U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Vehicle Technologies Program

Multi-Year Program Plan

2011 – 2015

December 2010

MULTI-YEAR PROGRAM PLAN
2011 - 2015

Vehicle Technologies Program

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Vehicle Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

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Executive Summary

The Vehicle Technologies Program (VTP) supports new technologies to increase energy security in the transportation sector at a critical time for global petroleum supply, demand, and pricing. Consequences of our vehicles' dependence on oil as their source of energy were shown by the "first oil shock" brought on by the petroleum embargo of October 1973 and "the second oil shock" of 1979. However, this oil dependence continues to increase unabated to the present and the oil price run up of July 2008 ($147 per barrel of crude) illustrated the rapidity with which these discontinuities can occur. As such, the lack of widely available and viable alternative non-petroleum based fueling options for ground transport vehicles constitutes a high risk to stable economic activity. Some means of providing energy to move vehicles that greatly reduces or eliminates petroleum consumption must be developed. This challenge is greatly complicated by the fact that virtually all alternatives have some inherent fossil fuel component.

Additionally, VTP facilitates environmental responsibility by advancing technologies to reduce passenger and freight emissions. A primary responsibility concomitant with oil dependence is reducing greenhouse gas emissions (primarily carbon emissions) from man-made activities such as use of oil for our vehicles. Neither petroleum reduction goals nor carbon emissions reduction goals can be achieved without new and more efficient vehicle technologies. Moreover, new vehicle technologies alone are unlikely to be sufficient and additional approaches to transportation (e.g., intermodal shifts which largely lie outside the current VTP portfolio) are necessary. While achieving petroleum and GHG reduction goals will be extremely challenging, such challenges represent a unique opportunity for the U.S. to establish a sustainable energy infrastructure.

This Vehicle Technologies Multi-Year Program Plan, FY 2011 – 2015, outlines the scientific research and technologies developments for the five-year timeframe (beyond the FY 2010 base year) that need to be undertaken to help meet the Administration's goals for reductions in oil consumption and carbon emissions from the ground transport vehicle sector of the economy. The guiding principles for VTP's longer-term planning are the goals of reducing carbon emissions level of 2005 by over 40 percent by 2030 and over 80 percent by 2050[1]. Achieving these aggressive targets requires a comprehensive strategy that includes R&D, Consumer Education, fuel prices, policies, regulatory mechanisms, collaborations with other agencies (e.g., DOT, FRA, etc.), or other incentives not already in existence. The strategy consist of two parts: a) VT will continue to focus RD&D on ground transportation vehicles within its purview; and b) VT will collaborate with other agencies on transportation vehicles in areas outside of its purview. The strategies differentiate between personal and commercial vehicles: some percentage of personal travel (VMT – Vehicle Miles Traveled) can be discretionary while freight transport (ton-miles of transport) is essential for economic growth and therefore different strategies for passenger and commercial vehicles are needed. For these strategies, potential benefits estimated are oil reduction in million barrels of oil equivalent per day (MMBDOE), and reduction of CO_2 and other greenhouse gases in million metric tons of CO_2 equivalent per year (MMTE).

Advanced vehicle technologies RD&D is critical, but alone is unlikely to be sufficient to meet the aggressive goals. Additional focus should be given to potential new VT work and/or areas for collaboration with other agencies on different approaches to transportation (e.g., intermodal shifts) on areas which lie outside of VT's current purview. VTP staff will collaborate with other Federal Agencies in support of their missions and serve as a gateway to the R&D capabilities of the DOE National Laboratories through appropriate Interagency Agreements.

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[1] *EERE Strategic Technology for Energy Plan (STEP)*, Discussion Draft, November 2009.

The Technology Areas

VT works in collaboration with industry to identify the priority areas of research needed to develop advanced vehicle technologies to reduce and eventually eliminate petroleum use, and reduce emissions of greenhouse gases, primarily carbon dioxide from carbon-based fuels. These research areas and associated activities described in this Plan are Batteries and Electric Drive Systems, Vehicle and Systems Simulation and Testing, Advanced Combustion Engine R&D, Fuels Technology, Materials Technology, and Outreach, Deployment, and Analysis.

- ***Batteries and Electric Drive Systems*** funds R&D on the core technologies necessary for hybrid and electric vehicles to achieve significant improvements in fuel economy without sacrificing safety, the environment, performance, or affordability. The subprogram focuses its work on the basic building-blocks of electric drive vehicles: advanced batteries and power electronics & electric motors (the electric drive).
- ***Vehicle and Systems Simulation and Testing*** includes a number of crosscutting activities that tie all of the VTP hardware R&D activities together. The VSST activity comprises work in five areas: 1) modeling and simulation; 2) component and systems evaluations; 3) laboratory and field vehicle evaluations; 4) electric drive vehicle codes and standards; and 5) heavy vehicle systems optimization.
- ***Advanced Combustion Engine R&D*** provides dramatically improved internal combustion engine efficiency, GHG and emissions reduction, by significantly reducing petroleum consumption.
- ***Fuels Technology*** supports research on the effects of changing fuel composition on engine efficiency, GHG and other emissions. Lubricant R&D provides vehicle users with cost-competitive options that improve fuel economy, lower emissions, and enable petroleum displacement.
- ***Materials Technology*** includes the development of high-strength, lightweight materials for the frame, body, chassis, and powertrain systems for passenger and commercial vehicles.
- ***Outreach, Deployment, and Analysis*** accelerates the adoption and use of alternative fuels and advanced technology vehicles to help meet national energy and environmental goals. It also contributes to the training of a specialized workforce suited for the advanced vehicle technologies of the future.

Successful attainment of VT goals will provide the pathway for the United States to dramatically change its energy use and petroleum dependence. This will greatly reduce emissions and the transportation sector's contribution to greenhouse gases while sustaining mobility and the freedom of vehicle choice. This vision is necessary for future national energy security and a stable national economy. Figure ES-1 shows the potential reduction (projected to 2030) in petroleum consumption and greenhouse gas emissions with the successful commercialization of VTP technologies.

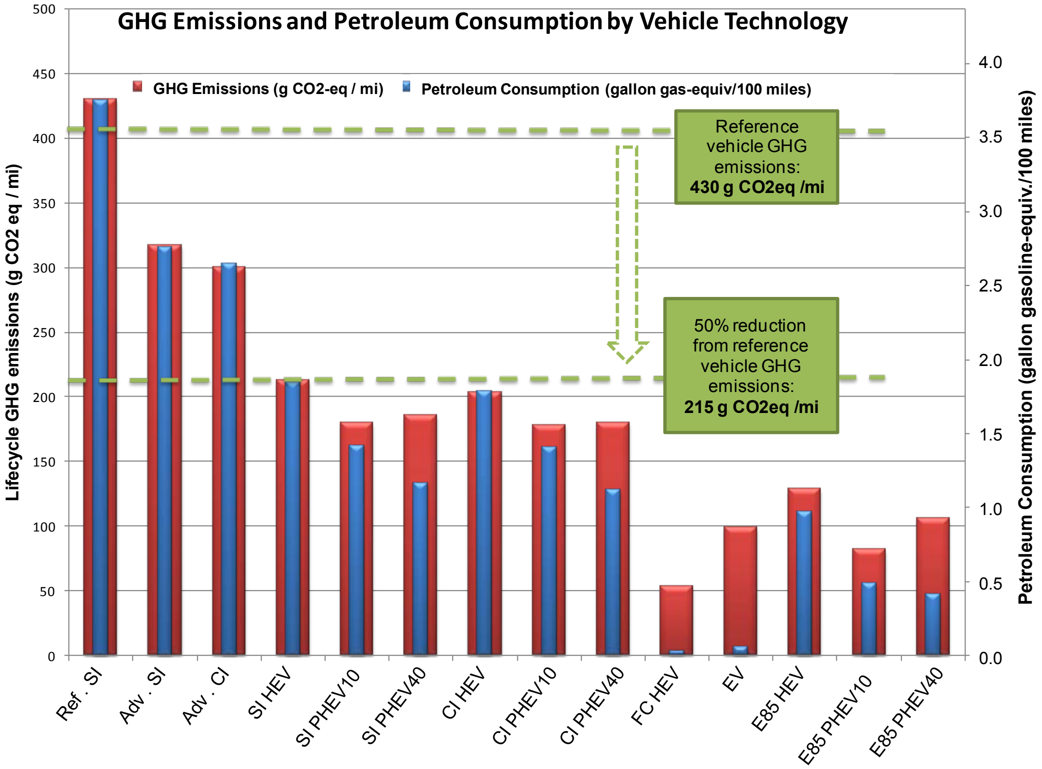

Figure ES-1.GHG Emissions and Petroleum Consumption by Vehicle Technology Projected to 2030

Legend:

Ref. SI – reference spark-ignition gasoline engine vehicle
Adv. SI – advanced spark ignition gasoline engine vehicle
Adv. CI – advanced compression-ignition diesel engine vehicle
SI HEV – spark-ignition gasoline engine/hybrid electric vehicle
SI PHEV10 – spark-ignition gasoline engine/plug-in hybrid electric vehicle (10-mile all electric range)
SI PHEV40 – spark-ignition gasoline engine/ /plug-in hybrid electric vehicle (40-mile all electric range)
CI HEV – compression-ignition diesel engine/hybrid electric vehicle
CI PHEV10 – compression-ignition diesel engine/plug-in hybrid electric vehicle (10 mile all electric range)
CI PHEV40 – compression-ignition diesel engine/plug-in hybrid electric vehicle (40-mile all electric range)
FC HEV – fuel cell/hybrid electric vehicle
EV – electric vehicle
E85 HEV – 85% biomass-gasoline blend/hybrid electric vehicle
E85 PHEV10 – 85% biomass-gasoline blend/plug-in hybrid electric vehicle (10-mile all electric range)
E85 PHEV40 – 85% biomass-gasoline blend/plug-in hybrid electric vehicle (40-mile all electric range)

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1.0 Program Overview

The Vehicle Technologies Program (VTP) supports new technologies to increase energy security in the transportation sector at a critical time for global petroleum supply, demand, and pricing. It has been 36 years since the petroleum embargo of October 1973 and 31 years since "the second oil shock" of 1979. Both of these events illustrated the dependence which transportation vehicles have on oil as their source of energy. This dependence continues to increase unabated to the present (see Figure 1.1-1). In addition, the oil price run up of July 2008 ($147 per barrel of crude) illustrated the rapidity with which these discontinuities can occur. As such, the lack of widely available and viable alternative non-petroleum based fueling options for ground transport vehicles constitutes a high risk to stable economic activity. Some means of providing energy to move vehicles that greatly reduces or eliminatespetroleum consumption must be developed. This challenge is greatly complicated by the fact that virtually all alternatives have some inherent fossil fuel component.

The U.S. transportation sector used about 13.5 million barrels of oil equivalent per day in 2009. It consumed more oil than the total U.S. domestic oil production. On-highway vehicles (passenger and commercial vehicles) used over 11 million barrels of oil equivalent per day, which accounts for over 79 percent of the total transportation oil use and over 59 percent of total U.S. oil use.[1] The Vehicle Technologies Program focuses on ground transportation vehicles because of their dominant contribution to the nation's oil use, as shown in Figure 1.1-1.

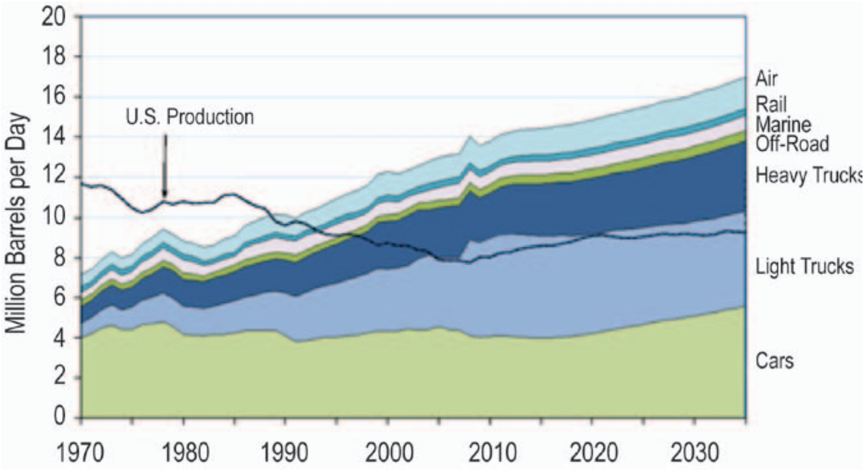

Figure 1.1-1. Transportation Energy Use by Mode, through 2035.

Sources: Historical information from Transportation Energy Databook 28, forecasts from the Energy Information Administration Annual Energy Outlook 2010.

Additionally, VTP facilitates environmental responsibility by advancing technologies to reduce passenger and freight emissions. This document outlines a set of strategies important to reducing the greenhouse gas emissions (primarily carbon emissions) level of 2005 by over 40 percent in 2030 and over 80 percent by 2050. While the carbon reduction strategies discussed do not completely fall within the mission of the DOE Vehicle Technologies Program (VTP), neither petroleum reduction goals nor carbon emissions reduction goals can be achieved without new and more efficient vehicle technologies. Moreover, new vehicle technologies alone are unlikely to be sufficient and additional approaches to transportation (e.g., intermodal shifts which largely lie outside the current VTP portfolio) are necessary. VTP staff will continue to expand collaboration with other Federal Agencies in support of their missions and serve as gateway to the R&D capabilities of the DOE National Laboratories through appropriate Interagency Agreements. While achieving these petroleum and GHG reduction goals will be extremely challenging, such challenges represent a unique opportunity for the U.S. to establish a sustainable energy infrastructure.

This Vehicle Technologies Multi-Year Program Plan, FY 2011 – 2015, outlines the scientific research and technologies developments for the five-year timeframe that need to be undertaken to help meet the Administration's goals for reductions in oil consumption and carbon emissions from the ground transport vehicle sector of the economy.

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[1] *Annual Energy Outlook 2010*, Energy Information Administration, 2010.

1.1 Mission and Goals

The Mission of the Vehicle Technologies Program (VTP) is to develop and assist in the deployment of more energy-efficient and environmentally friendly technologies for highway transportation passenger and commercial vehicles that will meet or exceed performance expectations and environmental requirements, enabling the U.S. to use significantly less petroleum and reduce greenhouse gas emissions. VTP focuses on highway vehicles, which account for over 59 percent of total U.S. oil use ─ more than all U.S. domestic oil production. Cost-competitive, more energy-efficient and fuel diverse vehicles will enable individuals and businesses to accomplish their daily tasks while reducing consumption of gasoline and diesel fuels. This will reduce U.S. demand for petroleum, lower carbon emissions, and decrease energy expenditures. These Program efforts tie directly into several Department of Energy strategic goals: energy security, environmental responsibility, and scientific discovery and innovation.

Specific shorter and longer term goals for VTP to achieve Administration goals for oil consumption and carbon emissions reductions are outlined below. The VT Program funds and performs the advanced technology R&D needed to achieve these goals. In the near to mid-term, transportation energy use can be reduced through improved vehicle energy efficiency from more efficient advanced combustion engines, hybrid-electric (HEV) and PHEV vehicle powertrains, and reducing vehicle weight. Other fuels, such as ethanol, natural gas, electricity with storage, and biodiesel, can also provide attractive means for reducing oil use through fuel displacement.

Light-Duty Vehicles

- By 2015, develop technologies and a set of options to enable up to 50 percent reduction in light-duty vehicle petroleum-based consumption.
- By 2030, develop technologies and deployment strategies enabling up to 80 percent of the energy for light-duty vehicles to be from non-carbon or carbon neutral energy sources.

Heavy-Duty Vehicles

- By 2015, demonstrate a 50 percent improvement in freight hauling efficiency (ton-miles per gallon).
- By 2030, through working collaboratively with the DOT/Federal Railroad Administration provide capabilities to enable the great majority of long haul ton-miles traveled (greater than 500 miles) to be shifted to rail.
- By 2030, provide capabilities through hybridization of medium-duty vehicles to enable up to 80 percent of short haul ton-miles traveled with improved efficiency and on lower-carbon or non-carbon energy sources.

1.2 Program Design

The Vehicle Technologies Program carries out its mission by focusing its R&D investments on long-term, high risk technology projects that are unlikely to be pursued by industry alone, but have significant potential public benefits. Various external factors, including market barriers, may impact the ability of the Program to achieve its goals, so collaborations are vital. VTP works collaboratively with its industry partners in the FreedomCAR and Fuel Partnership, and the 21st Century Truck Partnership, to analyze and identify technical R&D opportunities for passenger and commercial vehicles, respectively. Funding Opportunity Announcements (FOAs) are made for R&D in specific technology areas that support the VT mission and goals. Cost-shared multi-year projects are competitively selected and awarded.

The FreedomCAR and Fuel Partnership, and the 21st Century Truck Partnership are strategic R&D partnerships with industry and its suppliers, universities, the national laboratories, and other Federal agencies. Technology Outreach and Deployment activities are undertaken with state and local governments, and other stakeholders through the Clean Cities

Coalition. These partnerships are integral and critical to the overall VT approach. They ensure the best RD&D is undertaken; they facilitate the technical coordination of activities, attract cost sharing to provide leveraged benefits for the American taxpayer, and attain the maximum benefit from the Program.

1.3 Approach for Reducing the Carbon Footprint of Transportation

The guiding principles for VTP's longer-term planning are the goals of reducing carbon emissions level of 2005 by over 40 percent by 2030 and over 80 percent by 2050[2]. Achieving these aggressive targets requires a comprehensive approach that includes R&D, consumer education, fuel prices, policies, regulatory mechanisms, collaborations with other agencies (e.g., DOT, FRA, etc.), or other incentives not already in existence. Some aspects of the approach are summarized in the following tables: a) Table 1 - focus RD&D on ground transportation vehicles within VT's purview; b) Table 2 - collaborate on transportation vehicles in areas outside of VT's purview. It should be noted that some percentage of personal travel (VMT – Vehicle Miles Traveled) can be discretionary while freight transport (ton-miles of transport) is essential for economic growth and therefore different strategies for passenger and commercial vehicles are needed. Estimates of potential benefits – oil reduction in million barrels of oil equivalent per day (MMBDOE), and reduction of CO_2 and other greenhouse gases in million metric tons of CO_2 equivalent per year (MMTE) – are indicated[3]. This is an initial approach. Key studies are underway which may alter areas of emphasis.

Table 1: VT Approach – Focus RD&D on Ground Transportation Vehicles

Elements of the Approach	Approach/RD&D Program Areas	Expected Oil Reduction from 2005 (MMBDOE)	Expected CO_2 Reduction from 2005 (MMTE)	Barriers	Likelihood of Success
	Passenger Vehicles (R&D)				
Ever-greater Electrification of Passenger Vehicles ► Hybridization ► Plug-in vehicles ► All electric vehicles ► More electric accessories/ auxiliaries (drive-by-wire, electric water pumps)	► Battery R&D ► Ultracapacitors R&D ► Power Electronics and Electric Machines R&D ► Solid State (Thermoelectric) Energy Conversion R&D	► 0.3 – 0.64 MMBDOE (2030) ► 3.67 – 5.47 MMBDOE (2050) NOTE: ► 60% of personal vehicle miles can be all electric with PHEV40; 100% with all-electric vehicle (EV) (but this cannot handle all needed trips). ANL estimates that a 150 mile range EV would handle about 82% of the VMT	► 37.4 – 79.5 MMTE (2030) ► 458.5 – 682.9 MMTE (2050)	Public acceptance of electric drive as central vehicle choice. ~ 15 years for a very successful technology to reach maximum penetration in new vehicle sales; another 15 years for the technology to be ubiquitous. High % of electricity generated from fossil fuel combustion, but essential to decline over time, such that by 2050 almost no fossil fuel would be used. Battery cost and durability.	Starting in 2015, need to sell 20 million EVs per year for the next 15 years to have all electric drive vehicle population in 2030. *(Only 10 million cars were sold in 2009.)*
		MMBDOE – million barrels of oil equivalent per day	*MMTE – million metric tons of CO_2 equivalent*		

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[2] *EERE Strategic Technology for Energy Plan (STEP)*, Discussion Draft, November 2009.

[3] Estimates from VTP Portfolio Benefits from STEP Calculator baseline, VTP Analytic Team, April 2010.

