-duty, medium-duty, and heavy-duty vehicles. This activity supports the mission of FCVT to develop more energy-efficient and environmentally friendly highway transportation technologies that enable the United States to use less petroleum. This activity is focused on improving engine efficiency while meeting future federal and state emissions regulations through a combination of (1) combustion technologies that minimize in-cylinder formation of emissions and (2) aftertreatment technologies that further reduce exhaust emissions. More-specific goals are to improve the peak brake thermal efficiency of ICEs for light-duty applications from 30 to 45% by 2010, and for heavy-duty applications from 40 to 55% by 2012 while meeting cost, durability, and emissions constraints. Work is done in collaboration with industry, national laboratories, and universities and in conjunction with the FreedomCAR partnership and the 21st CTP.

Advanced ICEs are a key element in the pathway to achieving the goals of the President’s FreedomCAR and Hydrogen Fuel Initiative for transportation. Advanced engine technologies being researched and developed will allow the use of hydrogen as a fuel in ICEs, providing an energy-efficient interim hydrogen-based powertrain technology in the ultimate transition to hydrogen-/fuel-cell-powered transportation vehicles. The FCVT Advanced Combustion Engine R&D activity is broken down into sub-activities and outputs, along with collaborations, as shown in Figure 17.

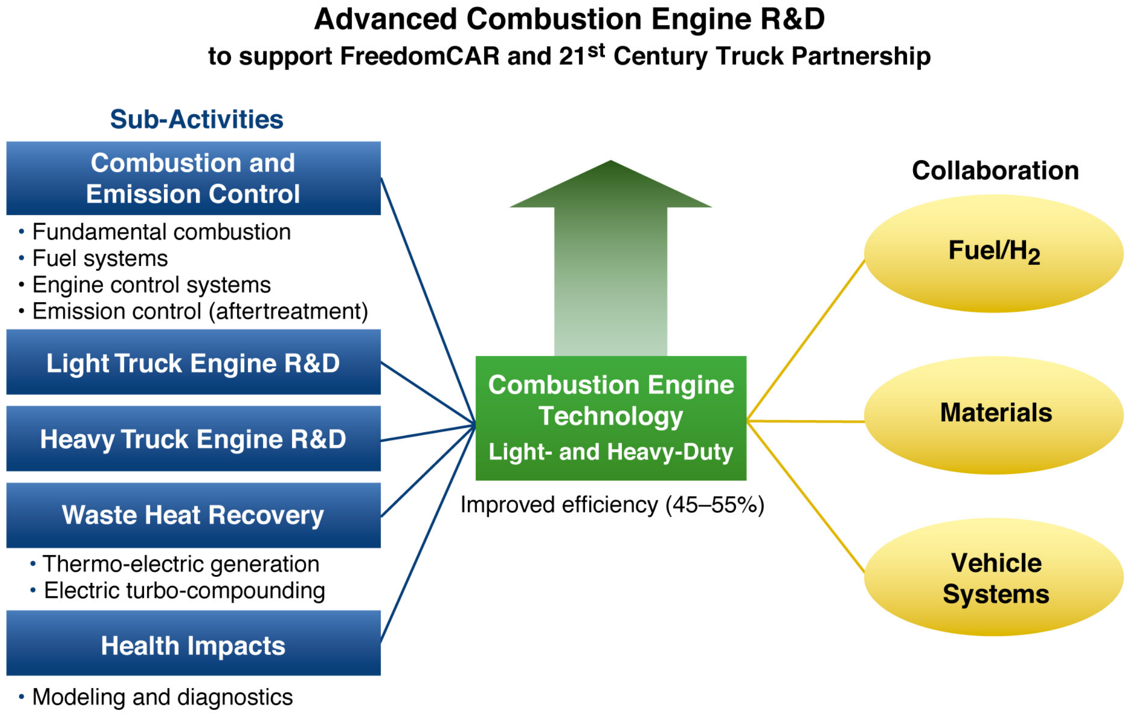


Figure 17. Advanced Combustion Engine R&D sub-activities, outputs, and collaborations.

4.5.1 Combustion and Emission Control R&D

The Combustion and Emission Control R&D sub-activity focuses on enabling technologies for energy-efficient, clean vehicles powered by advanced ICEs using clean hydrocarbon-based and non-petroleum-based fuels and hydrogen. R&D has been focused on developing technologies for light-, medium-, and heavy-duty compression ignition direct-injection (CIDI) engines and is being transitioned to developing technologies for advanced engines operating in combustion regimes that will further increase efficiency and reduce emissions to near-zero levels.

Goals

The FreedomCAR partnership technology goals for ICEs are as follows:

- By 2010, an ICE powertrain system costing \$30/kW, having a peak brake engine efficiency of 45% and meeting emission standards.
- An ICE powertrain system operating on hydrogen with a cost target of \$45/kW by 2010 and \$30/kW in 2015, having a peak brake thermal efficiency of 45% and meeting emissions standards (this goal is shared with HFCIT).

The following goals are intended to enable FCVT to meet energy-efficiency improvement targets for advanced combustion engines (consistent with the FreedomCAR Partnership goals) suitable for passenger cars and light trucks, as well as to address technology barriers and R&D needs that are common between light- and heavy-duty vehicle applications of advanced combustion engines.

- By 2004, achieve CIDI engine efficiency of at least 43% and, combined with emission control devices, meet EPA Tier 2, Bin 5 full-useful-life emissions in a light-duty vehicle using diesel fuel (specified by the Fuels Technology activity) with a fuel economy penalty of not more than 5%.
- By 2007, achieve CIDI engine efficiency of at least 45% and, combined with emission control devices, meet EPA Tier 2, Bin 5 in a light-duty vehicle using diesel fuel (specified by the Fuels Technology activity) with a fuel economy penalty of not more than 3%.
- By 2010, develop the understanding of novel low-temperature engine combustion regimes needed to simultaneously enable engine efficiency of 46% with a fuel economy penalty of less than 1%.

Programmatic Status

The CIDI engine, an advanced version of commonly known diesel engines, is the most promising technology for achieving dramatic energy-efficiency improvements in light-duty vehicle applications where it is suited to both conventional and hybrid-electric powertrain configurations. The CIDI engine is also the primary engine for heavy-duty applications because of its high efficiency and durability. Moreover, the CIDI engine offers a propulsion platform with the potential for further significant efficiency improvements beyond its current capabilities. Although it is more efficient than conventional gasoline engines, if the CIDI engine is to become widely used in automotive applications and remain viable for heavy-duty applications, advancements will be required in the mid-term to further improve efficiency while meeting more stringent future emissions standards. Advancements will be required in clean combustion, emission control technology, and clean diesel fuels. Work on the CIDI engine for all applications, from light to heavy duty, supports the near- to mid-term goals of the FreedomCAR partnership and 21st CTP, more specifically, the continued development of advanced technologies that will dramatically reduce the fuel consumption and emissions of all petroleum-fueled vehicles while meeting mandated emissions regulations.

The advanced combustion engine work being undertaken will be applicable to both passenger vehicles (cars and light trucks) and commercial vehicles (medium and heavy trucks and buses). Laser diagnostics are used for measuring fuel injection, fuel-air mixing, combustion, and emissions formation processes in-cylinder. The results provide the knowledge base needed to (1) design combustion systems that enable maximum engine efficiency and compliance with emissions standards and (2) develop the simulation tools for effectively optimizing engine designs. In the longer term, further improvement of the advanced engine designs to be considered (e.g., increased expansion ratio, improved exhaust heat recovery, variable valve timing, reduced friction) and minimization of the emission reduction fuel economy penalty offer the potential for even further fuel efficiency gains for heavy- and light-duty vehicles.

Work is also undertaken in hydrogen-fueled ICE research that will provide an interim hydrogen-based powertrain technology that promotes the longer-range FreedomCAR Partnership goal of transitioning to a hydrogen-fueled transportation system. This goal is shared by FCVT and HFCIT. Hydrogen engine technologies being worked on have the potential to provide CIDI-like engine efficiencies with near-zero emissions.

Advanced fuel formulations and fuel quality are also crucial to achieving higher energy efficiencies and meeting emissions targets. The EPA rule mandating that the sulfur content of highway diesel fuel be reduced to less than 15 ppm starting in 2006 will greatly benefit the effectiveness, durability, and life of emission control devices. Because of the importance of clean fuels in achieving low emissions, R&D tasks will be closely coordinated with the relevant tasks of the Fuels Technologies Activity described in Sect. 4.7.

Targets

Presented in Table 22 are the technical targets for the Combustion and Emission Control sub-activity. Shown also are the FreedomCAR Partnership goals for both hydrocarbon- and hydrogen-fueled ICEs. These mostly apply to light-duty vehicles. The major technical targets in engines for light trucks and heavy trucks are discussed in Sections 4.5.2 and 4.5.3, respectively.

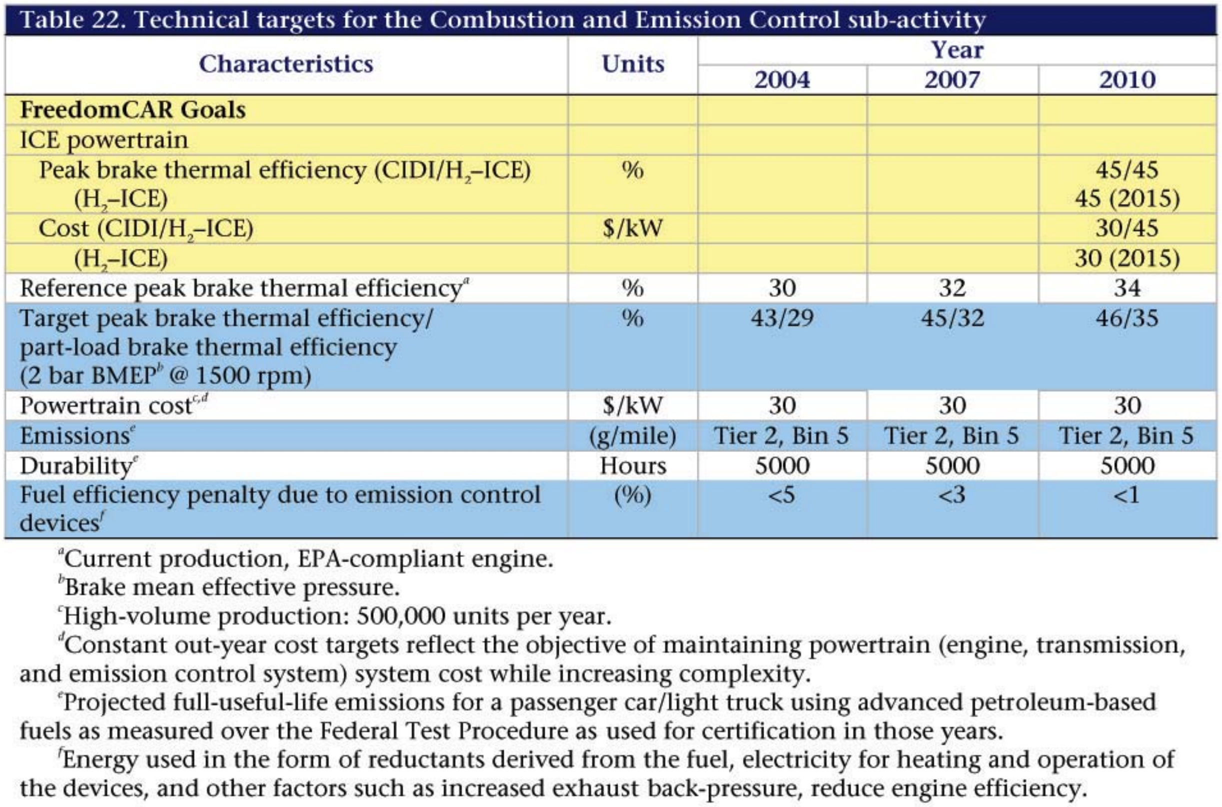


Table 22. Technical targets for the Combustion and Emission Control sub-activity

Characteristics	Units	Year		
		2004	2007	2010
FreedomCAR Goals				
ICE powertrain				
Peak brake thermal efficiency (CIDI/H_2–ICE) (H_2–ICE)	%			45/45 45 (2015)
Cost (CIDI/H_2–ICE)	$/kW			30/45
(H_2–ICE)				30 (2015)
Reference peak brake thermal efficiency[a]	%	30	32	34
Target peak brake thermal efficiency/ part-load brake thermal efficiency (2 bar BMEP[b] @ 1500 rpm)	%	43/29	45/32	46/35
Powertrain cost[c,d]	$/kW	30	30	30
Emissions[e]	(g/mile)	Tier 2, Bin 5	Tier 2, Bin 5	Tier 2, Bin 5
Durability[e]	Hours	5000	5000	5000
Fuel efficiency penalty due to emission control devices[f]	(%)	<5	<3	<1

[a] Current production, EPA-compliant engine.

[b] Brake mean effective pressure.

[c] High-volume production: 500,000 units per year.

[d] Constant out-year cost targets reflect the objective of maintaining powertrain (engine, transmission, and emission control system) system cost while increasing complexity.

[e] Projected full-useful-life emissions for a passenger car/light truck using advanced petroleum-based fuels as measured over the Federal Test Procedure as used for certification in those years.

[f] Energy used in the form of reductants derived from the fuel, electricity for heating and operation of the devices, and other factors such as increased exhaust back-pressure, reduce engine efficiency.

Barriers

The barriers to achieving the technical targets are as follows.

A. **Fundamental knowledge of engine combustion.** Engine efficiency improvement, engine-out emissions reduction, and minimization of engine technology development risk are inhibited by inadequate understanding of the fundamentals of fuel injection, fuel-air mixing, thermodynamic combustion losses, and in-cylinder combustion/emission formation processes over a range of combustion temperature regimes of interest, as well as by an inadequate capability to accurately simulate these processes. The lack of knowledge base will inhibit the development of combustion systems using advanced, low-temperature combustion (LTC) or mixed-mode combustion systems that operate effectively over the full load range of an engine. These advanced combustion systems offer significant potential for providing engines that operate with CIDI-like engine efficiencies over the full load range while meeting EPA Tier 2 emissions standards with greatly reduced aftertreatment system requirements.

B. **Emission control.** Meeting EPA oxides of nitrogen (NO_X) and particulate matter (PM) emissions standards with little or no fuel economy penalty will be one of the keys for market entry of CIDI and advanced combustion engines. NO_X adsorbers appear to be the most viable NO_X reduction devices for light-duty vehicles, but they are very sulfur-sensitive, resulting in an increased energy penalty over time to compensate for loss of activity. Others under consideration have their own technical barriers as well. Particulate trap technology is costly, and some regeneration technologies are energy-intensive. The most effective particulate trap technologies cause reductions in engine efficiency through increases in backpressure. While there is more experience with PM emission control devices than with NO_X control devices, PM control technology will likely be pushed to its limits in favor of controlling NO_X emissions, which currently is the more intractable of the two problems.

C. **Engine controls.** Effective sensing and control of various parameters will be required to optimize operation of engines in advanced LTC regimes over a full load-speed map similar to that of the CIDI engine. These include control of (1) ignition timing across the load-speed map, (2) the rate of heat release, and (3) transients and cold starts.

D. **Cost.** The emission control devices required by engines to meet emission targets add costs to the system. Better use of advanced LTC modes to reduce the formation of emissions in-cylinder will reduce aftertreatment system requirements and associated costs. In addition, CIDI engines and some of the engines envisioned that use LTC are more expensive than conventional, port fuel-injected, spark-ignited engines because the engine structures must be stronger to accommodate the inherently higher combustion pressures, and the high-pressure fuel injection systems must be correspondingly more robust.

Approach

The Combustion and Emission Control sub-activity will simultaneously address in-cylinder combustion and emission control, exhaust aftertreatment technologies, and fuel formulation strategies for the most cost-effective approach to optimizing advanced combustion engine efficiency and performance while reducing emissions to meet future EPA standards. Experimental data and validated computer simulation models will be developed to provide a more definitive understanding of the in-cylinder fuel injection, combustion, and emissions formation processes and the evolution of emissions in the aftertreatment systems. The models that will be developed will enable rapid and effective optimization of the fuel injection and combustion systems and the aftertreatment devices for maximum overall system efficiency, compliance with emissions standards, and cost-effectiveness. The experimental research and modeling tasks will allow a more effective evaluation of potential technologies and validation of technology selection. Working at the forefront of these new technologies will enhance the knowledge base that can be used by industry partners and suppliers (e.g., original equipment manufacturers, engine manufacturers, emission control device manufacturers, catalyst suppliers) to develop energy-efficient, cost-effective advanced engine/emission control systems.

Fundamental combustion R&D will focus on developing greater understanding of the combustion and emissions processes and their dependence on fuel spray characteristics, in-cylinder air motion, and fuel selection so that pathways to higher engine efficiencies and lower NO_X and PM from the engine can be identified. R&D tasks will include the identification of advanced combustion system concepts that enable high efficiencies and fuel injection strategies for implementing the advanced combustion systems, research on combustion systems for advanced fuels, investigation of mechanisms and strategies to reduce thermodynamic combustion losses, investigation of NO_X and PM formation mechanisms in the engine, and identification of potential fuel-derived reductants. Numerical and chemical kinetics models will be developed to guide the experimental combustion research.

Advanced combustion engine technologies that will be pursued operate in LTC regimes that can provide high, diesel-like efficiencies and have ultra-low engine-out NO_X and particulate levels. The engines that will be investigated include engines operating purely on LTC modes, such as the homogeneous charge compression-ignition engine (HCCI); and engines that use conventional CIDI or spark-ignited (SI) combustion modes for starting and at higher loads, and use LTC modes at moderate to light loads, referred to as mixed-mode operation. In the case of mixed-mode operation with CIDI at high loads, the high-efficiency, high-load capabilities of CIDI are coupled with the high-efficiency, low-emission capabilities of the LTC modes, overcoming the deficiencies in CIDI aftertreatment systems at light loads and the limited high-load capabilities of LTC modes. In the case of mixed-mode operation with SI at high loads, CIDI-like engine efficiencies can be achieved by using LTC at moderate to light loads to eliminate part-load throttling losses and to control emissions, while maintaining the high-load capabilities of conventional port-fuel-injected engines.

Research will also be undertaken to develop a fundamental knowledge base on very lean, low-temperature hydrogen combustion under high-pressure in-cylinder conditions. This will support both the development of advanced hydrogen-fueled engines and the simulation tools used to aid the development of the knowledge base and the optimization of engines. This will require improved understanding of hydrogen injection and fuel-air mixing processes; combustion stability, combustion duration and pre-ignition phenomena; emissions formation; and the effects of engine speed and load, combustion chamber geometry, and in-cylinder air motion (e.g., swirl) on hydrogen combustion and emissions processes.

Fuel systems R&D focuses on injector controls and fuel spray development. The fuel injection system pressure and fuel spray development influence the spray penetration and fuel-air mixing processes and thus combustion and emissions formation within the combustion chamber. These phenomena are being researched using X-ray and optical diagnostics. In-cylinder emissions reduction can also be achieved with very careful control of injection timing, duration, and rate shape. Recent developments have shown that the application of multiple injections in a cycle can result in much lower engine-out emissions.

Engine control systems R&D will focus on developing precise engine control and flexibility in engine controls that are enabling technologies for improved efficiency and emission reduction in advanced combustion engines. These control system technologies will facilitate adjustments to parameters such as intake air temperature, fuel injection timing, injection rate, variable valve timing, and exhaust gas recirculation (EGR) to allow advanced combustion engines to operate over a wider range of engine speed/load conditions. In addition, control strategies will be developed to enable the effective transition from low-temperature, low-emission modes of combustion used at lighter loads to conventional CIDI or SI combustion at higher loads (i.e., control strategies for mixed-mode operation).

Complex, precise engine and emission controls will require sophisticated feedback systems employing new types of sensors. NO_X and PM sensors are in the early stages of development and require additional advances to be cost-effective and reliable, but they are essential to control systems for these advanced engine/aftertreatment systems.

Development of technologies enabling LTC will be undertaken to achieve the best combination that enables meeting maximum fuel economy and performance requirements. These include variable compression ratio (VCR), variable valve timing, variable boost, advanced sensors, and exhaust emission control devices (to control hydrocarbon emissions at idle-type conditions) in an integrated system. Variable valve control, independent valve control, and VCR offer the potential for operating with the highest efficiency and providing control of ignition timing through control of in-cylinder temperature or internal EGR. These technologies can reduce engine-out NO_X emissions and thus reduce the need for ancillary systems such as external EGR.

Emission control system R&D tasks will focus on reducing the energy-efficiency penalty of emission control systems through development of more-effective emission control devices for reducing NO_X and PM in exhaust systems.

Research on improving the effectiveness of NO_X adsorbers for diesel engine exhaust aftertreatment will focus on (1) defining the optimum regeneration schedule with a lean-burn engine, (2) improving NO_X reduction at the lower exhaust temperatures of the duty cycle for light vehicles, and (3) determining long-term degradation mechanisms and susceptibility to sulfur poisoning. Work will continue on selective catalytic reduction (SCR) of NO_X using urea (ammonia) as a reductant. Several challenges will be addressed, such as issues of ammonia slip and other unregulated emissions, the complexity of the urea injection and control system for transient engine operation, and exploration of alternatives to urea. As lower engine-out emissions are achieved, continuous lean-NO_X catalysis again becomes a viable alternative. High-throughput combinatorial chemistry will be employed to develop lean-NO_X catalyst materials with higher conversion rates and greater durability. Several common issues—such as sulfur tolerance, reductant optimization, and long-term degradation mechanisms—crosscut among all the NO_X-reducing technologies and will be investigated.

PM-reduction devices face challenges in the areas of long-term degradation and the ability to regenerate effectively despite the relatively cool exhaust temperatures typical of light-duty CIDI-engines. The focus will be on the refinement of existing technologies and development of novel and innovative PM control technologies. Three different PM-reducing technologies—the catalyzed diesel particulate filter, the continuously regenerating diesel particulate filter, and the microwave-regenerable filter—will continue to be pursued. Research will focus on evaluations of their potential to meet the PM emissions targets, especially in conjunction with NO_X-reducing technologies. To help improve the understanding of PM formation and in-cylinder control, especially during engine transients, new high-energy, laser-based diagnostics with real-time capabilities for measuring and characterizing PM emissions at low concentrations will be used. Other PM enabling technologies that will be investigated include sulfur traps, sulfur-tolerant catalysts, and oxidizing catalysts used in conjunction with PM-reducing devices.

Task Descriptions

A description of each task, along with the estimated duration and the barriers associated with the task, is provided in Table 23. These tasks support the FreedomCAR Partnership short- and mid-term goals. They were initiated in January

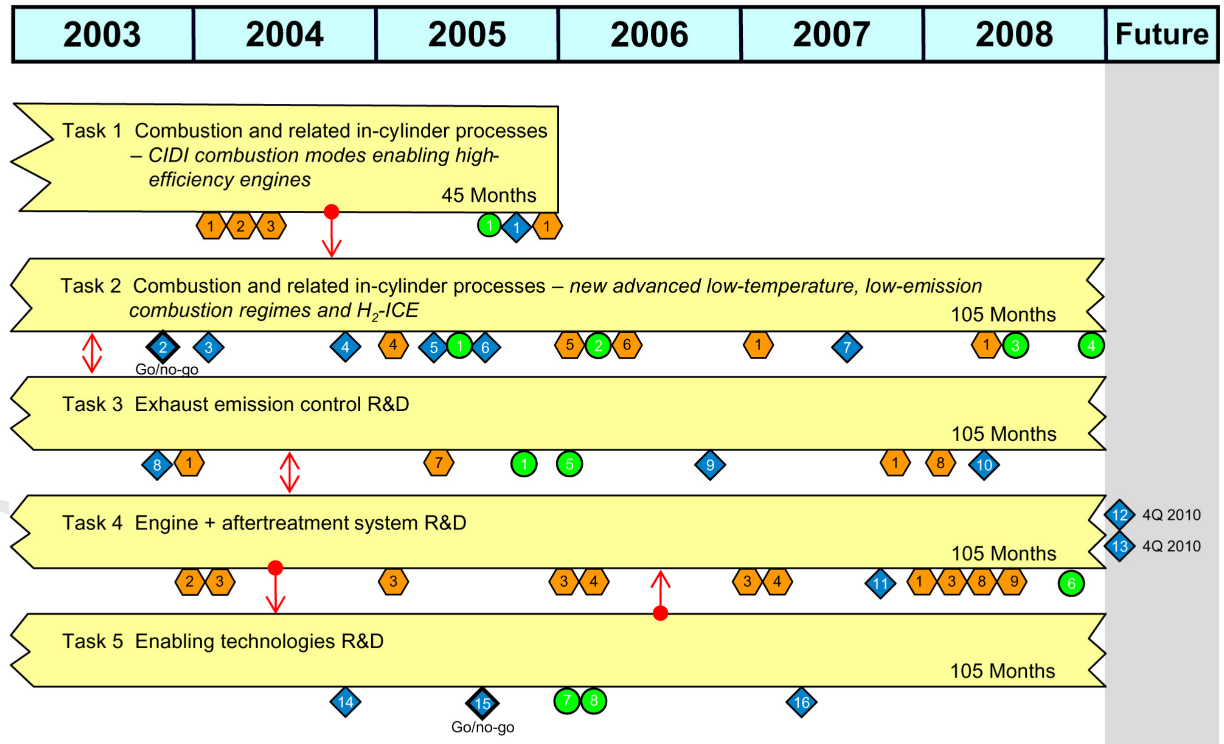
Table 23. Tasks for Combustion and Emission Control R&D

Task	Title	Duration/ barriers
1	Combustion and related in-cylinder processes—CIDI combustion modes enabling high-efficiency engines • Improve fundamental understanding of combustion and in-cylinder emissions formation processes and their dependence on fuel injection, combustion chamber, in-cylinder air motion, and chemical kinetic processes through experimental and modeling/simulation approaches	45 months Barriers A, B
2	Combustion and related in-cylinder processes—new advanced low-temperature, low emission combustion regimes and H_2-ICE • Develop fundamental understanding of LTC regimes and their control over a range of engine loads and speeds through experimental and modeling/simulation approaches • Exploit emissions characteristics of LTC regimes and methods of coupling to aftertreatment systems to achieve maximum efficiency • Establish relationships between new combustion regimes and potential efficiency gains and develop paths to efficiency targets • Develop understanding and methods for mixed-mode approaches that must alternate between conventional and new combustion regimes • Fundamental combustion and modeling of H_2-ICE	105 months Barriers A, B, D
3	Exhaust Emission Control R&D • Improve the scientific foundation of NO_x adsorber–catalyst performance and degradation mechanisms to mitigate the trend of greater efficiency loss as catalyst ages • Develop strategies for mitigating sulfur effects on aftertreatment, including catalyst tolerance, regeneration methods, and further reduction of sulfur sources (lubricants) • Improve the catalyst materials and systems for lean NO_x catalysis with urea and alternative reductants for performance over wider temperature range. • Improve the simulation capability for exhaust aftertreatment devices to accelerate the design of the most efficient and effective emission control systems • Improve the technologies and strategies for PM filters to achieve reliable regeneration at low exhaust temperatures	105 months Barriers B, D
4	Engine + Aftertreatment System R&D • Develop and demonstrate integrated controls and strategies for engine and aftertreatment systems with maximum fuel economy at the necessary emissions levels	105 months Barriers A, B, C
5	Enabling Technologies R&D • Develop and validate NO_x and PM sensors for engine and aftertreatment control and diagnostics • Develop advanced engine control methods and strategies for operation over a range of loads and speeds • Research, develop, and evaluate sulfur trap technologies for both on-board fuel lines and SO_2 in exhaust	105 months Barriers B, C

2002 together with the inception of the FreedomCAR Partnership and, with the exception of Task 1, which ends in 2005, will continue through 2010.

Milestones

Combustion and Emission Control R&D sub-activity milestones are provided in the following network chart.



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Milestone

1. Complete essential experiments and models of "conventional" diesel combustion
2. Confirm simultaneous NOx and PM reductions feasibility on the order of >80% at up to 40% load using LTC modes. **Go/no-go** on LTC path
3. Complete upgrades of experimental labs for study of LTC regimes
4. Complete H_2-ICE laboratory
5. Improve KIVA-3V simulation of new combustion modes.
6. Determine the mixing characteristics of H_2 under direct-injection conditions
7. Expand operating range of HCCI combustion
8. Validate new simulations for aftertreatment devices and transfer to industry
9. Validate NO_X and PM control device efficiencies (sufficient to limit NO_X to 0.07 g/mile and PM to 0.01 g/mile, respectively) using 15-ppm sulfur-content fuel with durability to projected full-useful-life requirements
10. Complete evaluation of catalyst materials using combinatorial chemistry
11. Validate 45% thermal efficiency with <3% fuel economy penalty for meeting standards with emission control devices using a fuel formulation recommended by the Advanced Petroleum-Based Fuels (APBF) sub-activity
12. Validate 45% peak thermal efficiency H_2-IC engine
13. Validate 46% thermal efficiency with <1% fuel economy penalty for meeting standards with emission control devices using a fuel formulation recommended by the APBF sub-activity
14. Test and validate the operation of prototype NO_X/PM sensors as part of an engine system
15. Determine the feasibility of exhaust sulfur trapping, including durability, regeneration, and efficiency. **Go/no-go** on using sulfur traps
16. Evaluate sensors to control HCCI combustion

Technology Program Output

1. Transfer of technical data/information to industry
2. Technical results to Light Truck Engine R&D
3. Technical results to Heavy Truck Engine R&D
4. Engine/emission control system model that predicts fuel effects on the system, to Fuels Technologies R&D
5. Fuel Property requirements for HCCI, to Fuels Technologies R&D
6. Technical results on H_2-ICE to Hydrogen, Fuel Cells, and Infrastructure Technologies Program
7. Rapid aging protocol for NO_X adsorber system, to Fuels Technologies R&D
8. Technical results and feedback to Fuels Technologies
9. Technical results to Vehicle Systems R&D

Supporting Input

1. Fuel formulation that enables emission control system to meet useful life requirements, from Fuels Technologies R&D
2. Input from Hydrogen, Fuel Cells, and Infrastructure Technologies Program
3. Fuel-derived reductant for emission control use, from Fuels Technologies R&D
4. Fuels composition that meets requirements of HCCI, from Fuels Technologies R&D
5. Technical data on fuel sulfur trap, from Fuels Technologies R&D
6. Validated catalyst and PM filter materials to enable fuel efficiency and meet 2007 – beyond emissions goals, from Heavy Vehicle Propulsion Materials
7. Validated emission control devices (sensors, PM filter), from Automotive Propulsion Materials
8. New, high performance material for heavy vehicle fuel systems to meet fuel efficiency and 2007 and beyond, from Heavy Vehicle Propulsion Materials

4.5.2 Light Truck Engine R&D

The Light Truck Engine R&D sub-activity uses the expertise of U.S. heavy-duty diesel engine manufacturers in developing high-efficiency, low-emission diesel engines for light trucks [pickup trucks, vans, and sport-utility vehicles (SUVs)] that can achieve at least a 50% improvement in on-road fuel economy over gasoline-fueled vehicles and provide the power needed for four-wheel drive, hauling, and towing (popular features of pickups and SUVs).

Goals

The specific goal of this sub-activity is

> By 2004, in collaboration with industry partners, complete development of advanced clean diesel engine technologies that enable commercial production of pickup trucks, vans, and SUVs that achieve at least a 50% fuel economy improvement relative to current gasoline-fueled trucks while demonstrating Tier 2 emission standards.

Programmatic Status

The Light Truck Engine R&D sub-activity was initiated in 1997 as a means of impacting the fuel consumption of the rapidly growing U.S. light truck market, which is dominated by inherently low-fuel-economy (miles-per-gallon) gasoline-fueled vehicles. Diesel engines are offered in the heavier light trucks (over 8500 lb gross vehicle weight), which have maintained solid sales (approximately 300,000 units per year) for the last 5 to 8 years. Additional sales are limited by engine supply and lack of availability of a nominal 200–250 hp diesel engine capable of meeting the more stringent vehicle emissions standards applicable to light trucks of less than 8500 lb gross vehicle weight, which represent a majority of light trucks. Penetration of high-efficiency diesel engines in this light truck market segment will require a very different engine design—one that meets EPA Tier 2 vehicle emissions standards and is competitive with the gasoline engine in performance and noise, vibration, and harshness (NVH), with greater engine service life and consumer-desired attributes, including cost. Accordingly, the Light Truck Engine R&D sub-activity focuses on the development of clean diesel engines for the light truck market.

This sub-activity has completed dynamometer tests of light trucks with prototype diesel engines installed to replace production gasoline engines and has validated the achievement of at least a 50% improvement in fuel economy (miles per gallon) and EPA Tier 2 emissions. This sub-activity is due to be completed in 2004 with achievement of the technical targets.

Targets

The targets for Light Tuck Engine R&D are shown in Table 24.

Table 24. Technical targets for Light Truck Diesel Engine R&D

Characteristics	Units	Year	
		2002 status	2004
Engine power	hp	225–300	225–325
Fuel economy increase over equivalent gasoline vehicles	%	>50	>50
Engine cost (compared with equivalent gasoline engine)	%	<120	<120
Engine weight (compared with equivalent gasoline engine)	%	<110	<110
NVH (compared with equivalent gasoline engine)	db difference	<3	<1
NO_x emissions[a]	g/mile	<0.30	<0.07
PM emissions[a]	g/mile	<0.01 for 20 h in test cell	0.01
Durability[b] (on lab dynamometer, computer-simulated vehicle miles)	Miles (equivalent)	>20,000	>100,000

[a] Projected full-useful-life emissions for an SUV (using advanced petroleum-based fuels with 15 ppm sulfur) as measured over the Federal Test Procedure as used for certification in those years.

[b] Projected full-useful-life durability, as measured over the Federal Test Procedure as used for certification.

Barriers

A. **Cost.** Although pricing practice does not always reflect cost, the diesel option, for the few vehicles where it is available, costs at least $1000 more (in some cases, much more) than the base gasoline engine. The fuel injection system for diesels, necessarily complex to achieve fine control of injection spray at high pressure, is one of the key cost drivers. The fuel injection system is critical to engine performance, efficiency, and emissions. Further adding to the cost is the air-handling system, including the turbocharger, aftercooler, and related hardware that diesels need in order to have competitive power density and responsiveness.

B. **Emissions.** Meeting NO_X and particulate emission regulations with engines of high efficiency and low cost is a significant barrier, particularly in the higher power range necessary for light trucks. For in-cylinder controls, further development of EGR is necessary for heavy-duty diesels if they are to be scaled down for pickups. Cooled EGR has not been adequately developed for full commercialization. Fuel injection systems have achieved recent advancements, but additional control of injection rate is thought to be needed. Aspects of the fuel/air mixing process are still insufficiently understood and modeled to optimize engine design. Additionally, lean-burn NO_X aftertreatment systems are not sufficiently developed for commercial application. Current oxidation catalysts eliminate only 30–40% of PM, which may be inadequate for future emission goals.

C. **Noise, vibration, and harshness.** While the diesel has a recognized advantage over the gasoline engine in fuel efficiency, it is also perceived to have significant relative shortcomings in the areas of NVH. These shortcomings are being ameliorated through improved design and component development.

Approach

Under cooperative agreements (with 50% cost share), three teams (led by heavy-duty diesel engine manufacturers and in partnership with U.S. automakers) will continue R&D of clean diesel engines of the power rating and duty cycle appropriate for light trucks under 8500 lb gross vehicle weight rating. A second-generation pre-production prototype clean diesel (200 to 250 hp) engine will be optimized for emissions, performance, cost, and noise. The engine cost and weight are expected to be about 20% higher than for production gasoline engines. NVH levels are expected to be similar to those of the gasoline engine. The optimized engine will be installed in a light truck (SUV or pickup truck) to be tested in real-world driving conditions. The clean diesel engine–powered light truck should show a fuel economy improvement of 50% over comparable gasoline engine–powered vehicles. At the current pace of development, after two teams are successful in meeting the fuel economy goals, the focus will be on achieving the low emission requirements while maintaining high fuel economy. Vehicle emission levels should not exceed EPA Tier 2 emissions at this stage. The third team will continue to focus on the development of advanced combustion technologies and emission controls that will set new low levels for engine-out NO_X and particulates.

Task Descriptions

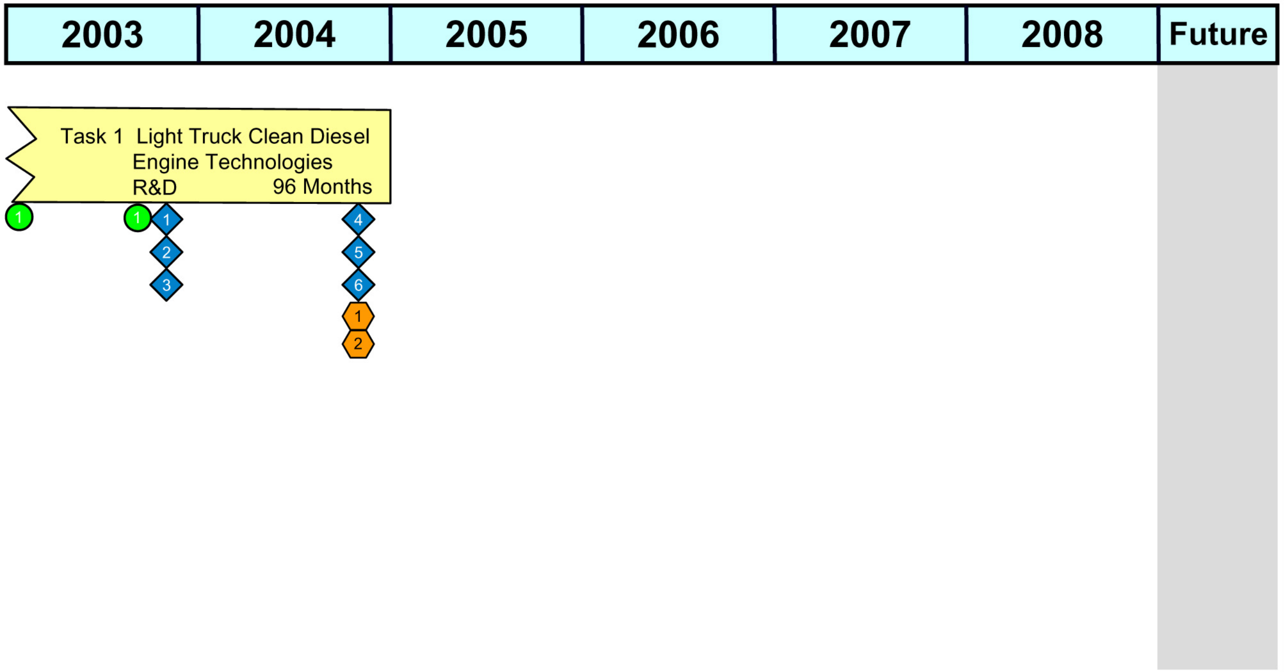
A description of each technical task, along with the estimated duration and technical barriers associated with the task, is provided in Table 25.

Table 25. Task for Light Truck Engine R&D

Task	Title	Duration/ barriers
1	Light Truck Clean Diesel Engine Technologies R&D • Develop pre-production prototype clean diesel engine (200 to 250 hp) that is optimized for efficiency, performance, emissions, cost, and noise • Install advanced clean diesel engine in a representative light truck and conduct in-vehicle testing under real-world driving conditions • Develop advanced combustion technologies and emission controls for advanced clean diesel engine	90 months Barriers A, B, C

Milestones

Light Truck Engine R&D sub-activity milestones are provided in the following network chart.



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Milestone

1. Reduce light truck diesel engine weight to not greater than 1.1 times that of an equivalent gasoline engine
2. Increase diesel engine power output to between 225 and 325 hp
3. Increase fuel economy of diesel-powered light truck to at least 1.5 times that of comparable gasoline vehicle with Tier 2 emission compliance in a laboratory
4. Validate NVH levels in production prototype engine to within 1 db of comparable gasoline engine
5. Validate on-road vehicle fuel economy of diesel-powered light truck of at least 1.5 times that of a comparable gasoline vehicle, with EPA Tier 2 emissions
6. Validate compliance with EPA Tier 2 Bin 5 for 120,000 miles equivalent

Technology Program Output

1. Technical data to industry
2. Technical data to Vehicle Systems R&D

Supporting Input

1. Input from Combustion and Emission Control R&D

4.5.3 Heavy Truck Engine R&D

Heavy Truck Engine R&D is focused on increasing heavy-duty diesel engine efficiency significantly above current levels, as well as addressing efficiency penalties resulting from technologies required to meet increasingly stringent emissions standards. The engine efficiency losses would result in higher operating costs to truck owners and operators and, ultimately, higher costs to consumers. On a national scale, increased heavy truck fuel efficiency will result in reduced petroleum demand.

Goals

The long-term (2012) goal of this sub-activity is to develop the technologies that will increase the thermal efficiency of heavy-duty diesel engines to at least 55% while reducing emissions to near-zero levels. More specifically,

- By 2005, increase the efficiency of heavy-duty diesel engines from 40 to 45% while meeting EPA 2007 emission standards.
- By 2012, increase the thermal efficiency of heavy truck engines to 55% while meeting prevailing EPA emissions standards.

This sub-activity also supports the goal of 21st CTP to develop and validate a commercially viable, 50% efficient, emissions-compliant engine system for Class 7 and 8 highway trucks by 2010.

Programmatic Status

With the acceleration to October 2002 of the enactment of the 2004 EPA heavy-duty engine statement-of-principles emissions standards, the Heavy Truck Engine R&D sub-activity was initiated in FY 1999 to address the anticipated heavy-duty diesel engine efficiency penalty that would occur. Having to meet the standards sooner using only currently available emissions control technologies was expected to result in an efficiency penalty of as much as 10% in heavy-duty diesel engines. In addition, the sulfur content of available diesel fuel has deleterious effects on the performance of emission control devices. The primary objective of this research is to increase the engine thermal efficiency and develop emission control technologies that would have minimal impact on engine efficiency.

In December 2000, EPA enacted the 2007 Heavy-Duty Diesel Engine Emissions Standards. EPA also issued a rule in January 2001 requiring that 80% of all on-road diesel fuel have less than 15 ppm sulfur, starting in 2006. This rule is in conjunction with the phase-in of standards in the 2007–2010 timeframe. The rule on sulfur content of diesel fuel is expected to greatly benefit the performance and durability of emissions control technologies under development. The Heavy Truck Engine sub-activity supports the development of technologies needed to significantly improve the efficiency of heavy-duty diesel engines beyond present levels while meeting the 2007 heavy-duty engine emissions standards, as well as anticipated future standards.

Targets

The technical targets for Heavy Truck Engine R&D are shown in Table 26.

Table 26. Technical targets for Heavy Truck Diesel Engine R&D

Characteristics	Year			
	2002 status	2005	2007	2012
Engine thermal efficiency, %	>40	>45	>50	>55
NO_x emissions,[a] g/bhp-h	<2.0	<1.2	<0.20	<0.20
PM emissions,[a] g/bhp-h	<0.1	<0.01	<0.01	<0.01
Stage of development	Commercial	Prototype	Prototype	Prototype
Durability, miles (equivalent)	>100,000	>200,000	>400,000	

[a] Using 15-ppm sulfur diesel fuel.

Barriers

The technical barriers to achieving dramatically improved efficiency and near-zero emissions in heavy truck engines are as follows:

A. **Efficiency.** There are several barriers to improving engine efficiency. In-cylinder NO_X reduction methods in conventional diesels, using traditional combustion modes, limits 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.

B. **Emissions.** The key barriers to achieving the emissions reduction targets for heavy truck diesel engines include (1) maintaining efficiency and low NO_X while keeping PM down; (2) incomplete development of aftertreatment technology, especially for NO_X; and (3) immature simulation and control systems integration, as well as static and dynamic optimization of multiple emission reduction systems. Common to each barrier is a lack of adequate simulation capabilities and readily implemented sensing and process control systems. Improved simulation capabilities are needed to optimize both the combustion and aftertreatment systems so as 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.

C. **Durability.** The barrier to achieving 435,000-mile durability for heavy-duty engines and their emission control systems is the premature degradation of the emission control devices due to operation under high-temperature and high-flow-rate conditions.

Approach

An integrated systems approach involving engine design, fuels, and aftertreatment technologies is required to simultaneously address fuel efficiency and emissions. R&D in combustion, materials, fuels, and aftertreatment devices provides the foundation for technology advancement, including simulations (virtual labs) in concert with controls development and experimentation.

Approaches to improving engine efficiency are effectively built upon understanding the energy losses. The combustion process, mechanical friction, heat transfer, air handling, and exhaust losses all are important in improving engine efficiency. Major elements of the technical approach 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 tasks. Conduct, on a continuing basis, analysis and supporting validation tests to assess progress toward goals.
- Optimize the mechanical design and combustion system for increased expansion ratio and thermodynamic efficiency.
- Develop and integrate cost-effective exhaust-heat-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 LTC 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.
- Continue the refinement of piston/cylinder designs, valve trains, and other mechanical components for reduced friction losses.
- Develop accurate, robust sensors for control systems.
- Conduct materials R&D in support of engine efficiency (this area is covered in the Materials Technology Section).

Simultaneous attainment of thermal efficiency targets and future required emissions reductions requires unprecedented attention to the effective 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, given 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. A high-priority need is the advancement of computational simulation capabilities for all systems, especially for aftertreatment systems, which are currently in an immature state of development. Major elements of the technical approach to meet emissions targets also include these:

- Further develop flexible fuel-injection systems and engine control strategies and new combustion regimes for their emissions reduction potential, integrating modeling and simulation with engine controls development.
- Optimize cooled EGR for maximum NO_x reduction and minimum PM emission, mitigating durability concerns with EGR through materials engineering and operational controls.
- 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.
- Develop strategies for mitigating the effects of sulfur on aftertreatment, including catalyst tolerance, regeneration, and further reduction of sulfur sources (lubricants).
- Improve the scientific foundation of NO_x adsorber-catalyst performance and degradation mechanisms. Improve the catalyst materials and systems for lean NO_x catalysis with urea and alternative reductants for performance over a wider temperature range. Determine plasma benefits.
- Improve methods for generating and introducing NO_x reductants to catalysts.
- Develop suitable technologies and procedures for urea supply for selective catalytic reduction systems.
- Develop and apply sensors in controls and diagnostics of engine and emission control processes.
- In the development of emissions control devices, include features necessary to make the devices suitable for retrofit on existing trucks.
- Conduct materials R&D in support of emission reduction (addressed in Materials Technology, Section 4.6.)

Fuel properties, in particular sulfur content, are pivotal in whether NO_x adsorber catalysts will be successful. Work in fuels is coordinated with the Fuels Technology Team and is discussed in Fuels Technology, Section 4.7.

Task Descriptions

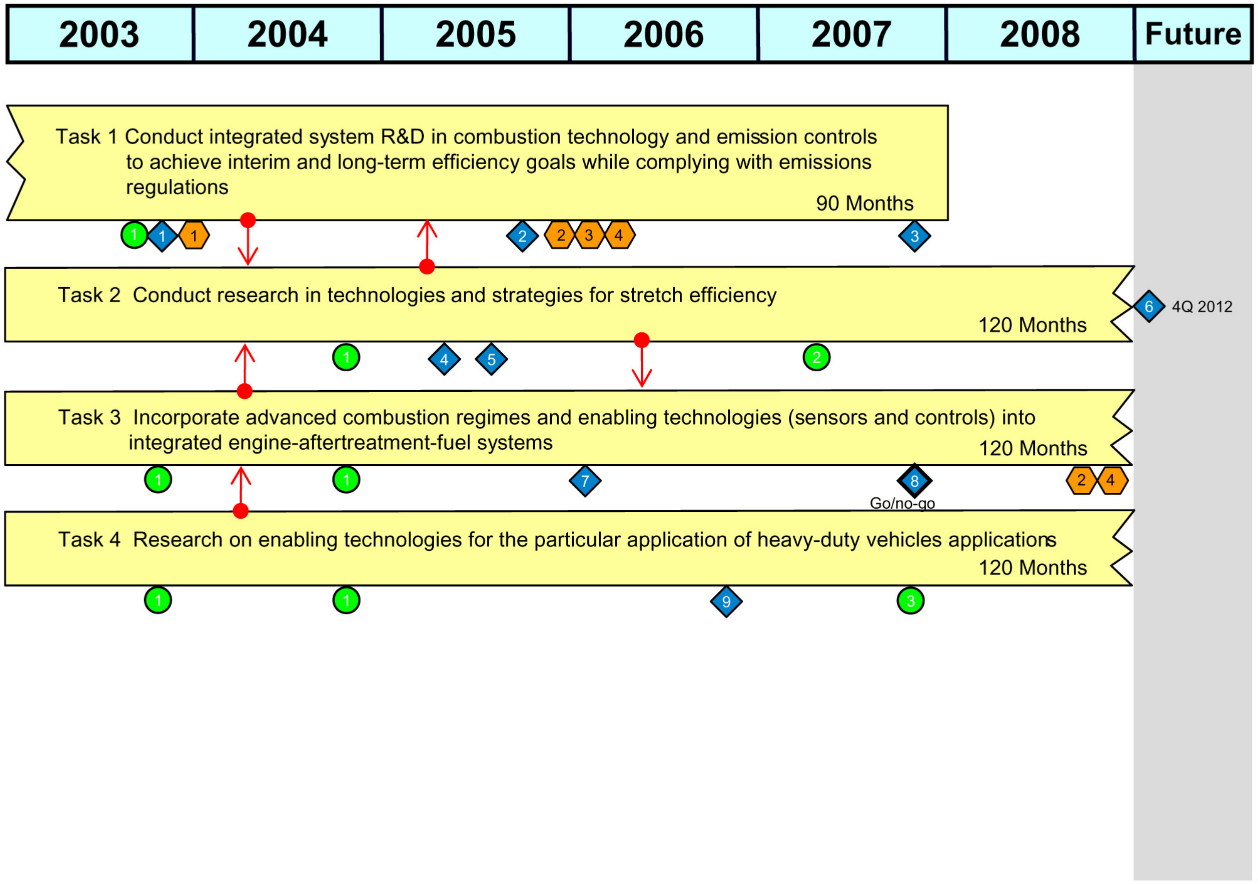
A description of each technical task, along with the estimated duration and technical barriers associated with the task, is provided in Table 27. Tasks 2, 3, and 4 commenced with the rejuvenation of 21st CTP in November 2002 and will continue through 2012.

Table 27. Tasks for Heavy Truck Engine R&D

Task	Title	Duration/ barriers
1	Conduct integrated system R&D in combustion technology and emission controls to achieve interim and long-term efficiency goals while complying with emissions regulations	90 months Barriers A, B, C
2	Conduct research in technologies and strategies for stretch efficiency • exhaust heat utilization • mitigating thermodynamic combustion losses • reduced parasitic losses • reduced air handling losses • improved thermal management	120 months Barrier A
3	Incorporate advanced combustion regimes and enabling technologies (sensors and controls) into integrated engine–aftertreatment–fuel systems	120 months Barriers A, B, C
4	Conduct research in enabling technologies for the particular application of heavy-duty vehicles, for example • sensors • sulfur traps • catalyst and filter fundamentals	120 months Barrier B

Milestones

The Heavy Truck Engine R&D sub-activity milestones are provided in the following network chart.



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Milestone

1. Demonstrate at least 45% peak thermal efficiencies for heavy-duty diesel engines while meeting 2.0 g/bhp-h NO_X and 0.10 g/bhp-h PM
2. Demonstrate at least 45% peak thermal efficiency for heavy-duty diesel engines while meeting 2007 EPA emissions standards [1.18 g/bhp-h NO_X (fleet average) and 0.01 g/bhp-h PM]
3. Validate at least 50% peak thermal efficiency for diesel engines while meeting 2007 federal emissions levels
4. Evaluate energy recovery devices for improved efficiency
5. Validate technologies to reduce friction while improving efficiency
6. Demonstrate at least 55% peak thermal efficiency for heavy-duty engines while meeting prevailing federal emissions standards
7. Evaluate fuel injection system for mixed-mode operation
8. Demonstrate commercially viable heavy-duty engine with 50% efficiency and compliant with 2010 emissions regulations. Go/no-go on durability testing
9. Complete evaluation of catalyst material for high-temperature operation

Technology Program Output

1. Technical requirements to Waste Heat Recovery R&D
2. Technical data to industry
3. Materials requirements to Heavy Vehicle Propulsion Materials
4. Technical data to Vehicle Systems R&D

Supporting Input

1. Technical data from Combustion and Emission Control R&D
2. Technical data on surface modification technology to reduce friction, from Vehicle Systems R&D
3. Commercially available, cost-effective high temperature stainless steel to meet performance requirements of advanced fuel-efficient heavy-duty diesel engines, from Heavy Vehicle Propulsion Materials

4.5.4 Waste Heat Recovery

The Waste Heat Recovery sub-activity develops technologies to convert waste heat from engines to useful energy (e.g., electrical energy) to improve overall thermal efficiency and reduce emissions.

Goals

The longer-term goal of this sub-activity is to develop the technologies for recovering engine waste heat and converting it to useful energy that will improve overall diesel engine thermal efficiency to 55% while reducing emissions to near-zero levels. More specifically,

- By 2010, enable commercially viable turbocompound units that can produce more than 10 kW of additional power from light-duty engine waste heat recovery.
- By 2012, enable commercially viable turbocompound units that can produce up to 40 kW of additional power from heavy-duty engine waste heat recovery.
- By 2012, achieve at least 35% efficiency in quantum well electric devices for waste heat recovery.

This sub-activity also supports the overall engine efficiency goals of the FreedomCAR partnership and 21st CTP.

Programmatic Status

Recovery of energy from the engine exhaust represents a potential for 10% or more improvement in overall engine thermal efficiency. Turbochargers are used to recover part of this energy. Turbochargers currently have efficiencies of around 50 to 58%, which could be increased to 72 to 76% with enhancements such as variable geometry. An electrically driven turbocharger with increased transient response would be another approach. Turbocompounding and direct thermal-to-electric conversion could also improve the overall thermal efficiency. Bulk semiconductor thermoelectric devices are currently 6 to 8% efficient. Recent developments in quantum well thermoelectrics suggest a potential improvement to over 20% is possible.

Targets

The technical targets for Waste Heat Recovery are shown in Table 28.

Barriers

A. **Device/system packaging.** The electro-turbocompound system, including its power electronics and overall system controller, must fit under the vehicle hood with adequate space for cooling. All of the power must be absorbed by the integrated motor/starter/generator or by accessories converted from belt-driven to electric-motor-driven. The turbocharger that has the motor/alternator attached between the turbine and compressor operates at 55,000 rpm for Class 7 and 8 heavy trucks and 120,000 rpm for light trucks. This is pushing the state of

Table 28. Technical targets for Waste Heat Recovery

Characteristics	Units	Year		
		2003 status	2005	2008
Electrical turbocompound system				
Light-duty vehicles				
Power	kW	<2	>5	>10
Projected component life	hours	<10	>2,000	>5,000
Class 7–8 trucks				
Fuel economy improvement	%	<1	>5	>10
Power	kW	<10	>20	>30
Projected component life	hours	<10	>5,000	>10,000
Thermoelectric devices				
Efficiency				
• bulk semiconductor	%	6–8	—	—
• quantum well			>10	>15
Projected cost/output (250,000 production volume)	$/kW	—	500	180

the art for the light truck application. This system will increase exhaust gas backpressure, which should be beneficial for NO_x reduction. However, because these systems must not adversely affect emissions, a minimum amount of bearing lube oil can be introduced into the compressor air discharge. The electrocompound system must not cause drivability or NVH problems.

B. **Scale-up to a practical device.** The quantum well thermoelectric concept is a recent technological development. The successful system is essentially a nanostructure consisting of alternate N and P layers about 100 Angstroms thick deposited on an extremely thin silicon substrate. The challenge is to develop coating techniques that can deposit a sufficient number of layers to achieve the efficiency goal. This entails dramatically increasing the size of early devices. Heat transfer in these nanostructure films is exploring new technology. Adequate techniques for measuring key parameters in these nanofilms need to be developed.

C. **Component/system durability.** Specific durability requirements must be met by the waste heat recovery systems. The electric turbocompound system must perform for 250,000 miles and 500,000 miles in light and heavy truck applications, respectively. Quantum well thermoelectric devices will have to survive vibrations encountered in vehicle applications. Although lessons learned with the thermoelectric generator developed with bulk semiconductors will be useful, anticipated problems present a much more difficult challenge.

D. **Cost.** The electrocompound system capital cost to the owner and operator should be repaid in 24 months or less. This payback period will depend on the cost of the fuel or a tax incentive. For nanothermoelectrics, achieving the large-scale production goal of devices for direct conversion of heat to electricity would require large-scale sputtering equipment that could cost-effectively deposit the layers, possibly in a highly automated manner.

Approach

Iterative test and redesign efforts will be conducted for electric turbocompound systems to validate the electric power produced and the resulting overall engine efficiency gains. In addition, improvements in the low-speed torque will be measured in the context of reducing engine size for the same performance. Validation will be undertaken by motoring the turbocharger during acceleration to reduce turbolag and improve emissions. Testing will also be conducted with EGR-equipped engines to validate NO_X reduction achieved due to increased exhaust back pressure.

The technical approach to developing commercially competitive thermoelectric devices[1] for transportation applications is first to validate the bulk semiconductor-based 2-kW thermoelectric generator. The emphasis will be to develop quantum well thermoelectrics (or "nanothermoelectrics") so that they can perform power generation (using the Seebeck effect) or heating/cooling (using the Peltier effect) for vehicular applications within the cost criteria for commercial production. A measurement technique for these ultra-thin devices will be developed. Multilayer devices will be made by sputtering with alternate N and P layers (on the order of 1000 layers). Multilayer systems that will initially be investigated include Si/$Si_{0.8}Ge_{0.2}$ and B_4C/B_9C deposited on 0.5-mm-thick silicon substrates. Coating parameters will be optimized, and heat transfer issues will be addressed.

Task Descriptions

A description of each technical task, along with the estimated duration and technical barriers associated with the task, is provided in Table 29.

Table 29. Tasks for Waste Heat Recovery R&D

Task	Title	Duration/ barriers
1	Thermoelectric generator • Produce 2 kW of electricity from a heavy truck (Class 7/8) with a bulk semiconductor thermoelectric generator • Fabricate quantum well device with at least 21% efficiency	120 months Barriers B, C, D
2	Electric turbocompound system for light trucks • Develop electric turbocompound system to deliver 1.8 kW electric power for 2500 h • Test and evaluate a turbocompound system on an SUV engine and validate 10% fuel economy improvement	120 months Barriers A, C, D
3	Electric turbocompound system for heavy trucks • Develop a system to provide an additional 40 kW of electric power • Integrate an electric turbocompound system with heavy truck engine controls and validate through laboratory tests that 40 kW can be produced for over 10,000 h for a 10% fuel economy improvement • Redesign the system using laboratory test results, install the modified electric turbocompound system in a Class 7/8 heavy-duty truck engine, and validate a 10% fuel economy improvement over 10,000 h	120 months Barriers A, C, D

Milestones

The Waste Heat Recovery R&D sub-activity milestones are provided in the following network charts.

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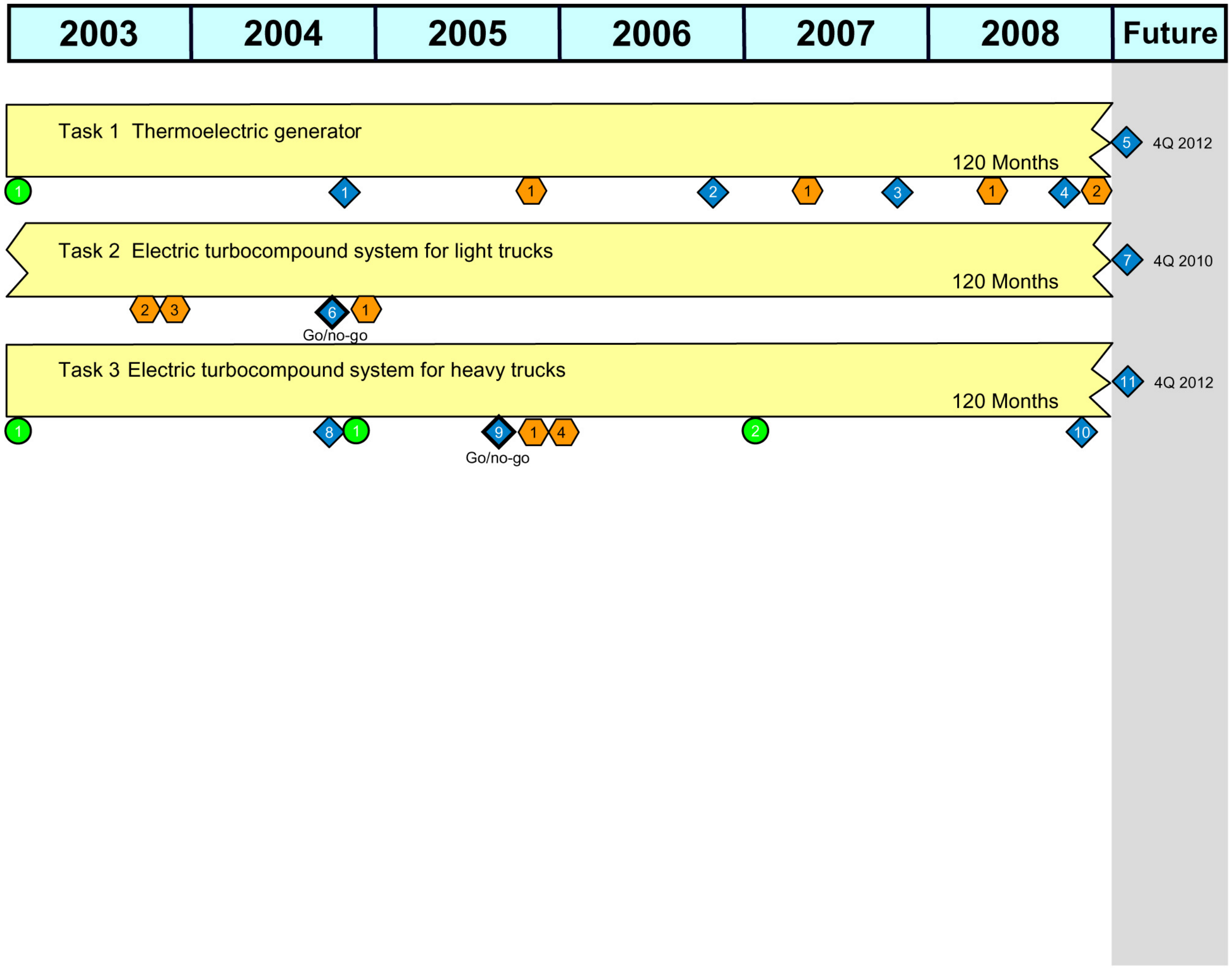
[1] A detailed discussion of past efforts in thermoelectrics, the current state of the art for quantum well thermoelectrics, available approaches for improved thermoelectric device performance, present and past R&D tasks by DOE and other entities, as well as detailed steps of the technical approach appears in the document *R&D Approaches to Exploit Recent Major Breakthroughs in Thermoelectrics, for FY 2003–2007,* Office of FreedomCAR and Vehicle Technologies, U.S. Department of Energy, 1000 Independence Avenue, SW, Washington DC 20585, September 2003 draft.



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◆ **Milestone**

1. Evaluate the quantum well thermoelectric concept for practical devices for at least 20% conversion of waste heat to electricity
2. Complete test of full complement of 72 quantum well 45-W modules in the diesel truck thermoelectric generator
3. Complete test of full complement of 72 quantum well 80-W modules in the diesel truck thermoelectric generator
4. Complete in-vehicle tests
5. Evaluate potential for 35% efficient quantum well device
6. Complete test of electric turbocompound concept on an SUV engine to validate fuel economy improvement. Go/no-go to continue development for light-duty application
7. Demonstrate potential for greater than 10-kW electric turbocompound unit for light-duty vehicles
8. Complete lab tests of electric turbocompound concept for heavy-duty truck engine to validate fuel economy improvement
9. Integrate electric turbocompound unit with engine control system and validate that up to 20 kW can be produced from heavy-duty engine waste heat. Go/no-go to continue development for heavy-duty application
10. Evaluate potential for 30-kW electric turbocompound unit for heavy-duty engine waste heat recovery
11. Evaluate potential for 40-kW electric turbocompound unit for heavy-duty engine waste heat recovery

⬢ **Technology Program Output**

1. Technical data to Vehicle Systems R&D
2. Technical data to industry
3. Technical data to Light Truck Clean Diesel R&D
4. Technical data to Heavy Truck Engine R&D

● **Supporting Input**

1. Input from Heavy Truck Engine R&D
2. Input on turbocharger materials, from Heavy Vehicle Propulsion Materials

4.5.5 Health Impacts

The Health Impacts Research sub-activity supports the FCVT mission to ensure that the more energy-efficient advanced combustion engine technologies are environmentally friendly and do not produce adverse health impacts. This sub-activity seeks to identify, analyze, quantify, and, if possible, avoid potentially deleterious health impacts of new vehicle technologies, specifically of emissions from vehicles using conventional as well as alternative fuels. The emphasis is to place transportation emissions in a proper context, focusing on providing a balance to the health research portfolio by others.