Elements of the Approach	Approach/RD&D Program Areas	Expected Oil Reduction from 2005 (MMBDOE)	Expected CO_2 Reduction from 2005 (MMTE)	Barriers	Likelihood of Success
Fuel Economy (miles per gallon improvement) ▶ More efficient combustion engines ▶ Smaller displacement engines	▶ Advanced Combustion R&D ▶ Solid State (Thermoelectric) Energy Conversion R&D ▶ Propulsion System Materials R&D	▶ 0.32 – 0.58 MMBDOE (2030) ▶ 0.83-0.87 MMBDOE (2050) NOTE: ▶ over 9 gallons of fuel saved for every 100 miles driven with a 10%mpg increase.	▶ 39.5 – 72.0 MMTE (2030) ▶ 103.3-108.7 MMTE (2050)	Fuel economy not currently the top criterion for vehicle choice for purchase; may change as fuel prices continue to increase and fluctuate.	New CAFE requirements of 38.0 mpg for cars and 28.3 mpg for light trucks by 2016 have been mandated; further improvements potentially possible with vehicle technologies R&D
▶ Vehicle lightweighting	▶ Lightweight Materials R&D	▶ 0.58 – 0.63 MMBDOE (2030) ▶ 1.05 – 1.22 MMBDOE (2050) NOTE: ▶ Over 5.7 gallons of fuel saved for every100 miles driven with a 10% reduction in vehicle weight.	▶ 72.8 – 79.3 MMTE (2030) ▶ 132.7 – 154.5 MMTE (2050)	Higher cost of lightweight materials such as aluminum, magnesium alloys, carbon fiber polymer matrix composites	
		MMBDOE – million barrels of oil equivalent per day	*MMTE – million metric tons of CO_2 equivalent*		
Low-Carbon or Carbon-Neutral Fuels ▶ Biofuels ▶ Non-petroleum based fuels (natural gas, gas-to-liquids, synfuels, LPG)	▶ Fuels Technology R&D ▶ Advanced Combustion Engine R&D	▶ 0.3 MMBDOE (2030) ▶ 0.6 MBDOE (2050)	▶ 33.9 MMTE (2030) ▶ 71.2 MMTE (2050)	Limited production of renewable liquid fuels; other uses of the resource may take priority (e.g., air travel). GHG (CO2) increased emissions from synfuels (gas-to-liquids). High GHG contribution from methane (natural gas) leakage. Low efficiency of natural gas engines.	Likely unavailability and/or very high fuel cost decrease likelihood of increased usage of alternative fuels. Inadequate alternative fueling infrastructure.
▶ Improved lubricants		▶ 0.3 MMBDOE (2030) ▶ 0.4 MMBDOE (2050)	▶ 28.3 MMTE (2030) ▶ 43.3 MMTE (2050)		
Commercial Vehicles (R&D)					
Improve Fuel Efficiency (ton-miles per gallon) of Medium- and Heavy-Duty Vehicles ▶ SuperTruck (over 50% improvement)	▶ Advanced Combustion Engine R&D ▶ Fuels Technology R&D ▶ Materials R&D ▶ Hybrid electric systems R&D	▶ 1.0 MMBDOE (2030); 25% penetration of 50% more efficient trucks ▶ 1.2 MMBDOE (2050)	▶ 135 MMTE (2030) ▶ 150 MMTE (2050)	Increased cost of hybridization (medium duty) and higher efficiency heavy-duty powertrains (turbocompound heavy – duty engines/high efficiency transmissions)	"SuperTruck" cooperative R&D agreements in place.

Elements of the Approach	Approach/RD&D Program Areas	Expected Oil Reduction from 2005 (MMBDOE)	Expected CO_2 Reduction from 2005 (MMTE)	Barriers	Likelihood of Success
Low-Carbon or Carbon-Neutral Fuels for Medium- and Heavy-Duty Vehicles ▶ LNG and CNG for medium-duty short haul ▶ Liquid fuels for long-haul	▶ Fuels Technology R&D ▶ Advanced Combustion Engine R&D	▶ 0.3 MMBDOE (2030) ▶ 0.6 MBDOE (2050)	▶ 33.9 MMTE (2030) ▶ 71.2 MMTE (2050)	Fueling Infrastructure for LNG and CNG; on-board storage Renewable liquid fuels supply	Truck companies beginning to show some interest in LNG as fuel for long haul heavy duty trucks.
Outreach, Deployment, and Analysis					
▶ Consumer information, outreach, and education ▶ Local community and coalition support ▶ Partnership development ▶ Technical and financial assistance	▶ Clean Cities ▶ Dissemination of information through internet (www.fueleconomy.gov) or hardcopy material			Public inertia. despite constant warnings, public tends to become complacent. Lack of sufficient alternatives (PHEVs, EVs, LPG/NG vehicles)	Very high fuel price and limited future petroleum availability will necessitate usage to the large numbers of legacy vehicles.
Improving the Fuel Economy (mpg) of Legacy Vehicles ▶ Driver fuel economy feedback devices (fuel economy driver interfaces[4]) ▶ Low rolling resistance tires ▶ Engine Block heaters ▶ Advanced lubricants ▶ Efficient driving and vehicle maintenance tips ▶ Programs to remove older vehicles from service	▶ Dissemination of information through internet (www.fueleconomy.gov) or hardcopy material ▶ Use the Clean Cities network	▶ 1.2 MMBDOE (2030) ▶ 1.1 MMBDOE (2050) NOTES: ▶ Over 9 gallons of fuel saved for every 100 miles driven (over 10% mpg increase with feedback devices, depending on driver response to information ▶ 1%-4% mpg improvement when tire rolling resistance reduced by 25%-30% ▶ With engine block heaters, up to 25% fuel savings over an urban driving cycle relative to cold starting (at -25°C)[5]	▶ 147 MMTE (2030) ▶ 141.5 MMTE (2050)	Public acceptance; requires changes in driver habits and expenditure in aftermarket technology/devices. Safety concern – another driver distraction	Very high fuel price and limited future petroleum availability will necessitate usage by the large numbers of legacy vehicles. Requires additional consumer expenditure. Vehicle warranty concerns

Inasmuch as new vehicle technologies RD&D alone are unlikely to be sufficient to meet the aggressive goals, the approach summarized in Table 2 focuses on potential new VT work and/or areas for collaboration with other agencies on different approaches to transportation (e.g., intermodal shifts) on areas which lie outside of VTP's current purview. VTP staff will collaborate with other Federal Agencies in support of their missions and serve as a gateway to the R&D capabilities of the DOE National Laboratories through appropriate Interagency Agreements.

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[4] *Fuel Economy Driver Interfaces: Design Range and Driver Opinions*, DOT/NHTSA, August 2009.

[5] *Envirozine Issue 40*, Environment Canada, Feb. 12, 2004, http://www.ec.gc.ca/EnviroZine/english/issues/40/any_questions_e.cfm

Table 2: VT Approach – Collaborate on Areas Outside of VT Purview

Elements of the Approach	Approach	Expected Percent Oil Reduction from 2005	Estimated CO_2 Reduction from 2005	Barriers	Specific Requirements/ Status
	Passenger Vehicles				
VMT Reduction ▶ Reduce personal vehicle travel, encourage public transport, ride sharing	▶ Legislation, policy, incentives, fuel price increases, collaborations with FTA	▶ Over 1.2MMBDOE reduction with 15% VMT reduction (2030) ▶ Over 1.6 MMBDOE with 20% VMT reduction (2050). ▶ NOTE:Fuel price fluctuations between 2007 and 2009 reduced VMT by 3.4% and energy demand by 0.34 MMBDOE[6]	▶ 175 MMTE (2030) ▶ 231 MMTE (2050)	Public acceptance, inadequate public transport capacity	Requires about a 25% reduction in projected VMT. Statistical abstract data: of workers surveyed, over 76% drove alone, about 10% carpooled, and less than 5% took public transport[7]. Initial meetings with FTA underway.
Commercial Vehicles					
Medium- and Heavy-Duty Vehicles ▶ Reduction in ton-miles travel (TMT) of freight delivery by shifting to other modes	▶ Collaboration with FRA, AAR	▶ Over 0.4 MMBDOE saved by shifting 10% of freight from truck to rail (2030) ▶ Over 0.7 MMBDOE saved by shifting 15% of freight from truck to rail (2050)	▶ Over 60 MMTE (2030) ▶ Over 100 MMTE (2050)		VT staff has initiated contacts with FRA/AAR.
Rail ▶ Shift commercial transport from trucks to rail ▶ Rail electrification ▶ Upgrade rail capacity, improve rail beds & track (technology) ▶ Train density (technology), number of rails (cost); speed ▶ Modernize tracking/scheduling/ switching technology (technology) ▶ Develop improved transfer capabilities (infrastructure/ technology)	▶ Collaboration with FRA, AAR ▶ Transportation Research Board for identifying technical, regulatory, and societal barriers ▶ State and local governments	▶ Slight increase in rail energy use (tens of KBDOE*) by shifting 10% of freight from truck to rail (2030) ▶ Slight increase in rail energy use (tens of KBDOE) by shifting 15% of freight from truck to rail (2050) NOTE: ▶ Rail is1.9 to 5.5 times more efficient (in ton-miles per gallon of fuel) than long-haul trucks[8] *KBDOE – thousand barrels of oil equivalent per day	▶ Slight increase in rail CO_2 emissions (little over 3 KMTE**) (2030) ▶ Slight increase in rail CO_2 emissions (little less than 4 KMTE) (2050) **KMTE – thousand metric tons of CO_2-equivalent	High capital cost; aging rail system; antiquated system for freight tracking/signal system. Rails are owned and maintained by the operators and not subsidized by fuel taxes and user fees as are roads and airports (Policy)	Mandatory to achieve 80% CO_2 reduction by 2050. VT staff has begun initial contacts with FRA/AAR.

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[6] *Annual Energy Outlook 2010 Early Release*, EIA, December 2009.
[7] *Statistical Abstract of the United States: 2010 (129th Edition)*, U.S. Census Bureau, 2009, http://www.census.gov/statab/www.
[8] *Comparative Evaluation of Rail and Truck Fuel Efficiency on Competitive Corridors, Final Report*, Federal Railroad Administration, November 19, 2009

Elements of the Approach	Approach	Expected Percent Oil Reduction from 2005	Estimated CO_2 Reduction from 2005	Barriers	Specific Requirements/ Status
Non-Highway and Off-Highway ► Apply efficiency improvement technologies developed for Heavy Trucks to these vehicles where applicable. ► Develop new efficiency technologies where needed. ► Determine the most appropriate low-carbon fuel for each vehicle type and foster their introduction. ► Electrification of auxiliaries (water pump, fuel pump, replacement of hydraulics via electric motors)	► Work with agencies to develop roadmaps and introduce technologies	Projected oil savings: ► 0.9 MMBDOE (25% savings in 2030) ► 3.0 MMBDOE (70% savings in 2050) NOTE: ► Preliminary analysis indicates that: air efficiency improves 10% in 2030 and 25% in 2050; ship efficiency improves 5% in 2030 and 10% in 2050; biofuels use for air transport is 25% in 2030 and 50% in 2050.	Projected GHG reductions: ► 110 MMTE (20% savings in 2030) ► 318 MMTE (50% savings in 2050).	No RD&D activities currently in VT portfolio.	

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2.0. Technology Research, Development and Deployment Plan

The VT Program has worked with industry to identify the priority areas of research needed to develop advanced vehicle technologies to reduce and eventually eliminate petroleum use. This section covers the technical details and includes discussion of Program element goals, technical and market challenges, strategies for addressing those challenges, and key milestones and decision points toward achieving the goals. Also, addressed are cross-cutting activities, including communications and outreach. This technical portion of the Plan describes the activities over the period 2010 through 2015 necessary to achieve the goals and is based on reasonable budget projections consistent with prior years and current guidance from Congress and OMB. This Plan is a living document with periodic updates and will be adjusted in the future to address changes in Appropriations and Administration guidance.

The Program areas described in this section of the Plan are: Batteries and Electric Drive Systems, Vehicle and Systems Simulation and Testing, Advanced Combustion Engine R&D, Fuels Technology, Materials Technology, and Outreach, Deployment, and Analysis.

- ***Batteries and Electric Drive Systems*** funds R&D on the core technologies necessary for hybrid and electric vehicles to achieve significant improvements in fuel economy without sacrificing safety, the environment, performance, or affordability. The subprogram focuses its work on the basic building-blocks of electric drive vehicles: advanced batteries and power electronics & electric motors (the electric drive).
- ***Vehicle and Systems Simulation and Testing*** includes a number of crosscutting activities that tie all of the VTP hardware R&D activities together. The VSST activity comprises work in five areas: 1) modeling and simulation; 2) component and systems evaluations; 3) laboratory and field vehicle evaluations; 4) electric drive vehicle codes and standards; and 5) heavy vehicle systems optimization.
- ***Advanced Combustion Engine R&D*** provides dramatically improved internal combustion engine efficiency, GHG and emissions reduction, by significantly reducing petroleum consumption.
- ***Fuels Technology*** supports research on the effects of changing fuel composition on engine efficiency, GHG and other emissions. Lubricant R&D provides vehicle users with cost-competitive options that improve fuel economy, lower emissions, and enable petroleum displacement.
- ***Materials Technology*** includes the development of high-strength, lightweight materials for the frame, body, chassis, and powertrain systems for passenger and commercial vehicles.
- ***Outreach, Deployment, and Analysis*** accelerates the adoption and use of alternative fuels and advanced technology vehicles to help meet national energy and environmental goals. It also contributes to the training of a specialized workforce suited for the advanced vehicle technologies of the future.

Successful attainment of VT goals will provide the pathway for the United States to dramatically change its energy use and petroleum dependence. This will greatly reduce emissions and the transportation sector's contribution to greenhouse gases while sustaining mobility and the freedom of vehicle choice. This vision is necessary for future national energy security and a stable national economy.

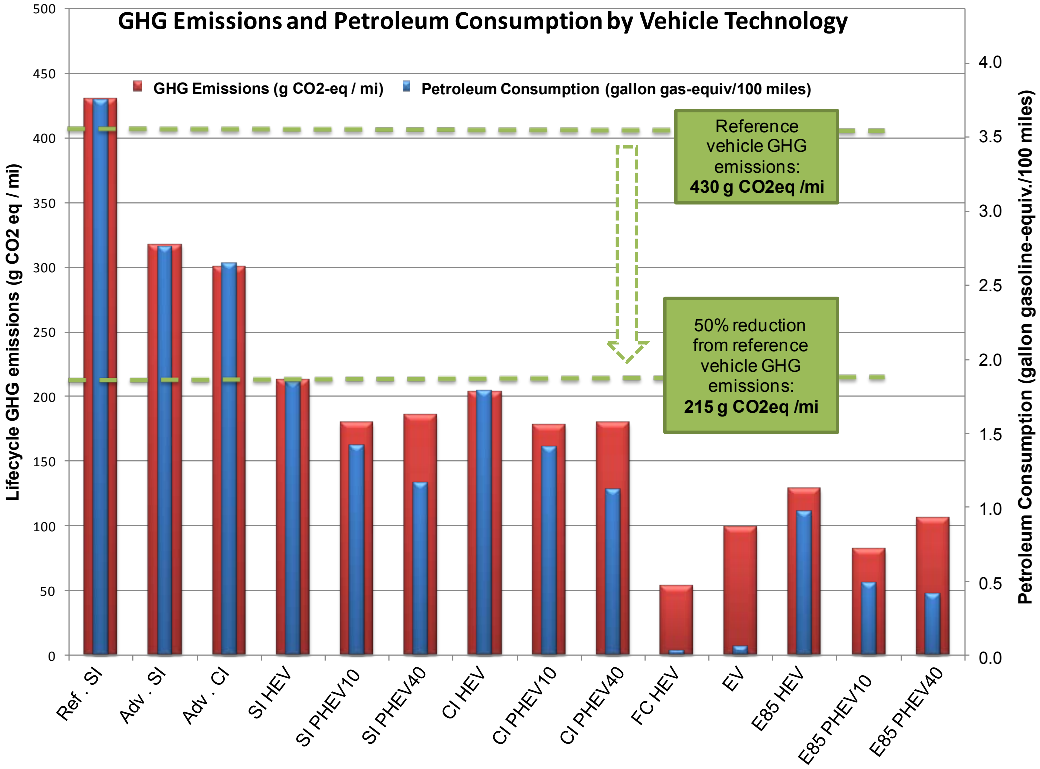

Figure 2.0-1.GHG Emissions and Petroleum Consumption by Vehicle Technology Projected to 2030

Figure 2.0-1 shows the potential reduction in petroleum consumption and greenhouse gas emissions (projected to 2030) with the successful commercialization of VTP technologies.

Legend:

Ref. SI – reference spark-ignition gasoline engine vehicle
Adv. SI – advanced spark ignition gasoline engine vehicle
Adv. CI – advanced compression-ignition diesel engine vehicle
SI HEV – spark-ignition gasoline engine/hybrid electric vehicle
SI PHEV10 – spark-ignition gasoline engine/plug-in hybrid electric vehicle (10-mile all electric range)
SI PHEV40 – spark-ignition gasoline engine/ /plug-in hybrid electric vehicle (40-mile all electric range)
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FC HEV – fuel cell/hybrid electric vehicle
EV – electric vehicle
E85 HEV – 85% biomass-gasoline blend/hybrid electric vehicle
E85 PHEV10 – 85% biomass-gasoline blend/plug-in hybrid electric vehicle (10-mile all electric range)
E85 PHEV40 – 85% biomass-gasoline blend/plug-in hybrid electric vehicle (40-mile all electric range)

2.1 Batteries and Electric Drive Technology

The Batteries and Electric Drive Technology (BEDT) subprogram funds R&D on the core technologies necessary for hybrid and electric vehicles to achieve significant improvements in fuel economy without sacrificing safety, the environment, performance, or affordability. The subprogram focuses its work on the basic building-blocks of electric drive vehicles: advanced batteries and power electronics & electric motors (the electric drive).

- Battery/Energy Storage R&D (formerly Energy Storage R&D) addresses the first building block of a hybrid-electric vehicle (HEV): electricity storage. Electrochemical batteries are the dominant electrical energy storage device today. The needs of "regular" hybrid vehicles and plug-in hybrids are similar, but not identical: plug-in hybrids need to be able to store considerably more total energy in their batteries. Developing batteries that are rugged, long-lasting, affordable, lighter, hold a substantial charge, and work in all climates and seasons is still a major R&D challenge.

- Advanced Power Electronics and Electric Motors R&D addresses the second building block, which is the collection of electric and electronic devices that connect the energy and power stored in the battery to the vehicle's drivetrain: power control circuits, charging circuits, electric motors, logic to synchronize the power from the battery and motors with the main vehicle engine, and other related components. The power electronics for a plug-in hybrid will be considerably more complex than for a regular hybrid to accommodate additional charging modes and more complex driving cycles.

2.1.1. Battery/Energy Storage R&D

Goals

The Energy Storage activity supports a number of research areas (including focused fundamental research, applied research, and technology development) for advanced energy storage technologies (batteries and ultra-capacitors) with the ultimate goal of developing low cost energy storage devices that will enable more fuel-efficient light duty vehicles that can reduce U.S. dependence on petroleum without sacrificing performance.

Energy storage devices enhance the efficiency of the prime power source in hybrid electric vehicles (HEV) by leveling the load, and they capture regenerated braking energy to produce more fuel efficient and cleaner vehicles. In addition, in plug-in HEVs (PHEV) they provide the primary power source for a number of "all-electric" miles, after which the vehicles operate in HEV mode. The ultimate goal of vehicle electrification is the pure electric vehicle (EV). The advantages of EVs include very high efficiency compared to standard internal combustion engine (ICE) vehicles, HEVs, and PHEVs, and the increased flexibility they offer in terms of a primary energy source. Electricity used to charge the EVs can be generated from coal, natural gas, wind turbines, solar energy, nuclear or any other resource.

Better energy storage systems are needed to expand the commercial markets for HEVs and to make PHEVs and EVs commercially viable. Specifically, lower-cost, abuse-tolerant batteries with higher energy density, higher power, better low-temperature operation, and longer lifetimes are needed for the development of the next-generation of HEVs, PHEVs, and EVs. Lithium-based batteries offer the potential to meet the requirements of all three applications and ultra-capacitors may offer a more cost effective solution for low energy, high-power micro- and start/stop HEVs.

Recently, the performance and lifetime of high-power Li-ion batteries have reached or exceeded most of the HEV goals of the United States Advanced Battery Consortium (USABC). However, cost projections are still higher than the DOE goal. This technology is just now being introduced into the marketplace. Accordingly, DOE has shifted significant R&D efforts into high-energy density batteries for PHEVs and EVs, to meet the cost reduction and other performance goals.

The Energy Storage subprogram is focused on achieving the following specific goals:

- Develop technologies to reduce the production cost of a PHEV battery with a 40 mile all-electric range from the present $1,000/kWh to $300/kWh by 2014 enabling cost competitive market entry of PHEVs..
- Reduce the production cost of a high-power 25kW battery for use in passenger vehicles from $3,000 in 1998 to $500 by the end of 2010, enabling cost competitive market entry of hybrid vehicles.

As noted above, some developers currently estimate that their next generation technology will meet most HEV performance targets while meeting or almost meeting cost targets.

Table 2.1-1 details a subset of the specific technical targets that have been developed by VTP with its USABC industry partners. Please see http://www.uscar.org/guest/article_view.php?articles_id=85 for more energy storage goals.

Table 2.1-1. End of Life Targets for Energy Storage Systems for HEVs, PHEVs, and EVs.