Goals

The goal of the Health Impacts Research sub-activity is to provide a sound scientific basis for the relationship between mobile-source emissions from new vehicle technologies (engines, fuels, and engine operating conditions or vehicle drive cycles) and their health impacts; more specifically, it is to identify and quantify potential health hazards associated with the use of fuels in transportation vehicle engines.

Programmatic Status

New, “clean” high-efficiency vehicle and fuel technologies may often have negative environmental and health impacts unforeseen by their advocates. Examples include groundwater contamination by methyl tert-butyl ether (MTBE), an EPA-mandated gasoline additive to reduce carbon monoxide emissions, and findings of carcinogenic compounds (formaldehyde, benzene, 1,3 butadiene) in natural gas vehicle emissions. For example, proponents of some other technologies have tended to focus on the hazards of diesel emissions while dismissing as insignificant the hazards of gasoline and the potential impacts of alternative fuels such as natural gas. These opponents sometimes cite studies that are dated and based on emissions data from old-technology diesel engines with no emission controls, rather than studies that are current or based on the more-advanced diesel engine technologies using clean fuels and advanced aftertreatment technologies.

To avoid unexpected adverse impacts from the vehicle technologies being developed by FCVT, the Health Impacts Research sub-activity pro-actively investigates the impacts of changes in fuel, engine, and aftertreatment technologies on the ecosystem and human health. FCVT research on advanced vehicle and fuel technologies is in the exploratory and developmental stages and therefore is not yet sufficiently commercial for EPA regulatory oversight. In addition, this research investigates the health impacts of complex mixtures (e.g., engine exhaust) where toxic synergisms are enhanced and develops information that puts the health impacts of advanced technologies in context with respect to relative risk.

Targets

To determine the impacts of changes in fuels, engines, and aftertreatments on toxics emitted and potential health hazards, accurate measurement methods and tools need to be developed that can be applied to achieve the following:

- Characterize the chemical and physical properties of vehicle emissions and possibly differentiate emissions from various mobile sources (e.g., gasoline- , diesel- , natural gas-fueled vehicles).
- Establish the proper apportionment of emissions among the various mobile sources, e.g., cars vs. heavy trucks.
- Characterize the chemical and physical properties of emissions from farm and construction equipment and locomotives as a function of fuel composition, lubrication technology, and duty cycle.
- Identify potential health impacts from the introduction of new materials, especially composites, into vehicles.
- Establish a scientific basis for determining the impacts of emissions on human health.

Barriers

A. Lack of analytical tools (rapid assay techniques relevant to human toxicity)
B. Lack of credible validated models for mobile source apportionment
C. Lack of validated models for predicting health effects of advanced vehicle technologies

Approach

This work is focused on the development of accurate measurement methods and tools that could be used to place the health hazards from diesel emissions into a proper context relative to emissions from other source. The contribution of emissions from various mobile sources to the total emissions inventory will be established, as well as the composition of volatile organic compound emissions from petroleum-based diesel, biodiesel, and alternative fuels. Emissions from new and in-use technologies and non-petroleum-based fuels will be evaluated. The atmospheric reactivity of exhaust emissions from alternative-fuel engines will be evaluated to assess the impact on urban air quality relative to conventional fuels. The approach for emissions sampling is as follows:

- Collect samples from in-use vehicles under standardized conditions.
- Measure emission rates.
- Analyze the samples physically and chemically.
- Conduct rapid toxicity tests on samples to determine the potential for cancer and non-cancer effects.
- Compare the types and potencies of toxicity among fuels (e.g., gasoline, diesel, natural gas), engine types, and operating conditions.
- Integrate the analytical and toxicity results into a preliminary understanding of associations between toxicity and physical-chemical classes.

Morphology of the PM emissions will be incorporated into the research task. Impacts of diesel and gasoline PM emissions in atmospheric air will be investigated, compared, and contrasted. Work will also contrast primary and secondary particulates associated with the use of different fuel formulations.

Cooperative research with the Office of Science will be conducted to evaluate the health impacts of particulates from engines combusting alternative fuels and non-petroleum-based fuel blends.

Task Descriptions

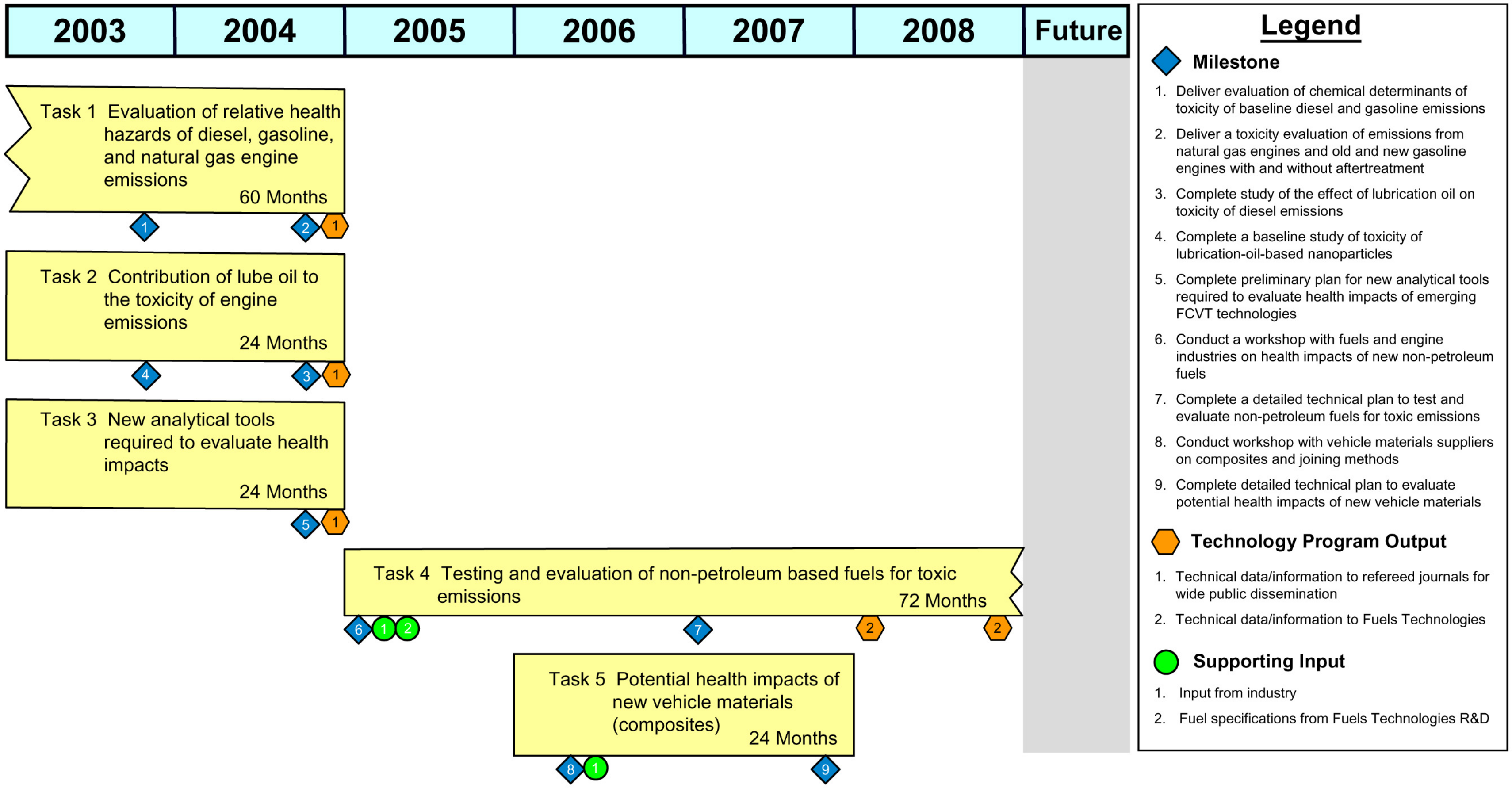
A description of each technical task, along with the estimated duration and technical barriers associated with the task, is provided in Table 30.

Table 30. Tasks for Health Impacts Research

Task	Title	Duration/ barriers
1	Evaluate the relative health hazards of diesel, gasoline, and natural gas engine system(s) emissions	60 months Barriers A, B, C
2	Evaluate contribution of lubrication oil to the toxicity of engine emissions	24 months Barriers A, B, C
3	Develop new analytical tools required to evaluate health impacts of emerging FCVT technologies	24 months Barriers A, B, C
4	Test and evaluate non-petroleum-based fuels for toxic emissions	72 months Barriers A, B, C
5	Evaluate potential health impacts of new vehicle materials (composites)	24 months Barriers A, B, C

Milestones

Health Impacts Research sub-activity milestones are provided in the following network charts.



Legend

Milestone

1. Deliver evaluation of chemical determinants of toxicity of baseline diesel and gasoline emissions
2. Deliver a toxicity evaluation of emissions from natural gas engines and old and new gasoline engines with and without aftertreatment
3. Complete study of the effect of lubrication oil on toxicity of diesel emissions
4. Complete a baseline study of toxicity of lubrication-oil-based nanoparticles
5. Complete preliminary plan for new analytical tools required to evaluate health impacts of emerging FCVT technologies
6. Conduct a workshop with fuels and engine industries on health impacts of new non-petroleum fuels
7. Complete a detailed technical plan to test and evaluate non-petroleum fuels for toxic emissions
8. Conduct workshop with vehicle materials suppliers on composites and joining methods
9. Complete detailed technical plan to evaluate potential health impacts of new vehicle materials

Technology Program Output

1. Technical data/information to refereed journals for wide public dissemination
2. Technical data/information to Fuels Technologies

Supporting Input

1. Input from industry
2. Fuel specifications from Fuels Technologies R&D

4.6 MATERIALS TECHNOLOGIES

The FCVT Materials activity aims to develop and validate advanced materials and processing technologies that can lead to achievement of the FreedomCAR Partnership and 21st CTP goals. The weight reduction and vehicle system technologies pursued in this activity address the critical materials needs for frame, body, chassis, and powertrain systems for cars, light trucks, heavy trucks, and buses. Because of the broad scope of technologies needed to address these varied applications, the activity is divided into five sub-activities that focus on a basket of technologies best suited to the appropriate application (Figure 18).

The Automotive Lightweighting Materials and Automotive Propulsion Materials sub-activities interface with the FreedomCAR Partnership to establish industry needs. The High-Strength Weight Reduction and Heavy Vehicle Propulsion Materials sub-activities interface with the 21st CTP to establish industry needs. The High Temperature Materials Laboratory sub-activity provides critical support to the entire transportation industry for materials research requiring unique characterization equipment. The Automotive Lightweighting Materials and High-Strength Weight Reduction sub-activities are focused on structural materials for

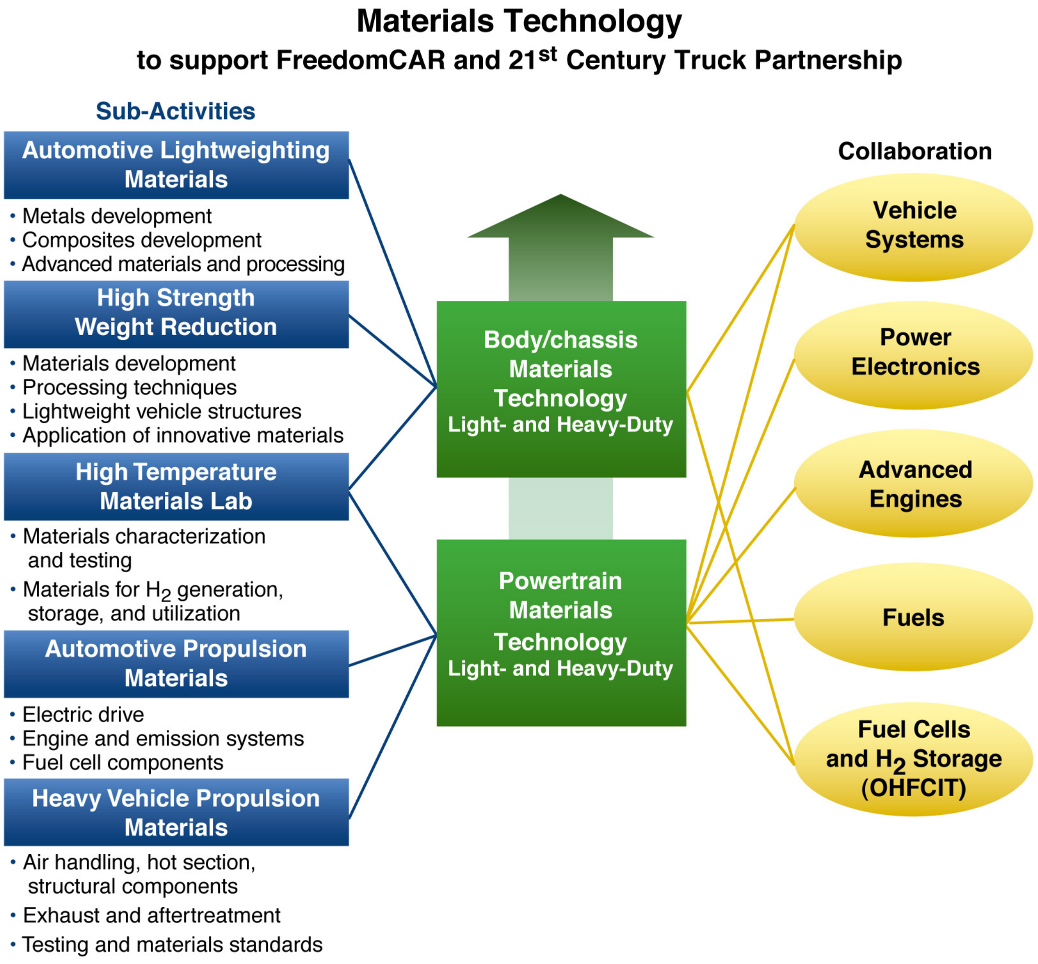


Figure 18. Sub-activities, applications and collaborations in Materials Technologies.

body and chassis applications; they collaborate with the Vehicle Systems activity and the Office of HFCIT to establish requirements. The Automotive Propulsion Materials and Heavy Vehicle Propulsion Materials sub-activities are focused on powertrain applications and establish their requirements through collaborations with the Power Electronics, Advanced Engines, and Fuels Technologies and the Office of HFCIT.

The goals, status, technical targets, barriers, and research plans for each of the materials sub-activities are described in the following subsections.

4.6.1 Automotive Lightweighting Materials

The vision of the Automotive Lightweighting Materials (ALM) sub-activity is to develop and validate cost-effective lightweighting materials technologies that could significantly reduce automobile weight without compromising vehicle cost, performance, safety, or recyclability. Research performed under this sub-activity is primarily focused on light vehicle applications; however, it is recognized that the technologies may also have application on heavy vehicles. Management of this sub-activity and the High-Strength Weight Reduction sub-activity are coordinated to ensure that they are complementary, rather than duplicative.

Goals

The goals of this sub-activity include the priority FCVT goal identified in Section 3.0 for the production cost of carbon fiber. In addition, the goals directly support the FreedomCAR goal, “Technology for high-volume production which enables simultaneous attainment of 50% weight reduction of vehicle structure and subsystems, affordability, and increased use of recyclable/renewable materials.”

- By 2006, reduce the production cost of carbon fiber from $12 per pound (in 1998) to $3 per pound
- By 2006, develop and validate advanced material technologies that will
  - Enable significant reductions in the weight of body and chassis components and overall vehicle weight (50% reduction in weight of components and 40% reduction in overall vehicle weight relative to 1997 baseline five-passenger vehicles)
  - Exhibit performance, reliability, and safety characteristics comparable to those of conventional vehicle materials
  - Be cost-competitive, on a life-cycle basis, with costs of current materials
- By 2012, develop and validate advanced material technologies that will
  - Enable reductions in the weight of body and chassis components by at least 60% and overall vehicle weight by 50% (relative to 1997 comparative vehicles)
  - Exhibit performance, reliability, and safety characteristics comparable to those of conventional vehicle materials
  - Be cost-competitive, on a life-cycle basis, with costs of current materials

Programmatic Status

Significant progress has been made in the technologies required to manufacture vehicles that meet the FCVT weight reduction targets. Concept vehicles and vehicle designs by the industry partners are demonstrating that the weight targets are achievable. Unfortunately, the materials and manufacturing costs associated with these vehicles are still too high, so additional R&D is needed to achieve the affordability target of comparable cost with acceptable performance, safety, and recyclability.

The R&D tasks of the ALM sub-activity are being conducted through a variety of contractual mechanisms, including cooperative research and development agreements, cooperative agreements, university grants, subcontracts, and in-house research at national laboratories. Other research partners in these efforts include automotive companies, materials suppliers, and non-profit technology organizations.

To achieve the overall FCVT vehicle-level goals, it is imperative that lighter-weight materials be developed with sufficient strength and stiffness to replace conventional materials (i.e., mild steel) for body and chassis applications. FCVT is addressing these imperatives by developing materials and materials-processing technologies, validating these technologies through representative component prototyping, and developing adequate design data and design methodologies to facilitate their beneficial application.

Targets

The technical targets to be achieved by this sub-activity are listed in Table 31.

Barriers

A. **Cost.** Prohibitively high cost is the greatest single barrier to the viability of advanced lightweight materials for automotive applications.
B. **Manufacturability.** Methods for the cost-competitive, high-volume production of automotive components from advanced lightweight materials do not exist, except for some applications of cast aluminum and magnesium.
C. **Design methodologies.** Adequate design data (material property databases), test methods, analytical tools (i.e., models), and durability data are inadequate for widespread applications of advanced lightweight materials.
D. **Joining.** High-volume, high-yield joining technologies for lightweight and dissimilar materials do not exist.
E. **Recycling and repair.** Technologies for cost-effective recycling and repair of advanced materials, especially carbon-fiber-reinforced composites, do not exist.

Approach

FCVT research is focused on specific classes of materials using representative, nonproprietary components. As technical barriers are removed, the technology will be made available for industry to take in-house to perform proprietary, application-specific research.

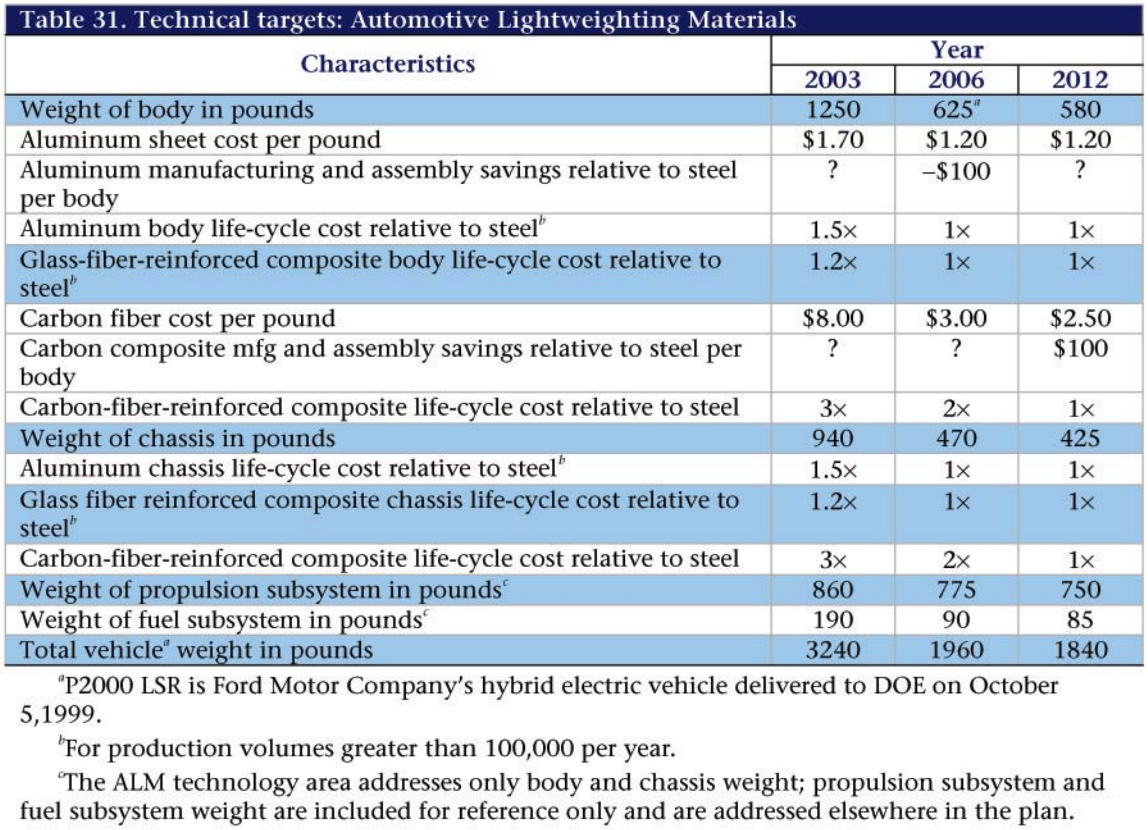


Table 31. Technical targets: Automotive Lightweighting Materials

Characteristics	Year		
	2003	2006	2012
Weight of body in pounds	1250	625[a]	580
Aluminum sheet cost per pound	$1.70	$1.20	$1.20
Aluminum manufacturing and assembly savings relative to steel per body	?	–$100	?
Aluminum body life-cycle cost relative to steel[b]	1.5×	1×	1×
Glass-fiber-reinforced composite body life-cycle cost relative to steel[b]	1.2×	1×	1×
Carbon fiber cost per pound	$8.00	$3.00	$2.50
Carbon composite mfg and assembly savings relative to steel per body	?	?	$100
Carbon-fiber-reinforced composite life-cycle cost relative to steel	3×	2×	1×
Weight of chassis in pounds	940	470	425
Aluminum chassis life-cycle cost relative to steel[b]	1.5×	1×	1×
Glass fiber reinforced composite chassis life-cycle cost relative to steel[b]	1.2×	1×	1×
Carbon-fiber-reinforced composite life-cycle cost relative to steel	3×	2×	1×
Weight of propulsion subsystem in pounds[c]	860	775	750
Weight of fuel subsystem in pounds[c]	190	90	85
Total vehicle[a] weight in pounds	3240	1960	1840

[a] P2000 LSR is Ford Motor Company's hybrid electric vehicle delivered to DOE on October 5,1999.

[b] For production volumes greater than 100,000 per year.

[c] The ALM technology area addresses only body and chassis weight; propulsion subsystem and fuel subsystem weight are included for reference only and are addressed elsewhere in the plan.

Lightweighting materials research addresses the five high-priority barriers identified as follows:

A. **Cost reduction.** Technologies will be pursued that are aimed at reducing the cost of manufacturing lighter-weight automotive structural components. These technologies include
   - Carbon fiber—Research will be pursued that seeks to use new classes of precursors and provide the tools for scaling up precursor volumes and that investigates alternate methods for manufacturing carbon fibers in large volumes.
   - Titanium alloys—The use of titanium alloys is limited because of the cost of the raw materials and the costs associated with manufacturing. Research will be conducted in both areas in order to take advantage of the potential of these alloys.
   - Advanced reinforcement development—Many advanced reinforcement technologies have been identified in recent years that offer the potential for providing low-cost polymer-based materials that are easily processable with exceptionally high performance. Research will be conducted to develop these technologies for application in the automotive industry.
   - Primary metal production—Research will focus on the basic methodologies for cost-effectively producing primary light metals (aluminum, magnesium, and titanium) that rely on energy-intensive, costly technologies. Research

will identify opportunities for optimizing these technologies to achieve efficiency improvements that will result in lower-cost primary metals.

- Magnesium alloys—The focus of research will be to develop improved alloying strategies for low-cost, creep-resistant magnesium alloys that can be die cast.
- Metal matrix composites (MMCs)—Research opportunities to reduce the cost of reinforcing materials, matrix materials, and preforms will be evaluated.
- Glazing materials— Research will be performed to address issues of safety, abrasion resistance, and light transmissibility for advanced glass materials while simultaneously addressing cost-competitiveness.
- Thermoplastic resin systems—Technologies for increasing the performance properties by 10–30% of less costly thermoplastic systems will be developed.

B. **Manufacturability.** Materials processing technologies will be pursued that yield the required component shapes and properties in a cost-effective, rapid, repeatable, and environmentally conscious manner. These technologies include

- Composite processing—Technologies will be pursued for high-volume production of both thermoplastic and thermoset composite materials. These technologies include but are not limited to high-volume injection molding, injection compression molding, pultrusion, net-shape forming, thermoplastic thermoforming, resin transfer molding, non-thermal curing methods, automated material handling systems, and the development of resin systems more amenable to the automotive industry. High-rate preforming techniques will be developed to obtain chopped-fiber preforms with consistently controlled fiber distribution and density at the volumes required by industry.
- Light metals—Research will focus on processing improvements that result in more-reliable cast components made of magnesium with improved performance capabilities to enable increased use of such components in automotive structural applications. Technologies that apply alternative forming processes to take advantage of the weight reduction opportunities of aluminum, magnesium, titanium, and high-strength steel in a cost-effective manner also will be validated through full-scale components.
- MMCs—Strategies for reducing the cost of reinforced MMC components will be pursued with the intent of (1) developing low-cost powder metallurgy techniques, (2) reducing the costs of reinforcing additives, (3) reducing costs of preforms, and (4) reducing costs of processes for introducing reinforcing particles into cast components.
- Nondestructive evaluation—Rapid, reliable, repeatable methods for inspecting metal and composite parts in the manufacturing plant will be developed. The methods must be robust enough and fast enough for a typical assembly plant but sensitive enough to detect critical flaws.
- Low-cost carbon fiber—Production methods will be developed for significantly reducing the cost of carbon fiber; they include microwave carbonization, radiation stabilization, plasma oxidation, and improvements in line speed and production downtime. Because of interface issues between

different technologies and the relative young age of the carbon fiber industry, it will be necessary to integrate the wide variety of new technologies into a single demonstration line and designate that line as a "DOE User Facility."

C. **Design methodologies.** To best take advantage of the properties of polymer composite and lightweight metals in automotive structural components, a significant shift must be made in component design philosophy. Additionally, the differences in properties of materials under consideration require the development of enabling technologies to predict the response of materials after long-term loading, under exposure to different environments, and in crash events. The following research is being pursued to address these problems:

- Long-term effects—Research will be pursued to develop the understanding and predictive capability to assess the effects of low-energy impacts, creep, fatigue, automotive fluids, temperature extremes, and other influences to which materials will be subjected in an automotive environment. Predictive models will be developed that account for the synergistic effects of environmental factors. Models will be developed that can predict the deformation behavior and the performance of lightweight materials.
- Design methods—Efforts will be pursued to develop design methodologies and material use philosophies that take advantage of the positive properties of composite materials, aluminum, advanced high-strength steels, magnesium, and titanium while minimizing the effects of their less desirable properties. These efforts will be pursued through joint DOE/ industry tasks for developing test articles that represent automotive structures and subsystems.
- Energy management testing and models—Theoretical and computational models will be developed and validated for predicting the energy absorption and dissipation in automotive composites and other lightweight materials. The combination of the models and the experimental data will give designers the tools to minimize component weight while maximizing occupant safety.

D. **Joining.** Nonferrous materials require significantly different joining methods than steel. Joining methods must be rapid, affordable, repeatable, and reliable and must provide at least the level of safety that currently exists in production automobiles. The following technologies are being pursued for joining nonferrous materials:

- Aluminum, magnesium and high strength steel joining—Methodologies will be pursued for optimizing joining techniques for aluminum, magnesium and high-strength steel using alternative technologies.
- Composite joining—Research will be performed on alternative technologies for joining composites to composites, composites to steel, and composites to aluminum.
- Nondestructive inspection—Thermal imaging, ultrasonic, and other methods for evaluating joint integrity will be developed that are able to qualify and quantify joint strength. These methods must be robust enough

for a manufacturing facility, fast enough for a production line, and reliable enough to ensure passenger safety.

E. **Recycling and repair.** Methods for separating and recycling nonferrous materials will be pursued that look at the in-plant and post-consumer waste streams. This work will be conducted in conjunction with industrial consortia and other organizations as appropriate.

- Resin/fiber separation and reuse—Methods will be pursued for separating carbon fiber from thermoset and thermoplastic resin systems. Economically viable uses for recycled fiber and resins will be developed, and methodologies for further blending and compounding for reuse will be investigated.
- Post-shred residues—Technology for the cost-effective recovery of materials from post-shred residues will be developed and demonstrated.
- Light metals—Methods will be developed for sorting aluminum, magnesium, and other shredded automotive light-metal scrap. Purification of in-plant and post-consumer magnesium scrap will be addressed. Technologies to recycle MMCs into high-value products will be pursued.
- Repair of aluminum, magnesium and composites—Robust methods will be developed for rapidly and reliably repairing aluminum, magnesium, and composite structures. The cost-effectiveness of repair vs. replacement of components will be considered; the outcome will influence the joining technologies needed to incorporate alternate materials.

Research will focus on technologies for achieving the priority FCVT goals and FreedomCAR partnership goals. To achieve these measures and goals, a significant portion of the steel and iron must be replaced with aluminum or reinforced composites. Magnesium may replace many cast aluminum components and some ferrous components. In addition, advanced high-strength steels, MMCs, and titanium will be required for some applications that cannot be satisfied by polymer matrix composites, magnesium, or aluminum. It is anticipated that weight reduction research on components currently fabricated with copper, brass, zinc, rubber, and glass will be supported by industry, other agencies, and/or DOE efforts on an as-required basis.

Task Descriptions

Table 32 describes the tasks necessary for successful development of the various types of materials, including task descriptions, durations, and pertinent barriers. The schedule for and the relationships among the tasks are shown on the ALM network chart at the end of this sub-section. Milestones have been established and are shown in the network chart.