DOE Energy Storage Goals	HEV(2010)	PHEV(2015)	EV(2020)
Characteristics			
Equivalent Electric Range, miles	N/A	10-40	200-300
Discharge Pulse Power, kW	25-40 for 10 sec	38-50	80
Regen Pulse Power (10 seconds), kW	20-25	25-30	40
Recharge Rate, kW	N/A	1.4-2.8	5-10
Cold Cranking Power @ -30 ºC (2 seconds), kW	5-7	7	N/A
Available Energy, kWh	0.3-0.5	3.5-11.6	30-40
Calendar Life, Years	15	10+	10
Cycle Life, cycles	300k, shallow	3,000-5,000, deep discharge	750, deep discharge
Maximum System Weight, kg	40-60	60-120	300
Maximum System Volume, l	32-45	40-80	133
Operating Temperature Range, ºC	-30 to 52	-30 to 52	-40 to 85
Selling Price @ 100k units/year, $	500-800	1,700-3,400	4,000

Challenges and Barriers

PHEV and EV batteries face many of the same challenges associated with HEV batteries (uncertain calendar life, cost, abuse tolerance) plus additional challenges with energy density and specific energy, particularly for the EV and 40 mile PHEV batteries. There is also concern that the deep cycling required of high-energy batteries will be more difficult than the shallow HEV cycling. The major challenges to developing and commercializing batteries for PHEVs and EVs are as follows:

A. Cost. The current cost of Li-based batteries is approximately $800 - $1,000/kWh, a factor of about three times too high on a kWh basis. The main cost drivers are the high cost of raw materials and materials processing, the cost of cell and module packaging, and manufacturing costs. Cost is not the sole barrier; however, it is an overriding factor for market success in conjunction with other technical targets (e.g., life, weight, and volume). Addressing the cost barrier requires identifying key cost issues; developing and evaluating lower-cost components, packaging alternatives, and processing methods; and working with U.S. suppliers to implement these low-cost solutions. Substantial public/private investment will be needed to achieve the required technology and cost breakthroughs.

B. Rare Earth Minerals. Widespread deployment of hybrid-electric and battery electric vehicles may increase worldwide demand for rare earth elements and certain other materials. In addition to lithium, an alkali metal, there are rare earth elements (neodymium, praseodymium, cerium, and lanthanum) in advanced batteries and electric motors. It is likely that future supply of these materials especially the rare earths may not be able to meet the demand from these technologies.[1]

C. Performance. Much higher energy densities are needed to meet both volume and weight targets. Current batteries are approximately a factor of two to three times too heavy and large compared to the 40 mile PHEV requirements. An increase in energy density will also reduce the amount of material and supporting hardware needed to construct the entire battery and will thus further reduce the costs associated with battery systems.

D. Abuse Tolerance, Reliability and Ruggedness. It is critical that any new technology introduced into a vehicle be abuse tolerant under both routine and extreme operating conditions. Many Li batteries are not intrinsically tolerant to abusive conditions such as short circuits, over charge, over discharge, crush impacts, or exposure to fire and other high-temperature environments. The use of large format Li cells increases the urgency with which these issues must be addressed. In addition, current thermal control technologies, although adequate to dissipate heat in high-power and high-energy systems, are too expensive and significantly add to the systems' weight and volume.

E. Life. The barriers related to battery life are the loss of available power and energy due to use and aging, and the lack of accurate life prediction capability. For high-energy batteries in a PHEV or EV application, a combination of energy and power fade are anticipated to be issues as the battery must provide significant energy over the life of the vehicle and either provide full vehicle power (for an EV) or high-power HEV cycling (for a PHEV) near the bottom of its State of Charge (SOC) window. Today, batteries designed for HEVs can deliver 300,000 shallow discharges. However, batteries with a higher energy density have difficulty meeting the requirement of 5,000 deep discharge cycles over the life of the battery.

Approach for Overcoming Barriers/Challenges

Over the past five years (FY2006 to FY 2010) the Battery/Energy Storage R&D activity within the Vehicle Technologies Program has experienced a tripling of the budget (separate from the funding for the ARRA projects). In response, the activities in this area have expanded in both breadth and depth to accelerate overcoming the barriers to energy storage market penetration. Table 2.1-2 presents a high level overview of the Battery/Energy Storage R&D activities. The work funded by and/or related to the Battery/Energy Storage R&D activity currently falls broadly into five areas:

- Electric Drive Vehicle Battery Manufacturing
- Advanced Battery Development, Systems Analysis, and Testing Activities (The Developer Program)
- High-Energy and High-Power Cell R&D (Applied Battery Research)
- Advanced Materials Research (Focused Fundamental Research)
- Basic Research on Electrochemical Materials and Phenomenon and Transformational Research for Electrochemical Energy Storage Related to Transportation Systems

Electric Drive Vehicle Battery Manufacturing is an initiative funded and implemented as part of the FY2009 American Recovery and Reinvestment Act (ARRA). Work under **Basic and Transformational Research** represents additional energy storage research that is being funded by Advanced Research Projects Agency-Energy (ARPA-E), Basic Energy Sciences Energy Frontier Research Centers (BES EFRCs), National Science Foundation (NSF), and other

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[1] *Critical Materials Strategy,* U.S. Department of Energy, December 2010.

government agencies, and is relevant to VTP's efforts. The VTP energy storage team has been communicating and coordinating research with each of these organizations. The remainder of the listed task areas comprises the VTP Battery/Energy Storage R&D portfolio. Some of the critical targets associated with the VTP-activities in Table 2.1-2 are:

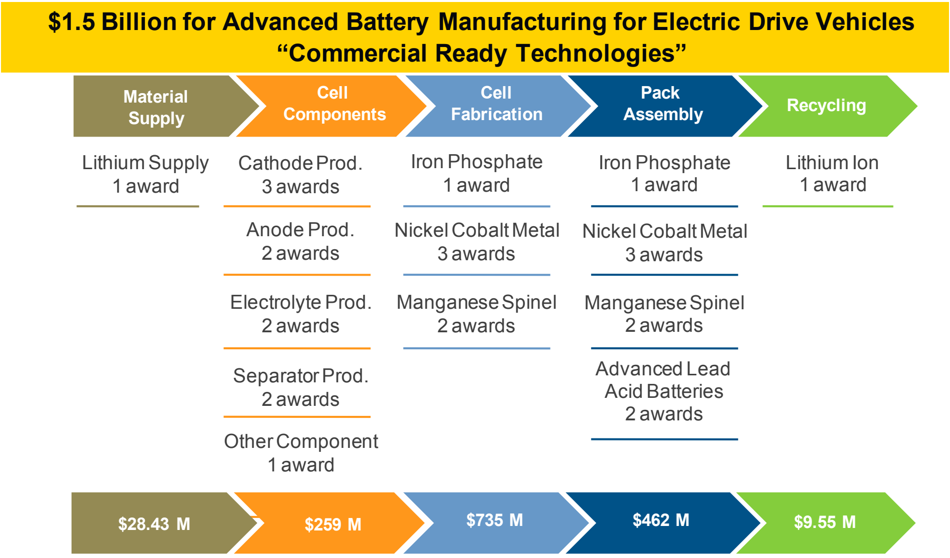
- By 2014, reduce PHEV battery costs to competitive levels ($300/kWh);
- By 2017, reduce PHEV battery costs to $270/kWh; and
- By 2020, reduce EV battery costs to $150/kWh

Table 2.1-2. Overview of Out-Year Plans for Energy Storage R&D

ROADMAP	2010	2015	2020
1: Commercial Facilities Setup under ARRA Authority	Large-scale battery manufacturing (ARRA Battery Manufacturing)	Large-scale battery manufacturing (ARRA Battery Manufacturing)	Next generation EV battery commercialization
Budget ($, M)	$1,500	–	–
2a: Full Battery Development and Testing	Baseline Li-ion HEV/PHEV battery systems meeting performance, life, and cost targets (VTP)	Advanced Li-ion HEV/PHEV battery systems with low-cost design architectures (VTP)	Battery systems using next-gen anodes (Si) and cathodes (layered MnO_3/Mn_2O_4)
Pack-specific	150 Wh/kg	200 Wh/kg	250 Wh/kg
2b: Enabling of ES Technologies	Computer-aided engineering (CAE); Recycling and secondary use; innovative thermal management; Heavy vehicle applications (VTP)	CAE; Recycling and secondary use; innovative thermal management; Heavy vehicle applications; New manufacturing technologies (VTP)	CAE; Advanced manufacturing technologies (VTP)
3: High-energy and High-power Cell R&D	High capacity Li-ion PHEV/EV cells with improved safety, life, and cost (VTP)	Advanced Li-ion cells using high capacity anodes (Si)/cathodes and revolutionary cell architecture (VTP)	Li-Sulfur, Li-air cell integration and optimization; high-V dielectric capacitors, new battery architectures. (VTP)
Cell-specific	250 Wh/kg	350 Wh/kg	500 Wh/kg
4: Advanced Materials Research	Non-Li, high capacity cathodes, Li-sulfur, Li-air research (ARPA-E and Energy Storage Hub)	Li-S, Li-air research, high-V dielectric capacitors (ARPA-E and Energy Storage Hub)	Multivalent systems, high-V dielectric capacitors, low-temp sodium systems (ARPA-E and Energy Storage Hub)
	Next gen anodes (Si) and cathodes (layered MnO_3/Mn_2O_4) (VTP)	Li-S materials development, materials to enable revolutionary cell architectures (VTP)	Li-Sulfur, Li-air materials development; high-V dielectric capacitors, new battery architectures. (VTP)
Anode Capacity	1,000 mAh/g	900 mAh/g	760 mAh/g
Cathode Capacity	220 mAh/g	1,100 mAh/g	1,675 mAh/g
5: Basic Materials Research	EFRCs, BES, and SBIR research programs on new electrode materials, electrolytes, and electrochemical phenomenon.		
Funding	($BES/ARPA-E)	($BES/ARPA-E)	($BES/ARPA-E)

Activities	🟩 **VTP Energy Storage**	🟨 **Outside VTP**

Electric Drive Vehicle Battery Manufacturing Initiative. The American Recovery and Reinvestment Act (ARRA) of 2009 (Public Law 111-5) is an economic stimulus package enacted by the 111th United States Congress in February 2009. As part of ARRA implementation, $2.4 billion in grants were awarded in order to accelerate the development of U.S. manufacturing capacity for batteries and electric drive components as well as the deployment of electric drive vehicles to help establish American leadership in developing the next generation of advanced vehicles. The grantees were selected through a competitive process conducted by DOE. Funded were 48 new advanced battery and electric drive components manufacturing and electric drive vehicle deployment projects – including PHEV and EV demonstration and education projects – in over 20 states. The new awards included $1.5 billion in grants to U.S. based manufacturers to produce batteries and their components and to expand battery recycling capacity, distributed over all parts of the country. These grants cover a range of manufacturing areas including those associated with material supply, cell components, cell fabrication, pack assembly, and recycling. The composition of grants under the various categories is shown in Figure 2.1-1.

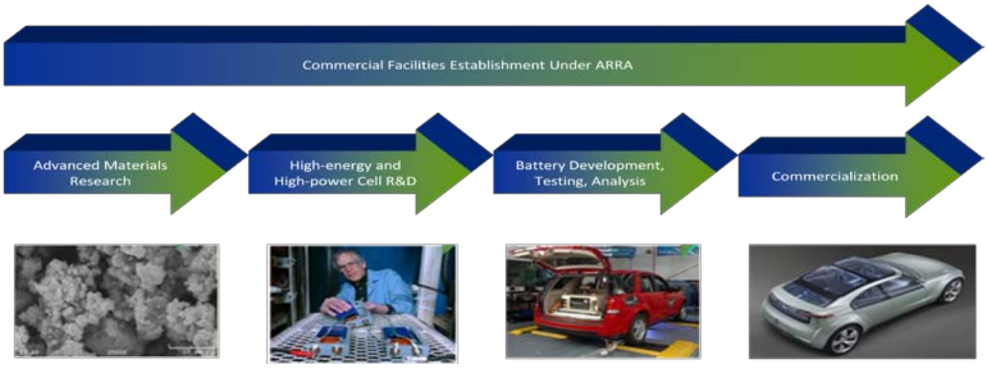


$1.5 Billion for Advanced Battery Manufacturing for Electric Drive Vehicles
"Commercial Ready Technologies"

Material Supply	Cell Components	Cell Fabrication	Pack Assembly	Recycling
Lithium Supply 1 award	Cathode Prod. 3 awards	Iron Phosphate 1 award	Iron Phosphate 1 award	Lithium Ion 1 award
	Anode Prod. 2 awards	Nickel Cobalt Metal 3 awards	Nickel Cobalt Metal 3 awards	
	Electrolyte Prod. 2 awards	Manganese Spinel 2 awards	Manganese Spinel 2 awards	
	Separator Prod. 2 awards		Advanced Lead Acid Batteries 2 awards	
	Other Component 1 award			
$28.43 M	$259 M	$735 M	$462 M	$9.55 M

Figure 2.1-1. American Recovery and Reinvestment Act (ARRA) 2009 grants distribution for battery and electric drive manufacturing

Materials Basic Research for Energy Storage. The work under this task represents the coordination that will be undertaken by VTP in response to the additional energy storage research that is being funded by the ARPA-E, BES EFRCs, NSF, and other government agencies. The VTP energy storage team is already involved in each of these efforts, either as advisors or as proposal reviewers. In addition, EFRC principal investigators were invited to the 2010 VTP annual merit review meeting. This coordination activity will grow in importance in the out years and is therefore included as a formal task, representing activities in coordination with agencies outside the VTP program, with cooperation and interaction and input from VTP on a project/topic specific basis.



- High energy cathodes
- Alloy, lithium anodes
- High voltage electrolytes
- Lithium air couples

- High rate electrodes
- High energy couples
- Fabrication of high-energy cells
- Ultracapacitor carbons

- Hybrid electric vehicle (HEV) systems
- 10- and 40-mile plug-in HEV systems
- Advanced lead acid
- Ultracapacitors

Figure 2.1-2. Progressive Stages of Development for Individual Energy Storage Technologies

Figure 2.1-2 shows the progression of stages associated with the development and commercialization of vehicular energy storage technologies. The stages include advanced materials research, high energy and high power cell R&D, battery development, testing and analysis and finally, commercialization. Depending on the progress made over time an individual technology may be categorized as currently located in a particular stage. Some of the main candidate technologies, along with their current location within the progression, are identified in Figure 2.1-2. Because of the large variation in the state of development for different battery technologies, the VTP energy storage effort also includes multiple activities – from hardware development, design optimization, testing and analysis with industry, to mid-term R&D predominately focused on advanced battery cell R&D, and advanced materials research focused on developing next generation cell component materials. The activities begin by establishing appropriate technical requirements for the energy storage technologies being developed within each of these areas of research and measuring progress against those requirements.

The Battery/Energy Storage R&D portfolio is comprised of projects in the following task areas:

- Advanced Battery Development, Systems Analysis, and Testing Activities (The Developer Program)
- High-Energy and High-Power Cell R&D (Applied Battery Research)
- Advanced Materials Research (Focused Fundamental Research)

A. Advanced Battery Development, Systems Analysis, and Testing Activities (The Developer Program)

The goal of this effort is to support the development of a U.S. domestic advanced battery industry whose products can meet the VTP/USABC technical goals. Focus is on the development of durable and affordable advanced batteries and ultracapacitors for use in advanced vehicles, from start/stop to full-power HEVs, PHEVs, and EVs. Nearer-term technology development is conducted both in collaboration with industry through the United States Advanced Battery Consortium (USABC), and directly through contracts or cooperative agreements with DOE. All contracts or agreements to develop advanced batteries are awarded under a competitive process and are at least 50 percent cost-shared by developers. This effort supports the creation of a U.S. domestic advanced battery industry whose products can meet the VTP/USABC technical goals. Several battery technologies (e.g., NiMH and Li-ion) have reached commercialization[2]. Work is supported in several areas for development of full battery systems and advanced materials for those systems including early-stage R&D for small business/entrepreneurs through the Small Business Innovative Research (SBIR) solicitation.

Full battery development and testing. Work is closely coordinated with industry to develop energy storage technologies for specific applications. Areas of focus include: material and cell development, system development, and benchmark testing.

> *Material and cell development***.** Work under current competitively awarded cost-shared cooperative agreements with industry focuses on improving the performance of high-energy materials, improving cells' inherent abuse response, reducing manufacturing cost, and detecting and mitigating internal short circuits. Future solicitations will concentrate on much higher-energy couples, and high-power couples that offer a revolutionary reduction in cost.
>
> *System development.* Work with industry, through cost-shared agreements, focuses on development of electrochemical energy storage technologies which will meet the VTP/USABC technical goals. The USABC provides technical and programmatic guidance of these projects which are at least 50 percent cost shared by the

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[2] *Linkages of DOE's Energy Storage R&D to Batteries and Ultracapacitors for Hybrid, Plug-In Hybrid, and Electric Vehicles*, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.

individual developer. The technologies include lithium-ion batteries, ultra-capacitors, and separators (which usually contribute significantly to the total system cost). Additional R&D involves the thermal management issues for battery systems, which need to be addressed to avoid degradation in battery performance, reduced life, and greater likelihood of abusive or unsafe conditions.

Benchmark testing. Emerging technologies are benchmarked to remain abreast of the latest industry developments. Battery technologies are evaluated according to the USABC Battery Test Procedures Manual (for EV, PHEV, and HEV batteries).

Products and Processes Validation. Each new material, new process, new cell, or battery design will be subjected to some level of testing and validation to ensure that the quality and performance of the products from that process or material are sufficient for the intended application. Tasks related to enabling the commercialization of battery/energy storage technologies include the following:

Energy storage requirements analysis. Investigation will continue into the effectiveness of various energy storage technologies and systems (e.g., a battery/ultra-capacitor system) towards reducing vehicle fuel consumption. These analyses have historically proven critical to establishing system requirements and recent analysis has confirmed the close correlation between vehicle gasoline mileage and some of the standard testing procedures used to characterize batteries and their aging.

Cell and battery testing and test analyses. National laboratories will continue providing independent, unbiased, and standardized testing of new cells, systems, and materials. The Idaho National Laboratory and Argonne National Laboratory will perform cycling and calendar life testing as well as accelerated testing and analysis, Sandia National Laboratory will conduct abuse testing and analysis, and the National Renewable Energy Laboratory will perform thermal performance testing and analysis.

Test procedure development. DOE, in collaboration with industry, has established standard test procedures to evaluate the performance, life, and safety of batteries. However, additional test procedures, sensors, and analytical techniques may be needed to diagnose, monitor, and improve the quality, performance, and life of new materials and batteries. They should address battery components (electrodes, separators, electrolyte, hardware, and containers), cells, module, and pack during R&D, cell manufacturing and pack integration.

Revolutionary cell and system packaging. All Li-ion batteries (packages of many cells) use a standard packaging approach. Cells are first individually packaged in either a cylindrical can or a laminate pouch and then further bundled and packaged into a full battery system involving hundreds of cells. The interconnects, voltage and temperature sensors, vents, and other hardware needed to manage each cell in this design add significant cost and manufacturing burden to the final product. Only a very small percentage of the final product’s weight (approximately 25 to 30%) is due to the active materials that actually store the energy in the battery. Reducing the number of “non active” components in both the cell and the battery pack significantly reduces the volume, weight, and cost of the finished product.

Improved thermal management approaches. Thermal management is critical to achieving system life and safety. Current thermal management technologies add weight, cost, and complexity to the energy storage system. The use of novel thermal management approaches could both appropriately manage the battery system’s temperature and potentially to reduce its overall cost. Approaches that significantly extend the upper or lower operating temperature ranges of the system are also of interest.

Codes and standards development. National laboratory and government staff will collaborate with automotive manufacturers, utilities, renewable energy suppliers, battery developers, recyclers, and others to understand the scope of the codes and standards needed for successful commercialization of batteries for vehicles.

Recycling and re-use R&D. Designing the battery for reuse or recycling may be critical in reducing battery cost. DOE will fund joint R&D projects with participation by battery developers, auto manufacturers, utilities, other users, and recyclers to explore new design paradigms that will ensure maximum value of each battery throughout its lifecycle. In addition, DOE will continue to support a secondary use study currently underway that is investigating the value of secondary use scenarios and the suitability of PHEV and EV advanced batteries to support them.

Life and cost modeling. DOE will continue to support efforts to understand and model the life limiting mechanisms in Li ion and other chemistries. One of the ongoing challenges of verifying a 10 to 15 year life is the need to rely on one to two years of testing data. This effort will continue work toward integrating and improving existing models to understand fade mechanisms and thus develop a more accurate model of battery life. In addition, cost models will be refined and improved to help developers and researchers concentrate on those specific items that will be most effective in reducing battery cost.

Supplemental research areas. Research will investigate the feasibility of high voltage dielectric capacitors, biologically inspired electrode active materials, and organic electrode materials. High voltage dielectric capacitors utilize a traditional parallel plate configuration, but separated by an extremely thin, very high dielectric constant separator, enabling the use of very high voltage and thus higher energy densities. This technology has a number of fundamental issues related to material properties, including maintaining the separator's high dielectric properties under severe usage conditions and minimizing the introduction of defects in the separator that then lead to shorts. Biologically inspired materials may self assemble, enabling low cost, high volume, and high purity production of materials with nanometer scale control of shape and morphology. Finally, organic electrode materials have historically exhibited rather poor energy density but remain attractive due to their low cost and abundant constituent materials.

B. High-Energy and High-Power Cell R&D (Applied Battery Research)

Focus of this activity is on assisting industrial developers of Li-ion batteries to overcome the key barriers to implementing this technology in high-energy plug-in hybrid electric vehicle (PHEV) applications. Undertaken is the development of higher energy materials, higher voltage electrolytes, more optimal cell chemistries that are more chemically, structurally, electrochemically, and thermally stable in the cell environment; as well as possessing cost advantages over current materials. Major market barriers for PHEV technologies are addressed including inadequate energy density and specific energy to meet the "charge-depleting" energy requirement, within the weight and volume constraints, for the 40-mile all electric range for a mid-size passenger PHEV and insufficient cycle life stability to achieve the 3,000-5,000 "charge-depleting" deep discharge cycles. The current areas of focus include:

Materials and Cell Development. Focus is on research, development, and engineering of higher energy advanced materials and cell chemistries that simultaneously address the life, performance, abuse tolerance, and cost issues. Argonne National Laboratory is currently installing an expanded prototype cell and battery production line to permit faster evaluation of promising materials in full sized cells. Capabilities and facilities for accelerated screening of new materials are being expanded at national laboratories. These include prototype scale mixers, coaters, dryers, filling, and formation. Also included are the latest microscopic and spectroscopic tools for studying the chemical, physical, and structural properties of materials, both in the bulk and at the electrolyte/electrode interfaces. The needed equipment and facilities will be established to facilitate full-time access for members of the applied R&D program.

Calendar and cycle life studies. This task will provide understanding of the factors that limit life in different Li-ion cell chemistries, which are used as feedback to the materials and cell development task. In-program cell fabrication capabilities will be established for use in these life studies of fabricated moderately sized (2-10Ahr) cells for performance and abbreviated (six-twelve month) aging studies.

Abuse tolerance studies. This activity deals with understanding the factors that limit the inherent thermal and overcharge abuse tolerance of different Li-ion cell materials, components, and cell chemistries, as well as developing approaches for enhancing their inherent abuse tolerance.

Development of advanced manufacturing technologies. A large component of battery cost is the cell cost, which in turn is directly related to the manufacturing speed. Thus, part of the applied research task will concentrate on improving existing manufacturing processes to enable faster, higher quality production of Li-ion batteries. This task will also include working with suppliers of cell materials and components to enable them to reduce the cost and improve the quality of their products. Finally, work in this area will concentrate on enabling the scale up and commercialization of advanced, high-energy materials that should enable electric drive vehicles with greater electric range.

Although many advanced materials have been developed under DOE's energy storage research programs, the introduction of these materials into commercial products is hindered by the fact that the U.S. lags behind Asia, and to some extent Europe, in its ability to commercially manufacture electrode materials and Li-ion cells. To facilitate and accelerate competitive domestic manufacturing, the advanced manufacturing R&D activity will include development of novel and optimized processing technologies, for both current state-of-the-art and advanced materials. This work will involve collaboration with the focused fundamental R&D activity and will include the active participation of battery developers, material and component suppliers, equipment manufacturers, universities, national laboratories, and end users such as automotive manufacturers and renewable energy technology producers and users. Several of the research topics that may be pursued include the following:

Improved formation. The formation of a solid electrolyte interphase (SEI) layer on the anode particles to protect them from parasitic reactions with the electrolyte often takes several days. Means to reduce formation time or completely eliminate this step, and/or alternate formation techniques will be studied.

Dry electrode processing. Today, all electrodes start out as a wet mixture of components that are pasted onto a current collector and then dried in a large oven. This process involves significant energy, time, and the use of environmentally harmful chemicals. Research will focus on revolutionary manufacturing techniques to permit the construction of electrodes through completely dry processes.

Optimized electrode formulations. The art of processing optimized electrodes will be studied and sufficiently understood, from a technical perspective, to introduce additional science and engineering into this process. For example, a complete understanding of why binders and other additives work (or do not work) is not available.

Particle size and shape control. This research will concentrate on quantifying the changes in performance with particle size and shape, and on developing processes for manufacturing the materials with the desired size and shape. This is one of the research areas that could significantly improve the performance of existing materials.

Manufacturing process scale up. This task area will research and test manufacturing processes for new and advanced high-energy materials. When a new material is identified and developed, only small quantities (grams) are available from laboratory experiments. The next step is to prepare larger quantities of the material for evaluation in prototype cells. While the engineering process is based on the conditions established in the laboratory, the processing generally must be modified to produce a larger quantity of materials.

Development of CAD/CAM software toolkit for battery design. Electrochemical performance, and thermal design software is beginning to reach the stage of maturity at which users believe that they might be integrated to form a full battery design suite. The process of testing new materials in multiple cell sizes, in multiple battery pack designs, and over many months is extremely time consuming, expensive, and ad-hoc. This software suite would include materials properties, electrode design, pack design for thermal management purposes, usage profiles, and aging data as input, and could greatly speed the design of new batteries and provide critical guidance to developers.

A related but distinct activity that might be pursued is in developing a battery life gauge. Battery developers and users require the ability to predict battery life. Currently, this is done empirically using a significant amount of data, onboard measurement and adaptive algorithms. This work is repeated by different users for different chemistries and batteries. It is proposed to develop a precompetitive battery life gauge to accurately monitor battery health. The gauge is envisioned to be composed of some combination of hardware (internal sensors and circuitry) and software (energy counters and adaptive algorithms). In addition to flagging maintenance actions, life-gauge readings would help determine the value of the battery for secondary-use markets (such as stationary energy storage) once the first-use life is complete.

C. Advanced Materials Research (Focused Fundamental Research)

Improved understanding of the fundamental problems of chemical and mechanical instabilities affecting cell and material performance, and lifetime limitations are critical to the development of the next-generation chemistries for PHEV and HEV batteries. This is multi-pronged research effort which involves development of new materials through a combination of material synthesis, structural calculations, and advanced diagnostics in concert with cell-level studies to evaluate the ability of these new materials to be used in desired applications. A number of ideas will be pursued to develop the next generation low-cost, abuse-tolerant, long-life, and high-energy batteries. Battery chemistries are monitored continuously with timely substitution of more promising components. This effort not only supports research that leads to incremental improvements to existing materials, but also into high-risk "leap-frog" technologies that might have a tremendous impact in the marketplace.

Materials Synthesis. To achieve higher energy, research will focus on the investigation of anodes and cathodes for cells that have greater specific capacity and/or higher cell voltage. Development of these higher-energy cells would also ensure a decrease in the cost of the battery when used in a vehicle because fewer cells will be needed for the same range. In order for batteries to have long life, these materials have to be stable from reaction with the electrolyte over a wide voltage range and be capable of being fully cycled over the entire rated capacity. Finally, as the batteries become larger, abuse tolerance becomes a primary concern, requiring greater stability between the electrodes and the electrolyte.

This effort involves the establishment of a baseline system that benchmarks the performance of systems that are possible today. Research will be performed to enable the development of a high-energy Li-ion battery through advancement in anodes, cathodes, and electrolytes with a target date of 2015. Subsequent research will be undertaken to enable a very high energy Li-S battery and an ultra-high energy Li-air battery, with a goal to establish new baselines by 2020 and 2030, respectively.

> *Baseline System (200 Wh/kg).* The baseline system will be established to serve as a test bed for understanding the issues related to both PHEV and EV applications, including the failure modes and the performance in real-world operating conditions. Once the baseline system is well established, research will start to identify new materials that will improve the energy density of the baseline system without compromising on cost, abuse tolerance, and power performance.

High Energy Li-ion Battery (300 Wh/kg) by 2015. Research will be undertaken to improve the three components of the battery (i.e., anode, cathode and electrolyte) while maintaining the overall concept of a Li-ion system and define a new baseline by 2015. Investigation will focus on Si-based alloy anodes, high-capacity layered cathodes, and high voltage electrolytes and additives.

*Very High Energy Li-S Battery (500 Wh/kg) by 2020 and Ultra High Energy Li-Air Battery (700 Wh/kg) by 2030***.** While the research on Li-ion is expected to lead to a significant decrease in the cost of batteries (via increases to the energy density) and enable the development of short-range EVs, further improvement in energy would be needed for widespread acceptance. Systems such as Li-sulfur and Li-air promise significant increases in energy density; however, the fundamental problem facing these systems is the Li metal anode and its poor cycling. The focus of this research will be on the anode with an approach of completely isolating the anode from the electrolyte. Once this is achieved, research will be pursued on the two high-capacity cathodes. Research will pursue high-efficiency Li-metal anode, sulfur cathode, and air cathode.

Cross-cutting Research to Support Material Synthesis. Materials synthesis tasks will be supported by cross-cutting efforts on diagnostics, modeling, and electrode/cell studies.

Diagnostics. Sophisticated diagnostic tools used together with materials synthesis will ensure rapid development of next-generation chemistries. *In situ* spectroscopic tools will be used to investigate model-electrode structures (*e.g.,* single particles, thin films, *etc.*) to advance fundamental understanding of the science of battery behavior. As energy density becomes more important, batteries are expected to be cycled through their complete state-of-charge range (as opposed to HEVs where the cycling range is limited). This can lead to trapped or blocked lithium and changes to the electrode/electrolyte interface that will limit the power capability of these systems during extended use. Efforts will be directed toward the use of spectroscopic tools to study changes in the bulk and interfacial behavior during deep-discharge operation of anodes and cathodes, as batteries are expected to be cycled through their complete state-of charge as energy density becomes more important. A new thrust area will be in the development of techniques that will allow for in situ diagnostics on full cells (as opposed to post-mortem analysis). This task will be a complement to the diagnostics on model electrodes and link fundamental changes in the active material to real-world performance.

Modeling and Simulation. Mathematical simulations, both on the structural and the macroscopic level, in combination with material synthesis, will provide novel ways of identifying next-generation chemistries. Computational tools will be used, for example, to calculate material properties of the separator that will allow the cycling of a cell with power capability meeting EV requirements, and to identify new electrolytes that can be used at high voltages. The performance of these new materials will be assessed for usefulness in real-world operation by utilizing macroscopic cell-level models. This will allow for an alternative methodology of extrapolating material performance to cell performance without embarking on an extensive battery-manufacturing effort. In addition, mathematical simulations will concentrate on predicting the life limitations of batteries, especially during deep-discharge operation. Finally, these models will be strengthened by incorporating the various microscopic features that characterize batteries, including anisotropic ion transport in materials, nucleation and growth of phases, expansion or cracking of particles, and conductivity within and between particles. These should allow simulations to play an integral part in developing next-generation batteries for PHEV and EV applications.

Model Electrode and Lab-Scale Battery Studies. New materials made in the laboratory will be evaluated in a consistent, standardized format. High-quality, fully characterized test-cells will be used for evaluating all components of the battery to better utilize active material components while model electrode structures of composite and thin-film electrodes will be developed to allow for rapid screening of new materials without the complexity of the engineering issues inherent in composite electrode fabrication.

Tasks

Specific tasks identified for Battery/Energy Storage R&D are shown in Table 2.1-3.

Table 2.1-3 Tasks for Battery/Energy Storage R&D

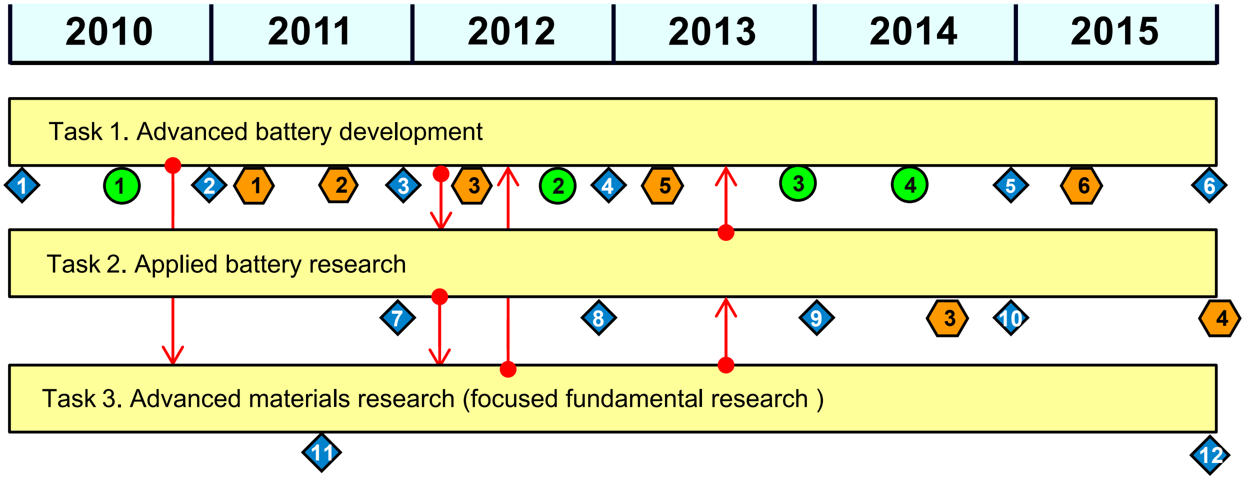
Task	Title	Barriers Addressed
Task 1	**Advanced Battery Development** • Develop and test new battery systems and advanced materials that promise to approach, meet, or exceed PHEV, HEV, and EV applications. – Evaluate and benchmark test battery technologies and commercial products as they become available, and identify areas for additional R&D. • Validate products and processes – Develop test procedures to benchmark performance – Develop revolutionary cell and system packaging – Investigate improved thermal management approaches – Support codes and standards development – Recycling and re-use R&D – Life and cost modeling • Supplemental research – Investigate ultracapacitor/battery system power and cost benefits	A. C,D, E
Task 2	**Applied Battery Research** • R&D and engineering of higher energy advanced materials and cell chemistries that meet life, performance, abuse tolerance, and cost requirements – Validate prototype cell production line to enable the building of high-energy or high-power cells to permit full evaluation of newly discovered advanced materials. – Screen/evaluate new high-energy and high-power materials using advanced diagnostic techniques to determine their performance and life expectations. – Apply diagnostic techniques to prototype cells designed and produced to pinpoint causes of fade in high-power and high-energy cells. Expose high-energy cells to abusive conditions to improve understanding of the chemical processes occurring that may result in thermal runaway and cell failure. • Develop advanced manufacturing technologies – Improved and faster formation, dry electrode processing, and use of precisely controlled particle size and shape to optimize electrode performance. • Develop CAD/CAM software toolkit for battery design – Improve speed of design of new batteries and provide critical guidance to developers	A, B, C, D, E
Task 3	**Advance Materials Research (Focused Fundamental R&D)** • Define baseline chemistry, assemble and test baseline cells, conduct diagnostics and modeling, and synthesize and evaluate novel materials. • Develop high-energy Li-ion battery through advancement in anodes, cathodes, and electrolytes with a target date of 2015. – Research will then be performed to enable a Very High Energy Li-S battery and	A, B, C, D, E

Table 2.1-3 Tasks for Battery/Energy Storage R&D

Task	Title	Barriers Addressed
	– Ultra High Energy Li-air battery, with a goal to establish new baselines by 2020 and 2030, respectively.	

Milestones and Decision Points

Battery/Energy Storage R&D



◆ **Milestone**

1. Establish technical targets with tech teams.
2. Synthesize materials that satisfy PHEV performance requirements .
3. Validate $20/kW for high power batteries by 2011 .
4. Evaluate hardware for ultracapacitor and battery combinations for battery electric vehicles by 2012.
5. Validate low-cost, energy-efficient thermal management system by 2014.
6. Reduce PHEV battery costs to $300/kWh by 2015.
7. Applied battery research: downselect to most promising next generation couple by 2011.
8. Demonstrate $500/kWh battery cost by 2012.

◆ **Milestone**

9. Demonstrate life and performance of promising next generation couple by 2013.
10. Demonstrate $300/kWh battery cost by 2014
11. Investigate new high energy Li-ion concepts using materials synthesis/diagnostics/ computation
12. Develop new baseline high-energy Li-ion battery with advanced anodes, cathodes, and electrolytes.

⬢ **Technology Program Output**

1. Revised or validated technical targets
2. New materials for incorporation into cell construction/testing

⬢ **Technology Program Output**

3. Validated battery cost
4. Reduced PHEV battery cost
5. Validated ultracapacitor/battery system life and other benefits
6. Validated low-cost thermal management system.

● **Supporting Input**

1. Cost models from U.S. developer
2. PHEV and EV battery cost estimates from USABC and other developer
3. Ultracapcitor/battery combination system from national lab testing
4. Prototype low-cost thermal management system

2.1.2. Advanced Power Electronics and Electric Motors R&D

Advanced power electronics and electric motors are critical components for advanced electric propulsion drive vehicles. Successful development and broad market acceptance of energy-efficient and cost-effective APEEM technologies is an important element in support of DOE's mission for energy security.

Goals

The Advanced Power Electronics and Electrical Motors (APEEM) R&D activity works to achieve the following goals:

- Develop technologies to reduce the costs of APEEM electric propulsion systems from today's approximate cost of $33/kilowatt (kW) to target costs of $12/kW peak by 2015 and to $8/kW peak by 2020.
- Accelerate the manufacturing capability and mass production adoption of energy-efficient and cost-effective APEEM technologies into electric propulsion drive vehicles—electric vehicles (EVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs).

The APEEM R&D activity, in cooperation with the private-sector FreedomCAR and Fuel Partnership, is conducting high-risk R&D to advance new and improved electric propulsion technologies to increase vehicle fuel efficiency in the midterm and facilitate the transition to more electrically dominant hybrid, electric, and plug-in hybrid vehicles in the mid-to-long term.

The APEEM activity has the following specific goal:

- By 2020, develop an integrated traction motor-inverter subsystem that has an operational lifetime of 15 years and costs $8/kW peak and can deliver at least 55 kW of power for 18 seconds and 30 kW of continuous power.

The cost portion of the performance goal is particularly important because the addition of power electronics, traction motor(s), and controls adds several thousand dollars to vehicle cost. As a result of these additional components, the cost of electric vehicles will continue to exceed that of conventional vehicles.

The performance goal and R&D technical targets (described in Table 2.1-4) are based on cost metrics (in current dollars), because manufacturer markup from cost to price is outside the scope of R&D efforts. It is recognized, however, that ultimately price (rather than cost) will be the most important criterion for consumers. A principal objective of the R&D program is to reduce component and subsystem cost so that a customer can recover the additional cost for an advanced electric vehicle in three years through fuel savings.

In addition to the cost objective, APEEM research focuses on the development of technologies that will enable the production of electric traction systems, accessory power converters, and on-board chargers that are significantly smaller, lighter, and more reliable than existing systems.

Table 2.1-4 details the technical targets that have been developed to achieve the APEEM performance goal. The targets for 2010 are based upon a liquid coolant with a maximum temperature of 90°C, and the targets for 2015 and 2020 are based upon air or a liquid coolant with a maximum temperature of 105°C. It is important to note that the targets have been defined irrespective of the system cooling architecture and do not include an allowance for a separate cooling system. Thus, if a separate cooling system is added to the vehicle to meet the APEEM system cooling needs, it must be accounted for in the APEEM system cost, weight, and volume. This may substantially impact the system's ability to meet the performance targets. For example, the cooling system used in today's HEVs alone represents about 40% of the allowable 2020 cost.

Table 2.1-4. Technical Targets for Electric Traction System

	2010[a]	2015[b]	2020[b]
Cost, $/kW	<19	<12	<8
Specific power, kW/kg	>1.06	>1.2	>1.4
Power density, kW/L	>2.6	>3.5	>4.0
Efficiency (10%-100% speed at 20% rated torque)	>90%	>93%	>94%

[a] Based on a coolant with a maximum temperature of 90°C.
[b] Based on air or a coolant with a maximum temperature of 105°C.
[c] A cost target for an on-board charger will be developed and is expected to be available in 2010.

Current HEV solutions primarily rely on an added cooling system dedicated solely to the APEEM system. This enables relatively low coolant temperatures (on the order of 70ºC) to be supplied to the APEEM system, resulting in smaller heat sink areas and greater reliability of the APEEM components. However, this approach adds cost, weight, and volume, all of which are at a premium in electric vehicles. Integrating the APEEM cooling system with an existing onboard cooling system such as the engine cooling or transmission cooling systems offers several advantages, eliminating the added cost, weight, and volume of the separate cooling system, which is highly desirable and may be required to meet the performance targets. However, operating with higher coolant temperatures may place greater demands on the components by raising operating temperatures. Although it is a challenge, the requirement for higher-temperature components may be desirable because it is likely to lead to higher power densities.

The electric propulsion system includes all necessary components to add an electric traction function to the vehicle. This includes, at a minimum, one traction motor and an inverter (including a controller). Additionally, the system may include a DC/DC boost converter, any necessary additional gears, and a dedicated coolant loop. The scope of APEEM research does not include the battery, DC cables from the battery, or power split. The technical targets are appropriate for an HEV application. For other applications, the targets may be adjusted on a case-by-case basis.

Power level scalability is being incorporated as an important consideration in APEEM research. Table 2.1-5 illustrates the approximate peak power requirements for various classes of vehicles. As shown in Table 2.1-5, the 55 kW peak power would be suitable for a mid-sized hybrid sedan, but would not be suitable for larger vehicles. Using a power level near the low end of the range is appropriate for APEEM R&D because that is where the challenge of meeting the specific power and power density targets would be greatest. Meeting the targets for more powerful systems should be easier because some of the “overhead” items would not have to be entirely proportional to the power.