Table 32. R&D tasks for Automotive Lightweighting Materials

Task	Title	Duration/ barriers
1	Aluminum Alloys Phase 1 (Completed) • Developed continuous casting technologies and non–heat treatable aluminum alloy sheet, optimized cast-product design knowledge, developed cost-effective semi-solid forming technology, and developed technologies to extend life of dies for aluminum die-casting	36 months Barriers A, B
	Phase 2 • Evaluate and improve forming processes for aluminum automotive components • Complete development and optimization of electroforming technologies • Complete development of advanced forming technologies such as hydroforming, warm forming, and variable binder control for aluminum components	30 months Barrier B (began 4Q 2002)
	Phase 3 • Evaluate and develop alternative technologies for low-cost processing of sheet aluminum alloys, e.g. spray rolling, for automotive applications • Develop low-cost continuous casting technology for production of high-quality 6xxx series aluminum sheet for application in outer panels	36 months Barriers A, B (begin 3Q 2005)
2	Composite Processing Phase 1 (Completed) • Developed rapid preforming and processing technologies for glass-reinforced composites	42 months Barrier B
	Phase 2 • Develop the processing capability to use rapid preforming technology for carbon fiber composites for automotive preforms that achieve automotive production rates and 1.5-mm thicknesses • Optimize discontinuous fiber composite processing technologies to achieve realistic production speeds, quality, and cost-effectiveness	42 months (began 1Q 2001)
	Phase 3 • Develop the processing capability to combine rapid preforming with thermoplastic resins to accomplish preforming and molding on one machine, followed by thermoforming • Demonstrate production-ready molding and forming technologies in a full-scale demonstration based on carbon fiber composites	42 months (begin 3Q 2004)
	Phase 4 • Develop the processing capability to combine rapid preforming technology for carbon fibers and glass to make hybrid material automotive preforms that achieve automotive production rates and 2.0-mm thickness • Begin processing studies using advanced polymer fibers as reinforcements	60 months (begin 1Q 2008)
3	Enabling Technologies Phase 1 (Completed) • Developed a design database, design methodology, joining methodologies, non-destructive evaluation techniques, and durability protocol for glass-fiber composites and joining processes for dissimilar materials and aluminum	72 months Barrier C

Table 32 (continued)

Task	Title	Duration/ barriers
	Phase 2 • Develop a design database and design methodology for thermoset carbon-fiber composites, including durability and processing parameters • Develop reliable joint test methodologies and novel joint design technologies for hybrid material joints • Evaluate reliable joining processes for dissimilar materials, including mechanical fastening, pulse bonding, friction stir welding, and other advanced joining techniques • Develop nondestructive evaluation processes for fiber-reinforced-composite and metallic components and installed parts, including predictive performance capability • Develop designer-usable joint models to aid structural engineers in designing joints for weight reduction and occupant safety optimization • Develop models for prediction of the response of metallic components to deformation during forming and during use • Develop predictive tools for polymer composite property retention • Demonstrate joining technologies for application to joining of different product forms, e.g., hydroformed tubes to castings • Develop on-line and near-real-time nondestructive evaluation methods for inspection of joining processes to determine bond quality and quantify defects • Develop nondestructive evaluation methods to measure and/or verify lay-up of fibers, resin fill, resin infiltration, fiber wetting, and curing for polymer composites	60 months Barrier C (began 1Q 2001)
	Phase 3 • Develop aluminum rivets for joining of aluminum components • Develop predictive models for dimensional control of welded assemblies • Develop a design database and design methodology for thermoplastic automotive fiber-reinforced composites, including durability and processing parameters. Glass fibers, carbon fibers, or other advanced reinforcements may be used • Integrate all joining-related tasks into demonstrations that highlight the benefits of all technologies developed earlier and demonstrate industry-acceptable assembly • Develop joining and assembly technologies to ensure adequate dimensional control	60 months Barrier C (begin 1Q 2005)
4	Low-Cost Carbon Fiber Phase 1 (Completed) • Demonstrated the technical and economic viability of using alternate, low-cost precursor materials and production processes for making carbon fiber	36 months Barriers A, B
	Phase 2 • Optimize a nonthermal process of carbonizing and graphitizing carbon fiber from polyacrylonitrile • Complete development of alternate precursors for producing low-cost carbon fiber and demonstrate feasibility of an advanced much lower-cost precursor • Develop non-thermal methods for stabilizing and oxidizing carbon-fiber precursors while demonstrating technical and economic feasibility	48 months Barriers A, B (began 1Q 2000)

Table 32 (continued)

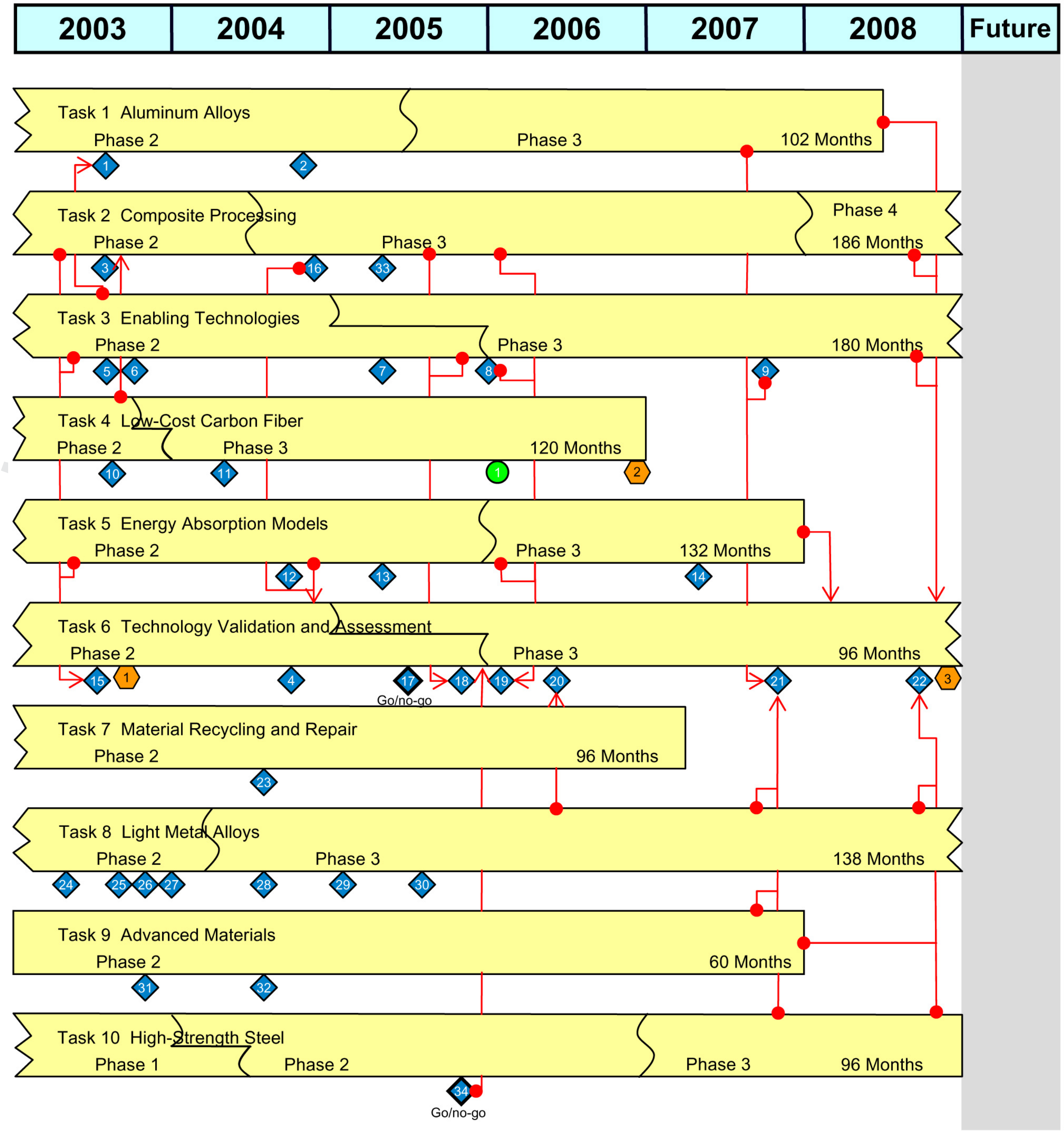
Task	Title	Duration/ barriers
	Phase 3 • Develop a carbon-fiber research user facility • Complete development of advanced stabilization and oxidation methods • Validate scaled-up processes through economic and technical analysis • Assist industry in implementing the new technologies	36 months Barriers A, B (began 4Q 2003)
5	Energy Absorption Models Phase 1(completed) • Developed and validated energy absorption material models for advanced structural materials and a composite-intensive vehicle	60 months Barrier C
	Phase 2 • Develop the capability to do high-rate testing and data acquisition for validation of models and development of novel design concepts • Evaluate the energy-absorption capability of a hybrid-material body-in-white • Develop understanding of the effect of strain-rate-dependent materials on crash energy absorption capabilities • Evaluate the energy absorption capabilities of bonded and mechanically fastened structures • Develop an energy management design database for magnesium alloys and structures • Develop test methods, constitutive materials models, and finite-element analysis guidelines for simulation of crash energy absorption of high-strength steels and magnesium	48 months Barrier C (began 1Q 2002)
	Phase 3 • Develop and validate energy-absorption subsystem models and integrate those models into a vehicle structure • Validate vehicle-level models in crash tests	24 months Barrier C (begin 1Q 2006)
6	Technology Validation and Assessment Phase 1 (Completed) • Verified that technologies developed yielded a 25% weight reduction of body and chassis at acceptable cost. Completed a demonstration based on glass fiber composites	
	Phase 2 • Through modeling and analysis, verify that technologies developed will yield >50% weight reduction of body and chassis • Develop tooling and demonstrate key component technologies enabling at least 50% weight reduction for body and chassis components • Complete a demonstration that integrates all of the carbon-fiber-based research tasks to demonstrate technical and economic viability	36 months Barriers A, B, C, D, E 54 months (began 1Q 2003)
	Phase 3 • Develop tooling for all components, fabricate and assemble components, and demonstrate weight reduction and quality assurance processes required for high-volume production for thermoplastic composite structures • Complete a demonstration that integrates all of the thermoplastic composite and advanced reinforcement development research to demonstrate technical and economic viability of the technologies	60 months (begin 1Q 2005)
7	Material Recycling and Repair Phase 1 (Completed) • Evaluated processes for sorting aluminum alloys, recovering carbon fiber, and recycling magnesium scrap	36 months Barrier E

Table 32 (continued)

Task	Title	Duration/ barriers
	Phase 2 - Extend aluminum scrap-sorting technologies to other light metals, such as magnesium and titanium - Develop recovery processes for separating the high-value fiber from the resin Provide recycled fiber for process trials - Develop and demonstrate technologies for "post-shred" residue materials recovery - Pursue development of technology for removal of PCBs and other substances of concern from recycled automotive materials - Scale-up fiber-reinforced composites recovery and separation processes and implement them in a large-scale recycling system for full vehicle parts - Develop technologies for repair of structural/safety components - Develop technologies for recycle of metal matrix composites, high-strength steels, etc.	60 months Barrier E (began 2Q 2002)
8	Light Metal Alloys Phase 1(Completed) - Developed improved alloying for creep-resistant magnesium alloys and performed exploratory research on processing technologies with a potential for low-cost ($5/lb) primary titanium	42 months Barrier A
	Phase 2 - Develop and optimize processing technologies for direct reduction of MgO to produce primary magnesium at reduced cost - Evaluate the economic feasibility of emerging processes for cost-effective production of titanium - Evaluate properties of test components produced from titanium powders made using low-cost processing techniques - Develop compositional variants of magnesium alloys to optimize properties - Optimize design knowledge and product capabilities for cast magnesium components with improved strength and ductility and validate with full-size components - Explore optimized secondary processing of cast aluminum metal matrix composites, develop lower-cost finishing technologies, and demonstrate on full-sized component - Develop coating technologies to improve corrosion and wear resistance of magnesium alloy components	36 months Barrier A (began 2Q 2001)
	Phase 3 - Perform R&D on processing technologies that have proved successful through the exploratory research phase and have a potential for low-cost ($5/lb) primary titanium - Develop low-cost manufacturing and machining processes for titanium components, including direct casting of titanium bar and rod products - Conduct validation tests on cast magnesium structural and powertrain components - Develop warm-forming technology for magnesium sheet - Investigate the potential for lost-foam casting of magnesium alloys for powertrain components	60 months Barrier A (begin 2Q 2004)

Table 32 (continued)

Task	Title	Duration/ barriers
9	Advanced Materials Phase 1 (Completed) Phase 2 • Develop technologies for cost-effective fabrication and assembly of advanced metal components • Develop technologies for lightweight, cost-effective alternatives to glass closure panels • Develop advanced polymer reinforcing fibers and micro-particle composite reinforcement technologies • Develop non-thermal methods for cross-linking thermoplastic resins with and without reinforcements • Develop the concept for hybrid material structure focal project and initiate tasks to develop necessary technologies • Develop and validate cost-effective technologies for fabrication of ultralight tailored structural materials, including metal foams, syntactic materials, and novel composites • Investigate properties of nanostructured materials made from machining chips and identify potential applications	60 months Barrier B (began 1Q 2003) Barrier A
10	High-Strength Steel Phase 1 • Develop forming technologies for advanced high-strength steels to enable 25% mass savings in front end structure • Conduct stamping trials and compare them with computer simulations • Develop durable die materials for hot metal gas forming of high-strength steels	36 months Barriers B, C (began 3Q 2001)
	Phase 2 • Develop an understanding of the formability of high-strength steel sheet during tubular hydroforming • Optimize forming and joining technologies for transformation-induced-plasticity (TRIP) steels • Improve accuracy and confidence in finite element modeling of high-strength steel forming • Develop an understanding of steel-lubricant interactions during forming	36 months Barriers B, C (begin 1Q 2004)
	Phase 3 • Extend investigations of the forming technologies for advanced high-strength steels for front-end structures to the passenger compartment and rear-end structure	24 months Barriers B, C (begin 1Q 2007)



Legend

◆ **Milestone**

1. Establish formability criteria for finite element modeling of aluminum, using stress-based or damage models of failure
2. Complete development of binder control system for stamping of aluminum sheet components
3. Complete processing study of the molding of P4 carbon preforms by the injection/compression process using the Automotive Composites Consortium B-pillar shaped mold
4. Validate carbon-fiber rapid preforming technology
5. Publish report, *Durability-Based Design Criteria for Chopped-Carbon-Fiber Composite*
6. Determine joint performance of dissimilar aluminum alloys and steels (dual-phase and HSLA350) with and without adhesive
7. Complete development of predictive models for dimensional control of welded assemblies
8. Demonstrate welding technologies for application to joining of different product forms of aluminum (e.g., hydroformed tubes to castings)
9. Demonstrate dimensional control for welded aluminum
10. Complete development of the required underlying technology (hardware, process conditions) and the demonstration of a continuous 24 inch/minute production line speed, multiple-tow, microwave-assisted plasma carbonization processing unit
11. Demonstrate technical and economic ability to use lignin as the base for precursors for low-cost carbon fiber
12. Develop an understanding of the effect of strain-rate-dependent materials on crash energy absorption capabilities
13. Complete evaluation of energy-absorption capabilities of prototype bonded and mechanically fastened structures.
14. Validate vehicle-level models for energy absorption in crash tests.
15. Complete detailed design of entire composite-intensive body-in-white, along with cost, weight, and performance analysis
16. Complete part fabrication for composite-intensive body-in-white
17. **Go/no-go**: Complete cost, weight, and performance analysis of composite-intensive body-in-white
18. Complete composite-intensive body-in-white testing and verification
19. Complete design for hybrid materials focal-project structure
20. Complete vehicle testing of magnesium powertrain components.
21. Complete hybrid-material body-in-white assembly
22. Complete first prototype of hybrid materials focal-project structure and identify manufacturing process
23. Complete evaluations of technologies for bulk separation of shredder residue, including electrostatic separation, hydrodynamic floatation, and gravity table separation
24. Complete castability trials of selected Mg alloys to ensure that alloys with best high-temperature properties are castable into powertrain components
25. Complete casting trials of highly reinforced aluminum metal matrix composite prototype brake rotor, having 40 volume percent reinforcement
26. Demonstrate technologies for producing low-cost cast aluminum metal matrix composites in full-size components
27. Review cost analysis of cast Mg engine cradle to verify that the process achieves the best quality, performance, and economic value
28. Complete development of creep-resistant magnesium alloys and initiate validation tests of automotive component
29. Develop corrosion/wear coatings for completed magnesium components
30. Optimize design knowledge and product capabilities for cast magnesium structural components and validate with full-size component tests
31. Complete the noise prediction models and issue a technical report describing the model and side-door glass optimization studies
32. Demonstrate 50% mechanical property improvement over unreinforced resins using micro-composite technology
33. Demonstrate proof-of-principle feasibility to crosslink commercial resin systems using non-thermal energy methods
34. **Go/no-go**: Demonstrate and validate 25% mass savings in front-end structure made of advanced high-strength steels

⬢ **Technology Program Output**

1. Composite intensive body-in-white weight and performance analysis available to Vehicle Systems Analysis
2. Validated technologies for production of Carbon Fiber at a cost of $3/lb available to industry
3. Hybrid body-in-white weight and performance data available to Vehicle Systems Analysis

● **Supporting Input**

1. Validated carbon fiber oxidation technologies provided from the High Strength Weight Reduction Materials technology area

4.6.2 Automotive Propulsion Materials

The vision of the Automotive Propulsion Materials (APM) sub-activity is to improve engine efficiency and reduce the costs of fuel cell systems and power electronics. The APM is an integral partner with and provides enabling technologies for the Advanced Power Electronics, Advanced Combustion Engine, and Fuel Cells for Transportation R&D activities. Research performed under this sub-activity is primarily focused on light vehicle applications; however, it is recognized that the technologies may also have application on heavy vehicles. Management of this sub-activity and the Heavy Vehicle Propulsion Materials sub-activity are coordinated to ensure that they are complementary, rather than duplicative.

Goals

The technical goals of the APM sub-activity are the goals of the Advanced Power Electronics, Fuel Cell, and Advanced Combustion Engine activities and are not repeated here. The goals for Advanced Power Electronics and Advanced Combustion Engines are listed in Sections 4.4 and 4.5, respectively, of this report. The goals for Fuel Cells are contained in the HFCIT R&D Plan. In addition, APM-specific goals are these:

- By 2007, validate carbon foam durability and effectiveness in power electronic cooling applications.
- By 2005, complete the testing and validation of a diesel particulate filter with 95% effectiveness for the life of the vehicle.

Programmatic Status

A microwave-regenerated exhaust filter system has been developed. This pleated filter system has about 1/20th of the backpressure of conventional filters, captures more than 95% of the diesel particulates, and is cleaned using an onboard microwave. Significant progress has been made in the development of smaller, lighter-weight, high-temperature electronics and advanced cooling systems. Porvair Fuel Cell Technology, through technology transfer, is developing and manufacturing carbon composite bipolar plates that are lighter in weight, thinner, and less costly than conventional plates.

Targets

The APM sub-activity supports the achievement of the goals and objectives of three core FreedomCAR research areas as indicated in Table 33.

Table 33. Automotive Propulsion Materials technical targets

Automotive Propulsion Materials	Technical targets
Thermal management materials	Durability and effectiveness for 15 years
Fuel cell materials, membranes that operate at temperatures >150ºC	See *Office of Hydrogen, Fuel Cells and Infrastructure RD&D Plan*
Diesel particulate filter materials	Greater than 95% removal for the life of the vehicle

Barriers

The barriers for APM are shown as system barriers in Table 34. The associated enabling materials barriers are shown and are keyed to the system barriers.

Table 34. Automotive Propulsion Materials barriers

System barriers	Materials barriers
Current NO_x and PM emissions from advanced combustion engines exceed the targets by a factor of four to eight	A. Materials and technologies used to reduce NO_x and PM emissions are ineffective and unreliable
Thermal management	B. Heat transfer of materials used in heat exchangers and heat sinks is too low
Cathode activity is insufficient for the desired operating voltage	C. Materials used as electrodes lack sufficient activity and are intolerant of CO, NH_3, and sulfur
Stack material costs are too high and performance is too low	D. Materials used as bipolar plates and membrane electrode assemblies are too costly
Cost of electric drive systems, advanced combustion engines, and fuel cells	E. Materials and manufacturing methods for electric drive systems, advanced combustion engines, and fuel cells are too costly

Approach

To achieve the sub-activity goals and overcome the technical barriers, the Automotive Propulsion Materials sub-activity has initiated enabling research that addresses the materials barriers identified.

Emissions reduction. Current technologies used to reduce NO_x and PM emissions from diesel engines create significant backpressures and are ineffective, unreliable, and very costly. New technologies such as microwave-regenerated particulate traps, non-thermal plasma systems, and improved NO_x catalysts are being developed to reduce NO_x and PM emissions.

Thermal management materials. Faster computer chips and higher-power components are being developed that will generate more heat and be more difficult to cool than today's electronics. Advanced cooling technologies that use spray or evaporative cooling and/or high-conductivity carbon foam are being developed.

Electrode performance. In order to meet efficiency targets, improved cathodes will need to be developed to increase the operating voltage or power density. These improved materials will need to be non-noble in nature, operate at higher temperatures, and be much more tolerant of impurities such as carbon monoxide, ammonia, and sulfur.

Stack material cost/performance. Present polymer electrolyte membrane fuel cell stacks use high-cost bipolar plates, high-cost membranes, and precious metal catalysts. Innovative research on higher-temperature membranes (~150ºC) and non–precious-metal catalysts will be required for more dramatic cost reduction. Modeling and simulation will be carried out in parallel to accurately predict lifetimes of the membrane electrode assembly and calculate catalyst loadings.

Cost. The materials and manufacturing methods used to fabricate small, lightweight, electric-drive systems; fuel cells; and advanced combustion engines are very costly. Processes are being developed to fabricate smaller, lighter, and less-costly electronics, engines, and fuel cells.

Task Descriptions

Table 35 describes the tasks necessary for successful development of the materials and technology to address the pertinent technical barriers of this sub-activity. The task descriptions and duration of the tasks are shown in Table 35.

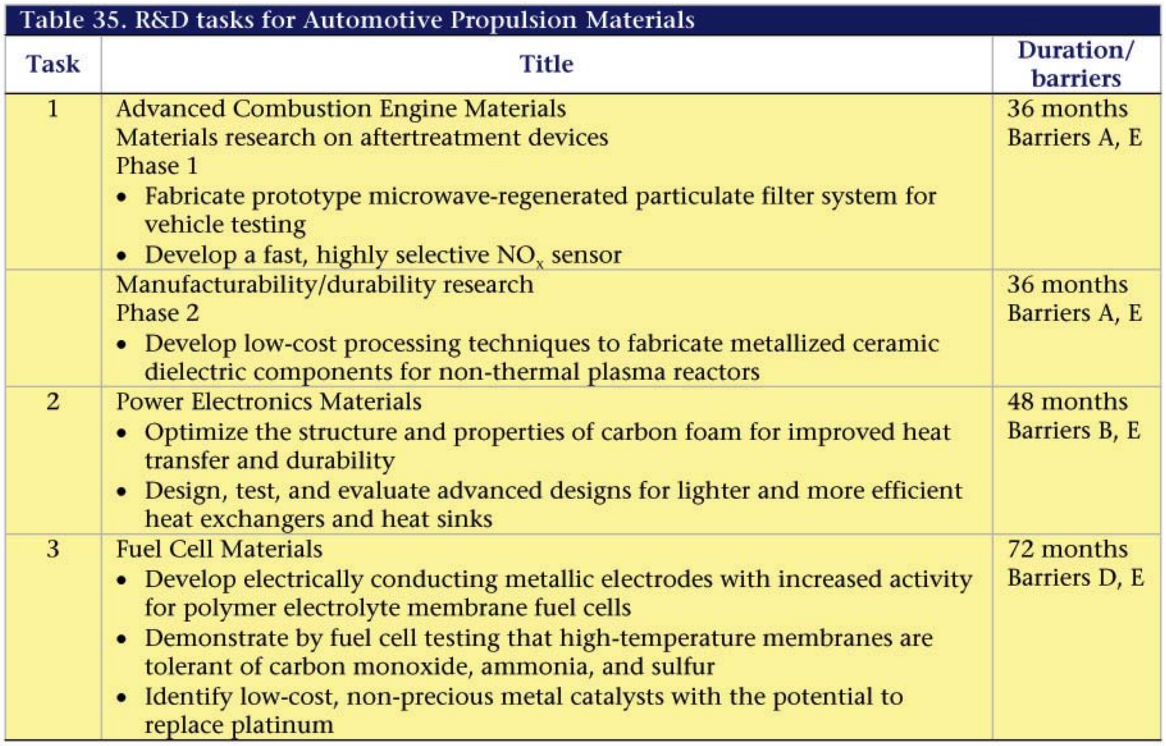
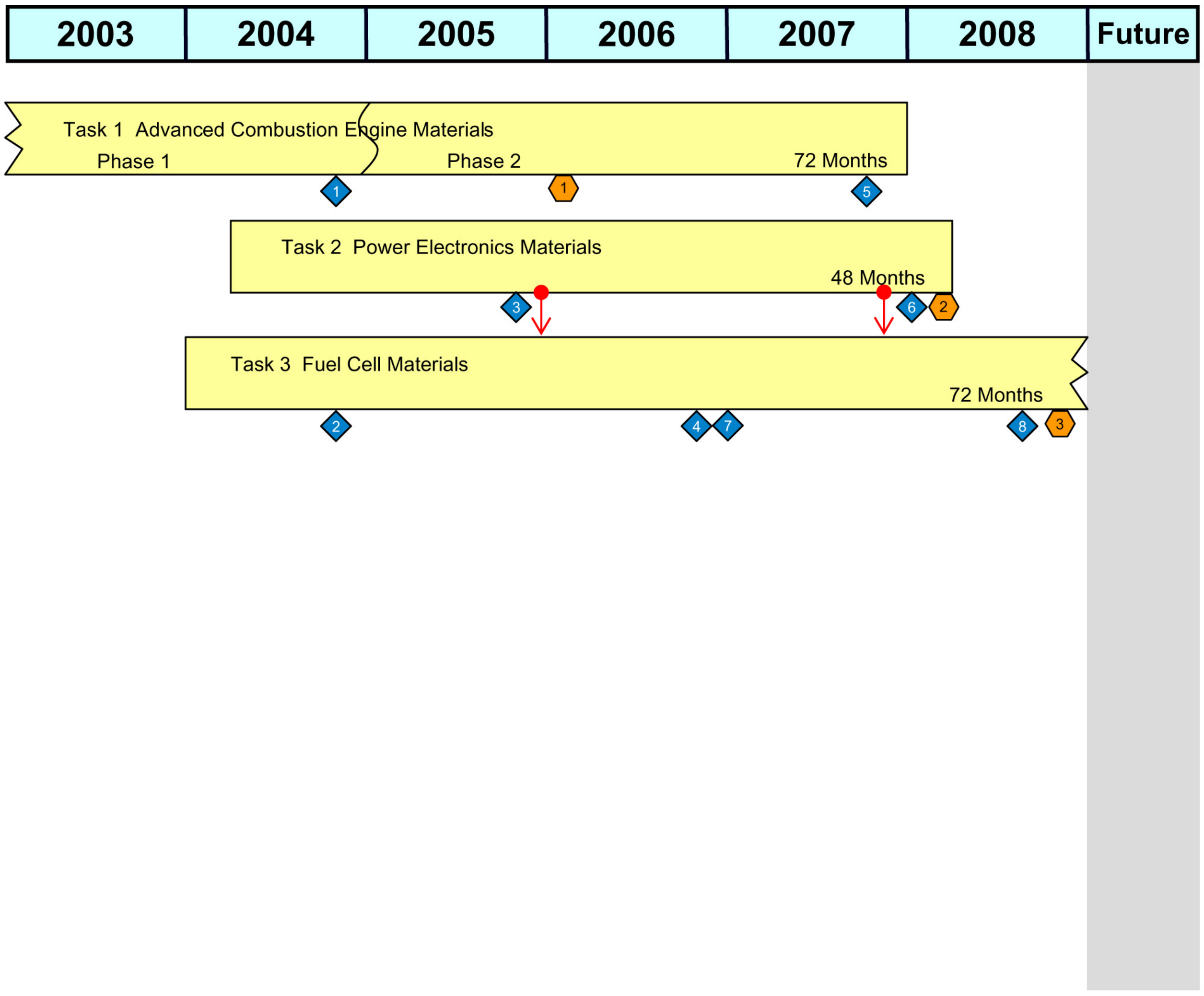


Table 35. R&D tasks for Automotive Propulsion Materials

Task	Title	Duration/ barriers
1	Advanced Combustion Engine Materials Materials research on aftertreatment devices Phase 1 • Fabricate prototype microwave-regenerated particulate filter system for vehicle testing • Develop a fast, highly selective NO_x sensor	36 months Barriers A, E
	Manufacturability/durability research Phase 2 • Develop low-cost processing techniques to fabricate metallized ceramic dielectric components for non-thermal plasma reactors	36 months Barriers A, E
2	Power Electronics Materials • Optimize the structure and properties of carbon foam for improved heat transfer and durability • Design, test, and evaluate advanced designs for lighter and more efficient heat exchangers and heat sinks	48 months Barriers B, E
3	Fuel Cell Materials • Develop electrically conducting metallic electrodes with increased activity for polymer electrolyte membrane fuel cells • Demonstrate by fuel cell testing that high-temperature membranes are tolerant of carbon monoxide, ammonia, and sulfur • Identify low-cost, non-precious metal catalysts with the potential to replace platinum	72 months Barriers D, E



Legend

Milestone

1. In collaboration with industrial partners, demonstrate advanced emissions treatment systems to comply with regulations for PM and NO_X
2. Identify non-precious metal materials that have sufficient catalytic activity to replace Pt catalysts in PEM fuel cells
3. Demonstrate the advantages of using high-conductivity carbon foam in advanced cooling technologies such as spray cooling and evaporative cooling
4. Evaluate the performance of single-cell PEM fuel cells that utilize non-precious metal catalysts
5. Provide emission control systems to diesel engine manufacturers for performance, reliability, and durability testing
6. Demonstrate advanced power electronics cooling technology that is lighter, is lower in cost, and can accommodate the increased cooling needs of higher-power-density electronics
7. Demonstrate the performance of high-temperature polymer membranes
8. Demonstrate the electrical and mass transport properties of a scaled-up single-cell PEM fuel cell (~1 ft square) that uses a high-temperature membrane

Technology Program Output

1. Validated emission control devices available to industry, Vehicle Systems, and Advanced Combustion Engine R&D
2. Validated Power Electronics cooling technology available to industry and Vehicle Systems
3. High temperature membrane technology to HFCIT

4.6.3 High-Strength Weight Reduction Materials

The vision of the High-Strength Weight Reduction (HSWR) Materials sub-activity is to reduce parasitic energy losses due to the weight of heavy vehicles. In addition, it is recognized that improved materials may enable implementation of other technologies that can further improve the fuel efficiency of the vehicles. The research will achieve this vision by identifying lightweighting materials and materials processing technologies that can contribute cost-effectively to reducing the weight of the vehicle without sacrificing functionality, durability, reliability, or safety. Research performed under this sub-activity is primarily focused on heavy vehicle applications; however, it is recognized that the technologies may also have application on light vehicles. Management of this sub-activity and the ALM sub-activity are coordinated to ensure that they are complementary, rather than duplicative.

Goals

The goals of this sub-activity include the priority FCVT goal identified in Section 3 for the reduction of tractor-trailer combination weight. In addition, the goals directly support the 21st CTP goal for weight reduction of vehicle structure and subsystems.

- By 2010, reduce the weight of an unloaded tractor-trailer combination from the current 23,000 lb (2003) to 18,000 lb, a reduction of 22%.
- Enable significant reductions in the weight of heavy vehicles. (For example, the 21st CTP goal is a 15–20% reduction in weight of Class 8 tractor-trailer combinations relative to 2002 vehicles. Goals for other classes of heavy vehicles vary between 10 and 33% reductions in vehicle weight, depending on performance requirements and duty cycles.)

These goals will be met with the constraint that the materials

- Exhibit performance, durability, reliability, and safety characteristics comparable to those of conventional vehicle materials
- Be cost-competitive, on a life-cycle basis, with costs of current materials
- Be consistent with the materials regulation requirements of our socially and environmentally responsible national industries

Programmatic Status

To achieve the priority FCVT goal to reduce vehicle weight by 22% by 2010, HSWR Materials has been developing a broad spectrum of advanced materials technologies that can be applied to a wide array of body, chassis, and suspension vehicle components. The research required to develop these technologies is too high-risk to be pursued independently by the heavy vehicle industry because of substantial uncertainties regarding return on investment.

Although a number of tasks have been initiated to address weight reduction targets, significant barriers still exist that prevent timely application of these materials to heavy vehicles. The R&D tasks of HSWR Materials are being conducted through a variety of contractual mechanisms. Research partners include heavy vehicle manufacturers, first-tier and materials suppliers, national laboratories, and other non-profit technology organizations. By virtue of a natural overlap of interests in materials, the interactions of the HSWR Materials sub-activity are primarily the same as those identified for the ALM sub-activity. However, frequent and detailed communication ensures effective collaboration and technology development that benefits both sub-activities. Yet they differ inasmuch as the performance requirements for heavy vehicle components are typically several times larger than those for passenger and light-duty vehicles.

Targets

The technical targets to be achieved by the HSWR Materials sub-activity are listed in Table 36.

Table 36. Technical targets: High Strength/Weight Reduction Materials (Class 8 over-the-road tractor)

Characteristics	Year				
	2003	2006	2009	2012	2015
Weight of cab, closures, and interior[a] (Note: Cab weight reduction is larger than 20% to make up for lower weight reductions in powertrain and exhaust aftertreatment)	3230	2940	2560	2310	1970
Aluminum cab life cycle cost relative to steel	2×	1.5×	1×	1×	1×
Hybrid glass/carbon fiber reinforced composites life-cycle cost relative to steel	3×	2.5×	2×	1.5×	1×
Hybrid metal/fiber reinforced composite life-cycle cost relative to steel	3×	2×	1.5×	1×	1×
Carbon fiber reinforced composite life-cycle cost relative to steel	4×	3×	2×	1.5×	1.5×
Weight of chassis in pounds[b]	3570	3330	3090	2850	2610
Aluminum/magnesium chassis life-cycle cost relative to steel	1.5×	1.5×	1.2×	1×	1×
Carbon and/or carbon/glass fiber reinforced chassis life-cycle cost relative to steel	3×	2.5×	2×	1.5×	1.5x
Weight of drivetrain subsystem in pounds[c]	4590	4300	4000	3670	3370
Aluminum/magnesium intensive drivetrain subsystem life-cycle cost relative to steel	2×	1.5x	1×	1×	1×
Carbon and/or carbon/glass fiber reinforced composite intensive drivetrain life-cycle cost relative to steel	4×	3×	2×	1.5×	1.5×
Weight of powertrain system in pounds[d] (Note: Powertrain not expected to reach 20% weight reduction due to increased weight of aftertreatment)	5610	5330	5050	4770	4490
Total vehicle weight in pounds	17000	15900	14700	13600	12440

[a] Includes cab in white, sleeper unit, hood and fairings, interior and glass.