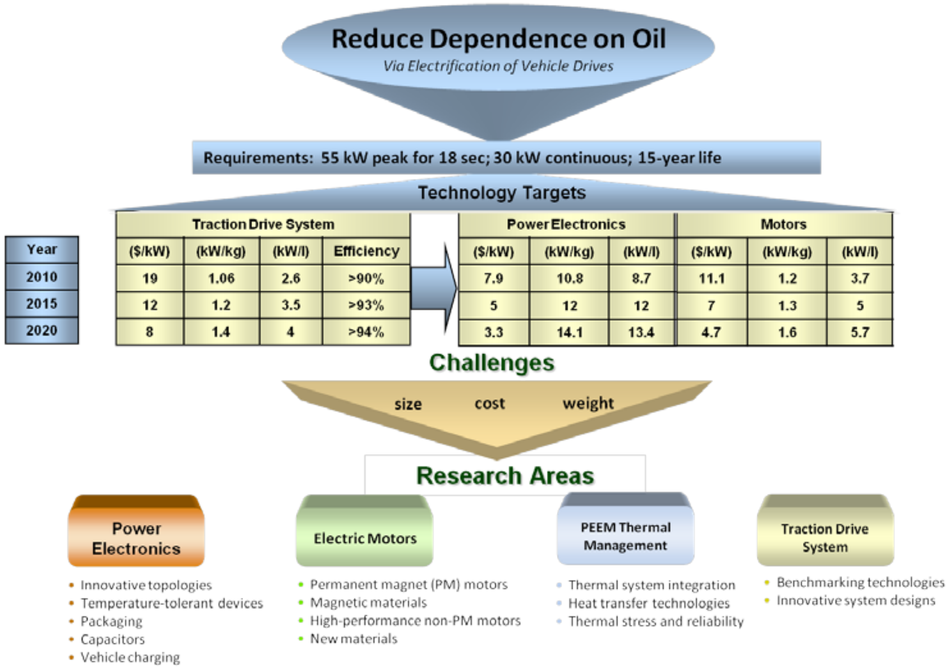
Table 2.1-5. Approximate Peak Power Requirements for Electric Propulsion System in Various Vehicle Classes

Vehicle Segment	Vehicle Class, kg	Peak Power, kW	
		FCV, EV, or EREV[a]	ICE Hybrid[b]
Compact	1,000	80	42
Mid-size sedan	1,300	104	55
Full-size sedan	1,700	136	72
Light SUV[c]	2,000	160	85
Pick-up truck	2,100	168	89
Full-size SUV	2,300	184	97

[a] FCV stands for fuel cell vehicle; EREV stands for extended range electric vehicle.
[b] ICE stands for internal combustion engine. Includes HEVs and PHEVs with blended operation.
[c] SUV stands for sport utility vehicle.

Figure 2.1-3 illustrates the basis for the APEEM R&D activity. Minimum requirements have been defined in order to address a range of vehicles. In addition, defined targets at the systems level have been disaggregated into power electronics and electric motors areas. It is important that system-level targets be met. However, the targets established at the power electronics and electric motors level can be traded off against each other. In response to the development challenges four research areas have been established:

1. Power electronics
2. Traction motors
3. Thermal management
4. Traction drive systems



Year	Traction Drive System				Power Electronics			Motors		
	($/kW)	(kW/kg)	(kW/l)	Efficiency	($/kW)	(kW/kg)	(kW/l)	($/kW)	(kW/kg)	(kW/l)
2010	19	1.06	2.6	>90%	7.9	10.8	8.7	11.1	1.2	3.7
2015	12	1.2	3.5	>93%	5	12	12	7	1.3	5
2020	8	1.4	4	>94%	3.3	14.1	13.4	4.7	1.6	5.7

Figure 2.1-3. APEEM R&D overview

For each research area, sub-element focus areas are identified (listed under each research area in Figure 2.1-3). To achieve the targets, contributions will be needed from most, if not all, of the focus areas and the parallel paths that are embedded in them. All focus areas need to be pursued simultaneously to support achievement of the cost and technical aspects of the performance goal.

Challenges and Barriers

A. Cost. The primary barrier to greater adoption of advanced electric propulsion drive vehicles is cost. As shown in Figure 2.1-4, hybrid vehicle sales in the United States increased steadily from 1999 through 2007 and decreased slightly in 2008, with that decrease reflecting the general decrease in total automobile sales that year. In spite of the rapid average growth rate, hybrid vehicles still represented only about 2%–3% of all vehicles sold in the United States. The level of market penetration is expected to remain low until hybrids are more cost-competitive with conventional vehicles. Current consumers typically have concluded that fuel savings are not sufficient to offset the higher cost of a hybrid vehicle. Achieving a market share that is large enough to justify large-scale manufacturing will require reducing cost to a level at which consumers can economically justify purchasing an advanced vehicle.

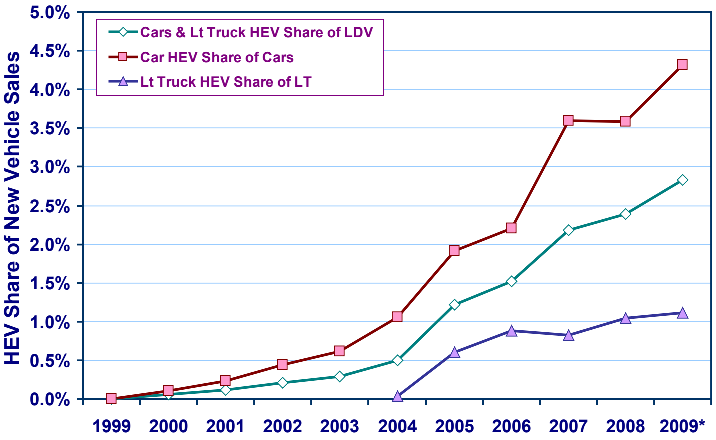


Figure 2.1-4. U.S. Hybrid Sales

Although growth in production volumes will help reduce costs, significant technological advancements will also be needed to achieve the necessary cost reductions. Figure 2.1-5 shows that the unit costs of developing technologies have historically decreased very slowly as cumulative production increases.

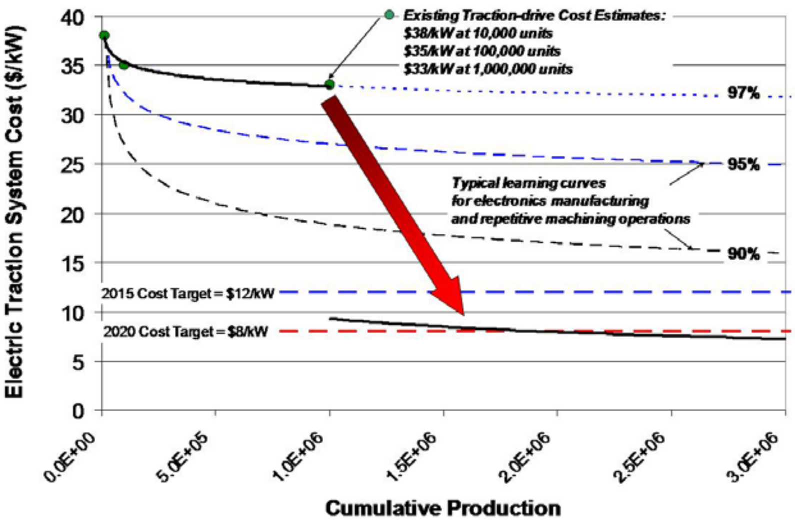


Figure 2.1-5. Required technology shift to achieve the cost target for electric drive technology

The curves in the figure relate unit costs to cumulative production volume, and they are defined by cost entry points and progress ratios. A progress ratio of 90% describes a product or technology that experiences a 10% reduction in cost for every doubling of cumulative production. Studies have shown that progress ratios for repetitive electronics manufacturing are typically between 90%

and 95%, with similar rates for repetitive machining operations.[3,4]

The uppermost curve in the figure shows existing traction-drive cost estimates that were derived from three cost assessments conducted on the Gen I Toyota Prius[5], the Gen II Toyota Prius, and the 2007 model year Toyota Camry[6]. The projected progress ratio for these data points is approximately 97% (representing a 3% cost reduction for every doubling of cumulative production). This progress ratio indicates a somewhat lower rate of cost reduction for these three traction-drive technologies compared to the referenced values for electronics manufacturing and repetitive machining operations. While there is some uncertainty in the exact progress ratio that will be experienced, the figure shows that the ultimate cost target of $8/kW for the electric propulsion system is not likely to be reached from efficiencies gained by production volume alone or by incremental technology advances. A significant shift (sometimes referred to as a paradigm shift) in the cost curve will be required. Substantial investment in R&D also is typically required to achieve the type of technology breakthroughs that will enable the cost targets to be reached.

Although cost is the main barrier, other important barriers include the weight and volume of the components, and the ability of the materials and components to withstand the temperatures that they will encounter.

B. Rare Earth Minerals. Widespread deployment of hybrid-electric and battery electric vehicles may increase worldwide demand for rare earth elements and certain other materials. Neodymium, praseodymium, dysprosium, and samarium are used in permanent magnet motors. It is likely that future supply of these materials may not be able to meet the demand from these technologies.[7]

C. Weight. Weight reductions are essential because fuel efficiency is inversely proportional to weight. The heaviest parts of a permanent magnet motor are the stator core, the rotor core, and the copper windings. Almost 70% of the weight of an inverter consists of the heat sink, the capacitors, and the bus bars.

D. Performance and Lifetime. The performance and lifetime of many power electronics components degrade rapidly with increasing temperature. The overall technical challenge for thermal management of automotive PEEM systems is to develop an efficient and reliable method for removing several kilowatts of heat in a confined space under harsh ambient conditions without adding to the overall system cost, complexity, or parasitic-power requirements. The technical challenges associated with thermal management of power electronics include heat generation due to component inefficiencies, steady-state and transient heat dissipation, device-temperature limitations, temperature-dependant efficiency, high heat flux, low thermal resistance, balanced thermal expansion, and reduced overall system complexity and parasitic-power concerns.

E. Efficiency. The efficiency of the inverter is largely dependent on the power components comprising the inverter. These include the semiconductor switches and diodes. The losses within the switches comprise both switching and conduction losses. These are frequency and temperature dependent as well as being a function of the optimum operational point for the device. The diode voltage drop is also one of the prominent factors affecting the inverter efficiency. Semiconductor manufacturers are constantly striving to develop improved devices in an effort to lower these losses.

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[3] L.M. Delionback, "Learning Curves and Progress Functions," *Cost Estimators Reference Manual*, R. Stewart et al., ed. (New York: John Wiley and Sons, 1995).

[4] International Energy Agency, *Experience Curves for Energy Technology Policy* (Paris, France: International Energy Agency, 2000), http://iea.org/textbase/nppdf/free/2000/curve2000.pdf.

[5] K.G. Duleep, *Technology and Cost of MY 2004 Toyota Prius*, ORNL/TM-2007/132, 2006.

[6] K.G. Duleep, *Technology and Cost of MY 2007 Toyota Camry HEV*, ORNL/TM-2007/132, 2007.

[7] *Critical Materials Strategy,* U.S. Department of Energy, December 2010.

Secondary barriers to increasing the inverter efficiency include the bus capacitor's equivalent series resistance (ESR), the resistance in the module's bus bar structure, as well as all the cabling present in and external to the inverter.

Approach for Overcoming Barriers/Challenges

The following are important elements of the APEEM R&D strategic approach to support achievement of the cost and technical aspects of the performance goal:

- *Development of technologies, not vehicles*: The intent of the R&D is not to design or build a vehicle, but rather to develop a set of technologies that original equipment manufacturers (OEMs) and their suppliers can adopt (and modify, if necessary) to enable them to manufacture an APEEM system that meets the technical goals. Because different manufacturers will have different requirements and design strategies, it is important that a variety of technologies be developed.
- *Multiple technologies*: Because no single new technology is likely to be able to meet all of the performance targets, the APEEM activity must deal with a wide variety of technologies and make improvements to both the motor and the power electronics. For the motor, issues such as new designs, magnet materials, and manufacturing methods must be considered. For the power electronics, semiconductor switches, capacitors, magnetics, packaging, and new topologies must be considered. Added to those issues is the challenge of controlling the temperature of the modules through cooling innovations and packaging.
- *Parallel paths*: To meet the very challenging technical targets, the APEEM activity must pursue high-risk concepts and reduce the overall risk of technical failure by pursuing more than one path toward each objective. Multiple parallel paths will also be more likely to produce technologies that meet the needs of more than one manufacturer.
- *Technology transfer*: New technologies will not have an effect on fuel consumption until they are incorporated into commercial vehicles. Although the basic mission of DOE is long-term, high-risk R&D, APEEM needs to carry out some short-term R&D to advance the technologies to the point at which industry can adopt them. In many cases, this shorter-term R&D will either be conducted in partnership with industry or by industry alone.

Figure 2.1-6. APEEM R&D Structure

The APEEM R&D structure, shown in Figure 2.1-6, consists of three developmental stages: core research, application of core technology into modules, and vehicle solutions. Within this structure, development flows from a basic technology concept (e.g., a new magnet material or a new inverter topology) through to the development of a motor, inverter, or traction drive system that can be used on a vehicle. In the early stages of development, the work is usually conducted at research organizations such as national laboratories, small businesses, and universities. As the technologies mature and are integrated to form modules (e.g., an inverter package and topology are combined with an advanced thermal management technology into an inverter), the work is performed through collaboration between the national laboratories and industry (primarily the supplier base). At the end of the development cycle, industrial teams (OEMs and suppliers) produce vehicle-ready APEEM solutions.

Under the American Recovery and Reinvestment Act (ARRA), $500 million in grants were awarded to U.S.-based manufacturers to produce electric drive components for vehicles, including electric motors, power electronics, and other drivetrain components. These projects, selected through a highly competitive process by DOE, will accelerate the development of U.S. manufacturing capacity for electric drive components as well as the deployment of electric drive vehicles, helping to establish American leadership in creating the next generation of advanced vehicles. Figure 2.1-7 shows the composition of the ARRA grants to assist industry in preparing to supply the electric drive components that will be required.

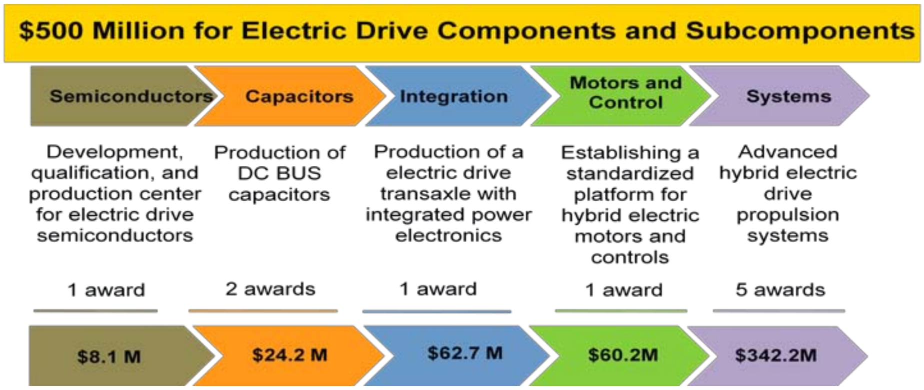


Figure 2.1-7. ARRA grants distribution for Electric Drive Component and Subcomponent Manufacturing Facilities

Long-Term, Post-2020 Challenges

There are substantial challenges in the 2015 to 2020 timeframe, particularly with regard to meeting costs while simultaneously meeting the power density requirements. As PHEVs become dominant in the market and battery requirements grow, it is anticipated that a focused effort will be required beyond 2020 on materials and manufacturing in order to realize an ever increasing need for cost reduction. Achieving reduced vehicle costs will necessitate awareness of system level interactions to optimize the power electronics. In the area of motor development it is probable that concern will increase about the availability of rare earth magnets. It is anticipated that the availability of raw materials will become an increasing challenge for the future. Demand for materials like platinum, nickel, steel and copper will have significant upward impact on prices. From the aspect of competitiveness, the challenge for the industry will be how to use rare raw materials in the most efficient way so as to continue production and avoid supply crises due to continuing increasing demand. Examples of anticipated future R&D needs and challenges include:

- Material Development
    - Optimal utilization of raw materials and electrical components and their re-use and recycling at the end of life
    - Performance improvements of components and systems (reduced weight and power consumption, higher efficiency), enabled by intelligent materials with emphasis on the integration of nanostructures and nanotechnologies into macro systems

    - Light weight motors and new high efficiency materials
- Power Electronics and Component Development
    - Wide bandgap devices for efficiency and higher temperature operation
    - Higher temperature packaging concepts enabling increased silicon temperature operation
    - Substrate development to eliminate thermal mismatches and reduce costs
    - Components, failure prediction, self diagnosis, shut down process, and self healing capabilities
- Motors
    - Enabling adaptive control technologies for in wheel motors that take into account the driver's intentions, the state of the road and the state of charge of the battery to allocate power to different wheels
    - Improvements in vehicle regeneration efficiency

Responding to the pre- and post 2020 challenges, the Advanced Power Electronics and Electric Motors (APEEM) R&D activity currently falls broadly into four areas:

- Power Electronics Research and Development;
- Electric Motor Research and Development;
- Thermal Management Research and Development; and
- Systems Research and Development.

A. Power Electronics Research and Development

The power electronics area has undergone several changes in focus throughout the history of the APEEM activity. Initially, with the use of low-temperature coolants, traditional inverter packages were acceptable. However, with the possible use of high-temperature coolants, innovative heat transfer and packaging concepts would become necessary. The emerging requirement for a boost converter made target achievement more difficult, and emphasis on integrating boost functionality within the inverter was initiated. Power electronics R&D is organized into five subtasks.

New Topologies. The topology work focuses on minimizing the need for bus capacitance and integrating functionality. Topologies are being explored to reduce the required bus capacitance need by 50% or more, thereby helping to attain the volume targets. By integrating multiple functionalities into the inverter (such as integrating the boost converter and the inverter or integrating inverter function for the traction drive system and accessory loads), reduced part counts are possible, thus saving cost, volume, and weight, and increasing reliability.

WBG Semiconductors. Wide band gap (WBG) semiconductors using SiC or GaN offer higher temperature capability and would be very useful in applications where the inverter is subjected to high ambient temperatures (such as under hood or on the transmission) or where higher temperature coolants are employed. In addition, they offer the potential for increased inverter efficiency such that, if they were available at no or small cost premium (when compared to Si switches), they would be the favored technology.

Packaging. Attaining the size, weight, and cost reductions and reliability requirement needed to meet the 2015 and 2020 targets will require innovative module and device packaging. At the module level, the elements associated with removing heat (the spreader, thermal-interface material, and cold plate) occupy a substantial volume. Industry trends associated with cost reduction paths are likely to result in these elements getting larger. The desire to reduce cost by using less silicon will increase the heat flux that must be accommodated, which will increase the size of these heat rejection components. Integrating the power electronics cooling system with an existing cooling system (as a means of reducing cost) is likely to result in higher-temperature coolants that will further exacerbate the situation. If packaging advances are not made, the volume implications of these trends are that the volume of the heat transfer components themselves could equal or exceed the inverter volume targets for 2015 and 2020. Innovative module packaging can mitigate these size increases by eliminating existing interface layers and providing cooling at or very near the heat sources. This could also enable high-temperature coolants to be used with existing silicon devices, resulting in further potential cost savings.

Packaging could also result in reliability and performance improvements through improved bus structures, die-attach methods, materials that provide thermal-expansion matching, as well as techniques that enable double-sided cooling. Advanced device packaging could also result in packing techniques (such as three-dimensional formations) that would contribute greatly to achieving volume targets.

Power electronics packaging improvements go beyond just looking at semiconductor-device-level innovations. There are opportunities to reduce size, weight, and costs of the power electronics through improvements in gate-drive packaging, current sensors, and capacitors and magnetics that will provide better performance and more reliable and higher temperature operation.

Capacitors. Current power electronics solutions employ a voltage source inverter (VSI), which uses a bus capacitor to protect the battery from ripple currents generated in the inverter. In a typical inverter, the bus capacitor occupies about 35% of the inverter. This volume nearly equals the 2015 volume target for the complete inverter and exceeds the 2020 inverter volume target. The situation may be exacerbated by recent trends that result in inverter temperature increases because the ability of capacitors to accommodate ripple currents is severely impacted by elevated temperatures. For example, increasing the capacitor operating temperature from 85°C to 105°C decreases the ability of current commercial polymer-film capacitors to handle ripple currents by 80%. This results in the capacitor size growing by fivefold to accomplish its ripple filtering function. Capacitor performance improvements, particularly at temperatures in the 100°C to 125°C range, can provide the PE development effort with smaller capacitor volumes, which will be important if inverter volume targets are to be achieved.