[b] Includes frame rails, cross-members, brackets, fifth wheel, fuel systems, and fasteners.

[c] Includes drive axles, steer axles, suspension system, and set of ten wheels and tires.

[d] Includes engine and cooling, exhaust and exhaust aftertreatment systems, transmission, engine accessories, and batteries. The HSWR Materials program does not directly address engine weight reduction efforts.

Barriers

A. **Cost.** Prohibitively high cost is the greatest single barrier to the viability of advanced lightweighting materials for heavy vehicle applications.

B. **Design and simulation technologies.** Adequate design data for heavy vehicle structures (e.g., materials property databases for properties of interest for heavy vehicles, such as durability, corrosion, and fatigue), test methodologies, analytical simulation tools, and durability data do not exist for many lightweight materials.

C. **Manufacturability.** Methods for the cost-competitive production of components for heavy vehicles in volumes of interest to the heavy vehicle industry are not sufficiently well developed.

D. **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 high.

E. **Joining and assembly.** High-yield, robust, joining technologies for lightweight materials are not sufficiently developed.

F. **Maintenance, repair, and recycling.** Technologies for cost-effective maintenance and repair are inadequate for many lightweight materials.

Approach

To achieve the HSWR goals, it is imperative that lighter-weight materials be developed to replace conventional materials (i.e., mild steel) for body, chassis, and suspension applications while still meeting the demanding performance requirements of heavy vehicles (e.g., strength, stiffness, durability, reliability). These imperatives will be addressed by developing materials and processing technologies, validating these materials through component prototyping, and developing adequate design data and design methodologies to facilitate their beneficial application.

Relevant materials include light metals; advanced engineered materials, such as MMCs and ultralight materials (e.g., engineered laminate materials and foams); materials that enable lightweighting, such as advanced high-strength steels or stainless steels; and reinforced polymer composites. These materials must be strategically applied to optimally match their special properties to key application needs. This approach will allow reduced weight at minimal or no cost penalty while still addressing the optimization of strength and stiffness; improvement of vehicle dynamics, handling, and safety; and improvement of durability and maintenance. It will also be necessary to develop robust, flexible, and reliable manufacturing processes to optimize for part consolidation, net shape forming, lower assembly costs, and low-cost tooling. Finally, the total life cycle costs to the trucking industry demand that maintenance, repair, and recyclability be addressed. Within the timeframe of this plan, materials research will be balanced between nearer-term objectives and longer-term, higher-risk materials research. Research tasks have been identified to address the most significant barriers within the technical activities that the materials community considers higher-risk but that, if successfully developed, would result in significant progress toward the activity goals. The technology development tasks have been identified through workshops, white papers, and planning assessments and have led to supported efforts on composites, steel, aluminum, magnesium, and titanium. Six areas of research have been identified.

A. **Cost reduction.** The number-one need for all lightweight materials is lower cost for primary materials. However, in many cases, such as the extraction of metals from ore, the technology development need is beyond the scope of the HSWR Materials sub-activity. In some cases, it is being addressed elsewhere. Nonetheless, the feasibility of novel technologies with potential to address this basic need will be explored when appropriate. The life cycle costs of lightweight materials will also be addressed by (1) developing technologies that enable parts consolidation and reduce the cost of secondary processing during manufacturing and (2) materials developments that enhance the durability of these materials so that replacement intervals can be extended.

B. **Design and simulation technologies.** User-friendly databases will be developed that are easier to use for both design and simulation. They must reflect accurately the performance needs of heavy vehicles, including durability, corrosion, and fatigue. Materials-specific design methodologies will be developed, for both advanced metals and composites, that take advantage of the inherent characteristics of the various materials and allow designs to be optimized for weight, manufacturability, performance, safety, and cost. Development of both system-level and component-level design and manufacturing modeling tools will be pursued to enable industry to realize the advantages provided by lightweight materials, either alone or in combination. Accelerated test methods that simulate materials behavior under operating conditions must also be developed. Theoretical and computational models will be developed and validated to optimize the microstructure of materials for heavy vehicle applications with respect to mechanical and environmental performance. Finally, simulation tools will be developed that can predict the behavior of materials during the manufacturing process, as well as the response of materials after long-term loading, under exposure to different environments, and in crash events.

C. **Manufacturability.** Processing technologies will be pursued that yield the required component shape and properties in a cost-effective, rapid, repeatable, and environmentally conscious manner. It is important that these technologies maximize component function and reduce part count, assembly cost, and weight. Technologies must be developed to enhance the capability to produce a class A finish for polymer composites. Alternative processes that take advantage of the weight reduction opportunities cost-effectively will also be pursued.

D. **Tooling and assembly.** Because the number of vehicles produced annually by the heavy vehicle industry is low compared with the number produced by the automotive industry, the cost of tooling is more significant. The development of lower-cost, flexible tooling approaches will be pursued for shape forming of all materials, e.g., casting of magnesium, aluminum, and titanium; stamping of aluminum, magnesium, and advanced high-strength steels; and processing of composites. Faster tooling development processes that shorten lead-time and reduce prototyping steps will be developed.

E. **Joining and assembly.** Lightweight materials require different joining methods than plain carbon steel. New joining methods must be rapid, affordable, repeatable, and reliable and must provide at least the level of durability and safety that currently exists in production vehicles. In addition, joint designs for lightweight materials, either individually or in combination, must be developed to accommodate the higher performance requirements of heavy vehicles. Methods will be developed for evaluating joint integrity and strength. These methods must be robust and fast enough for a manufacturing facility while being durable and reliable enough to ensure vehicle safety.

F. **Maintenance, repair, and recycling.** Market dynamics and incentives must be understood as the major drivers for maintenance, repair, and recycle decisions. Maintenance and repair issues for cab structures are primarily associated with durability, i.e., fatigue-related failure and corrosion. The combination of dissimilar materials systems and extended exposure to wet, corrosive, and abrasive road conditions present significant challenges. Research will be focused on developing low-cost corrosion-resistant materials and coatings. Improved methods for detecting and monitoring corrosion to replace visual inspection will also be developed to allow for timely preventive maintenance. Major damage modes for trailers are structural damage from impacts (driver-related), structural damage due to forklift impacts, and corrosion. Low-cost, robust, field-deployable repair procedures must be developed for lightweight materials and hybrid materials systems. Techniques for cost-effective disassembly will be investigated.

Task Descriptions

Table 37 describes the tasks necessary for successful development of the various types of materials, including task descriptions, durations, and the pertinent barriers. The schedule for and the relationships among the tasks are shown on the network chart at the end of this sub-section. Milestones have been established and are also shown on the network chart.

Table 37. R&D tasks for High-Strength Weight Reduction Materials sub-activity

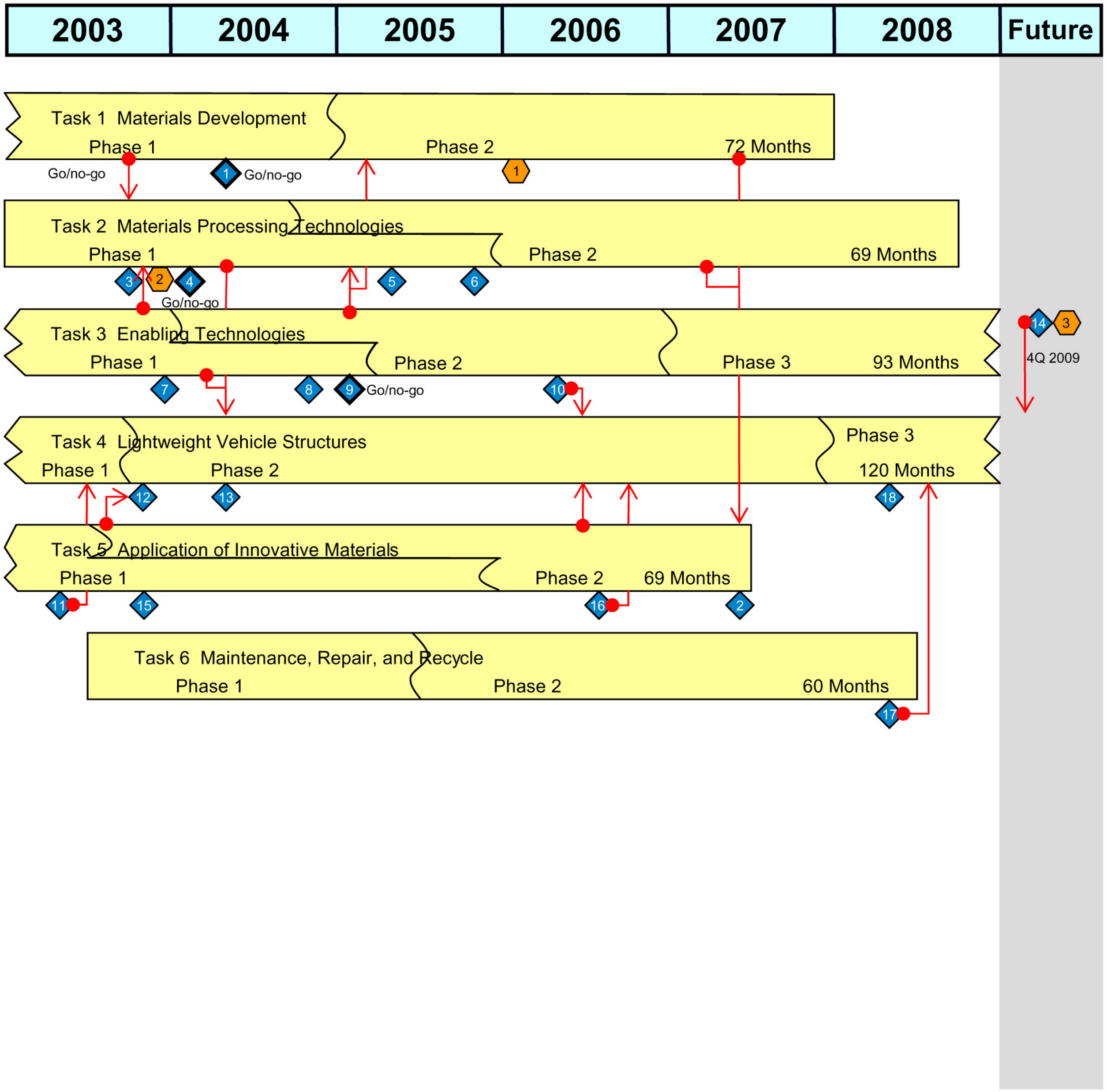
Task	Title	Duration/ barriers
1	Materials Development Phase 1 • Develop wrought magnesium alloys for high-strength, reduced-weight truck components • Develop carbon-fiber sheet molding compound materials that meet heavy vehicle manufacturers' needs for properties, manufacturability, and surface finish • Evaluate the application of high-strength stainless steels for lightweighting applications in heavy vehicles to improve corrosion resistance and durability • Develop cast magnesium alloys with improved properties for structural applications	36 months Barriers A, C (began 1Q 2002)
	Phase 2 • Develop low-cost corrosion-resistant materials and coatings • Develop polymer materials or protective treatments to improve UV resistance and tolerance for weather and impact damage • Develop advanced, low-cost cermets and carbon-carbon brake friction materials that provide reduce weight and improved safety • Develop low-cost magnesium metal matrix composites for heavy vehicle applications	36 months Barriers A, C, F (begin 1Q 2005)
2	Materials Processing Technologies Phase 1 • Develop advanced casting processes for the production of high-integrity aluminum, magnesium, and metal matrix composites for heavy vehicle applications • Develop technologies for reducing the cost of carbon fiber by significantly reducing processing time • Evaluate and improve forming processes for aluminum components • Develop innovative processing technologies that result in improvements in the formability of wrought magnesium	36 months Barriers A, C (began 1Q 2003)
	Phase 2 • Develop surface treatment technologies as cost-effective techniques for reducing friction and wear • Develop lower-cost processing and manufacturing processes for titanium • Complete development of advanced stabilization and oxidation methods for carbon fiber composites and integrate them into the processing line. (This research is complementary to Task 4 of the ALM sub-activity) • Scale-up processing technologies for production of formable magnesium alloy sheet and validate performance on prototype components • Develop new, innovative manufacturing and assembly techniques for carbon fiber composites and hybrid material structures, including the capability to produce class A surfaces • Develop improved casting technologies for light metals and high-strength steels that result in thinner, lighter castings with improved fatigue and corrosion resistance • Develop casting technologies that provide flexibility in controlling and varying wall thicknesses of large drivetrain and suspension castings	48 months Barrier B (begin 3Q 2004)
3	Enabling Technologies Phase 1 • Extend the capability of the friction stir process for joining high-strength materials • Evaluate reliable joining processes for dissimilar materials	36 months Barrier E (began 2Q 2002)

Table 37 (continued)

Task	Title	Duration/ barriers
	Phase 2 • Develop design and modeling tools that optimize the microstructure, manufacturability, and performance of materials for heavy vehicle applications with respect to mechanical and environmental performance • Assess technologies for manufacturing tooling for lightweight materials, evaluate state-of-the-art capabilities for rapid low-cost tooling, and develop a technology roadmap for the development of high-impact, rapid, low-cost tooling • Evaluate or develop ultrasonic joining techniques for application to lightweight materials for advanced transportation systems • Develop attachment techniques for heavy truck composite chassis members • Develop designer-usable joint models to aid structural engineers in designing joints for weight reduction, durability, and occupant safety optimization • Develop design data and methodologies for hybrid material structures that take advantage of inherent characteristics of the materials and allow optimization for weight, performance, and cost • Develop accelerated testing methods to simulate materials and structural performance in operating environments that are acceptable to truck OEMs	36 months Barriers B, D, E (begin 1Q 2004)
	Phase 3 • Integrate all joining-related tasks into demonstration efforts that highlight the benefits of all earlier developed technologies and demonstrate industry-acceptable assembly	36 months Barriers C, E (begin 1Q 2007)
4	Lightweight Vehicle Structures Phase 1 • Develop a high-performance, lightweight stainless steel transit bus structure weighing 50% less than a conventional transit bus • Develop a design and the manufacturing technology for a lightweight frame for a pickup truck/SUV that is 30% lighter at 1.25 times the cost of a standard vehicle • Develop selective reinforcement technology for hybrid materials that can be applied to large truck cab structures to improve strength and reduce weight by 40% • Develop the use of hybrid materials/composites as production Class 8 truck components that reduce weight by 40%	36 months Barriers C, E (began 4Q 2000)
	Phase 2 • Begin to competitively bid cost-shared efforts with truck OEMs to develop technologies for reduction in weight of Class 7 and 8 tractor-trailers	48 months Barriers A, B, C (began 4Q 2003)
	Phase 3 • Complete design for hybrid materials focal project for Class 8 vehicles • Complete prototype of hybrid materials focal project structure and identify manufacturing processes	36 months Barriers B, C, E (begin 4Q 2007)
5	Application of Innovative Materials Phase 1 • Develop a cost-effective carbon fiber sheet molding compound hood system conforming to the manufacturer's quality standards and reducing system mass by at least 35% for a Class 8 tractor • Develop long-fiber-reinforced polymer structural chassis components for Class 8 trucks so that the mass is 60% less than the incumbent design • Develop a carbon-fiber-reinforced polymer structural door surround for a Class 8 tractor cab that is 50% lighter	48 months Barrier C (began 1Q 2002)

Table 37 (continued)

Task	Title	Duration/ barriers
	Phase 2 • Develop long-fiber-reinforced polymer chassis support structures (lateral cross-members and frame rails) for Class 7 and 8 trucks so that the component mass is 50% lighter • Develop test methods, constitutive materials models, and finite element analysis guidelines for simulation of crash energy absorption for lightweight components and structures • Develop processing technologies for low-cost magnesium metal matrix composite materials	48 months Barrier C (began 3Q 2003)
6	Maintenance, Repair, and Recycle Phase 1 • Evaluate the effect of ice-clearing chemicals on the corrosion of heavy vehicle materials and components, especially brake materials, and develop procedures for controlling the corrosion	24 months Barrier E (began 3Q 2003)
	Phase 2 • Develop improved, inexpensive, field-deployable systems that allow early detection of component degradation (due to corrosion or fatigue) to allow preventive maintenance • Develop technologies for repair of structural/safety components made of lightweight materials • Develop cost-effective disassembly procedures for maintenance, repair, and recycle • Develop technologies for recycle of metal matrix composites and light metals such as magnesium and titanium	36 months Barrier E (begin 3Q 2005)



Legend

Milestone

1. **Go/no-go:** Demonstrate technical ability to oxidize carbon fiber precursors using non-conventional methods
2. Complete fabrication of low-cost magnesium metal matrix composite component and initiate vehicle testing
3. Complete testing of Mg alloy sheet produced using plasma arc lamp and pinch roller treatment and validate properties
4. **Go/no-go**: Complete the report detailing design of lightweight, one-piece cast frontwall for a Class 8 truck and present results to Freightliner and DOE program managers
5. Scale-up processing technologies for production of formable Mg alloy sheet and validate performance on prototype components
6. Demonstrate continuous production of aluminum connecting rod with improved mechanical properties using advanced casting process
7. Validate friction stir processing process models using instrumented process samples and mechanical property test results
8. Demonstrate cost-effective, rapid friction stir process for joining high-strength materials
9. **Go/no-go:** Demonstrate ability of microstructural level simulation model to predict the response of a 1500 series steel during machining of heavy-vehicle component
10. Demonstrate newly developed attachment techniques for carbon fiber composite heavy truck cross-members on full-size frame
11. Select cab structural component design and perform baseline finite element and modal analysis
12. Review proposals for "Development of Technologies for Reduction in Weight of Class 7 and 8 Tractor Trailers," announce awards, and initiate work
13. Complete development of prototype lightweight stainless steel bus structure weighing 50% less than conventional steel bus
14. Complete demonstration project integrating newly developed joining technologies and demonstrate industry-accepted assembly of subsystem
15. Complete advanced characterization studies of advanced carbon gas storage materials and publish paper
16. Complete validation testing of carbon-fiber-reinforced polymer structural door surround for Class 8 tractor cab that is 50% lighter
17. Complete development of field-deployable system for early detection of component degradation to allow for preventive maintenance and begin vehicle testing
18. Complete design for hybrid materials focal project for Class 8 vehicles

Technology Program Output

1. Validated carbon fiber oxidation technologies provided to the Automotive Lightweighting Materials technology area
2. Report detailing design of lightweight, one-piece cast firewall for a Class 8 truck available to industry subject to nondisclosure agreement
3. Composite of dissimilar joining technologies available to industry

4.6.4 Heavy Vehicle Propulsion Materials

The vision of the Heavy Vehicle Propulsion Materials (HVPM) sub-activity is to identify and provide improved and new materials to enable cost-effective, high-energy-efficiency, heavy-duty engines with high durability and reliability and substantially lower emissions. Lightweight materials applications in heavy-duty engines may also provide an opportunity to reduce weight-induced parasitic energy losses, provided that the same cost, durability, and reliability requirements can be met. Research performed under this sub-activity is primarily focused on heavy vehicle applications; however, it is recognized that the technologies may also have application on light vehicles. Management of this sub-activity and the APM sub-activity are coordinated to ensure that they are complementary, rather than duplicative.

Goals

The technical goals of HVPM, listed as follows, are in direct support of the Advanced Combustion Engine Activity, described in Section 4.5.

- By 2005, develop and validate advanced materials technology that will substantially reduce the erosion and corrosion in heavy-duty engines as a result of the use of EGR.
- By 2006, complete the development of materials solutions that will enable heavy-duty diesel engines to achieve efficiencies of over 50% while meeting EPA 2007 emissions standards.
- By 2008, develop applications in advanced diesel engines for titanium materials (metal or intermetallic alloys or composites) to substantially increase fuel efficiency and durability by virtue of the unique properties of titanium.
- By 2010, develop and validate a new class of materials based on advanced surface modifications or treatments and other compositional/microstructural modifications to increase the reliability and durability of diesel engine components.

Programmatic Status

Durable, cost-effective materials are being developed to enable the designing and manufacturing of advanced diesel engines, consistent with the goals of the FCVT Program and the 21st CTP, in general, and the overall priority FCVT goals, in particular. The HVPM sub-activity has been developing materials and materials-processing technologies, validating these technologies through representative component prototyping, and developing adequate design data and design methodologies to facilitate their beneficial application.

Targets

The advanced engine system designs needed to meet the 21st CTP goals push the requirements for materials outside the envelope of the existing materials now used in engines. The technical targets for the HVPM sub-activity are for materials technologies that will enable the 21st CTP goals to be met with respect to engine systems (referring to the combination of fuel, engine, and emissions aftertreatment equipment). Specific materials technologies that must be developed are identified in concert with the U.S. heavy-duty diesel engine community. These include material compositions and properties, as well as manufacturing technology, component cost, life prediction, and durability. Work is undertaken in collaboration with the engine manufacturers, component suppliers, and materials suppliers to develop practical, low-cost, and durable materials systems. The technical targets are shown in Table 38.

Table 38 Heavy Vehicle Propulsion Materials targets

Heavy Vehicle Propulsion Materials	Heavy Vehicle Engine technical targets
Fuel system materials	Efficiency > 50% (2010) >55% (beyond 2012)
Materials for air-handling, hot-section, engine structures	Engine life > 1 million miles
Exhaust aftertreatment materials	Compatible with future fuels

Barriers

The principal barriers to meeting the HVPM goals are in the areas of performance, manufacturability, and cost.

A. **Performance.** The technologies currently under consideration for reducing emissions result in significant fuel-efficiency penalties. In addition, many of these technologies may decrease the reliability and durability of the engine, for example, by increasing pressures and temperatures within the engine and introducing corrosive and erosive species into the engine. Materials needed to achieve the performance objectives in specific engine components may not exist today as durable, reliable materials.

B. **Manufacturability.** Advanced materials, by virtue of their unique physical and mechanical properties, are often difficult to manufacture with current technology. Other issues include joining of dissimilar materials, inspection, standards, availability of cost-effective and high-quality precursors and powders, and durability and cost of tooling.

C. **Cost.** Key advanced materials required to meet the efficiency and emissions goals for heavy vehicles are not available today in high volumes and do not have the required precision, reproducible quality, or acceptable cost.

Approach

The following materials research efforts are critical to meeting the HVPM sub-activity goals.

Fuel system materials. The fuel system and air-handling system contribute significantly to the cost of a heavy-duty diesel engine. Enabling materials and cost-effective, precision manufacturing processes will be instrumental in developing improved fuel injection systems. The electronic fuel injectors on heavy-duty diesel engines operate at ~20,000 psi to minimize particulate emissions. The fuel injection pressure is likely to increase to as much as 35,000 psi to meet emerging emissions regulations while maintaining engine performance. The high-pressure fuel injection results in challenges with wear and scuffing of fuel injector plungers and with erosion, wear, and fatigue of fuel injector nozzles. In addition, low-sulfur fuels required to meet the low emissions targets typically do not lubricate the fuel injector components as well as current diesel fuel; therefore, wear- and scuff-resistant materials are necessary. Improved high-precision manufacturing and inspection methods for the injector components also are needed.

Exhaust aftertreatment materials. The sulfur in diesel fuel is a major barrier to several promising aftertreatment technologies. Currently available U.S. diesel fuel contains up to 500 ppm of sulfur. The sulfur content of highway diesel fuel will be reduced to less than 15 ppm. Even when less than 15 ppm sulfur fuel becomes available starting in 2006 (in conjunction with the EPA 2007 heavy-duty diesel engine emissions standards), catalyst poisoning will continue to be an issue for the durability of exhaust aftertreatment devices. Development of sulfur-tolerant catalysts and sulfur removal technologies (SO_X absorbers) is considered critically important to meeting future emissions regulations.

Catalyst materials with stable microstructures are needed that can operate at high efficiency over a wide range of exhaust conditions, including low temperatures and varying levels of oxygen and unburned fuel. R&D tasks are expected to include synthesis and processing studies, bench test and engine exposures, and postmortem analysis of the chemistry and microstructure of the catalyst systems.

Durability of exhaust aftertreatment systems in heavy vehicles is a major concern. Lifetimes of at least 500,000 miles are expected, and lifetimes of 1,000,000 miles are desired. Characterization of the effects of exposure in service on the microstructure and microchemistry of the aftertreatment systems will be needed. The characterization may lead to the development of more-durable systems and may point to material development paths that result in an optimized temperature window for aftertreatment operation.

Additional engine controls may be required that will depend on new sensors developed for reliable, real-time measurement of NO_X, O_2, temperature, and possibly some unregulated emission species over a wide range of temperatures and operating conditions. The sensor materials currently available are limited in range or require long lag times to respond to a change and thus are inadequate for measuring transient or rapid changes in operating conditions.

Materials for air-handling, hot-section, and structural components. Turbocharging and associated air-handling equipment are important elements of engine control for heavy-duty diesel engines, and advanced engines will place new demands on the air-handling system. Cost-effective materials and manufacturing methods are needed to meet the performance requirements for air-handling components at an acceptable cost.

EGR, which is being used to meet 2003 emission requirements, introduces corrosion of heat exchanger components (for cooling the EGR) and makes it necessary to increase the turbocharger boost to maintain the necessary oxygen partial pressure in the combustion chamber. The durability and fuel efficiency of the new 2003 engines may be a concern, and improved materials and designs for EGR systems are desired.

Better materials are needed for the linkage to control the variable-geometry turbocharger inlet and the wastegate valve, which operates at high temperatures (up to 600ºC) without liquid lubrication. In addition, lower-mass materials are needed for turbocharger rotors because the inertia of the turbocharger limits the ability of the system to respond rapidly.

The 50%-efficiency goal for a heavy-duty engine that meets the emissions reduction goals will likely involve higher specific power. The higher pressures require cost-effective materials with higher strength and fatigue resistance for engine blocks and cylinder heads and either higher-quality cast iron or the use of high-strength materials to reinforce highly stressed areas in conventional cast iron components.

Higher peak cylinder pressures will also put additional stresses on pistons, liners, connecting rods, and crankshafts. Research is needed to evaluate the tribological characteristics of materials in piston-to-piston ring-liner systems, bearings and bushings, and gear systems.

Selected insulation of hot-section and exhaust components to reduce heat rejection has been used to increase diesel engine efficiency to over 55% in a previous DOE research effort. Although efficiencies of up to 55% were demonstrated in a single-cylinder engine, the insulating materials used in the demonstration are not available as durable, cost-effective components. Research is needed to develop hot-section components with lower heat rejection.

Materials for durable valve train components in advanced engines will be necessary. R&D is needed to develop lightweight, wear- and corrosion-resistant valve train materials (valves, valve seats, valve guides, rollers, and rocker arms) for use in all classes of heavy-duty diesel engines. New concepts for joining dissimilar materials (e.g., intermetallic valve head to steel shaft) are needed to reduce the cost of new valve materials.

Cost-effective manufacturing processes also are necessary for the widespread commercialization of stronger, higher-temperature, corrosion-resistant materials such as superalloys, intermetallics, and ceramics. If advanced materials are to be commercially viable, new machining technologies must be developed for them.

Testing and materials standards. Commercializing new materials will require extensive databases of materials properties. New design and testing methodologies will also be required. There will be an increasing need to simulate component performance and life to avoid expensive engine testing. New higher-resolution nondestructive evaluation techniques also will be required to ensure component survival during operation.

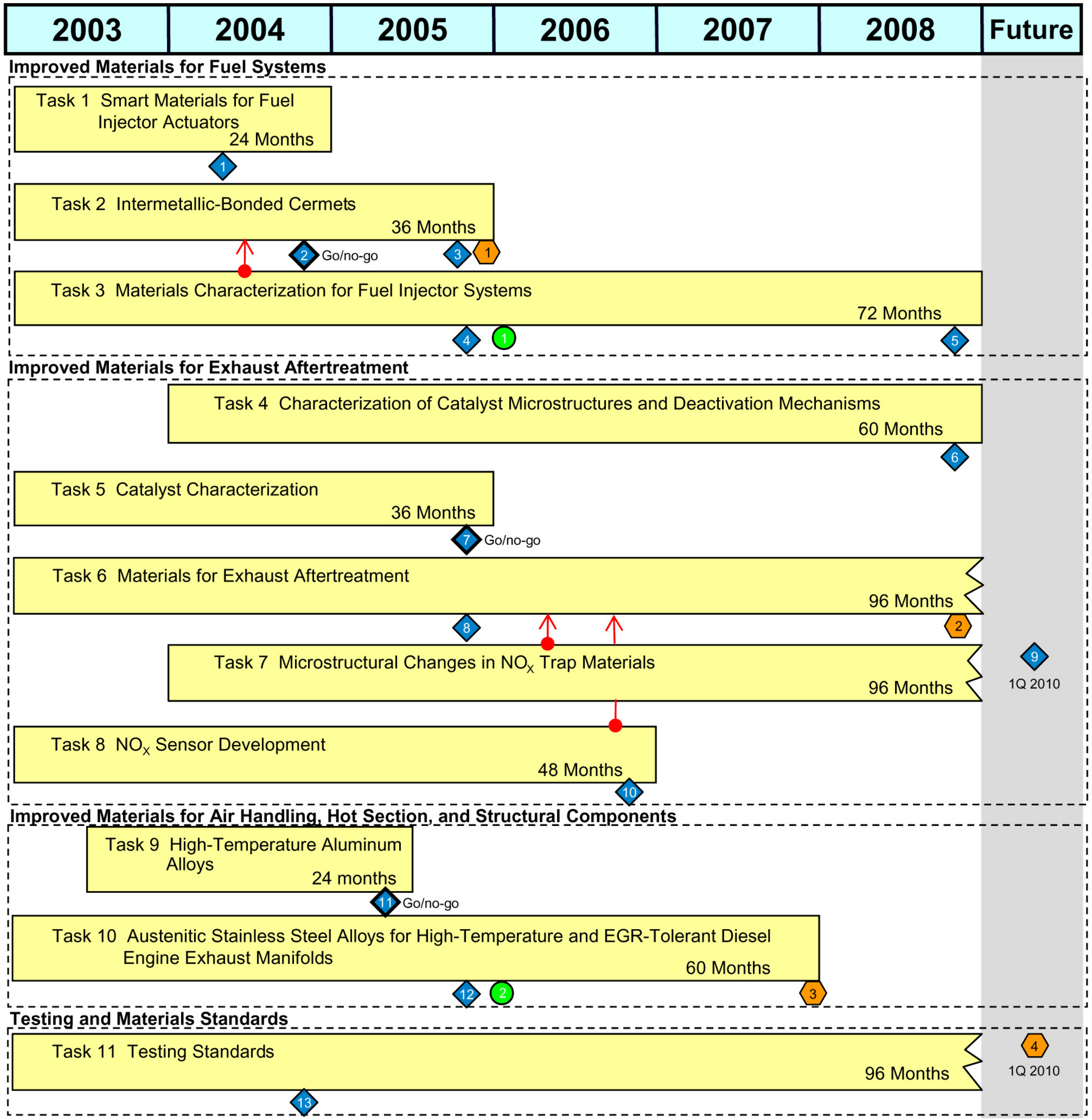
The commercialization of new materials and manufacturing processes depends on having standard testing methods that generate useful data for design and modeling and that are accepted by the industry. Materials testing standards in the United States are primarily voluntary consensus standards developed by the American Society for Testing and Materials (ASTM). ASTM standards are coordinated with international standards by the International Standards Organization (ISO).

Task Descriptions

The technical tasks are shown in Table 39.

Table 39. Tasks for Heavy Vehicle Propulsion Materials R&D

Task	Title	Duration/ barrier
Improved Materials for Fuel Systems		
1	Smart Materials for Fuel Injector Actuators • Evaluate new actuator technologies (dual- vs. single-actuator fuel injection), characterize materials requirements, and develop materials and processing for advanced actuators for better fuel injection control	24 months Barriers A, B, C
2	Intermetallic-Bonded Cermets • Develop Ni_3Al-TiC intermetallic-bonded cermets for applications in heavy-duty diesel fuel injection systems	36 months Barriers A, B, C
3	Materials Characterization for Fuel Injector Systems • Develop materials characterization and testing methodology to allow screening and evaluation of fuel injector component materials rapidly via bench tests	72 months Barriers A, B
Improved Materials for Exhaust Aftertreatment		
4	Characterization of Catalyst Microstructures and Deactivation Mechanisms • Conduct transmission electron microscopy studies of experimental catalyst materials subjected to simulated diesel exhaust in an ex-situ catalyst reactor system to determine catalyst durability • Conduct studies of model catalyst systems comprising heavy metal species on oxide supports to better understand the structures of catalytic materials from the atomic level	60 months Barriers A, B, C
5	Catalyst Characterization • Characterize crystal structure, morphology, phase distribution, particle size, and surface species of catalytically active materials supplied by CRADA partner using X-ray diffraction, Raman spectroscopy, and electron microscopy. Materials to come from all stages of catalyst's lifecycle: raw materials, as-calcined, sulfated, regenerated, etc.	36 months Barriers A, B
6	Materials for Exhaust Aftertreatment • Develop commercially viable catalytic materials and advanced aftertreatment technologies to reduce NO_x and particulates from diesel emissions to meet EPA 2007and 2010 standards	96 months Barriers A, B
7	Microstructural Changes in NO_x Trap Materials • Study microstructural changes that accompany the reaction of NO_x with trap materials under lean and rich conditions at high temperatures	84 months Barriers A, B
8	NO_x Sensor Development • Develop catalytically selective electrode materials that can be used for sensors that are selective to individual gas species for simpler, less expensive NO_x sensors	48 months Barriers A, B
Improved Materials for Air Handling, Hot Section, and Structural Components		
9	High-temperature aluminum alloys for high-efficiency, high-durability air-handling components in EGR environment. Creep, and low-cycle fatigue testing of diesel engine turbocompressor wheels of new high-temperature aluminum alloys	24 months Barriers A, B
10	**Austenitic Stainless Steel Alloys for High-Temperature and EGR-Tolerant Diesel Engine Exhaust Manifolds** • Evaluate mechanical properties for operation in high-temperature and high-EGR exhaust manifold • Evaluate advanced stainless steels for high-temperature exhaust valve applications	60 months Barriers A, B
Testing and Materials Standards		
11	**Testing Standards** • Develop new ASTM testing standards for advanced materials • Develop new ISO testing standards for advanced materials	96 months Barriers A, B



Legend

◆ Milestone

1. Complete engine testing of primary injection system candidate for fast-response advanced engines. Decision point for feasibility of scale-up and commercialization
2. **Go/no-go** Complete engineering development of scuff-resistant, durable, and manufacturable Ni_3Al-TiC intermetallic cermets. Decision point for scale-up and commercial development
3. Complete scale-up and commercial introduction of Ni_3AlTiC fuel system components
4. Complete development of bench tests for scuffing and coating adherence
5. Correlate ranking system based on bench tests with ring or engine tests
6. New or improved catalyst system developed as a result of advanced characterization effort
7. **Go/no-go** Complete characterization of catalyst materials from all stages of catalyst life (provided by CRADA partners). Decision point for CRADA partners with respect to commercialization of catalyst to meet 2007 emission requirements
8. Complete evaluation of materials/processing for microwave-regenerated particulate trap. Decision point for adoption of microwave assist for filter regeneration
9. Develop comprehensive understanding of catalyst deactivation mechanisms and corresponding microstructural changes
10. Determine commercial feasibility for catalytically selective electrode materials for low-cost NOx sensors.
11. **Go/no-go** Complete creep and low-cycle fatigue evaluation of high-temperature aluminum alloy for diesel turbocharger compressor wheel. Decision point for scale-up to commercial scale
12. Complete development of austenitic stainless steel alloy for high-temperature air-handling components for advanced heavy-duty engine. Decision point for extending advanced stainless steels to hot-section components, such as valves
13. Complete current annex of International Energy Agency agreement and document progress. Decision point for development of new international collaborations to support OFCVT

⬢ Technology Program Output

1. New, high-performance material available for heavy-vehicle fuel systems to meet fuel efficiency and exhaust emissions requirements of 2007 and beyond.
2. Validated catalyst and particulate filter materials to enable fuel efficiency and emissions requirements to Advanced Combustion Engine R&D.
3. Commercially available, cost-effective high-temperature stainless steels to Heavy Truck Engine R&D.
4. Consensus standards (ASTM, SAE, ISO) for engineering transportation materials completed and available for use by industry.

● Supporting Input

1. Fuel specification for material compatibility study from Fuels Technologies
2. Material requirements from Heavy Truck Engine R&D.

4.6.5 High Temperature Materials Laboratory

It is envisioned that the High Temperature Materials Laboratory (HTML) will play a critical role in assisting FCVT and HFCIT in realizing their goals by working with these programs' industrial and academic partners. These goals directly support the FreedomCAR and Hydrogen Fuel Initiative and the 21st CTP.

Goals

The HTML assists the industrial and academic partners in realizing the FCVT and HFCIT Program goals. The shared goals that HTML contributes to include these:

- Improve the efficiency of ICEs from 30 to 45% by 2010 for light-duty and from 40 to 55% by 2012 for heavy-duty applications while meeting cost durability and emissions constraints.
- Reduce the weight of an unloaded tractor-trailer combination from the current 23,000 lb to 18,000 lb by 2010, a reduction in weight of 22%.
- Develop reliable systems for future fuel cell powertrains, with costs comparable to those of conventional ICE/automatic transmission systems. The powertrain will consist of a 60% peak-energy-efficiency, durable fuel cell power system (including hydrogen storage) at a cost of $45/kW by 2010 ($30/kW by 2015).
- By 2010, enable clean, energy-efficient vehicles operating on clean, hydrocarbon-based fuels powered by either internal-combustion powertrains or fuel cells.
- By 2010, enable the transition to a hydrogen economy by ensuring widespread availability of hydrogen fuels and retaining the functional characteristics of current vehicles, including hydrogen storage systems demonstrating an available capacity of 6 weight percent hydrogen, specific energy of 6 kWh/kg, and an energy density of 1.5 kWh/L at a cost of $4/kWh.
- Develop ICE powertrain systems that operate on hydrogen with a cost target of $45/kW by 2010 and $30/kW in 2015, have a peak brake engine efficiency of 45%, and meet or exceed emissions standards.

Programmatic Status

Through 2002, HTML had worked with customers on 1181 user projects, and it continues to attract new proposals at the rate of 75 to 100 per year. Users are mainly from universities, but U.S. industry is well represented, and other government laboratories also participate. User agreements through 2002 had been signed with 358 industrial concerns, 261 universities and colleges, and 23 other institutions. Projects have ranged across the materials topics that are of interest to DOE, from alloys and MMCs to advanced ceramics to electronic materials. In direct support of FCVT, HTML has developed four major research areas: Engine and Vehicle Materials; Emissions Reduction Materials; Materials for Hydrogen Generation, Storage, and Utilization; and Partnering with Industry.

Targets

HTML will assist FCVT and HFCIT in achieving their technical targets by making its unique user centers and expertise available to program participants.

Barriers

HTML provides materials expertise and unique facilities to address materials-related technical barriers that are elucidated in the previous sections describing the various R&D tasks of the Materials Technologies sub-program. HTML also works to overcome materials-related technical barriers to the success of HFCIT. The HTML User sub-activity endeavors to assist in overcoming these barriers by supporting the universities, industries, and other governmental agencies involved in FCVT and HFCIT.

Approach

The technical approach taken by HTML and its User sub-activity is to maintain state-of-the-art materials characterization facilities and equipment operated by skilled technical staff and provide them to users. The facilities and equipment are typically either one-of-a-kind items or provide a collection of characterization equipment in one facility that is unavailable elsewhere in the world. HTML provides access to such sophisticated equipment as atomic-resolution electron microscopes, synchrotrons, and neutron beamlines.

In 2003 and 2004, HTML will be receiving, setting up, and beginning experiments with the Aberration-Corrected Electron Microscope (ACEM), the first of its kind in the United States. ACEM is a state-of-the-art electron microscope that will provide sub-angstrom resolution, allowing the location and determination of individual atoms, such as those on automotive emission catalysts. Also, HTML staff will be working with staff of the Spallation Neutron Source to locate an instrument called VULCAN on one of its beamlines. VULCAN will allow residual stresses to be measured on articles such as engine components at higher resolutions and speeds than is now possible anywhere. VULCAN will also be extremely sensitive to hydrogen atoms, making it useful for determining hydrogen storage mechanisms.

Task Descriptions

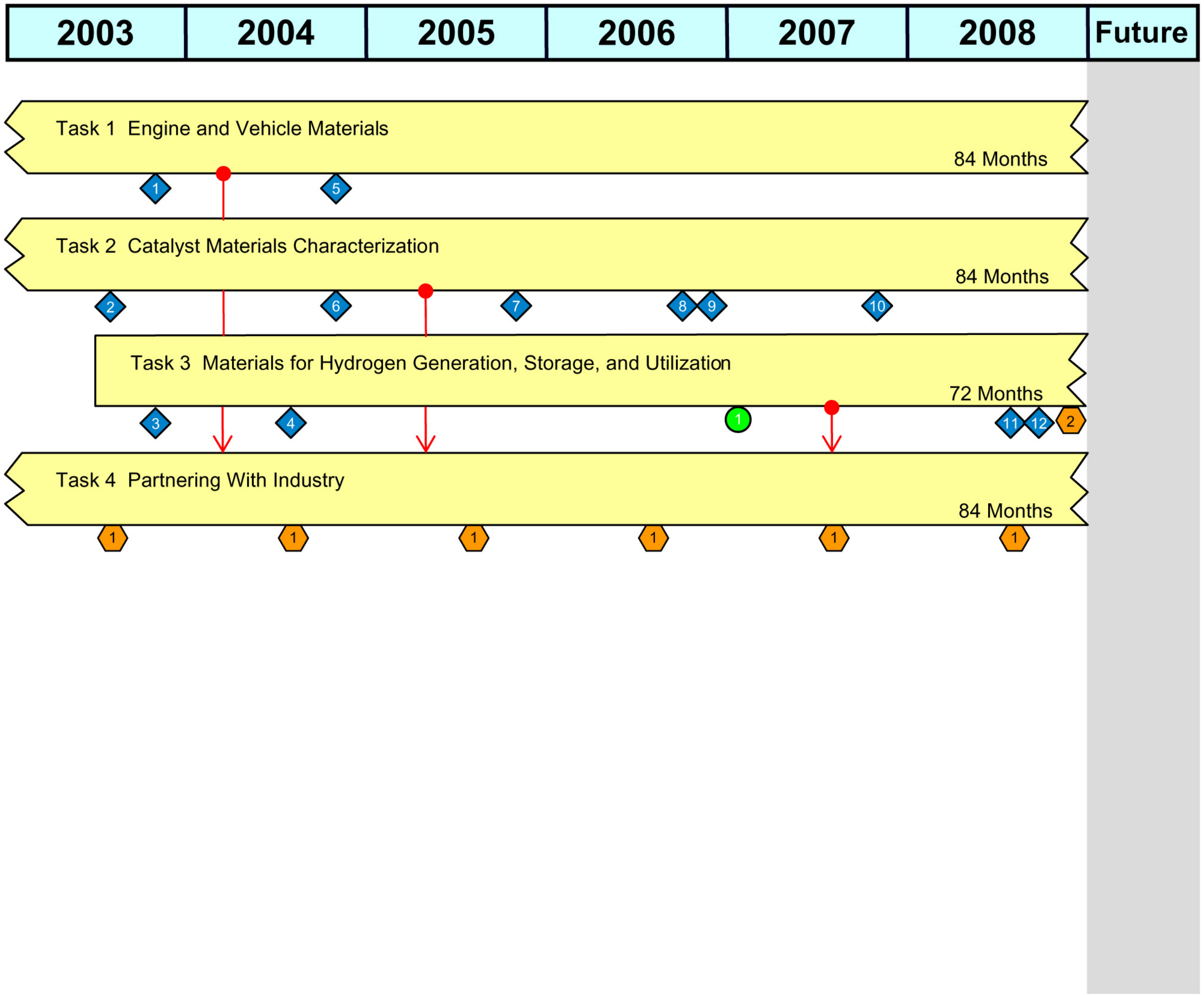
A description of each technical task, along with the estimated duration and technical barriers associated with the task, is provided in Table 40.

Milestones

The HTML sub-activity milestones are shown in the following network chart.

Table 40. Tasks for High Temperature Materials Laboratory

Task	Title	Duration/ barriers
1	Engine and Vehicle Materials • Characterize the mechanisms of interaction and the properties of an interface or joint formed between two lightweighting materials • Collaborate with FCVT industry partners and technical teams to determine and characterize materials-related life-limiting mechanisms and failure modes of engine system components • Assist FCVT industrial and academic partners in developing advanced materials and processes for engine and vehicle components	84 months
2	Catalyst Materials Characterization • Identify and characterize mechanisms of functioning and degradation of lean-burn engine emission control catalysts • Assist FCVT industrial and academic partners in developing advanced materials and processes for emissions reduction components • Assist FCVT and HFCIT industrial and academic partners in developing advanced, low-cost catalysts and processes for emissions control, fuel cells, and hydrogen generation	84 months
3	Materials for Hydrogen Generation, Storage, and Utilization • Resolve storage sites within a high-hydrogen density storage material • Assist FCVT and HFCIT industrial and academic partners in developing advanced materials and processes for fuel cells, and hydrogen generation, storage, distribution, and use	72 months (begin 3Q 2003)
4	Partnering With Industry • Develop and maintain the state-of-the-art science and tools required to characterize advanced materials of interest to FCVT and HFCIT and their partners • Support a robust user community specifically including the automotive and heavy–vehicle industries, supporting industries, and materials characterization requirements of other EERE partners	84 months



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◆ **Milestone**

1. Characterize the structure and durability of joints formed between conventional aluminum components by two low-temperature alternatives to molten welding
2. Correlate measured performance to HTML characterization results on a commercially available diesel engine emissions control catalyst
3. Initiate a user effort characterizing hydrogen storage in an absorption media
4. Use HFIR neutron beam to perform a hydrogen resolution experiment set up in Q3 of 2003 and initiate the Spallation Neutron Source experiment design
5. Characterize the structure and durability of joints formed between two otherwise intractable aluminum metal matrix composites
6. Identify and characterize mechanisms of functioning and degradation of lean burn engine emission control particulate and NO_X traps
7. Commission AMCL, showing that it provides environmental conditions necessary to support advanced electron microscopes
8. Use ACEM in the study of an experimental NO_X trap material, showing imaging capabilities not possible using any present-day microscopy capability at ORNL
9. Launch commissioning of VULCAN
10. Study 2 experimental diesel NO_X-reduction materials using a combination of HTML's ex situ catalyst reactor for TEM specimens and the imaging and spectroscopy of ACEM
11. Demonstrate the utilization of the Spallation Neutron Source (VULCAN) for time-resolved in-situ characterization of hydriding-dehydriding of hydrogen storage materials
12. Correlate atomic-level structure of a hydrogen-storage material, determined by ACEM, with structural phenomena revealed using neutron beams, to elucidate storage mechanisms

⬢ **Technology Program Output**

1. User project report to all partners
2. Characterization and technology related to atomic level understanding of hydriding and dehydriding of storage materials available to industry and HFCIT

● **Supporting Input**

1. Candidate hydrogen storage materials from HFCIT

4.7 FUELS TECHNOLOGIES

The Fuels Technologies activity supports R&D that will provide vehicle users with fuel options that are cost-competitive, enable high fuel economy, deliver lower emissions, and contribute to petroleum displacement. This activity supports the mission of FCVT to develop more energy-efficient and environmentally friendly highway transportation vehicles that enable America to use less petroleum.

Fuels Technologies tasks are key elements in the pathway to achieving the goals of FCVT and HFCIT for transportation. Advanced fuels technologies being researched and developed will enable current engines to be more efficient and will maximize the production of hydrogen reformed on-board fuel cell vehicles or at the refueling facility. Advanced fuels technologies will also identify and validate the fuel production and delivery infrastructure issues associated with the transition to hydrogen fuel cell vehicles using either ICEs or fuel cells.

The tasks of the FCVT Fuels Technologies activity are being coordinated closely with the R&D tasks of the FreedomCAR partnership and 21st CTP; the Biomass Program; HFCIT; and the Office of Fossil Energy to ensure maximum synergism and avoid duplication. In addition, the FCVT Fuels Technologies activity is being coordinated with appropriate DOE/industry technical teams; related automotive and energy industries; and federal, state, and other local agencies. The relevant outputs from the Fuels Technologies activity will be shared with the Advanced Combustion Engine R&D, Vehicle Systems, and Materials Technologies activities in FCVT, as well as others outside FCVT as appropriate.

The FCVT Fuels Technologies activity has three major sub-activities—Advanced Petroleum-Based Fuels (APBF) R&D, Non-Petroleum-Based Fuels (NPBF) R&D, and New Technology Impacts Research—as shown in Figure 19.

Discussion of the APBF and NPBF sub-activities is combined in Section 4.7.1 because of similarities and synergisms; New Technology Impacts Research is discussed in Section 4.7.2.

4.7.1 Advanced Petroleum-Based Fuels and Non-Petroleum-Based Fuels R&D Sub-Activities

The APBF and NPBF sub-activities are undertaken to (1) enable current and emerging advanced combustion engines and emission control systems to be as efficient as feasible while meeting future, more-stringent emission standards and (2) reduce reliance on petroleum-based fuels. To differentiate these two sub-activities, an APBF is envisioned as consisting of highly refined petroleum fuel derived from crude oil, possibly blended with performance-enhancing non-petroleum components derived from renewable resources such as biomass or non-petroleum fossil resources such as natural gas or coal. In contrast, an NPBF is envisioned as consisting of a fuel or fuel blending component derived primarily from non-petroleum sources such as agricultural products, biomass, natural gas, or coal.

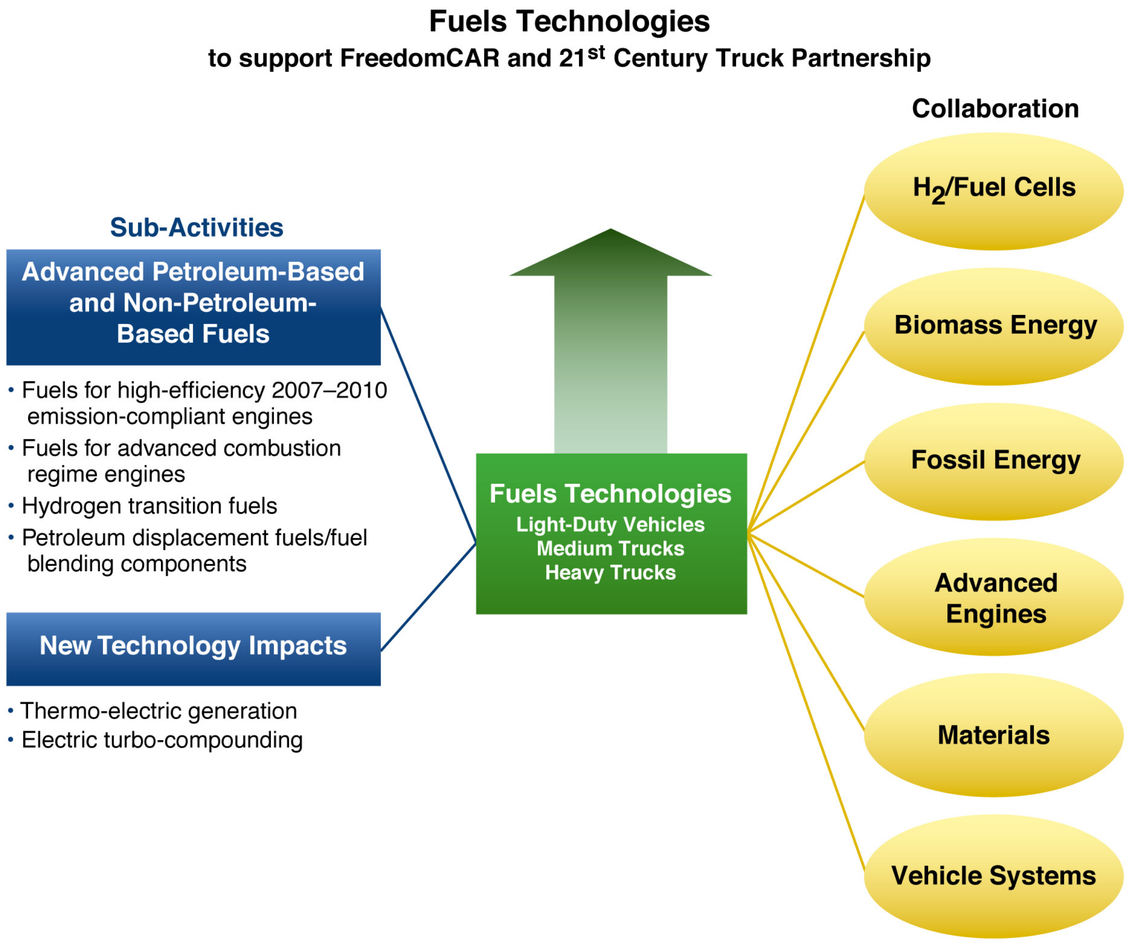


Figure 19. Sub-activities, collaborations, and outputs of the Fuels Technologies activity.

The APBF sub-activity is determining the implications of fuel formulations and fuel properties on the efficiency, performance, and emissions profile of emerging, advanced CIDI engines. Through this research, the APBF sub-activity will identify the most appropriate fuels for these engines. APBFs are envisioned as having properties that will enable development and commercialization of future generations of combustion engines with even higher fuel efficiencies than the CIDI engines and with very low emissions. These engines are collectively referred to as operating in advanced combustion regimes so as to include a broad range of in-cylinder strategies. The NPBF sub-activity will identify fuels and fuel blending components that are suitable for advanced-combustion-regime engines, which have the potential to significantly displace petroleum-based fuels and potentially serve as a bridge to a hydrogen-based transportation system. These fuels and fuel components are anticipated to be derived from fossil fuels such as natural gas, tar (oil) sands, and coal and from non-fossil fuels such as biomass, vegetable oils, and waste animal fats. The production of diesel fuel from these sources is well developed, yet none of these is in significant use in the United States because of their quality and/or cost.

Goals

The goal of the APBF and NPBF sub-activities is to identify fuel formulations with increasingly significant use of non-petroleum fuel components that will enable emerging advanced ICEs to be more energy-efficient while meeting future emissions standards. More specifically:

- By 2007, develop a fuel or fuels with suitable performance properties for advanced 2007–2010 technology engines that incorporate the use of non-petroleum-based blending component(s) with the potential to achieve at least a 5% replacement of petroleum fuels (priority FCVT goal and 21st CTP goal)
- By 2010, develop a fuel or fuels with suitable performance properties for advanced-combustion-regime engines (2010–2020 technologies) that operate in combustion regimes with high-efficiency and very low emissions, and validate that at least 5% replacement of petroleum fuels could be achieved in the following decade.
- By 2012, validate a pathway to greater hydrogen use in ICEs that addresses fueling infrastructure issues, using fuels that are good carriers of hydrogen or easily reformed to hydrogen.

Programmatic Status

APBFs are critical to enabling diesel-powered vehicles to achieve high fuel economy while meeting future emission standards. Future diesel-engine-powered vehicles will become dependent on exhaust emission control devices to control NO_X emissions. The most desirable NO_X emission control devices are deactivated by sulfur in currently available fuels. An important objective of the APBF sub-activity is to determine the diesel fuel sulfur level that can be tolerated by effective and durable NO_X emission control devices. The current base of knowledge suggests that the sulfur level in the fuel will need to be reduced well below the 2006 standard of 15 ppm. This will require the fuel to be treated downstream of the refinery with the goal of reducing the levels far below 15 ppm. Blends of NPBFs with APBFs can also be effective at reducing sulfur content, and their other properties have demonstrated the potential for synergistic emission reductions.

Although the EPA initially had not intended to issue a ruling on the sulfur content of diesel fuel, testing and analysis conducted by the APBF sub-activity in collaboration with EPA, the engine manufacturers, emission control device manufacturers, and fuel producers conclusively demonstrated that fuel sulfur content had immediate adverse effects on the effectiveness of emission control devices. This effort has resulted in the EPA's issuing a final rule on January 18, 2001, that established a single comprehensive national control program to regulate heavy-duty vehicle emissions and diesel fuel as a single system. It limited the amount of sulfur in diesel fuel to 15 ppm in conjunction with the implementation of the EPA 2007 heavy-duty diesel engine emissions standards. The emission standards (scheduled to phase in from 2007 to 2010) are the first for heavy-duty diesel engines that are based on emission controls. The new sulfur standards for highway diesel fuel will begin to take effect in June 2006.

On July 30, 2001, EPA announced that it would request an independent review of the 2007 heavy-duty diesel engine emissions standards and the diesel fuel sulfur content standard to provide "advice to the EPA on technology issues associated with the introduction of technology to reduce engine exhaust emissions and technology to lower the sulfur level of highway diesel fuel in accordance with the dates incorporated in the highway diesel program promulgated in 2001." The Clean Diesel Independent Review Panel was thus created to carry out this review. The specific objectives of the panel's charter were to assess

- the progress of manufacturers of diesel engines and emission control systems in developing technology to reduce engine exhaust pollutants
- the progress of the fuels industry in developing and demonstrating technologies to cost-effectively lower the sulfur level of highway diesel fuel

The panel was composed of leading experts from the public health community, petroleum refiners, fuel distributors and marketers, engine manufacturers, emission control systems manufacturers, and state governments. In its final report, the panel found that NO_X adsorbers and catalyzed particulate filter systems are the two leading emission control technologies for diesel engines. It also identified improving the durability of the NO_X adsorber, especially as it relates to desulfation (removing accumulated sulfur), as the most significant fundamental challenge that is being addressed currently. These findings directly support the research priorities of the Fuels Technologies activity. Although EPA has set a sulfur limit of 15 ppm, it is still unclear whether this is an adequately low sulfur level for advanced diesel engines with advanced emission control systems. The durability of these systems at this level of fuel sulfur has not been established. Also, with the pending introduction of emission control devices, the optimum fuel formulation for advanced diesel engines is undefined.

Since its inception through 2003, the APBF sub-activity has undertaken data collection and analysis of the effects of fuel and lubricant formulations and sulfur content on the engine-out emissions of advanced CIDI engines suitable for light-duty passenger vehicles, as well as heavy-duty diesel engines. An important objective for the APBF and NPBF sub-activities is to determine how optimum formulations can enable increased engine efficiency, reduce the fuel penalty of emission control devices, and enable advanced-combustion-regime technologies. A new objective beginning in 2004 will be to identify APBF and NPBF characteristics that enhance their ability to serve as resources for hydrogen production to facilitate the transition to the hydrogen economy.

Synthetic crude derived from oil sands is growing in use in Canada, and expansion into U.S. petroleum pools is beginning. Fischer-Tropsch diesel fuels, synthesized from natural gas, have been studied in numerous engine tests to determine their impact on emissions and have been used as a blending material in California diesel fuels since 1993. Desirable attributes for NPBFs include (1) the compatibility with all aspects of the existing fueling infrastructure, and thus the capability to be used as replacements for current fuels; (2) few or no undesirable components, such as sulfur and aromatics; and 3) the capability to be used directly in fuel cells or easily reformed to hydrogen. NPBFs with these characteristics are intended to enable the implementation of advanced-combustion-regime technologies. In addition, NPBFs will enable more-effective, more-durable, yet less-costly emission control systems requiring less energy for operation and reduced impact on engine efficiency.

Targets

In collaboration with the Advanced Combustion Engine activity (Sect. 4.5), fuels, engines, and emissions control devices are being addressed in the context of complete, integrated engine power systems. Table 41 lists the fuels-specific technical targets for APBFs and NPBFs that support crosscut targets with advanced combustion engine R&D (shown in *italics*), as well as petroleum fuel replacement and transition to hydrogen targets.

Table 41. Technical targets for advanced petroleum-based and non-petroleum based fuels

Characteristic	Unit	2007 targets	2010 targets
Crosscut Targets with Advanced Combustion Engine R&D			
Engine efficiency	*%*	*>50 (heavy-duty engine)*	*30–45 (light-duty engine)*
NOx emissions	*g/bhp-h*	*<0.20 (50% phase-in)*	*<0.20*
PM emissions	*g/bhp-hr*	*<0.01*	*<0.01*
Durability	*Miles (equivalent)*	*120,000 light duty)* *435,000 (heavy duty)*	*120,000 (light duty)* *435,000 (heavy duty)*
APBF and NPBF targets			
Fuel sulfur level (available fuel)	*ppm*	*15*	*15*
Fuel sulfur level (w/on-board removal)	ppm	<5	<3
Efficiency gain (w/optimized fuel)	%	At least 5	>5
Emission control penalty reduction	%	50	>50
Fuel price differential	% of retail diesel	<5	<5
Potential for replacement of petroleum	%	At least 5	>5
Compatibility with fuel cells	NA	—	Validated
Compatibility with infrastructure	NA	Validated	Validated
Health effects	(by analysis)	No significant increase in composite risk compared with conventional fuels	No significant increase in composite risk compared with conventional fuels
Unregulated toxics and ultra-fine PM			
Health and safety of fuel			
Life-cycle greenhouse and criteria emissions	(by analysis)	No increase	No increase

Barriers

The primary goal of the APBF and NPBF sub-activities is to identify fuel formulations with increasingly significant non-petroleum components that could replace petroleum fuels and will enable emerging advanced ICEs to be more energy-efficient while meeting future emissions standards. The technical barriers to achieving this goal are as follows:

A. **Inadequate data and predictive tools for fuel property effects on combustion and engine optimization.** Existing data and models for engine efficiency, emissions, and performance based on fuel properties and fuel-enabled engine designs or operating strategies are inadequate. They are limited in scope, have unexplained differences among various engine types, and do not adequately account for the effects that the physical properties and molecular structures of fuels have on the dynamic operation of the fuel injection system and the ability to operate in low-emission, low-temperature combustion regimes. Also, the variability of the effects of refinery stream (blendstock) composition on the efficiency, performance, and emissions of engines appears to be significant but is poorly understood. The impacts on combustion and emissions are unknown for fuel strategies that enhance hydrogen infrastructure and foster the transition to a hydrogen economy.

B. **Inadequate data predictive tools for fuel effects on emissions and emission control system impacts.** The database on the extent to which petroleum fuel, non-petroleum components, and high-hydrogen-content components contribute to toxic emissions is inadequate and must be improved in order to optimize engine and aftertreatment systems from a fuel economy standpoint. The relationship between fuel properties and the formation of ultra-fine particles (i.e., particles of <0.1 nm in diameter) is not well established. Also inadequate are data on the effects of fuel properties (other than sulfur) on exhaust emission control systems, and widely accepted test procedures to measure these effects do not exist. Furthermore, suitable test equipment and universally recognized test procedures with which to generate this knowledge base are not available.

C. **Long-term degradation from fuel and lube constraints.** The knowledge base is inadequate on the effect of fuel properties on the deterioration rates and durability of emission control system devices and components. The effects of lubricating oil on engine emissions and emission control devices are not clearly understood. Improved understanding is needed in developing approaches that mitigate any deleterious effects caused by fuel properties, fuel components, and lube oils. Furthermore, new fuel formulations could require corresponding new lube oil formulations.

D. **Infrastructure.** The lack of a fueling infrastructure is a major barrier for fuels such as hydrogen, natural gas, and new liquid fuels that may or may not be fungible with current fuels in existing distribution systems. This barrier must be addressed for these fuels to have a significant impact on reducing the transportation sector's dependence on petroleum-based fuels (i.e., gasoline and diesel fuel). Existing infrastructure must be used to the extent possible during the transition years. It will be necessary to determine the feasibility of using existing infrastructure to distribute liquid and gaseous fuels suitable for internal combustion or reforming to hydrogen.

E. **Cost.** There are insufficient data on refinery economics and processing strategies to enable comparison options for APBFs and NPBFs. Also inadequate are the databases on the health, safety, and regulatory issues associated with most non-petroleum fuel components that might be used to replace petroleum-based fuels, and the knowledge base on the technical and economic impacts of non-petroleum fuel components on the distribution, storage, and fueling infrastructure.

Approach

The expertise of the national laboratories is used for in-house research (see Appendix A) and development efforts, in "working group"–level interactions in government-industry consortia, and in technical management. In the near term, the fuel issues associated with 2007–2010 engine and emissions control system technologies are addressed. Efforts are focused on identifying the maximum allowable sulfur level for engines and emission control devices that will allow them to meet useful life requirements and reduce the fuel penalty associated with emission control device operation. Included in this near-term focus are tasks that support removing sulfur from the fuel downstream of the refinery in order to provide a near-zero sulfur level, if necessary. For the long term, the challenge is development of a fuel that has the proper chemical makeup to enable operation of ICEs operating in advanced combustion regimes over a full range of load conditions. Another challenge is identifying compatible lubricants for use with the newly developed fuels.