Polymer-film capacitors and ceramic capacitors will be pursued; both have potential for large benefits but also face significant technical challenges. Recent research has produced polymer films with substantially higher temperature capabilities, but manufacturing problems have prevented the fabrication of large capacitors suitable for an inverter DC bus. The near-term emphasis will be to solve those manufacturing problems, and longer-term efforts will be devoted to reductions in cost and further improvements in performance. The near-term emphasis for ceramic capacitors will be to further demonstrate a design that will prevent catastrophic failures of thin-film capacitors based on ceramic ferroelectric materials, antiferroelectric/ferroelectric phase-switch ceramics, and glass ceramics. After benign failure modes are assured, future efforts will be devoted to material selection and processing methods to improve performance and reduce cost.

Vehicle Charging. Substantial petroleum savings are possible if grid electricity can be used to replace petroleum fuels in a vehicle. The PHEV concept seeks to capture this benefit and deliver petroleum savings. This is achieved by having a large battery pack on the vehicle and fully charging the pack using grid electricity. Several charging systems are being evaluated, ranging from stand-alone chargers to charging systems that utilize a modified inverter system as the charging circuitry. The latter offers many benefits (such as vehicle-to-battery, V2B, and vehicle-to-grid, V2G, capability) not currently available with stand-alone technology. The requirements and specifications for communication between PHEVs and the electric power grid, together with related vehicle test procedures, and for APEEM charging interfaces and infrastructure are currently being developed by industry technical committees, such as SAE and IEEE, and other stakeholders to facilitate the energy and economic benefits of grid electricity technology.

B. Electric Motor Research and Development

Although initial assessments indicated that traditional induction motors might be an acceptable option, it was determined after several years that their specific power and power density would not be able to meet the targets for hybrid electric vehicle (HEV) applications. Internal permanent magnet (IPM) motors became of interest because it appeared that they could meet the targets. By embedding permanent magnets within the rotor to create superior magnetic flux and distribution, smaller, lighter weight IPM motors could provide greater torque. However, the potential to meet the cost target is uncertain because of the increasing cost of the permanent magnets and the need for a boost converter in the power electronics to overcome the back electromagnetic force (EMF) generated by the motor. The following four subtasks comprise Motors R&D.

Permanent Magnet Motors. Because of their superior power density and specific power, IPM motors have become the industry workhorse in HEV applications, and this is anticipated to hold true for the next decade. The 2015 and 2020 cost targets for the traction motor are $385 and $260, respectively; to achieve the 2015 and 2020 cost targets, the motor cost must be reduced by as much as 65%. This requires reductions in all cost elements in the motor and application of advanced materials, designs, and manufacturing processes. Investigation of motor designs that use less-costly (but lower-performing) permanent magnets is also needed.

Magnetic Materials. Current IPM motors use neodymium iron boron permanent magnets because of their superior magnetic properties. However, these magnets are expensive; in a typical 55 kW IPM, the magnets cost in the range of $100 to $200 (this is about 50% of the 2015 motor cost target and 60% of the 2020 motor cost target). In addition, their Curie temperature places thermal limits on the motor that require either limiting the duty of the motor or investing in thermal management systems to transport heat from the motor. Magnetic materials that possess magnetic properties similar to neodymium iron boron magnets but cost less and have higher temperature limits are needed if the IPM has a reasonable chance of meeting the cost targets.

Non-Permanent Magnet Motors. The development of motors that do not use permanent magnets but yield IPM-like performance is being pursued. This program includes R&D to solve issues with existing motor designs that will allow their use in advanced vehicle applications, such as switched reluctance motors, as well as novel designs, such as the U-machine that was made possible by the novel flux-coupling method developed by the APEEM effort. The objective of these development efforts is to overcome the PM motor deficiencies noted above but yield characteristics (power density and specific power) similar to PM technology.

New Materials. Achieving cost targets will require improvement in all design elements of the motor. Because of their prominence in the motor cost, permanent magnets have been given much attention. However, they represent only about 30% of the motor cost for existing IPM designs. Attaining the levels of cost reduction required to meet 2015 and 2020 motor cost targets (50% to 75%) requires expanding the effort to all materials in the motor. New lamination materials, soft magnetic core materials, and a number of other alternatives should be examined, since they may enable new design freedoms that can reduce the gaps in reaching the targets.

C. Thermal Management Research and Development

The Advanced Thermal Management for Vehicle Power Electronics and Electric Machines research activity is focused on developing thermal management technologies that enable advanced power electronics and electric machine technologies that are efficient, small, light, low cost, and reliable. Specifically, it is concerned with addressing and overcoming any and all thermal barriers to these systems within the systems context of the entire vehicle—ultimately working towards a total vehicle thermal system that is low-cost, small, light, reliable, effective, and efficient.

Close cooperation with industry and research partners is important in developing candidate thermal management technologies to meet the program goals. Additionally, there are close ties to the power electronics packaging focus area. The power electronics package, including the device layout, material selection, and topology, define the package thermal resistance and required heat flux levels and the induced thermal stresses. Conversely, aggressive heat transfer performance may enable higher power densities and novel package designs. The thermal management research is organized into three distinct subtasks.

Thermal System Integration. The objective of this subtask is to facilitate the integration of APEEM thermal management technologies into viable advanced electric traction drive systems including hybrid electric, plug-in hybrid electric, electric, and fuel cell vehicles. It is widely recognized that innovative thermal management is needed to protect power-electronics components from excessive heat and is key to enabling program targets of cost, volume, weight, and life. However, there is a wide variety of potential thermal technologies; a given thermal solution can impact the electronics design space including package configuration, architecture, and material selection. Conversely, these parameters, along with the vehicle architecture, define the thermal requirements.

This research area is focused on understanding the tradeoffs and matching the thermal requirements of the electric traction drive with a range of packaging options and heat transfer mechanisms. Rapid parametric models are being developed and applied early in the design process to help select the most appropriate thermal management technology for a given traction drive system. Inputs into the models include fundamental heat transfer performance characteristics, package geometry, various material properties, and a range of system thermal requirements. Outputs include both steady-state and transient thermal loading and device temperatures under various conditions.

Characterization and Development of Heat-Transfer Technologies. This activity seeks to provide an accurate and objective characterization of the thermal performance of heat transfer technologies within the context of automotive requirements, and to further develop and demonstrate the promising technologies that enable reductions in cost, volume, and weight. On the characterization side, this research includes fundamental characterization of heat-transfer mechanisms such as the performance of single-phase and two-phase jets and sprays, air-cooled heat exchangers, pool-boiling techniques, surface-area-enhancement techniques as well as thermal-materials performance. Detailed numerical modeling of the technologies such as computational fluid dynamics and finite-element analysis are used to further understand the heat-transfer mechanisms and the conditions under which these technologies may be suitable for electric traction drive cooling.

Promising technologies from the fundamental investigations may be further refined and optimized to the point of a prototype development in which the heat exchanger is integrated into an actual inverter or other PEEM component. Recent examples include the floating-loop inverter, which used two-phase pool boiling of a refrigerant, a liquid jet-impingement heat exchanger that was integrated into an existing automotive inverter, and an inverter designed around a direct-cooled substrate concept. In each case, the total package with integrated heat exchanger was evaluated for performance and measured against program targets of cost, weight and volume. Performance data from both fundamental characterizations and prototype demonstrations are published and transferred to industry partners.

Thermal Stress and Reliability. This research activity will develop predictive modeling capabilities to assess the impacts of thermal stress on the life of advanced inverter package designs and to demonstrate the modeling approach by evaluating dynamic thermal stresses of advanced PEEM designs. Thermally induced stress is a major issue related to reliability, which is directly linked to heat dissipation and the electronics package configuration. Vehicle manufacturers and component suppliers must run extensive life and reliability testing on all new technologies and designs to understand the response to thermal cycling and environmental conditions.

This effort will closely engage industry to develop and validate advanced predictive modeling processes using techniques such as "physics of failure" to evaluate the impacts of new technologies on thermal stresses, life, and reliability. The ultimate goal is to reduce the amount of testing and the cost and time to market for new technologies. Predictive modeling tools, applied early in the development process can help guide research decisions, streamline development time, and identify potential barriers to meeting life and reliability goals. Physical modeling techniques will be used in conjunction with accelerated life testing to identify failure modes and relative impacts on reliability beyond what is currently available.

Analysis of the thermal requirements of competing electric traction drive system architectures and component topologies along with the thermal performance of candidate heat transfer technologies helps to guide thermal research objectives and increases the likelihood that technology meets program targets and is viable within an automotive system context.

D. Systems

Significant technical and cost advancements in electric drive technology must be achieved. The systems R&D includes:
Traction Drive System Development. Current on-the-road systems are modular in nature (i.e., an inverter is connected to a motor). Significant savings in cost, weight, and volume are possible with integrated systems where the motor and inverter are produced as a single unit. Countering these benefits, however, is a loss in system flexibility afforded by modular systems. (In a modular system, advances in inverters or motors can quickly be implemented because each is a separate unit while, in an integrated design, the entire unit must be redesigned.) Thus the focus of these efforts is to capture the benefits of integrated concepts but keep the design flexibility of the modular approach. In either concept, to significantly reduce system weight, cost, and volume, technologies must be developed that are capable of reliable higher-temperature operation. In order to attain long-term goals, technologies that advance the state of the art in the following areas must be considered: a) advanced cooling technologies; b) inverter and motor topologies; c) packaging innovations; d) bus structures; e) semiconductor devices; f) capacitors; g) sensors; h) magnetic; and i) rotor and stator manufacturing processes.

Benchmarking. Benchmark testing of HEV drive trains and power electronics and electric motor components is an integral part of the APEEM activity and complements the R&D portfolio. It is performed to fully characterize the performance of the technology across the complete range of electrical and thermal parameters that are applicable, and it is coordinated with the vehicle-level benchmarking within the DOE Vehicle Technologies Program. In most cases, this is information that is not available from the manufacturer or is information the manufacturer chooses not to make available. Benchmarking information is used to assist in program planning efforts, developing and executing specific projects, and supporting the partnership with the OEMs.

Tasks

Specific tasks for Advanced Power Electronics and Electric Motors R&D are summarized in Table 2.1-6.

Table 2.1-6 Tasks for Advanced Power Electronics and Electric Motors R&D

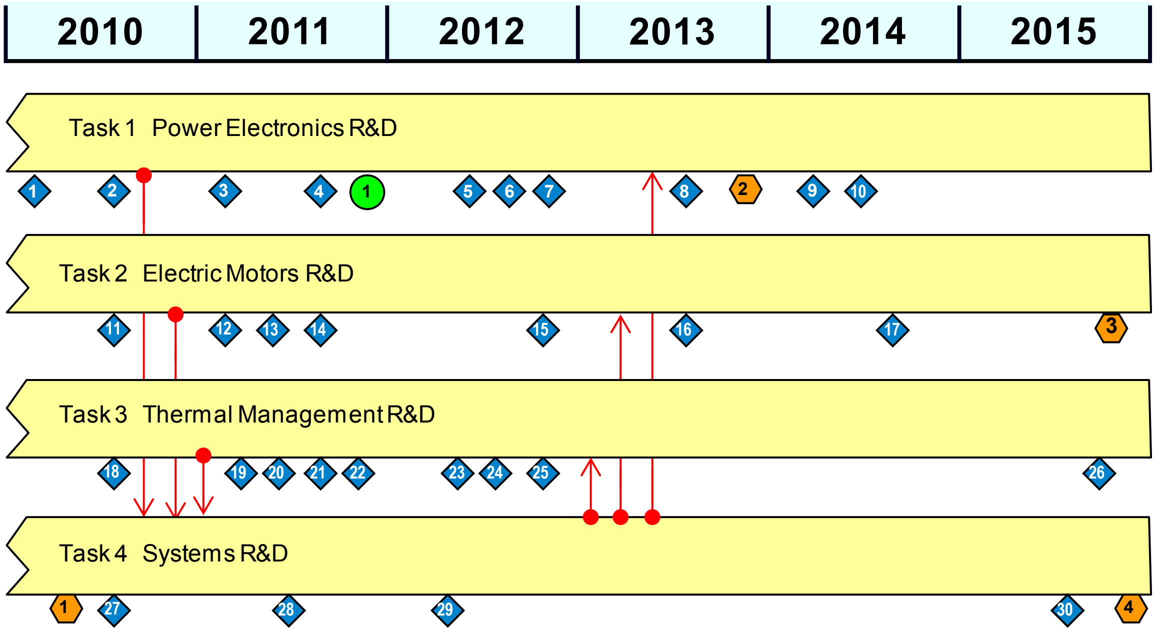
Task	Title	Barriers Addressed
Task 1	**Power Electronics Research and Development** *New Topologies*- achieve significant reductions in PE weight, volume, and cost, and improve performance: • Reduce need for capacitance by 50%–90%, to yield 20% – 35% inverter volume reduction and cost reduction • Reduce part count by integrating functionality, to reduce inverter size and cost, and increase reliability • Reduce inductance, minimize electromagnetic interference and ripple, and reduce current through switches, all resulting in reduced cost *WBG semiconductors* - higher reliability and higher efficiency, and enable high-temperature operation *Packaging* - greatly decrease size and cost • Develop module packaging to reduce inverter size by 50% or more, reduce inverter cost by 40%, enable use of air • Enable silicon devices to be used with high-temperature coolant to achieve a 25% cost reduction • Device packaging to reduce stray inductance, improve reliability, and enable module packaging options • Couple packaging improvements with heat transfer improvements *Capacitors* - Improved performance can reduce capacitor size by 25%, reduce inverter size by 10%, and increase temperature limit *Vehicle charging* - Provide the vehicle charging function with bidirectional capability in a policy-neutral manner at virtually no additional cost	A, B, C, D, E, F
Task 2	**Electric Motor Research and Development** *Permanent magnet motors* - cost reductions of 75% are required to meet the 2020 target • Work on all aspects of motor design may reduce cost by 25%–40%. *Magnetic materials* - magnetic material costs total 50%–75% of the motor targets for 2015 and 2020, respectively. Work focusing on reducing cost and increasing temperature capability could reduce motor costs by 5%–15%. *Non-PM motors* - match performance of IPM motors to reduce motor and system cost • Magnet cost (about $200) is about 75% of the 2020 motor cost target; eliminating PMs reduces motor cost by 30% • The back EMF of IPM requires a boost converter, which brings the power electronics cost above the 2015 or 2020 cost targets; eliminating the boost converter saves 20% in power electronics cost • Poor power factors for IPMs cause larger currents, increasing size and cost of PE; improved power factor saves 15% PE cost Increasing the constant power speed ratio to 8:1 (current systems are 4:1) can effect savings in transmission *New materials* – laminations and core materials could save 20% of motor cost.	A, B, C, D, E
Task 3	**Thermal Management Research and Development** *Thermal system integration* -	A, B, C, D, E

Table 2.1-6 Tasks for Advanced Power Electronics and Electric Motors R&D		
Task	**Title**	**Barriers Addressed**
	• Define thermal requirements and R&D objectives • Facilitate viable thermal solutions • Link thermal technologies to electric traction drive systems *Heat transfer technologies* - • Detailed characterization of performance of candidate heat transfer technologies • Provide experimental data and fundamental thermal models • Develop and demonstrate promising technologies to achieve APEEM targets *Thermal stress and reliability* - • Develop advanced predictive thermal stress and reliability modeling tools • Guide research decisions, streamline development time, and identify potential barriers to meeting life and reliability goals	
Task 4	**Systems Research and Development** *Traction drive system* - Provide modular and integrated solutions to meet size, weight, and cost (2015 and 2020) targets for the drive system *Benchmarking* - Vital to program planning and project performance activities	A, B, C, D, E

Milestones and Decision Points

The APEEM activity milestones are shown in the following chart.

Advanced Power Electronics and Electric Motors R&D



◆ **Milestone**

1. Begin testing and fabrication of high temperature capacitors
2. Demonstrate a 55 kW segmented inverter prototype that is capable of operating with an amount of bus capacitance reduced by at least 60% compared to a standard VSI.
3. Complete performance testing of prototype ZCSI inverter
4. Receive high-temperature inverter from Delphi
5. Development of new device packages
6. Demonstrate new SiC production technique (NASA)
7. Develop ZCSI concept for architectures using more than one motor
8. Demonstrate inverter prototypes meeting 2015 targets (new solicitation)
9. Complete fabrication and performance testing of air-cooled inverter
10. Advanced module and device packages
11. Fully model finalized ORNL SRM design in dynamic simulations.
12. Complete performance testing of motor using novel flux coupling
13. Complete performance testing of SR motor
14. Complete development of improved IPM from GE

◆ **Milestone**

15. Identify candidate non-rare earth magnet material compositions
16. Demonstrate motor prototypes meeting 2015 targets (new solicitation)
17. Select final non-rare earth magnet material composition
18. Conduct Thermal Analysis of APEEM Power Device Packaging concepts using Rapid Parametric Thermal Systems modeling techniques.
19. Complete assessment of surface enhancement technologies for single-phase and two-phase cooling
20. Develop design guidelines for a range of air cooling technologies
21. Develop reliability models for sintered interfaces
22. Develop parametric modeling techniques for assessing electric motor thermal management technology tradeoffs
23. Complete assessment of thermal performance and reliability of bonded interfaces
24. Complete assessment of thermal performance of alternative refrigerant
25. Publish reliability modeling techniques for advanced electronics package topologies

◆ **Milestone**

26. Demonstrate advanced thermal management technology into APEEM inverter / motor concept hardware
27. Complete Prius III benchmarking and TM report.
28. Test prototype integrated motor/inverter
29. Deliver 55kW integrated motor/inverter
30. Demonstrate traction drive system meeting 2015 targets

⬢ **Technology Program Output**

1. Traction drive system meeting 2010 targets
2. High temperature capacitor meeting targets
3. Non-rare earth permanent magnet material meeting targets
4. Traction drive system meeting 2015 targets

● **Supporting Input**

1. Charging standards for PHEV charging from the Grid Interaction TT

2.2. Vehicle and Systems Simulation and Testing

Vehicle and Systems Simulation and Testing (VSST) includes a number of crosscutting activities that are not specifically tied to battery and electric or hybrid drive technologies; rather, they tie all of the VTP hardware R&D together. The VSST activity comprises work in five areas: 1) modeling and simulation; 2) component and systems evaluations; 3) laboratory and field vehicle evaluations; 4) electric drive vehicle codes and standards; and 5) heavy vehicle systems optimization. This subprogram includes all of VTP's efforts directly related to the planning and modeling, development, and evaluation of advanced hybrid, electric, and plug-in hybrid drive systems for passenger and commercial vehicles. The subprogram also conducts simulation studies, component evaluations, and testing to establish needs, goals, and component/vehicle performance validation. This subprogram's funding contributes to the 21CTP and the FreedomCAR and Fuel Partnership.

System-level simulations help specify the necessary performance characteristics of the hardware to establish goals and predict the overall vehicle efficiency and performance for a given configuration. Both simulation and testing activities are used to evaluate the development and progress of individual components, and predict how well they will integrate with other components being developed. Tests and simulations also evaluate how well the program is approaching its whole-vehicle goals and provide technical inputs to mathematical models of projected oil reduction, greenhouse gas (GHG) emission reductions, and economic benefits.

Dynamometer, closed-track and on-road evaluations of advanced technology vehicles are utilized to identify potential limits to market penetration and petroleum reduction to inform R&D activities. These evaluations are also used to identify component, vehicle, and testing codes and standards that need to be updated for new vehicle technologies, and to develop and validate new codes and standards in partnership with government and industry stakeholders. In addition, the VSST activities include R&D to reduce heavy vehicle auxiliary loads and parasitic loses, many of which are also applicable to passenger vehicles.

2.1.1. Vehicle and Systems Simulation and Testing

The Vehicle and Systems Simulation and Testing (VSST) subprogram supports the development of advanced technology vehicles and components in an effort to maximize vehicle efficiency, and the displacement of imported petroleum used in the transportation sector, thereby reducing GHG emissions. VSST directs a portion of the Vehicle Technology research and development efforts of national laboratories, OEMs and their industry partners, and participating universities. The subprogram integrates modeling, systems analysis, and testing efforts to define R&D technical targets and requirements, guide technology development, and validate technology performance for passenger and commercial vehicles. The integration of advanced energy storage systems, power electronics, electric motors, and other technologies with the proper component and system controls is a primary focus of the VSST subprogram. Advanced computer models and simulation tools are used to:

- Develop performance targets for vehicle platforms and their components.
- Rapidly evaluate components and systems through Hardware-In-the-Loop testing.
- Develop advanced control strategies to optimize the performance and efficiency of advanced hybrid electric, plug-in hybrid electric, battery electric, and fuel cell vehicles.
- Collect and analyze advanced vehicle characteristics and performance data that are used to predict market potential and petroleum displacement, which then inform program-wide research.