The APBF and NPBF sub-activities will test and evaluate a wide variety of fuels to develop a better understanding of the relationships between fuel properties, engine emissions, and efficiency. Since exhaust emission control devices will be necessary to meet future emissions standards for diesel-powered vehicles, testing will also include these devices as they become available (through close collaboration with the Advanced Combustion Engine R&D activity).

Key deliverables from the APBF and NPBF sub-activities will be test data and test-data–based analyses of the sensitivity of the performance and emissions of engines and emission control devices to fuel and lubricant properties. As data accumulate in the database, it will become increasingly feasible to predict fuel formulations with favorable properties to reduce emissions of NO_X and PM. In addition, some emission control strategies rely on reductants derived from the fuel to operate effectively, a fact that will be taken into account as required reductant properties are identified by the Advanced Combustion Engine R&D activity.

Guidance on the fuels to be tested and other tasks will be provided by representatives from the automotive, energy, and engine companies; industry associations; and national laboratories. Government/industry technical and supporting groups will make specific recommendations for task elements, data analyses, and overall direction.

Task Descriptions

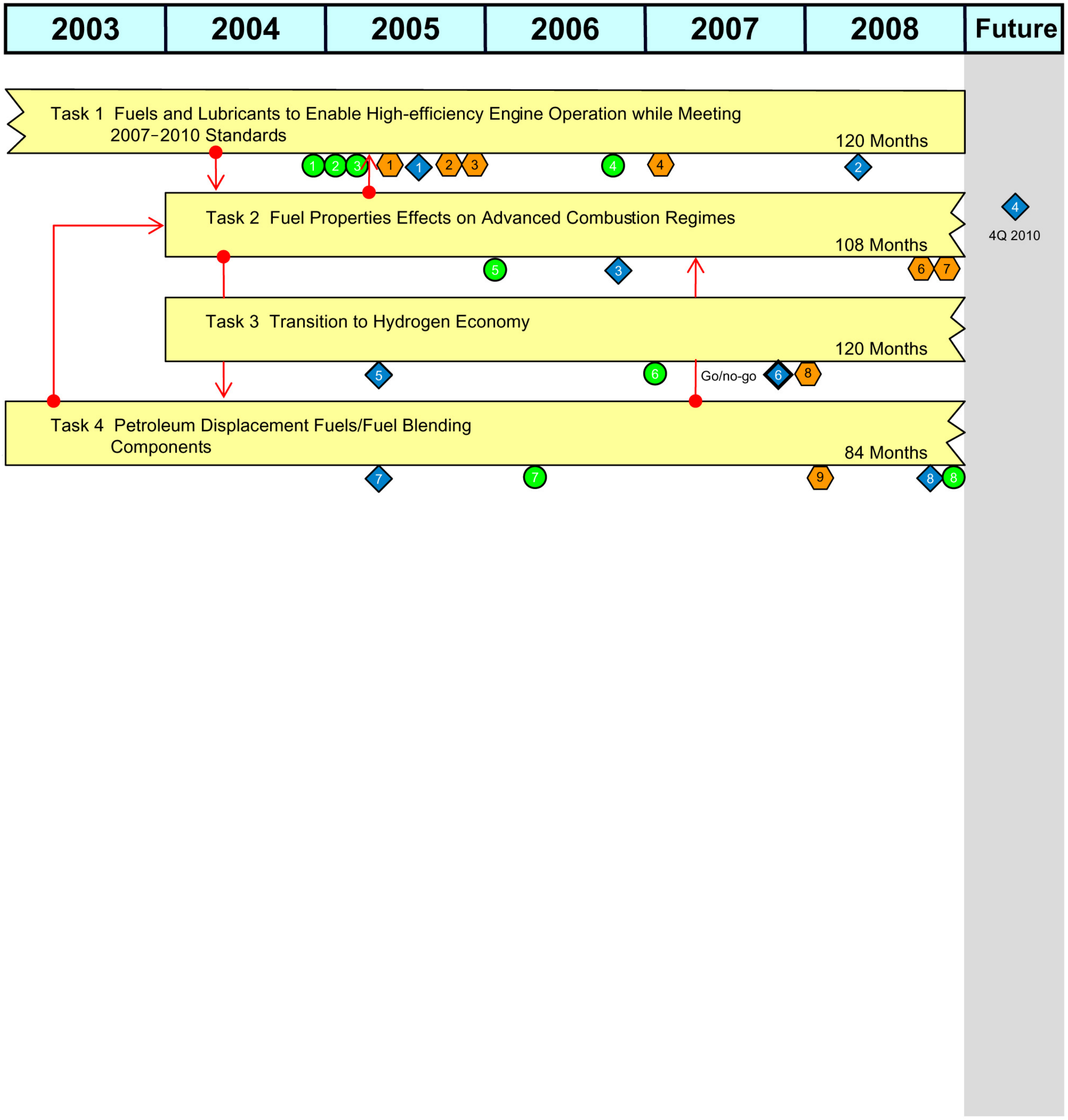
The technical task descriptions are provided in Table 42.

Milestones

The milestones for the APBF and NPBF sub-activities are listed in the network chart.

Table 42. R&D tasks for the APBF and NPBF sub-activities

Task	Title	Duration/ barriers
1	Fuels and Lubricants to Enable High Efficiency Engine Operation while Meeting 2007–2010 Standards • Evaluate long-term degradation and loss of effectiveness of light- and heavy-duty engines equipped with 2007–2010 technology emission control devices and using 15-ppm-sulfur diesel fuel • Improve fundamental understanding of the effect of fuel and lubricant composition on aftertreatment systems by applying experimental and modeling approaches • Identify fuel properties other than sulfur that are critical to improving the efficiency, performance, and emissions of light-duty diesel engines and aftertreatment systems • Develop measurement techniques and characterize unregulated emissions from 2007–2010 engines and aftertreatment systems • Study fuels-based in-cylinder strategies to achieve high-efficiency, low-emissions operation at high power density and to improve understanding of hydrocarbon molecular structure effects on the sooting tendency of diesel fuel constituents	120 months Barriers A, B, C, D, E
2	Fuel Properties Effects on Advanced Combustion Regimes • Develop fundamental understanding of fuel effects on in-cylinder combustion and emissions formation processes in advanced combustion regimes through experimental and modeling approaches • Develop predictive tools that relate molecular structure to ignition behavior and heat release for fuels used in advanced combustion engines • Evaluate new fuels and fuel blends for efficiency, emissions, and operating stability with advanced combustion regimes • Evaluate the potential of reforming small amounts of fuel to generate additives that can be used to achieve fast control in low-temperature combustion modes • Evaluate the performance of traditional lubricant formulations in engines using advanced combustion regimes and identify any performance deficiencies	108 months Barriers A, B, C, E
3	Transition to Hydrogen Economy • Develop strategies and technologies for gaseous fuel engines and systems that improve engine thermal efficiency by about 50% while meeting EPA 2007–2010 emissions standards. • Determine the feasibility of using existing infrastructure to distribute liquid and gaseous fuels (with potential for reforming to hydrogen) that could be dispensed to both internal combustion and fuel cell vehicles • Determine hydrogen specifications for use in ICEs • Establish gaseous fuel blends that maximize thermal efficiency, power, and torque while minimizing engine-out emissions • Determine performance attributes necessary in lubricants used in hydrogen ICEs • Develop gaseous fuel infrastructure strategies and technologies to reduce the initial capital investment requirements	120 months Barriers A, B, C, D
4	Petroleum Displacement Fuels/Fuel Blending Components • Study combustion and emissions-formation processes of NPBFs and blending components using experimental and modeling approaches • Identify renewable and synthetic fuel blending components that provide enhanced efficiency, performance, and emissions characteristics • Quantify the potential for improving engine and/or vehicle fuel economy through the use of renewable biolubricants • Enhance the use of petroleum displacement fuels and NPBF infrastructure development through technical forums and by providing specialized technical support to early adaptors of advanced NPBF vehicle technologies • Review and revise, as required, appropriate codes and standards to increase the availability of petroleum displacement fuels	84 months Barriers A, B, C, D, E



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Milestone

1. Determine the maximum tolerable level of sulfur and other contaminants in fuels and lubricants for emission control systems to enable them to meet full useful life requirements while reducing the emission control fuel penalty
2. Identify fuel formulations that validate >50% reduction in energy penalty from meeting 2007–2010 emission requirements (using a 7% penalty as baseline)
3. Establish fuel and lubricant constituents that are required for advanced-combustion-regime engines
4. Identify fuel and lubricant formulation for advanced-combustion-regime engines needed to achieve >50% efficiency, emissions compliance, and a power density >20 bar bmep
5. Determine the feasibility of using existing infrastructure to distribute liquid and gaseous fuels suitable for internal combustion or reforming to hydrogen
6. Validate at least 45% efficiency in gaseous fuel engines and systems using hydrogen/natural gas or other fuel blends with high hydrogen-to-carbon ratios, while meeting EPA 2007–2010 emissions standards. **Go/no-go** on further increase to 50%
7. Determine adequacy of existing codes and standards for fuels with non-petroleum and synthetic blending components
8. Validate >5% petroleum fuel displacement using renewable and synthetic fuel blending components without efficiency reduction, while meeting the EPA 2007–2010 emissions standards

Technology Program Output

1. Fuel formulation that allows emission control system to meet useful life requirements, to Advanced Combustion Engine R&D
2. Fuel formulation for materials compatibility evaluation, to Materials Technologies/Heavy Vehicle Propulsion Materials
3. Fuel formulation for use in fuel cell APU reformer, to Vehicle Systems R&D
4. Fuel-derived reductant for emission control use, to Advanced Combustion Engine R&D
5. Fuel formulation for materials compatibility evaluation, to Materials Technologies R&D
6. Fuels composition that meets requirements of HCCI, to Advanced Combustion Engine R&D
7. Fuel formulation for full scale vehicle system testing, to Vehicle Systems R&D
8. Gaseous hydrogen fuel blend for full scale vehicle testing, to Vehicle Systems R&D
9. Fuels formulation for health impacts testing to Advanced Combustion Engine R&D/Health Impacts Research

Supporting Input

1. Engine/emission control system model that predicts fuel effects on the system, from Advanced Combustion R&D/Combustion and Emission Control
2. Fuel formulation constraints for APUs, from Vehicle Systems R&D
3. Rapid aging protocol from Combustion and Emission Control R&D
4. Technical data on materials compatibility of fuel formulations, from Materials Technologies/Heavy Vehicle Propulsion Materials
5. Fuel physical property requirements for HCCI, from Combustion and Emission Control R&D
6. Technical data on performance characteristics of hydrogen enhanced fuels, from Vehicle Systems R&D
7. Technical data and information from industry
8. Technical data and information from Health Impacts activity of Advanced Combustion Engine R&D

4.7.2 New Fuels Technology Impacts

The New Technology Impacts Research sub-activity supports the FCVT mission to ensure that advanced fuel formulations, which may eventually replace petroleum fuels in transportation, are environmentally friendly and do not produce adverse impacts on the ecosystem. This sub-activity seeks to identify, analyze, quantify, and therefore avoid potentially deleterious ecosystem impacts of new technologies, specifically from fuels that are envisioned as replacing petroleum fuels. Frequently in the past it has been assumed that new technologies will be eco-friendly. However, experience with fuel additives such as tetraethyl lead and methyl tert-butyl ether (MTBE) has shown the fallacy of such assumptions.

Goals

The goal of the cross-cutting, comprehensive EERE-wide New Technology Impacts sub-activity is to help ensure that EERE technologies brought to the marketplace by industry will be friendly to the Earth's ecosystem by providing a sound scientific basis for differentiating the contribution and determining the potential impact of EERE technologies on the environment. A sound scientific basis will be established through more accurate data and validated models.

Programmatic Status

New fuels and fuel technology may have negative environmental impacts, oftentimes unforeseen by engineers and/or advocates. Examples include groundwater contamination by MTBE, an EPA-mandated gasoline additive to reduce carbon monoxide emissions, and high amounts of toxic compound emissions such as formaldehyde and 1,3-butadiene from natural gas-powered vehicles. In addition, complete analyses of pollutant emissions from new fuel technologies are seldom conducted, mostly because of the high costs associated with such analyses. Most often, emissions tests are performed only on new, well-maintained engines or vehicles, with few or no emissions data obtained from high-mileage engines or high emitters. Proponents and/or opponents of different fuel technologies have never performed complete emission analyses; hence, little information has been available regarding the true environmental impacts of new fuel technologies on the environment. Proponents of new technologies often cite studies that are dated and based on emissions data collected from old-technology engines, for example, with no emission controls; none of the comparison studies is based on the more advanced diesel or other engines using clean fuels and advanced aftertreatment technologies.

To avoid unexpected, adverse environmental impacts from vehicle technologies being developed by FCVT, the New Fuels Technology Research sub-activity proactively evaluates the impacts of changes in fuel, engine, and aftertreatment technologies on the ecosystem. The FCVT research on advanced vehicle and fuel technology is in the exploratory and developmental stages; therefore, those technologies are not yet sufficiently commercial for EPA regulatory oversight. In addition, FCVT research investigates environmental impacts of whole exhaust, where air quality impacts are enhanced; and the sub-activity develops information that places environmental impacts of advanced fuels technology in context with respect to environmental impacts of current fuels and technologies.

During 2003, this sub-activity completed the study of the causes of elevated ozone on weekends in California's South Coast (Los Angeles) Air Basin. Findings of this study were reported in six technical papers that were published in the *Journal of the Air & Waste Management Association*. This study demonstrated that NO_X emission reductions in urban areas produce an unintended consequence: higher ambient urban ozone levels. An article that summarized the overall effort was published in the July 2003 issue of *EM* magazine, the most widely circulated magazine for air pollution professionals.

Targets

To quantify the impacts of changes in fuels, engines, and aftertreatments on pollutants emitted and their influence on the ecosystem, reliable and validated measurement methods and techniques will need to be developed that can be applied to accomplish the following:

- measure the chemical and physical properties of vehicle emissions and distinguish emissions from different mobile source categories
- apportion emissions among various mobile sources, e.g., cars vs. trucks and one fuel type vs. another
- identify potential ecosystem impacts resulting from the introduction of new fuel technologies
- establish the scientific basis for quantifying impacts of emissions from new fuel technologies on the ecosystem

Barriers

A. **Lack of accurate measurement tools and techniques.** As emission standards are tightened, precise, accurate measurement and characterization of engine emissions become more difficult. In addition, effective planning of regional and national air quality strategies requires knowledge of the air-quality effects of changes in the mix of pollutants as a result of the introduction of new engines and fuels.

B. **Lack of validated models.** Several recent studies have highlighted major differences among measured emissions from various sources and emission inventories predicted by current models used to set policies to improve air quality (e.g., EPA's MOBILE6 vehicle emissions model). Such uncertainties are leading to the establishment of policies detrimental to specific technologies and exacerbating air quality problems by prescribing incorrect approaches.

C. **Lack of adequate information regarding ecosystem, health, and safety impacts.** Engine manufacturers are testing additional fuels and fuel technologies to meet increasingly stringent emissions regulations. However, little information currently exists regarding many possible impacts from those new fuel and technology combinations.

Approach

To validate or remediate the shortcomings of currently used models, several studies are conducted concurrently to enable a more scientific and rational approach to identifying and quantifying specific contributions of mobile-source emissions from new fuels and EERE-developed technologies. The sub-activity will be expanded to be inclusive of EERE-wide technologies. Planning sessions will be scheduled in 2004 to solicit input from EERE stakeholders.

Task Descriptions

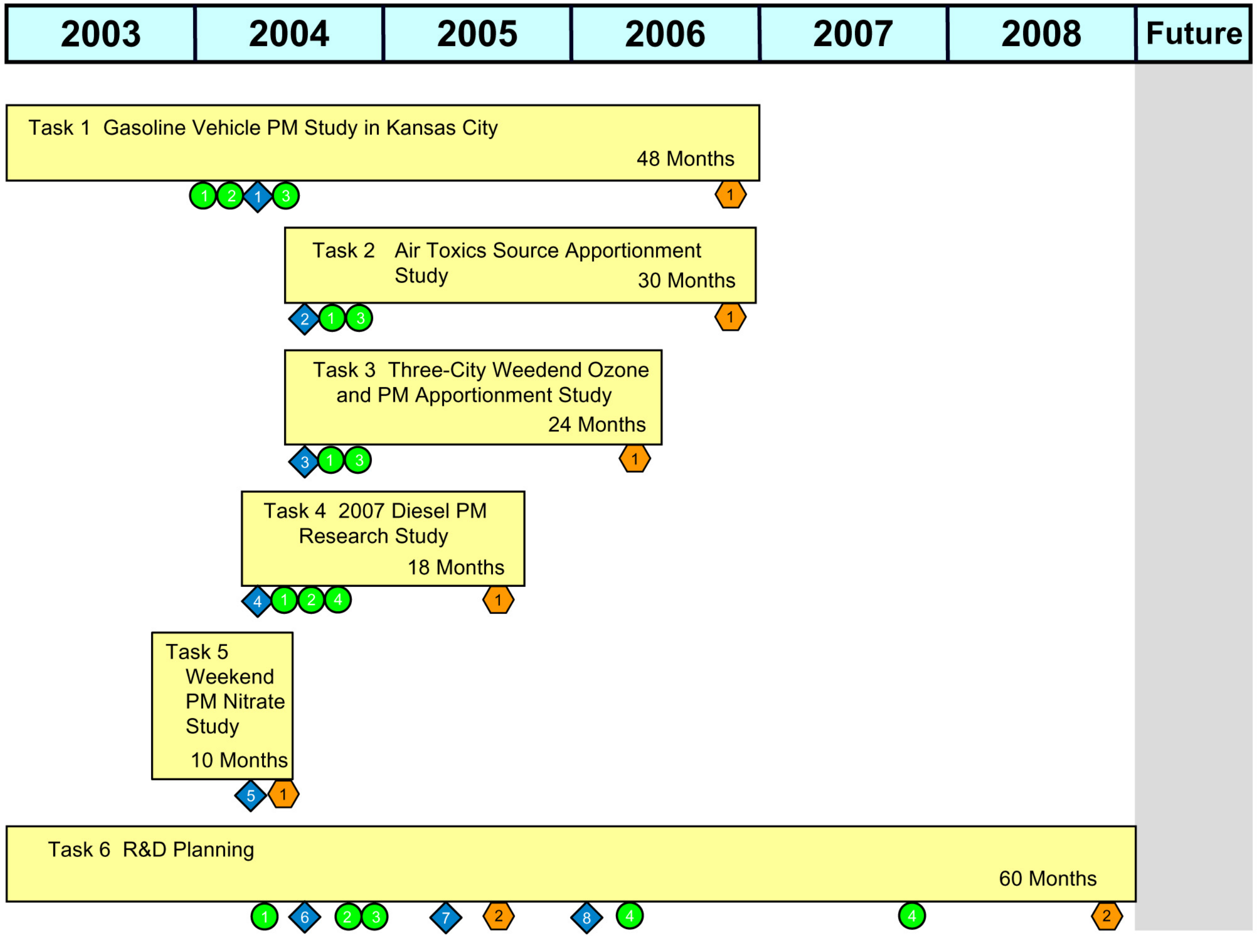
A description of each technical task, along with the estimated duration and technical barriers associated with the task, is provided in Table 43.

Table 43. Tasks for New Technology Impacts sub-activity

Task	Title	Duration/ Barriers
1	Gasoline Vehicle PM Study in Kansas City • Collect on-road vehicle emissions data to serve as a basis for validating and updating the EPA MOBILE6.1 vehicle emissions model	48 months Barriers A, B
2	Air Toxics Source Apportionment Study • Conduct an ambient study to identify pollution source types responsible for elevated air toxics pollutant concentrations in the Los Angeles area	30 months Barriers A, B
3	*Three-City Weekend Ozone and PM Apportionment Study* • Perform a field study to investigate weekend ozone levels and their relationship to emission changes that occur on weekends relative to weekdays, and perform source apportionment of ambient particulate matter in three U.S. cities	24 months Barriers A, B
4	2007 Diesel Particulate Measurement Research Study • Begin E-66 study, designed to develop and validate PM sampling methods needed to meet EPA's 2007 new heavy-duty engine certification standards	18 months Barriers A, B
5	Weekend PM Nitrate Study • Complete a study of the relationship between large decreases in weekend NO_x emissions and their influence on particulate nitrate concentrations in Los Angeles	10 months Barriers A, B
6	R&D Planning • Conduct workshops to provide technical support to EERE and to solicit EERE stakeholder input • Plan studies to evaluate the accuracy of emission inventories for elemental and organic particulate carbon emissions for global climate change issues • Provide technical input and support for the Advanced Collaborative Emissions Study	60 months

Milestones

The New Technology Impacts sub-activity milestones are provided in the network chart.



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◆ **Milestone**

1. Begin pilot study phase of Kansas City gasoline vehicle PM study
2. Begin air toxics source apportionment study in Los Angeles
3. Begin three-city weekend ozone and PM apportionment study
4. Begin 2007 diesel particulate measurement research study
5. Complete weekend PM nitrate study. Go/no-go
6. Conduct workshop to solicit stakeholder input for a more expanded scope of studies to identify ecosystem impacts of new technologies being developed by FCVT
7. Initiate multi-year planning for New Technology Impacts R&D; provide technical guidance for Advanced Collaborative Emissions Study
8. Complete R&D Plan

⬢ **Technology Program Output**

1. Results disseminated to industry, technical community, and the public through refereed journals
2. Technical data on ecosystem impacts of fuel formulations to the APBF/NPBF activities

● **Supporting Input**

1. Input on R&D opportunities from industry
2. Input on R&D opportunities from APBF/NPBF
3. Input on R&D opportunities from EERE programs
4. Fuels formulation for ecosystem impacts testing from APBF/NPBF activities

5. Management Plan

The Office of FreedomCAR and Vehicle Technologies (OFCVT) maintains overall authority and responsibility for managing and implementing DOE's FreedomCAR and Vehicle Technologies (FCVT) Program. Contract execution and administrative authority for many program elements are delegated to DOE's operations and field offices. OFCVT also works with the EERE regional offices, State Energy Offices, and National Association of Energy Offices for implementation of technologies at the regional and state level. This section describes how the portfolio of FCVT research activities will be managed and implemented.

5.1 PROGRAM MANAGEMENT

The DOE organizational structure responsible for managing the FCVT Program, including implementing the R&D Plan, is shown in Figure 20. The program resides within the Office of Energy Efficiency and Renewable Energy (EERE) and is one of 11 programs reporting to the DOE Assistant Secretary for Energy Efficiency and Renewable Energy. Management responsibility for the FCVT resides with the Program Manager of FCVT, who reports to the Deputy Assistant Secretary for Technology. In addition to managing day-to-day implementation of its research activities, OFCVT is responsible for implementing agency policy, formulating and modifying this R&D Plan, justifying and allocating resources, coordinating the various activities, establishing priorities among program activities, evaluating progress, coordinating with other government and private-sector organizations, and reporting to senior DOE management.

OFCVT has established four technical teams (see Figure 20), which are responsible for day-to-day management of the FCVT technology R&D activities. Management responsibilities for these teams are shown in Table 44. Contract administration and support is provided to FCVT by appropriate organizations at DOE Headquarters, operations offices, and field offices. Technical assistance is provided by selected personnel from the national laboratories who have expertise in many of the technologies addressed by the FCVT Program.

The OFCVT management structure, processes, and procedures are designed to ensure the overall effectiveness of the FCVT research agenda in terms of the following:

- setting R&D priorities and allocating resources in ways consistent with the mission and objectives of DOE and EERE
- obtaining the best available expertise in each technical area within industry, the national laboratory system, and universities
- conducting high-value R&D
- managing costs
- ensuring the high quality of work through strong oversight and internal program/external peer reviews
- transferring results to customers and otherwise responding to their needs
- achieving close coordination with government and industry partners

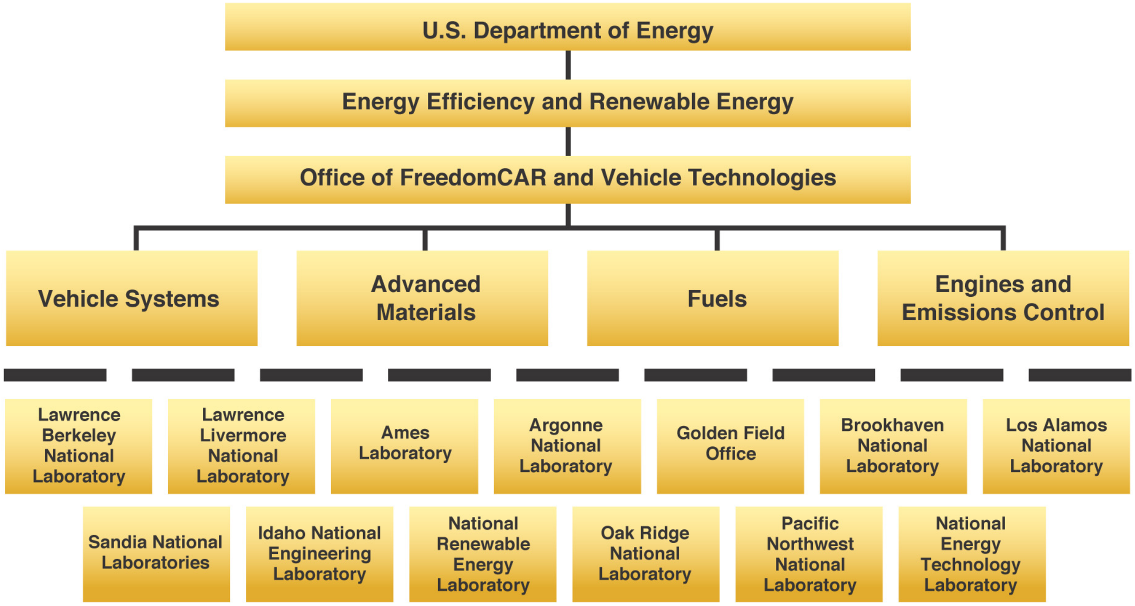


Figure 20. Department of Energy/Office of FreedomCAR and Vehicle Technologies organizational structure.

Table 44. FCVT Management Team responsibilities

Vehicle systems	Advanced materials	Fuels	Engines and emission control
• Heavy Vehicle Systems • Ancillary Systems • Simulation/Validation • Energy Storage • Advanced Power Electronics • Hybrid and Electric Propulsion • Testing and Evaluation	• Propulsion Materials (heavy and light) • Lightweight Materials (High-Strength Weight Reduction and Automotive Lightweighting Materials) • High Temperature Materials Laboratory	• Advanced Petroleum-Based Fuels • Non–Petroleum-Fuels and Lubricants • EPAct	• Combustion and Emission Control • Light Truck Engine • Heavy Truck Engine • Waste Heat Recovery • Off-Highway Vehicles

OFCVT is committed to embracing the best management practices and evolving into an organization with which its industry partners and stakeholders have enhanced interest to do business. Reflecting the overall priorities of DOE's strategic management process, OFCVT seeks continuous improvement in programmatic efficiencies through establishing clear lines of authority with minimal layers of management and through eliminating duplicated effort. An effective, flexible management structure has evolved within which different levels of management are performed at headquarters, field, and operations offices and at the national laboratories to capitalize on the strengths of each type of organization. To implement the various R&D efforts, OFCVT contracts directly with national laboratories, universities, and industries; cooperates with industry consortia; or delegates contracting and technical management authority to national laboratories or field offices. Implementation of R&D efforts with industry is carried out through competitive solicitations. Special competitive procurements are also aimed at small businesses and universities. National laboratories are directly funded based on their capabilities and performance. When appropriate, OFCVT creates and maintains synergistic, non-duplicating centers of excellence in the national laboratories. In determining the appropriate management approach for each activity and assigning management responsibilities, several criteria are considered:

- ability to acquire the necessary expertise—for example, in technical management or procurement
- proven track record of responsiveness and results
- expertise and facilities required to accomplish the desired work
- involvement of organizations expected to use/commercialize the results of the work
- productivity and efficiency

In a time of constrained budgets, actively balancing and managing the R&D portfolio is of vital importance. Given the large number of promising technologies and multitude of R&D approaches for each technology, effective management processes for setting R&D priorities and allocating resources are required. A decision and risk analysis methodology is employed to screen and compare priorities for the overall efforts and technology selection. The OFCVT management team, in coordination with the industry partners, defines and reviews strategic alternatives, finalizes selection criteria, reviews analyses conducted by support personnel, and makes decisions regarding program content, structure, and priorities.

In establishing technical directions and priorities, the program has obtained substantial inputs from energy and transportation experts from outside DOE through interaction of government–industry–laboratory technical teams, independent reviews with selected panelists, solicited review of DOE R&D plans, and critiques by organizations such as the National Academy of Sciences. The perspectives of these outside experts are extremely valuable in helping to ensure that the program’s research directions and priorities are aligned properly with the needs of auto and heavy vehicle manufacturers, equipment suppliers, energy companies, other federal agencies, state agencies, consumers, and other stakeholders. In addition, the program invests in technical program and market analysis and performance assessments in order to direct effective strategic planning.

Independent peer reviews of the program are an integral part of OFCVT’s management process. Feedback from such reviews often identifies areas within which corrective measures are required and provides information that DOE management can use for continual improvement of its R&D efforts.

5.2 PERFORMANCE-BASED PLANNING, BUDGETING, EXECUTION AND EVALUATION

The Program will follow the EERE management system as depicted in Figure 21.

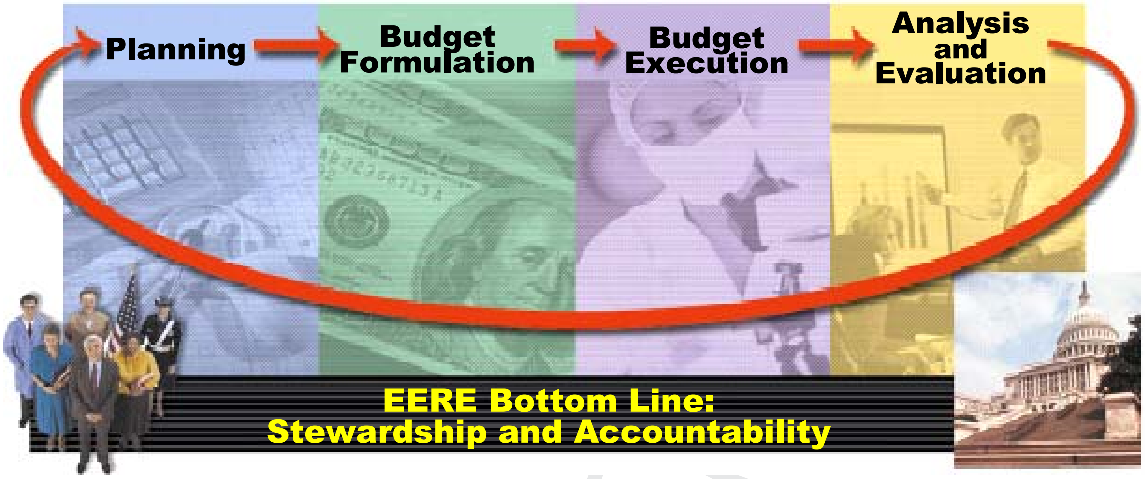


Figure 21. The four phases of EERE program management.

Program Planning

The National Energy Policy and the EERE Strategic Plan provide the planning foundation for the FCVT Technologies Program. The FCVT Program establishes priority goals that support the National Energy Policy and the EERE Strategic Plan and are aligned with the FreedomCAR and Hydrogen Fuel Initiative, the FreedomCAR Partnership, and the 21st Century Truck Partnership (21st CTP). The FCVT priority goals flow down to the appropriate activities. Within each activity, additional time-phased goals and technology targets have been established to address the critical technology barriers. This plan then identifies tasks, milestones, and schedules out to the year 2008 to meet the time-phased goals. The FCVT priority goals are included in Section 5.4.

Program Budget Formulation

The budget falls under the jurisdiction of the Interior and Related Agencies Appropriations Subcommittee of the U.S. Congress. Program budget performance is regularly evaluated by the Office of EERE through regular management reviews and the Annual Budget Summit. In addition, the Office of Management and Budget, in consultation with the Office of Science and Technology Policy, evaluates the Program budget performance annually from September through November prior to each new fiscal year. Each year, the Program reports the current status against the pre-established FCVT priority goals and performance measures. Budget resources are requested from Congress based on a number of factors. Foremost is that each of the activities must fall within the DOE, EERE, and FCVT Program mission and not another program or agency. Furthermore, it must be an activity that industry is not funding or would not fund by itself.

Program Budget Execution

Within each of the activities, the R&D tasks are executed by an industry contractor, a national laboratory, a university, or a team composed of these entities. Within each activity, tasks are prioritized by analyzing the current status against the out-year targets. Industry-contracted research is awarded through competitive solicitations. Depending on the risk, the federal cost share is usually between 50% and 80%. University research is also awarded through competitive solicitations, and the federal cost share is usually 80% or more.

Program Analysis and Evaluation

Evaluation is conducted at the program level and the activity level. Peer reviews conducted by the National Research Council, or an equivalent independent group, will be carried out every two years. Program budget performance, financial management, and overall program management are evaluated on a periodic basis by EERE management.

DOE managers of the activities semi-annually review all national laboratory and industry work. An annual progress report for each activity documents the data and progress achieved.

5.3 EXTERNAL COORDINATION

FCVT coordinates its research with its industrial partners, with other offices within EERE, with other offices within DOE, and with others through education and outreach.

U.S. Council for Automotive Research

OFCVT is the lead organization within DOE for the FreedomCAR Partnership, a research partnership between DOE and the auto industry's U.S. Council for Automotive Research (USCAR). As the lead government organization, FCVT serves as the department's FreedomCAR coordinating office and, in that capacity, will coordinate DOE FreedomCAR matters with USCAR. The management structure for the FreedomCAR Partnership is shown in Figure 3 of this plan.

Twenty-first Century Truck Partnership

FCVT is also the lead government office for 21st CTP. This partnership between the trucking industry and the government has the objective of significantly reducing the petroleum dependence of medium- and heavy-duty trucks. The government and industry participants in 21st CTP are shown in Figure 4 of this plan.

DOE Office of Hydrogen, Fuel Cells and Infrastructure Technology

The Office of Hydrogen, Fuel Cells and Infrastructure Technology (HFCIT), within EERE, is responsible for DOE's hydrogen research and FreedomCAR fuel cell research of the FreedomCAR and Hydrogen Fuel Initiative. Included within the mission of HFCIT are research and engineering development in the areas of hydrogen production, storage, and utilization for the purpose of making hydrogen a cost-effective energy carrier for transportation applications; and research, development and validation of fuel cells for transportation applications. Therefore, FCVT collaborates closely with HFCIT to ensure that the FCVT transportation vehicle technologies and the HFCIT hydrogen and fuel cell technologies are implemented in a synergistic fashion.

DOE Office of Fossil Energy

EERE and the Office of Fossil Energy are jointly conducting a government/industry program to develop (1) a portfolio of ultra-clean highway transportation fuels that can be derived from domestic feedstocks and (2) advanced technologies that will enable their market-viable production and nationwide distribution. This effort, the Ultra-Clean Transportation Fuels Program, addresses all elements of the vehicle power system (i.e., fuel, engine, emissions control) using an integrated systems approach.

Within the Ultra-Clean Transportation Fuels Program, the Office of Fossil Energy is responsible for the development of ultra-clean fossil-based fuels (including those that incorporate non-fossil fuels as blending stock) and associated fuels production technologies. EERE is responsible for biofuels development and production technologies and for engine/emissions-control technologies. FCVT and the Office of Fossil Energy, collaborating on the engine/emission-control technology development dimension of the Ultra-Clean Transportation Fuels Program, are conducting research to identify the optimum fuel formulations and properties for efficient, clean engine and fuel cell reformer operation.

DOE Office of Science

EERE-managed research activities are often leveraged with Office of Science research. These leveraged activities include co-funding of the Combustion Research Laboratory, using Office of Science–procured massively parallel computers for vehicle crash modeling, and performing applied research in the Advanced Photon Source. Many technologies discovered in the Office of Science Basic Energy Sciences Program are carried through applied research by this program and others within EERE.

Education and Outreach

The FCVT Program has efforts in education and outreach, including Graduate Automotive Technology Education (GATE), Advanced Vehicle Competitions, and the Technology Introduction portion of the Energy Policy Act of 1992 (EPAct) Replacement Fuels. The GATE effort aids in the development of interdisciplinary curricula to train the future workforce of automotive engineers. This is accomplished by setting up GATE Centers of Excellence at universities that have been competitively selected, establishing a focused curriculum, and providing funds for research fellowships. Advanced Vehicle Competitions provide educational opportunities for university students while pursuing novel approaches to and demonstrating the performance of critical vehicle technologies identified by DOE and its partners. Many students who graduate from these vehicle competitions go on to take jobs in the auto industry, where they bring with them an unprecedented appreciation and understanding of advanced automotive technologies. The Technology Introduction effort accelerates the adoption and use of alternative fuel and advanced technology vehicles to help meet national energy and environmental goals. This effort logically follows and complements successful technology development by industry and government. The primary functions of Technology Introduction include legislative and rulemaking supporting EPAct alternative fuel and fleet efforts, testing and evaluation of advanced technology vehicles, and advanced vehicle competitions. As identified in the National Energy Policy, consumer education and demonstration efforts are critical to accelerating the use of advanced energy technologies.

5.4 PERFORMANCE MEASURES

There are strategic-level and more detailed tactical-level performance measures for the portfolio of FCVT technology programs. The **strategic-level performance measures** are the measures by which progress toward the goals can be assessed. Historically, these definitive measures have been defined in the DOE Transportation Program Annual Performance Plan, Fiscal Year 2002, and have been reported on annually in the budget requests to Congress. The more detailed tactical-level measures are the technical targets that have been defined throughout this Plan. The strategic-level performance measures are

Performance Measure 1. Heavy Vehicle Systems: measured parasitic losses (aerodynamics, cooling, compressed air) (Figure 22).

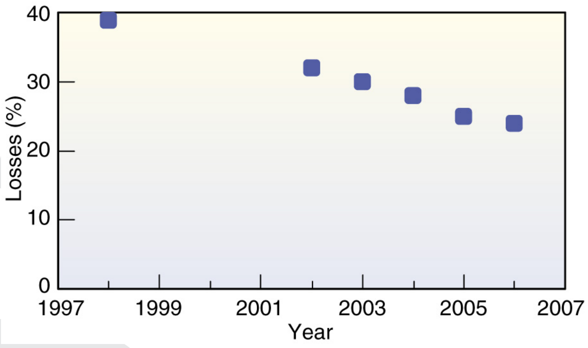


Figure 22. FCVT Performance Measure 1: Heavy vehicle parasitic losses.

Performance Measure 2. Hybrid Electric Propulsion: cost per 25-kW battery system (Figure 23).

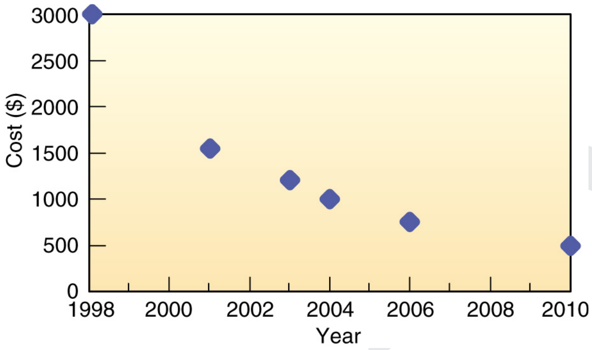


Figure 23. FCVT Performance Measure 2: Cost per 25-kW battery system.

Performance Measure 3. Advanced Combustion Engine R&D: efficiency of light- and heavy-duty internal combustion engines (Figure 24).

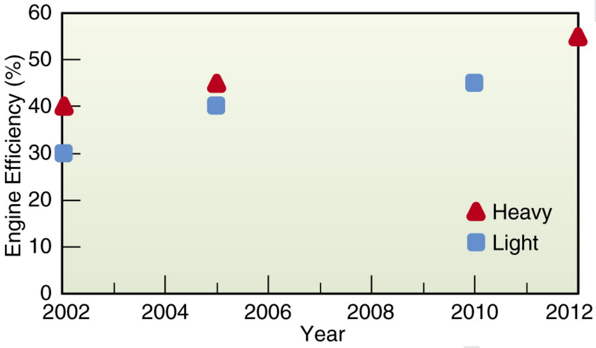


Figure 24. FCVT Performance Measure 3: Efficiency of light- and heavy-duty internal combustion engines.

Performance Measure 4. Materials Technologies: cost of carbon fiber (Figure 25).

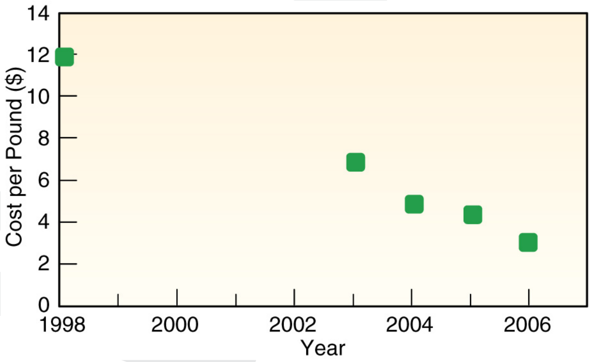


Figure 25. FCVT Performance Measure 4: Cost of carbon fiber.

Performance Measure 5. Fuels Technologies:

Develop a specification by 2007 for a fuel formulation that incorporates the use of a non–petroleum-based blending agent enabling a 5% diesel fuel replacement in 2010.

Performance Measure 6. Materials Technologies: truck weight (Figure 26).

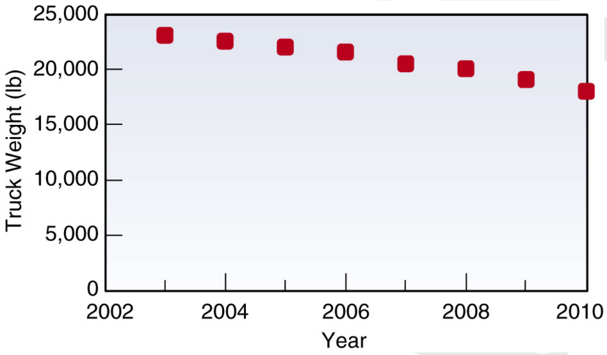


Figure 26. FCVT Performance Measure 6: Heavy tractor-trailer unloaded weight.

To assess progress toward achievement of these performance measures, targets have been established at intermediate dates. These are indicated in the charts. At the tactical level, technical targets have been established as presented throughout Section 4 of this Plan. FCVT-developed technologies are evaluated to validate that the FCVT-developed component/subsystem technologies meet the technical targets. This validation process involves the following methods:

- Computer simulations using the vehicle models updated with embedded component/subsystem models that virtually replicate the technology-representative point designs developed in the FCVT component/system technology development activities.
- "Hardware-in-the-loop" testing that replicates a complete vehicle by employing a blended combination of (1) actual test hardware provided by the FCVT component/subsystem technology development activities and (2) computer models.

Appendix A

The High Temperature Materials Laboratory at Oak Ridge National Laboratory

THE FACILITY

The High Temperature Materials Laboratory (HTML) is a facility designed to assist American industries, universities, and governmental agencies in developing advanced materials by providing a skilled staff and numerous sophisticated, often one-of-a-kind, pieces of materials characterization equipment. It is a nationally-designated user facility sponsored by the Department of Energy's Office of FreedomCAR and Vehicle Technologies, Energy Efficiency and Renewable Energy. Physically, it is a 64,500-ft^2 building on the ORNL site in which reside six "user centers," which are clusters of specialized equipment revolving around a specific type of properties measurements. Expansion of the HTML user effort since its inception in 1987 has made available new equipment and instrumentation located in other facilities of ORNL's Metals and Ceramics Division. HTML users also now have access to the X-14A S-ray beamline at the National Synchrotron Light Source at Brookhaven National Laboratory and a neutron diffraction instrument located at the High Flux Isotope Reactor at ORNL.

The HTML was conceived and built in the mid-1980s to provide a facility that would work directly with American industry, academia, and government laboratories to provide advanced high-temperature materials such as structural ceramics for energy-efficient engines. The scope of the HTML's work has since expanded to include other, non-high-temperature materials of interest to transportation and other industries.

THE USER CENTERS

Materials Analysis User Center

Researchers in this Center employ electron microscopy and surface chemical analysis to determine structure, surface chemistry and microstructure to the atomic level. Instruments include a Hitachi HF-2000 transmission electron microscope (TEM), a Hitachi HD-2000 scanning transmission electron microscope (STEM), a new JEOL 2010F STEM/TEM, a Phi 680 Scanning Auger nanoprobe, and a Hitachi focused ion beam instrument.

Mechanical Characterization and Analysis User Center

Researchers in this Center study the fracture toughness, tensile strength, flexure strength, and tensile creep of advanced materials at temperatures of up to 1500°C in air or controlled atmospheres. Instruments include nearly 100 creep frames, several outfitted with atmosphere control and numerous MTS, ATS, and Instron mechanical test frames for tensile, compressive, or bending testing at elevated temperatures. The center also has nanoindentation and fiber composite characterization capabilities, ranging from individual fibers to complete composite structures.

Residual Stress User Center

This Center has two principal parts: X-ray diffraction and neutron diffraction. The X-ray portion includes X-ray diffractometers to measure residual stress and texture in and near the surfaces of ceramics and alloys. Users can also access the National Synchrotron Light Source, located at Brookhaven National Laboratory, through this user center. The neutron residual stress facility includes a special neutron spectrometer for rapid data collection, plus computer capabilities for data analysis. The spectrometer instrumentation is located at the High Flux Isotope Reactor.

Diffraction User Center

This Center has both room-temperature and furnace-equipped X-ray and neutron diffractometers. The X-ray furnace is used for studies of materials properties at temperatures of up to 2700°C in vacuum and up to 1500°C in air. This center also has access to the National Synchrotron Light Source synchrotron.

Thermophysical Properties User Center

Researchers in this Center study the thermal stability, expansion, and thermal conductivity of materials at temperatures greater than 1400°C. Instruments include a Netzsch DSC, a Theta dual-pushrod dilatometer, and a laser flash instrument to measure thermal diffusivity to temperatures of up 1900°C. A separate capability is that of thermal mapping using a high-speed, high-sensitivity infrared camera.

Machining, Inspection, and Tribology Research User Center

This Center employs instrumented surface and cylindrical grinders to study hard material grinding on ceramics and special alloys. These grinders include high-stiffness surface grinders, a cylindrical grinder, and a creep-feed surface grinder. Other capabilities include instruments for determining the cylindricity and circularity of axially symmetric objects. A coordinate measuring machine is available.

This center also contains equipment for the measurement of friction and wear, including fretting, rolling, and sliding.

THE HTML SUB-ACTIVITY

Within the HTML are efforts that function to help outside researchers solve materials problems using state-of-the-art characterization instrumentation. In the "HTML User sub-activity," either nonproprietary or proprietary research can be performed by American industrial and academic researchers. The former is provided free of charge if the user publishes the information produced, while the latter requires payment. Non-proprietary research efforts typically last from one to three weeks at the HTML. The major proviso is that the results must be submitted for publication within 6 months after completion of the research.

For proprietary research, the user and the HTML staff estimate the cost of HTML staff time required to complete the work. The user agrees to pay for this time at an hourly rate specified by the Department of Energy before the start of the research. These efforts typically are more extensive than non-proprietary efforts, and the user owns the data from the research.

Appendix B

The Renewable Fuels and Lubricants Laboratory at the National Renewable Energy Laboratory

THE FACILITY

The Renewable Fuels and Lubricants Laboratory (ReFUEL) supports two principal efforts:

- Test and evaluate fuels and lubricants derived from renewable sources (and synthetic fuels and lubricants) in advanced vehicle and engine systems.
- Support DOE's heavy hybrid propulsion systems sub-activity.

The laboratory consists of heavy-duty chassis (vehicle) and engine dynamometers with emissions measurement capability. The chassis dynamometer is designed to test full-size buses and Class 8 trucks. It is capable of simulating from 8,000 to 80,000 lb of vehicle inertia through a combination of flywheels (mechanical inertia) and a dc motor (electrical inertia). The engine dynamometer is capable of absorbing 400 hp and performing the Federal Test Procedure for engine certification, which includes transient operation. Emissions measurement is performed using procedures consistent with the Code of Federal Regulations (CFR) applicable to heavy-duty engine certification. Extensive data acquisition and combustion analysis equipment are used to relate the effects of different fuels properties and engine settings to performance and emissions.

CHASSIS DYNAMOMETER

The Heavy-Duty Chassis Dynamometer is a rare resource in the test community. There are less than a half-dozen similar facilities in the United States that operate with laboratory-grade emissions measurement equipment. There is no standardization among these laboratories, so they are all distinct in their approach to the challenge of simulating driving conditions for heavy-duty vehicles.

The ReFUEL Chassis Dynamometer is installed in the main high-bay area of the laboratory and is sized to accept all highway-ready vehicles without modification. The dynamometer will accommodate vehicles with a wheelbase between 89 and 293 in. and can simulate vehicles of up to 80,000 lb at speeds up to 60 mph.

The chassis dynamometer is composed of three major components: the rolls—which are in direct contact with the vehicle tires during testing, the direct current (dc) electric dyno (380 hp absorbing/360 hp motoring), and the flywheels for mechanical inertia simulation.

The electric dyno is used to adjust the simulated inertia, either higher or lower than the 30,000-lb base weight, as the test plan requires. The simulation range of the system is up to 80,000 lb at an acceleration rate of up to 3 mph/s. This range can be extended by adjusting the mechanical inertia. The electric dyno will also be used to simulate grades and provide braking assist during deceleration.

The chassis dynamometer is supported by 72 channels of data acquisition in addition to the emissions measurement, fuel metering, and combustion analysis subsystems.

ENGINE DYNAMOMETER

The engine test cell is equipped with a dc electric dynamometer capable of absorbing up to 400 hp and operating at speeds of up to 5000 rpm. It is a transient test cell and is capable of performing the Federal Test Procedures (FTP) for Heavy-Duty Engine Certification.

The test cell controls are highly configurable and designed to perform complex test sequences with little or no human intervention. The cell is supported by 72 channels of data acquisition in addition to the emissions measurement, fuel metering, and combustion analysis subsystems.

EMISSIONS MEASUREMENT

The ReFUEL laboratory's emissions measurement system supports both the chassis and engine dynamometers. It is based on the full-scale dilution tunnel method with a constant velocity sampling (CVS) system for mass flow measurement.

Three-Venturi Parallel System

A system with three Venturis is employed to maximize the flexibility of the emissions measurement system. Featuring 500-scfm, 1000-scfm, and 1500-scfm Venturi nozzles and gas-tight valves, the system flow can be varied from 500 to 3000 scfm flow rates in 500-scfm increments. This allows the dilution level to be tailored to the engine size being tested (whether on the engine stand or in a vehicle), maximizing the accuracy of the emissions measurement equipment.

Gaseous Emissions Measurement

The gaseous emissions bench features analyzers for total hydrocarbons (HC), oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and nitrous oxide (N_2O). The system features auto-ranging, automated calibration and zero check and span check features, as well as integrating functions for calculating cycle emissions. It communicates with the ReFUEL data acquisition systems through a serial interface.

Bag Sampling

In circumstances where the emissions levels can be highly variable (such as a cold-start test on an aftertreatment-equipped vehicle), it can be difficult to accurately measure both very high and very low levels with the same instrument.

For this purpose, tedlar sample bags are used to collect a continuous sample proportional to the CVS flow via a mini-Venturi sample probe. This allows a post-test analysis of the bag that contains a mechanically integrated cycle average pollutant level.

Toxic Emissions Measurement

Bag samples can be analyzed for unregulated toxic species with the exhaust gas speciation capabilities. A gas chromatograph (GC) is used for the speciation and quantification of C_1-C_{13} hydrocarbon emissions including 1,3-butadiene and benzene. A high-performance liquid chromatograph (HPLC) is used to quantify emissions of aldehydes and ketones.

Particulate Matter Sampling

The particulate matter sample control bench is managed by the ReFUEL data acquisition systems through a serial connection. It maintains a sample flow rate through the particulate matter (PM) filters in proportion to the CVS flow, in accordance with the CFR. Filter holders are designed to the 2007 CFR requirements and use 47-mm-diameter filters.

Particulate Matter Filter Conditioning and Weighing

A dedicated clean room/environmental chamber is installed inside the ReFUEL facility. It is a Class 1000 clean room with precise control over the temperature and humidity (±1EC for temperature and dew point). This room is used for all filter handling, conditioning, and weighing.

The microbalance for weighing PM filters features a readability of 0.1 microgram and has static control, a barcode reader for filter identification and tracking, and a computer interface for data acquisition. The microbalance is installed on a specially designed table to eliminate variation in the measurement due to vibration.

COMBUSTION ANALYSIS

The ReFUEL Lab features a combustion analysis system, composed of a high-speed data acquisition system combined with software for rapid analysis of gathered data. This system is used to measure in-cylinder combustion pressure, diesel injector needle lift position, injector line pressure, intake/exhaust valve position, and any other high-speed engine-related phenomena as required.

The system features 24 channels capable of acquiring data at a rate of up to 800 kHz. The system can acquire data in either crank-angle-based or time-based mode, depending on the data required. It is composed of 3 modular units powered by 12 V and will be able to support the engine dynamometer and chassis dynamometer and be compatible with on-road testing (either as a whole or part of the overall system) in the event that such requirements become part of the ReFUEL mission.

FUELS TESTING

The ReFUEL Fuels Testing Laboratory features an Ignition Quality Tester (IQT™) that allows rapid measurement of the ignition delay of fuels. The IQT consists of a constant-volume combustion chamber that allows the user to specify charge temperature and pressure. The fully automated apparatus performs 47 sequential injections of the fuel sample and measures the ignition delay. This ignition delay can be related to the cetane number (relevant to CIDI engines) or the elevated-pressure auto-ignition temperature of the fuel (relevant to homogeneous charge compression ignition engines). This capability allows for the rapid screening for ignition quality of conventional diesel fuels, alternative fuels, blending components, and additivized fuels (with cetane improvers).

Appendix C

National Transportation Research Center

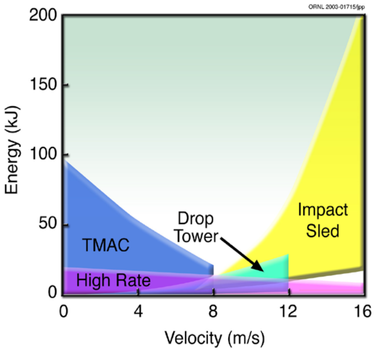
The National Transportation Research Center (NTRC) offers one of the largest multidisciplinary concentrations of transportation researchers in the United States, housing R&D efforts and laboratories from Oak Ridge National Laboratory (ORNL) and The University of Tennessee (UT). The NTRC was established to develop and evaluate advanced transportation technologies and systems, and to help the transportation industry deal with technology issues. The NTRC seeks to assist industry in utilizing state-of-the-art hardware and computing technologies to address problems of national and international significance such as declining air quality, dependence on unstable oil supplies, traffic congestion, and highway safety.

The NTRC houses several user centers that focus on different aspects of transportation, including commercial vehicle operations, supply chain management, commercial and military transportation logistics, geographic information systems, infrastructure materials, remote sensing, and heavy vehicle safety. User centers funded by the FreedomCAR and Vehicle Technologies Program are

- Composite Materials Laboratory, conducting controlled, programmable analysis of the deformation and failure response of lightweight materials in relation to impact velocity;
- Fuels, Engines, and Emissions Research Center, specializing in the detailed characterization of internal combustion engine emissions and efficiency; and
- Power Electronics and Electric Machinery Research Center, developing next-generation, cost-effective converters, adjustable-speed drives, motor controls, and efficient, compact electric machines.

COMPOSITE MATERIALS LABORATORY

Advanced lightweight materials, such as polymer composites and high-strength steels, offer better crash energy absorption per unit of mass than do traditional materials. When those materials are tested to assess their response to crushing, they exhibit different behaviors at different impact velocities. What happens in the transition zone between quasi-static impact rates (for example, 0.058 m/min) and high-velocity impacts (over 16 km/h) is not understood because the capability to conduct impact tests at intermediate velocities has been lacking. The Composite Materials Laboratory operates a unique servo-hydraulic test machine, the Integrated Physical and Virtual Test Machine for Automotive Crashworthiness (TMAC), to fill that gap.



Shaded areas compare the ranges of data collected by the TMAC and by other methods.

The TMAC is capable of conducting progressive crushing tests on composite automotive components at velocities ranging from 0 to 29 km/h and energy levels of up to 50 kJ. Using this machine, researchers can study component deformation and failure response in relation to impact velocity in a controlled and programmable manner that is made possible by a unique adaptive control feature of the software. The capability to test across this range of velocities and energy levels is providing the critical data needed for crash simulations that assess the safety of vehicle body structures manufactured from composites and other lightweight materials.

The TMAC was installed in October 2002. It was developed and funded through a collaboration between DOE and the Automotive Composites Consortium (ACC) of the U.S. Council for Automotive Research. The ACC identified the need for this capability; ORNL and the ACC jointly developed the specifications for the machine; and MTS Systems, Inc., designed and built the machine.

FUELS, ENGINES AND EMISSIONS RESEARCH CENTER

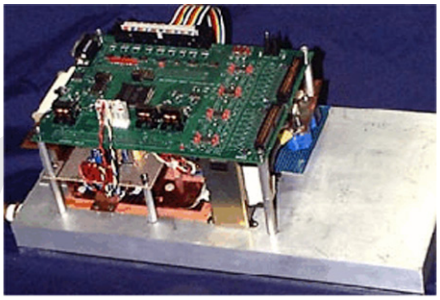
The FEERC specializes in detailed characterization of internal combustion engine emissions and efficiency. The facility's comprehensive capabilities include bench-top engine exhaust simulators, a wide range of dynamometers, and full vehicles. The FEERC boasts several special diagnostic and measurement tools—including many rarely found at other facilities around the country, plus unique instruments developed by Center staff—that aid in development and evaluation of engine and emission control technologies. The FEERC was originally designated a National User Facility in 1999 as the Advanced Propulsion Technology Center.

Current R&D at the center includes determining the effects of fuel sulfur on diesel emissions controls, gasoline and diesel engine particle emissions, advanced engine control strategies, and catalyst surface diagnostics. The Center is also active in research efforts on emission control via NO_X adsorber catalysts, urea selective catalytic reduction (SCR), exhaust gas recirculation (EGR), particulate filters, and controls with virtual sensing. Fuel property studies on performance and emissions have

Full-vehicle research complements bench-scale and engine dynamometer capabilities

included ethanol diesel fuel blends, new ultra-low sulfur diesel fuels, and biofuels. The direct sampling capillary mass spectrometer is finding use in studies of catalyst functions and EGR. For spark ignition engines, the center has gasoline direct injection engines and vehicles available for research, as well as natural gas engines. Innovative ignition concepts are being developed. In the analytical lab, NO_X sensors are being studied for time response and sensitivity. Previous work includes in-situ engine cylinder wall oil film diagnostics, applications of laser phosphor thermography of in-cylinder components, and mapping of vehicle emissions and fuel use in on-road modes.

POWER ELECTRONICS AND ELECTRIC MACHINERY RESEARCH CENTER



The compact topology of this dc/dc converter for fuel cell systems can power a high-voltage compressor motor expanding unit from a low-voltage battery until fuel cell voltage is established

The staff of the Power Electronics and Electric Machinery Research Center (PEEMRC) are recognized worldwide for their expertise in developing and prototyping advanced power converters, adjustable speed drives, and electric machines; power transmission and distribution research and development; and power quality, efficiency, and measurement. The Center provides unique expertise in power converter topologies, thermal management, packaging technologies for minimization of electromagnetic interference and for space and weight reduction, DSP-based control techniques for motor drives, system energy management, flywheel energy storage applications and ultra-high speed drive applications.

This expertise is applied to transportation to enable electric and/or hybrid vehicle traction drives, motor-assisted turbochargers, electric air conditioners, fuel cell converters, and other auxiliary drives. The PEEMRC is working with industrial partners to develop and evaluate automotive electric motor drive units and automotive integrated power modules and to address system integration issues. PEEMRC researchers use and develop the latest analysis, simulation, and design software to provide proof of principle prior to hardware implementation of their circuit and motor designs.

The PEEMRC also addresses power electronics and electric machinery technology needs, as well as issues in other areas such as electric power transmission and distribution, distributed energy generation systems, and motors and drives for special applications. Equipment available in the PEEMRC includes a dedicated 600-V, 600A, bi-directional dc power supply; a high-speed rotational equipment safety tank; and a 100-hp, 10,000-rpm, 4-quadrant dynamometer.

Appendix D

Combustion Research Facility

The Combustion Research Facility (CRF) is an internationally recognized Department of Energy Office of Science user facility located at Sandia National Laboratories, Livermore, California. The CRF conducts a broad range of basic and applied research and development in combustion science and technology, aimed at improving our nation's ability to utilize and control combustion processes.

Projects range from basic research on chemical reactivity and dynamics to applied studies that support industry's needs in such areas as engines and material processing. A strong emphasis on development and use of advanced optical diagnostic methods characterizes CRF experimental approaches.

The CRF's 74,000-ft^2 facility provides unique research capabilities for universities, industry and government and hosts more than 100 visiting scientists and engineers each year. The multi-building complex houses laboratories dedicated to

- Optical wave mixing
- Laser diagnostics development
- Chemical dynamics
- Chemical kinetics
- Specialized user-oriented lasers
- Flame structure studies
- Burner engineering research
- Coal combustion
- Laser remote sensing
- Engine research
- Spray combustion
- Industrial combustion simulation
- Sensor development
- Alternative fuels
- Hydrogen utilization
- Catalyst research
- High-resolution mass spectroscopy
- Reaction kinetics of energetic materials

AVAILABILITY

The CRF emphasizes collaborative investigations that lead to openly published results, but other models for supporting users can be arranged. For more information, contact the User Liaison.

ENGINE COMBUSTION RESEARCH

Sandia's Engine Combustion Research is a major user of the CRF. The effort is largely funded by DOE's Office of FreedomCAR and Vehicle Technologies and has closely interacted with U.S. engine manufacturers for more than 25 years to promote the fundamental understanding of in-cylinder processes governing efficiency and emissions. Engine combustion research partners include General Motors, Ford, DaimlerChrysler, Caterpillar, Cummins, Detroit Diesel, International, Mack/Volvo, John Deere, and General Electric. The information being developed is used by OEMs in their effort to design more efficient engines that meet stringent new emissions standards for passenger vehicles, light-duty trucks, and heavy-duty transport vehicles. The current emphasis in the effort is on developing the science base for advanced diesel combustion and low-temperature combustion strategies, e.g., homogeneous charge compression ignition (HCCI) and various forms of stratified charge compression ignition (SCCI) combustion. Low-temperature combustion strategies offer the potential for diesel-like efficiencies and extremely low emissions of NO_X and particulates. Advanced, laser-based diagnostics are employed in the research in conjunction with experimental hardware that closely mimics realistic engines while providing optical access. Research is also being conducted on traditional and non-traditional fuel property effects on combustion and emission processes, on hydrogen combustion in engines, and on new high-energy, laser-based diagnostic techniques for real-time characterization of particulate matter (PM) emissions from engines.

Eight laboratories in the CRF are dedicated to the engine research:

- Automotive HCCI Engine Laboratory
- HCCI/SCCI Dual-Engine Laboratory
- High-Speed, Small-Bore Diesel Engine Laboratory
- Diesel/LTC Combustion Simulation Facility
- Heavy-Duty Diesel Engine Combustion Laboratory
- Fuels Research Laboratory
- Hydrogen Engine Laboratory
- High-Energy Laser Diagnostics for PM Characterization

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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Appendix E

ANL Advanced Powertrain Research Facility

The Advanced Powertrain Research Facility (APRF) is a multi-dynamometer vehicle and component test facility to assess powertrain technology for light- and medium-duty propulsion systems using state-of-the-art performance and emissions measurement equipment and techniques. Component, subsystem, and vehicle test facilities support hardware-in-the-loop (HIL) testing, control system development, and technology validation. The facility has been designed for safe operation with gaseous and liquid fuels, including hydrogen.

- Engine/component dynamometers up to 300 hp
- 2WD and 4WD chassis dynamometers
- Battery/fuel emulator (controlled power supply) up to 150 kW
- Chassis dynamometer precision control environment (temperature and humidity)
- Very low emissions measurement capability (SULEV)
- Low-emissions raw bench (HC, CO,CO_2,NO_x and O_2)
- Ultra-fast (<5ms) HC and NO measurement
- Fast (10 Hz) direct diesel and gasoline fuel measurement
- Precision direct transient gaseous hydrogen fuel measurement
- Transient particulate measurement systems (LII and TEOM)
- Full-dilution particulate matter measurement
- Scanning Mobility Particle Sizer (10 nm)