The activity also performs R&D on heavy vehicle systems to achieve the fuel efficiency goals of the 21st Century Truck Partnership by:

- Collecting real-world heavy vehicle and fleet duty and drive cycle data
- Developing methods to predict and measure the effects of idle reduction technologies
- Developing advanced heavy vehicle systems models
- Reducing non-engine parasitic energy losses from aerodynamic drag, friction and wear, under-hood thermal conditions, and accessory loads

Goals

Key overall goals are as follows:

- Demonstrate market readiness of grid-connected vehicle technologies by 2015.
- Support the laboratory and field evaluations of large-scale demonstration fleets of advanced commercial and passenger PHEVs and EVs.
- Collect data on the interaction of electric-drive vehicles with charging infrastructure and the electric utility grid in order to understand electric-drive vehicle usage and charging patterns and their impacts.
- Address codes and standards needed to enable wide-spread adoption of electric-drive transportation technologies.
- Complete the successful deployment of *Autonomie* as an industry recognized advanced component and vehicle modeling and simulation tool, as well as the integration of a detailed vehicle cost model into *Autonomie*.
- Expand activities to develop and integrate technologies that address aerodynamic load reduction, hybridization, auxiliary load reduction, and idle reduction to greatly improve commercial vehicle efficiency.
- Validate, in a systems context, performance targets for deliverables from the Power Electronics and Energy Storage Technology R&D activities.

Challenges and Barriers

The barriers facing the VSST subprogram's strategic goals are:

A. ***Risk Aversion.*** Manufacturers are reluctant to invest in and introduce new technologies that may in the future become warranty or liability issues; this aversion is especially acute without a strong demand for the technologies from the marketplace. Unfortunately, high fuel economy in light-duty passenger vehicles has historically been a low priority to consumers.

B. ***Cost.*** Effective, timely evaluation of advanced vehicular components and configurations is needed. Historically, integration and evaluation of advanced technologies have required multiple vehicle builds and long term testing which are expensive and time consuming.

C. ***Infrastructure.*** For consumers to accept, purchase, and use vehicles with advanced propulsion systems, the proper facilities and infrastructure must be in place to enable the full utilization of the technology with minimal impact to the usage habits of the consumer.

D. ***Lack of standardized test protocols.*** Standardized test protocols for measuring performance and fuel economy are being developed through the efforts of the VSST subprogram. However, protocols do not exist to measure or quantify the environmental benefits, reliability/durability, or system level improvements in advanced vehicles. Furthermore, current heavy-duty 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 vehicle hybridization technology.

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

F. ***Constant advances in technology.*** Current and future advances in respective technologies require modeling and simulation tools to be continually updated and/or enhanced in order to ensure the accuracy of simulation results.

Approach for Overcoming Barriers/Challenges

In order to address the barriers and challenges it faces, the VSST subprogram activities are divided into five (5) main focus areas, as described below:

1. **Modeling and Simulation**
   Activities under this area have resulted in the development of a unique set of software tools to support Vehicle Technologies research. Among these tools are VISION, CHAIN, and GREET, which are used to forecast national-level energy and environmental parameters including oil use, infrastructure economics, and greenhouse gas contributions of new technologies. Additionally, PSAT (Powertrain Systems Analysis Toolkit) allows dynamic analysis of vehicle performance and efficiency to support detailed design, hardware development, and validation. *Autonomie* builds upon the experience gained with PSAT, and offers users a software environment and framework for automotive control system design, simulation and analysis. *Autonomie* enables the development, sharing, and rapid application of models, control algorithms and processes from the entire automotive community. The program is currently in the BETA stage of development.

2. **Component and Systems Evaluation**
   This focus area integrates modeling and simulation with hardware in the laboratory to develop and evaluate propulsion subsystems in a full vehicle level context. This is accomplished through Hardware-in-the-Loop (HIL) simulation, which provides a novel and cost effective approach to evaluating advanced automotive component and subsystem technologies. The versatile Mobile Automotive Technology Testbed (MATT) serves as a unique HIL platform for advanced powertrain technology evaluation in an emulated vehicle environment. Through this activity, production vehicle and components are extensively tested to ensure that VTP-developed technologies represent significant advances over technologies that have been developed by industry. In addition to the above activities, as components and systems are developed, analysis will be undertaken to identify and evaluate whether any potentially deleterious health impacts can be caused by these new technologies. One example may be the potential for inductive charging of electric vehicles to cause problems for individuals who rely on pacemakers for cardiac regularity.

3. **Laboratory and Field Vehicle Evaluation**
   Under this focus area, the Advanced Vehicle Testing Activity (AVTA) works with industry partners to accurately measure the real-world performance of advanced technology vehicles via a testing regime based on test procedures developed with input from industry and other stakeholders. Testing activities involve Baseline Performance Testing, Fleet Testing, and Accelerated Reliability Testing.

4. **Codes and Standards Development**
   A comprehensive and consistent set of codes and standards addressing grid-connected vehicles and infrastructure is essential for the successful market introduction of electric-drive vehicles. VSST is active in driving the development of these standards through committee involvement and technical support by the national labs. VSST also supports activities of the Grid Interaction Tech Team, a government/industry partnership aimed at ensuring a smooth transition for vehicle electrification by closing technology gaps that exist in connecting vehicles to the electric grid.

5. **Heavy Vehicle Systems Optimization**
   This focus area involves research and development on a variety of pathways to improve the energy efficiency of heavy vehicles. Projects in this focus area involve reducing the aerodynamic drag of heavy vehicles by controlling the tractor-trailer flow field and tractor-trailer integration. Thermal management approaches increase the engine thermal efficiency and reduce parasitic energy uses and losses. The development of advanced technologies is also undertaken to improve the fuel efficiency of critical engine and driveline components by characterizing the fundamental friction and wear mechanisms.

Activities from these five focus areas will target the previously described barriers and challenges through the following mechanisms:

- ***Industry collaboration.*** VSST will continue to collaborate with industry partners to develop modeling and simulation tools to identify areas of technology development that will result in the highest impact on vehicle efficiency at the lowest cost.
- ***Data collection and analysis.*** Through its operational and fleet testing activities, VSST will continue to collect and analyze data on the operational characteristics and usage patterns of electric-drive vehicles. This will enable the development of appropriate technologies and infrastructure, as well as inform educational and outreach programs so that consumers can make more informed vehicle purchasing decisions thereby stimulating market demand for electrified vehicles.
- ***Codes and standards development.*** VSST will expand its efforts in helping to develop codes and standards related to advanced vehicle test procedures, charging infrastructure, and electric grid connectivity. This will be accomplished by leading and participating in committees that develop standards such as SAE J1711 and J1634.
- ***Forward-looking modeling tools.*** VSST will continue the ongoing development and deployment of *Autonomie* and other advanced analytical tools and techniques to standardize the modeling, design, and simulation process. Furthermore, with substantial input from industry partners, these tools will be updated continually to accurately reflect the capabilities of the most advanced vehicle propulsion systems and component technologies.

Planned Activities

VSST will continue its ongoing activities supported by its annual operating budget through the previously described five focus areas. These research and development activities will be carried out through national laboratories such as Argonne National Lab, Idaho National Lab, National Renewable Energy Lab, Oak Ridge National Lab, Pacific Northwest National Lab, and Lawrence Livermore National Lab, as well as by industry partners contracted through the National Energy Technology Laboratory. The tasks, along with the associated barriers, are summarized in Table 2.2-1.

Table 2.2-1 Tasks for Vehicle and Systems Simulation and Testing

Task	Title	Barriers Addressed
1	***Vehicle Modeling and Simulation*** • Develop *Autonomie* vehicle modeling and simulation platform, and convert existing PSAT models and data into the new platform. • Develop detailed cost model(s) and integrate into *Autonomie*. • Conduct modeling studies for medium- and heavy-duty vehicles, including simulations of powertrain controls, performance impacts of under-hood thermal conditions, and the application of plug-in hybrid electric propulsion systems on medium-duty trucks • Evaluate potential PHEV powertrain efficiency improvements through proper configuration, sizing, and controls relative to driving behavior and prior knowledge of drive-cycle • Continue ongoing support for the Vehicle Systems Analysis Tech Team (VSATT), a government/industry partnership aimed at evaluating the performance and interactions of automotive powertrain components and subsystems • Continue validation of vehicle models through the collection of real-world performance data • Through modeling activities, evaluate issues such as the impact of thermal preconditions on energy storage systems in electric-drive vehicles, the potential impact of integrating renewable electricity generation with vehicle charging infrastructure, and the effects of advanced electric powertrain components on vehicle emissions	A, B, E, F
2	***Component and Systems Evaluation*** • Evaluate various control strategies for advanced electric-drive vehicle propulsion system using the Mobile Automotive Technology Testbed (MATT) • Demonstrate and evaluate smart-charging components and infrastructure. • Analyze the effects of thermal management strategies on battery systems using Hardware-in-the-Loop (HIL) • Develop the CoolCalc HVAC tool to evaluate the heating and cooling needs and the appropriate selection of components for passenger compartment comfort in heavy-duty trucks • Health impacts of inductive charging	A, B, D, E, F
3	***Laboratory and Field Vehicle Evaluation*** • Conduct real-world analysis and validation of emerging electric-drive vehicle technologies (To date, over 1.4 million miles of data has been collected on 258 different vehicles comprising of twelve models). • Conduct preliminary Level 1 and more comprehensive Level 2 testing of advanced electric-drive vehicles developed through the PHEV Technology Advancement and Demonstration Activity.	A, B, C, E, F

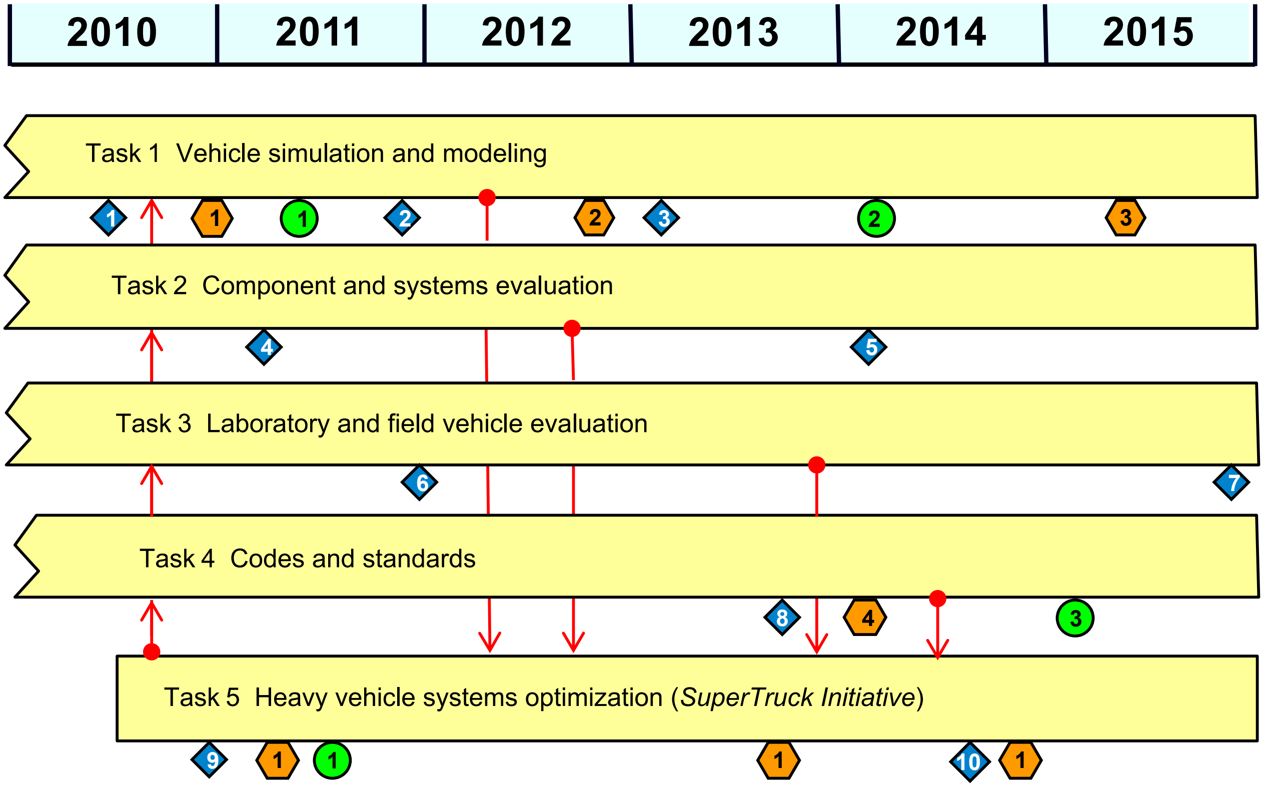
Table 2.2-1 Tasks for Vehicle and Systems Simulation and Testing

Task	Title	Barriers Addressed
	• Develop and support the Electric Drive Advanced Battery (EDAB) test vehicle to evaluate the performance of pre-production energy storage systems in on-road, in-vehicle conditions • Benchmark lean gasoline-direct-injection (GDI) engine combustion processes • Collect data and conduct analysis to evaluate the duty-cycle of various medium- and heavy-duty fleets • Install significant upgrades to the Advanced Powertrain Research Facility (APRF) at ANL, to support thermally loaded EPA 5-cycle testing	
4	***Codes and Standards Development*** Continue to participate (through the national labs and Grid Interaction Tech Team) in task forces and committees in developing the following standards related to vehicle/grid connectivity. • SAE J1711: *Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles* • SAE J1634: *Electric Vehicle Energy Consumption and Range Test Procedure* • SAE J1772: *Electric Vehicle Conductive Charge Coupler* • SAE J2847: *Communication Between Plug-In Vehicles and the Utility Grid* • SAE J2836: *Use Cases for Communication Between Plug-In Vehicles and the Utility Grid, Supply Equipment, and for Reverse Power Flow* • SAE J2344: *Guidelines for Electric Vehicle Safety*	A, D
5	***Heavy Vehicle Systems Optimization*** • Model, test, and validate that technologies developed by the VSST and the other VT subprograms collaborating on the *SuperTruck Initiative* contribute to achieving the goals. [The *SuperTruck Initiative* is a cross-cutting activity supported by several VT subprograms, including VSST, and funded by both ARRA and annual appropriations.]	A, B, D, E, F

Milestones and Decision Points

The milestones for VSST are shown in the figure that follows. VSST is dependent on the availability of data/models and experimental hardware from other VT research and development subprograms, as well as the availability of technologies from worldwide sources.

Vehicle and Systems Simulation and Testing



◆ Milestone

1. *Autonomie* beta release
2. Continue to validate *Autonomie* with real-world vehicle test results
3. Continue to generate and use real-world component and system performance to validate *Autonomie*
4. Evaluate control strategies for advanced electric-drive using Mobile Automotive Technology testbed
5. Evaluate smart-charging components and infrastructure
6. Complete 3 million miles of on-road HEV/PHEV evaluation.
7. Complete 112 million miles of on-road HEV/PHEV evaluation.

◆ Milestone

8. Finalize grid/vehicle bidirectional charging standards
9. Start *SuperTruck Initiative* projects
10. Complete evaluation of technologies needed to meet *SuperTruck* goals

⬢ Technology Program Output

1. Revised targets for advanced technology components and subsystems, to each technology area.
2. Full commercial deployment of *Autonomie*.
3. Demonstrated commercial viability of efficient Class 8 trucks.
4. Standardized grid/vehicle connectivity and interoperability protocols.

● Supporting Input

1. Revised program targets from each technology area.
2. Commercial availability of PHEVs.
3. Commercial availability of BHEVs.

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2.3. Advanced Combustion Engine R&D

The Advanced Combustion Engine R&D (ACE R&D) subprogram supports the mission of the Vehicle Technologies Program (VTP) to develop more energy-efficient and environmentally friendly technologies for highway transportation vehicles that will meet or exceed performance expectations, enable the United States to use significantly less petroleum, and reduce greenhouse gas and regulated emissions. Dramatically improving the efficiency of internal combustion engines and enabling their introduction in conventional vehicles, as well as hybrid-electric and plug-in hybrid electric vehicles (HEVs and PHEVs), is an extremely cost effective approach to increasing vehicle fuel economy over the next 30 years. Improvements in engine efficiency alone have the potential to increase passenger vehicle fuel economy by 25 to 40 percent and commercial vehicle fuel economy by 30 percent with a concomitant reduction in greenhouse gas emissions, more specifically, carbon dioxide emissions.

The National Research Council expressed full support for advanced combustion engine R&D in their 2010 report[1] -

> "There seems to be little doubt that, regardless of the success of any pathways discussed, the internal combustion engines (ICE) will be the dominant prime mover for light-duty vehicles for many years, probably decades. Thus it is clearly important to perform R&D to provide a better understanding of the fundamental processes affecting engine efficiency and the production of undesirable emissions. …it is important to maintain an active ICE and liquid fuels R&D program at all levels, namely, in industry, government laboratories, and academia, to expand the knowledge base to enable development of technologies that can reduce the fuel consumption of transportation systems powered by ICEs. …"

The ACE R&D subprogram focuses on removing critical technical barriers to the commercialization of higher-efficiency, advanced internal combustion engines for passenger and commercial vehicles. The R&D approach is to simultaneously improve engine efficiency and meet future federal and state emissions regulations through a combination of combustion and fuels technologies that increase efficiency and minimize in-cylinder formation of emissions, and cost effective aftertreatment technologies to further reduce exhaust emissions with minimal energy penalty.

The ACE R&D subprogram activities are undertaken in collaboration with industry, national laboratories, and universities, and in conjunction with the FreedomCAR and Fuel Partnership and the 21st Century Truck Partnership (21CTP).

The primary R&D directions are to:

- Improve the efficiency of light-duty engines for passenger vehicles (cars and light trucks) and heavy-duty engines for commercial vehicles (heavy trucks) through advanced combustion research and minimization of thermal and parasitic losses;
- Develop aftertreatment technologies integrated with combustion strategies for emissions compliance and minimization of efficiency penalty; and
- Explore waste energy recovery with mechanical and advanced thermoelectric devices to improve overall engine efficiency and vehicle fuel economy.

The Advanced Combustion Engine R&D subprogram consists of Combustion and Emission Control R&D, and Solid State Energy Conversion.

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[1] *Review of the Research Program of the FreedomCAR and Fuel Partnership: Third Report,* Committee on Review of the FreedomCAR and Fuel Research Program, Phase 3, National Research Council, 2010 .

2.3.1 Combustion and Emission Control R&D

The Combustion and Emission Control R&D activity focuses on enabling energy-efficient passenger and commercial vehicles powered by advanced combustion engines that use clean, petroleum- and non-petroleum-based fuels, and hydrogen**.** This research activity focuses on developing technologies for light-, medium-, and heavy-duty engines operating in advanced combustion regimes, including homogeneous charge compression ignition (HCCI) and other modes of low-temperature combustion (LTC), which will increase efficiency beyond current advanced diesel engines and reduce engine-out emissions of oxides of nitrogen (NO_x) and particulate matter (PM) to near-zero levels. The goal of this activity is to improve the thermal efficiency of combustion engines by optimizing combustion, fuel injection, air handling, emission control, and waste heat recovery systems, along with reducing friction and pumping losses,

In addition, this activity ensures that development of new vehicle technologies complies with existing emission standards, but also considers the possibility of unregulated emissions causing negative health impacts or unintended consequences. This activity proactively evaluates the potential air quality and human health impacts of changes in fuel composition, engine, lubricant, and aftertreatment technologies before they are widely implemented in transportation vehicles.

The Combustion and Emission Control R&D activities are closely coordinated with the activities of the Fuels Technology subprogram which supports R&D to provide vehicle users with fuel options that enable high fuel economy, deliver lower emissions, contribute to petroleum displacement, and are cost competitive. Different fuel characteristics and reduced property variability may be needed to meet engine efficiency and emissions goals. Without suitable fuels, high-efficiency advanced combustion engines may not be able to be introduced into the market and oil savings will not be realized. Work is also coordinated with the Vehicle and Systems Simulation and Testing (VSST) Subprogram to ascertain contribution of the R&D results to achieving the vehicle system fuel economy goals.

Goals

The following goals are intended to enable VTP to meet energy-efficiency improvement targets for advanced combustion engines suitable for passenger and commercial vehicles, as well as to address technology barriers and R&D needs that are common between passenger and commercial vehicle applications of advanced combustion engines. The peak thermal efficiency goal of 45 percent, initially set in 2003 for light-duty engines for passenger vehicles by the FreedomCAR and Fuels Partnership, will be demonstrated in 2010. Since engines for passenger vehicles rarely operate at the peak efficiency point, it is important to improve the engine efficiency over a broad operating range to maximize real-world vehicle fuel economy. Therefore, going forward, the goals for passenger vehicles are stated in terms of fuel economy improvements. For commercial over the road Class 8 trucks, however, since they do operate close to the peak engine efficiency point most of the time, the goals for heavy-duty engines are stated for peak efficiency and approximate fuel economy improvements.

- By 2015, improve the fuel economy of light-duty gasoline vehicles by 25 percent and of light-duty diesel vehicles by 40 percent, compared to the baseline 2009 gasoline vehicle.
- By 2015, improve heavy truck engine thermal efficiency to 50 percent with demonstration in commercial vehicle platforms. This represents about a 20 percent improvement over current engine efficiency.
- By 2018, further increase the thermal efficiency of a heavy truck engine to 55 percent which represents about a 30 percent improvement over current engines.

The Tables 2.3-1 and 2.3-2 show the technical targets for the Combustion and Emission Control (C&EC) Activity for passenger vehicle engines (cars and light trucks) and heavy truck engines for commercial vehicles, respectively. Through simulation and experimentation, this activity will also conduct R&D on advanced thermodynamic strategies that may enable engines to approach 60 percent thermal efficiency.

Table 2.3-1 Technical Targets for Passenger Vehicle Engines

Characteristics	Fiscal Year		
	2007	2010	2015
Reference peak brake thermal efficiency[a], %	32	34	*NOTE: After 2010, engine efficiency targets transitioned to vehicle fuel economy improvement targets*
Powertrain cost[b,c], $/kW	35	30	
FreedomCAR and Fuel Partnership Goals			
ICE Powertrain			
Peak brake thermal efficiency, %	42	45	
Part-load brake thermal efficiency, % (2 bar BMEP[d] @1500 rpm)	29	31	
Cost, $/kW	35	30	
VTP/C&EC Vehicle Level Goals			
Fuel economy improvement, % (gasoline/diesel)			25/40
Emissions[e], g/mile	Tier 2, Bin 5	Tier 2, Bin 5	Tier 2, Bin 2
Durability[e], hrs.	5000	5000	
Thermal efficiency penalty due to emission control devices[f], %	<3	<1	<1

[a] Current production, EPA-compliant engine.

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

[c] Constant out-year cost targets include maintaining powertrain (engine, transmission, and emission control system) system cost while increasing complexity.

[d] Brake mean effective pressure.

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

[f] Fuel-derived reductants, electricity for heating and operation of aftertreatment devices, and other factors such as increased exhaust back-pressure, reduce engine efficiency. A cycle average thermal efficiency loss of 1 to 2% is equivalent to a 3 to 5% fuel economy loss over the combined Federal Test Procedure drive cycle.

Table 2.3-2 Technical Targets for Heavy Truck Diesel Engines

Characteristics	Fiscal Year			
	2002 (baseline)	2006	2015	2018
Engine thermal efficiency, %	~40	50	50	55
NO_X emissions, g/bhp-h	<2.0	<0.20	<0.20	<0.20
PM emissions, g/bhp-h	<0.1	<0.01	<0.01	<0.01
Stage of development	Commercial	Laboratory Demo	Prototype	Prototype

Challenges and Barriers

A. ***Lack of fundamental knowledge of advanced engine combustion regimes.*** Engine efficiency improvement, engine-out emissions reduction, and minimization of engine technology development risk are inhibited by an 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 for regimes of interest, as well as by an inadequate capability to accurately simulate these processes. An insufficient knowledge base will inhibit the development of advanced 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 diesel-like efficiencies over the full load range while meeting prevailing EPA emissions standards with greatly reduced aftertreatment system requirements.

B*.** ***Lack of cost-effective emission control. Meeting EPA standards for oxides of nitrogen and particulate matter emissions with little or no fuel economy penalty will be a key factor for market entry of advanced combustion engines. Controlling NOx from lean-burn gasoline engines will be challenging and will add cost to the system especially since gasoline contains two to three times more sulfur than diesel fuel. 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 increasingly greater energy penalty over time to compensate for loss of activity. Selective catalytic reduction (SCR) systems that use urea or hydrocarbons (HC) as reductant are attractive due to their low cost and lesser sensitivity to sulfur but issues include useable temperature range, NOx conversion efficiency, and the need for more complex control systems. Particulate trap technology is costly, and certain regeneration technologies are energy-intensive. The most effective particulate trap technologies also cause reductions in engine efficiency through increases in backpressure.

C. ***Lack of modeling capability for combustion and emission control***. The capability to accurately model and simulate the complex fuel and air flows, ignition, combustion, and in-cylinder emission formation processes, as well as aftertreatment system components, is needed to predict and optimize engine performance (and minimize emissions) over a range of load conditions. Models are needed that embody the fundamental understanding of engine combustion and in-cylinder emission formation processes, and performance degradation of the exhaust aftertreatment system. In addition, computational models are needed for integrating engine with vehicle load conditions in order to predict or ascertain vehicle fuel economy improvements.

D. ***Lack of effective engine controls.*** Effective sensing and control of various parameters will be required to optimize operation of engines in advanced LTC regimes and lean-burn gasoline operation over a full load-speed map. Parameters and operations that need improved controls include ignition timing across the load-speed map, the rate of heat release, and transients and cold starts. A major barrier for advanced lean-burn direct-injection gasoline engine technology is control, from a systems perspective, to maintain robust lean-burn combustion for boosted down-sized engines.

E. ***Durability.*** The emission control system has to perform effectively for 120,000-miles in passenger vehicles (cars and light trucks) and 435,000 miles for heavy-duty engines in commercial vehicles. Materials property requirements must be met to prevent premature degradation of the emission control devices due to operation under high-temperature and high-flow-rate conditions, as well as for durability of engine components. In addition, current commercially viable materials and lubricants limit engine efficiency by limiting peak cylinder temperatures and pressures at which critical engine components can operate.

F*.** ***Lack of actual emissions data on pre-commercial and future combustion engines. The health impacts of future technologies (e.g., post-2010 EPA compliant production engines) have to be evaluated well in advance of their market introduction and, therefore, lack actual real-world emissions data. In addition, measurement of emissions from these engines is very difficult especially at the expected very low levels.

G*.** ***Cost. Engines that use LTC are expected to be more expensive than conventional, port fuel-injected, spark-ignited gasoline engines because of the inherently higher combustion pressures, higher-pressure fuel injection systems, and the air boosting system needed to increase power density. In addition, emission control devices required to meet emission targets add to the cost of the system. For heavy truck engines in particular, increased cost is a critical consideration to truck operators who need to be fully competitive in the prevailing markets.

Better use of advanced LTC modes to reduce in-cylinder formation of emissions will reduce aftertreatment system requirements and associated costs.

H. ***Market perception.*** There is increasing public awareness of adverse health impacts related to vehicle emissions. As a result market acceptance is contingent upon improved understanding and knowledge that these new technologies have considered mitigation of known health impacts and will have no unknown or unintended potential health impacts.

Approach for Overcoming Barriers/Challenges

The Combustion and Emission Control activity will simultaneously address in-cylinder combustion and emission control, exhaust aftertreatment technologies, and fuel formulation strategies, for the most cost-effective approach for optimizing advanced combustion engine efficiency, emissions, cost, and performance. Also important for improving engine efficiency is increasing understanding of energy losses in engine operation including mechanical friction, heat transfer, air handling, and exhaust losses.

Close coordination with the Materials Technology subprogram ensures that materials issues important to powertrains are addressed. Work involving fuels is coordinated with the Fuels Technology subprogram. Fuel properties, particularly sulfur content, are pivotal to the success of NO_X adsorber catalyst technology.

Fundamental combustion R&D will focus on developing greater understanding of the combustion and in-cylinder emissions formation processes and their dependence on fuel spray characteristics, in-cylinder air motion, and fuel selection so that pathways to higher engine efficiencies, and lower NOX and PM emissions from the engine can be identified. Numerical and chemical kinetics models will be developed in collaboration with the Office of Science to guide the experimental combustion research. Also, a focused effort for a major combustion simulation effort will be supported to produce science-based simulation tools that enable new engine designs to more cleanly and efficiently utilize future fuels. This comprehensive effort will require simultaneously advancing combustion science, computer hardware and software, and engineering applications. Truly predictive engine simulations reaching from molecular collisions to a full drive cycle testing of engines will require coordinated experimental verification and model validation. This effort will require integrating basic science research through applied R&D, executed through a partnership of key industrial, national laboratory, and academic leaders. R&D tasks will include:

- Investigation of advanced combustion system concepts that enable high efficiencies and fuel injection strategies for the implementation of advanced combustion systems;
- Investigation of mechanisms and strategies to reduce thermodynamic combustion losses;
- Investigation of in-cylinder NO_X and PM formation mechanisms;
- Research on combustion systems for advanced fuels; and
- Identification of potential fuel-derived reductants.

Advanced combustion engine technologies that will be pursued are those that operate in LTC regimes characterized by combustion under lean or dilute conditions without significant flame propagation. These combustion regimes can provide high, diesel-like efficiencies and have ultra-low engine-out NO_X and particulate levels. Engines to be investigated include engines operating purely on LTC modes such as HCCI; and engines that use conventional diesel 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. The gasoline HCCI and spark-assisted HCCI R&D efforts will be enhanced and complemented with R&D to advance the lean-burn, direct-injection SI technology for gasoline-fueled and flex-fueled engines, and achieving fuel efficiency gains through boosting and downsizing of these engines. These engines offer a potential for a greater than 25 percent fuel economy gain but with less complexity and cost compared to other high efficiency options.

Research will also be undertaken to develop a fundamental knowledge base on very lean, low-temperature hydrogen combustion under high-pressure in-cylinder conditions and 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.

Exhaust emission control system R&D tasks will focus on developing more effective approaches for reducing NO_X and PM in exhaust systems to reduce the energy penalty and cost of emission control systems. Issues common among all the NO_X-reducing technologies that will be investigated include, reductant optimization, long-term degradation mechanisms, and sulfur tolerance. NO_X adsorbers research will focus on: 1) improving methods for generating and introducing NOx reductants to the catalyst; 2) improving NO_X reduction at the lower exhaust temperatures of the duty cycle for light vehicles; and 3) defining the optimum regeneration schedule. As lower engine-out emissions are achieved, continuous lean-NO_X catalysis again becomes a viable alternative. Needed are lean-NO_X catalyst materials with higher conversion rates and greater durability. Research will focus on understanding lean-NO_X catalyst materials performance and degradation mechanisms to improve and maintain performance over a wider temperature range. Research on PM-reduction devices will focus on the refinement of existing technologies and development of novel and innovative PM control technologies to face the challenges of long-term degradation and the ability to effectively regenerate despite the relatively cool exhaust temperatures typical of light-duty engines. 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 enabling technologies for emission control that will be investigated include sulfur traps, sulfur-tolerant catalysts, and low temperature oxidation catalysts for control of HC and CO.

Engine System and Technologies R&D will focus on fuel systems, engine control systems, engine technologies and integrating these in complete engine/vehicle systems that will enable dramatic fuel economy improvements in passenger and commercial vehicles.

Fuel systems R&D will focus 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. In-cylinder emissions reduction can also be achieved with very careful control of injection timing, duration, and rate shape. These phenomena are being researched using X-ray and optical diagnostics with the experimental results used to develop spray models. 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 engine controls that are precise and flexible for enabling 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 regimes 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 diesel or SI combustion at higher loads (e.g., 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 will require additional advances to be cost-effective and reliable. These technologies are essential to control systems for these advanced engine/aftertreatment systems.

Engine technologies development will be undertaken to achieve the best combination that enables advanced combustion engines to meet maximum efficiency and performance requirements. These include variable compression ratio (VCR), variable valve timing,variable boost, advanced sensors, high-energy ignition, 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 for providing ignition timing control through control of in-cylinder temperature or internal EGR.

Engine system integration and demonstration of multiple, new engine technologies on an engine platform will be undertaken to simultaneously attain efficiency and performance targets, and future emission standards. The computational models to be developed will enable rapid and effective optimization of the fuel injection and combustion systems and the aftertreatment devices for maximum overall engine system efficiency, compliance with emissions standards, and cost-effectiveness. Work will be coordinated with the Vehicle and System Simulation and Testing (VSST) Subprogram for integration of the engine combustion and aftertreatment subsystems into a vehicle simulation model that will enable optimization of the engine system to ascertain potential contribution to the vehicle fuel economy improvement targets.

Health Impacts Research will focus on screening of emissions from advanced vehicle technologies for toxicity. In selected cases where possible, components responsible for toxicity will be determined and engineering solutions will be sought to reduce the toxic components. Of special interest are emissions from advanced combustion engines using fuels optimized for new combustion regimes such as HCCI. New aftertreatment technologies, e.g., urea selective catalytic reduction (SCR), are also prime candidates for additional investigations. The most accurate measurement methods and tools will be applied to characterize the physical and chemical properties of vehicle emissions and possibly to differentiate emissions from various mobile sources (e.g., gasoline-, diesel-, natural gas-fueled and other alternative fuel vehicles). This activity will provide a sound scientific basis to ensure that advanced combustion engine technologies being developed for commercialization by industry will not have adverse impacts on human health through exposure to toxic particles, gases, and other compounds generated by these new technologies.

The tasks, along with the associated barriers, are summarized in Table 2.3-3.

Table 2.3-3 Tasks for Combustion and Emission Control R&D

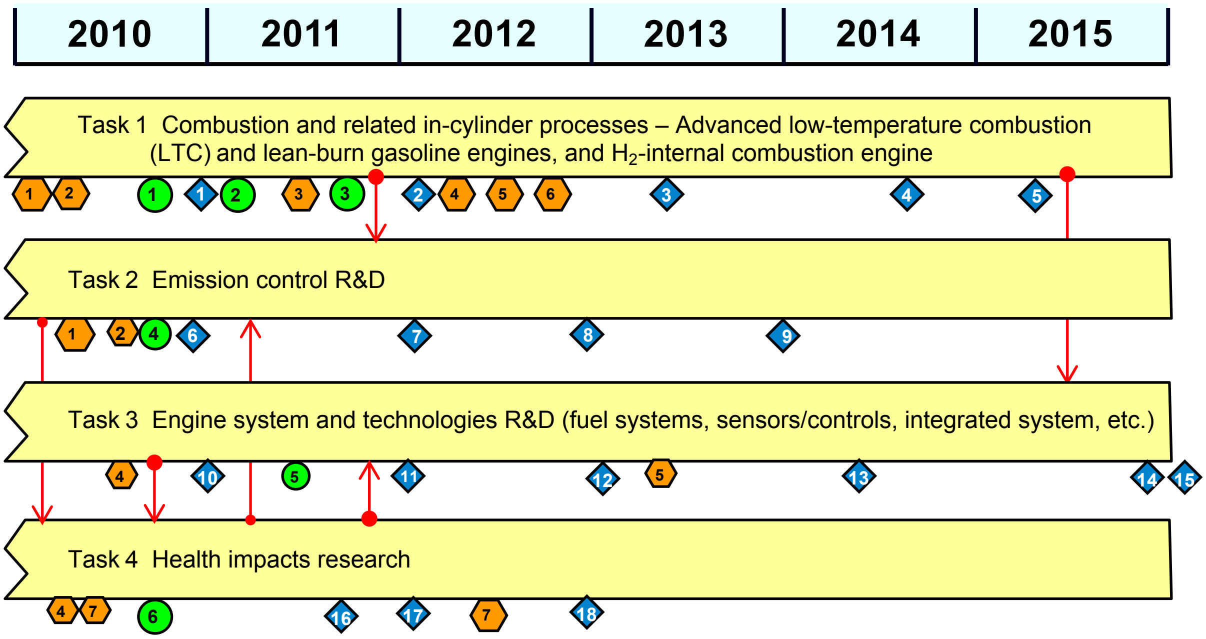
Task	Title	Barriers Addressed
1	***Combustion and related in-cylinder processes - Advanced low-temperature, low emission combustion regimes, and H_2-ICE*** • Develop fundamental understanding and control of low-temperature combustion (LTC) regimes over a range of engine loads and speeds through research engine experiments and modeling/simulation. • Exploit emissions characteristics of LTC regimes and methods of coupling to aftertreatment systems to achieve maximum efficiency • Develop understanding and methods for mixed-mode approaches that must alternate between conventional and new combustion regimes • Develop fundamental understanding of lean burn, direct injection, spark ignition gasoline engines and potential efficiency gains over a	A, B, C, D, G

Table 2.3-3 Tasks for Combustion and Emission Control R&D

Task	Title	Barriers Addressed
	wider operating range of engine loads and speeds leading to dramatic vehicle fuel economy improvements • Develop fundamental understanding of H_2-ICE combustion processes	
2	***Emission Control R&D*** • Improve the scientific foundation of NO_X adsorber–catalyst performance and degradation mechanisms to mitigate 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 modeling and simulation capabilities for exhaust aftertreatment devices to accelerate the design of the most effective emission control systems • Improve the technologies and strategies for PM filters to achieve reliable regeneration at low exhaust temperatures	B, C, D, G
3	***Engine Technologies R&D (fuel systems, sensors and controls, integrated systems, etc.)*** • 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 • Develop and demonstrate an engine system with integrated technologies, controls and strategies for maximum fuel economy at the necessary emissions levels • Investigate technologies for waste heat recovery, mitigating thermodynamic combustion losses, reduced air handling and parasitic losses, etc.	B, C, D, E
4	***Health Impacts Research*** • Generate, characterize emissions, and collect samples from 2010 EPA standards-compliant heavy-duty diesel engines and from selective catalytic reduction (SCR) urea aftertreatment devices. • Provide samples for toxicity and health impacts evaluation under the Advanced Collaborative Emissions Study (ACES). • Characterize toxic emissions from mobile sources and evaluate relative contribution to exposure levels.	F, H

Milestones and Decision Points

Combustion and Emission Control R&D



◆ Milestone

1. Validate 45% peak thermal efficiency LTC engine (9/10).
2. Complete initial optical engine combustion experiments of lean-burn direct-injection, highly boosted gasoline engines (10/11)
3. Identify strategies to maintain efficient operation of LTC engine over wide load conditions (12/13)
4. Validate lean-burn gasoline engine efficiency for over-the-road load operating range (7/14)
5. Validate combustion strategies for fuel economy improvement of 25% for gasoline passenger vehicles and 40% for diesel passenger vehicles (9/15).
6. Continue development of low-cost base metal catalysts for NOx reduction. (9/10)
7. Improve NOx conversion efficiency by 50% (10/11)
8. Integrate four aftertreatment components into one and reduce cost by 50% (9/12)
9. Complete validation of emission control strategy compatible with low temperature combustion (9/13)
10. Validate on a dynamometer, passenger vehicle engine brake thermal efficiency of at least a 45% and Tier 2, Bin 5 emissions. (9/10)
11. Complete testing to validate precision of feedback control NOx/PM sensors.(9/11)
12. Validate on a dynamometer, a 50% heavy-duty engine efficiency at prevailing EPA emissions standards.. (9/12)
13. Demonstrate at least a 20% fuel economy improvement of a Class 8 truck with heavy-duty engine operating on a real-world drive cycle (9/13)
14. Validate complete engine system for fuel economy improvement of 25% and 40% for gasoline and diesel passenger vehicles, respectively (9/15).
15. Validate on a dynamometer, at least a 50% peak thermal efficiency heavy-duty engine at prevailing EPA emissions standards (9/15)
16. Complete initial evaluation of potential health hazards from HCCI engines and fuels. (6/11)
17. Complete Advanced Collaborative Emissions Study (ACES) (9/11)
18. Evaluate potential health hazards from hybrid-electric duty cycles and fuels. (9/12)

⬢ Technology Program Output

1. Technical data/information to industry.
2. Fuel Property requirements for HCCI, to Fuels Technology Subprogram.
3. Technical results on hydrogen-ICE to Fuel Cell Technologies Program.
4. Technical results and feedback to Fuels Technology Subprogram.
5. Technical results to Vehicle and Systems Simulation and Testing Subprogram.
6. Technical materials requirements for high efficiency combustion engines to Materials Technology Subprogram.
7. Technical data/information to refereed journals for wide public dissemination.

● Supporting Input

1. Fuel formulation(s) with potential to enable efficient combustion with very low emissions, from Fuels Technology Subprogram.
2. Input fuel cell performance data (for comparison with H_2-ICE data), from Fuel Cell Technologies Program.
3. Validated small orifice fuel injector from Materials Technology Subprogram.
4. Fuel-derived reductant for emission control use, from Fuels Technology Subprogram
5. Validated emission control devices (PM filter, etc.), from Materials Technology Subprogram.
6. Input from industry.

2.3.2 Solid State Energy Conversion

The Solid State Energy Conversion R&D activity focuses on developing advanced thermoelectric systems to directly convert waste heat from engines and other sources to electricity for operating vehicle auxiliaries and accessories. In current production passenger cars, roughly 70 percent of the fuel energy is lost as waste heat from a gasoline engine operating at full power -- about 35 to 40 percent is lost in the exhaust gases and another 30 to 35 percent is lost to the engine coolant. In commercial vehicles (diesel engine powered long haul trucks) about 60 percent of the fuel energy is lost as waste heat. Effective use of waste heat from combustion engines would significantly increase the overall engine efficiency and reduce emissions.

Thermoelectric devices can also be used for vehicular cooling or heating by simply reversing the polarity of the applied DC current. The automotive dispersed or zonal thermoelectric cooling approach provides a refrigerant gas-free, more energy efficient alternative for maintaining occupant comfort. The refrigerant gas, R134a, used in current mobile air conditioners is a greenhouse gas with a warming potential that is over 1,300 times that of carbon dioxide (CO_2). Also, the current practice of cooling the whole cabin uses more energy than cooling the driver and passengers individually. The potential CO_2-equivalent greenhouse gas reduction will come from the elimination of refrigerant gas leakage and frontal collisions wherein the refrigerant gas is released to the atmosphere, which amounts to 44 million metric tons of CO_2 equivalent released to the atmosphere. In addition, fuel used to run the current air conditioners is reduced by 50 percent in vehicles with only the driver.

Goals

The goal of the Solid State Energy Conversion activity is to develop advanced thermoelectric technologies for recovering engine waste heat and converting it to useful energy that will help improve overall engine thermal efficiency to 55 percent for Class 7 and 8 trucks, and 45 percent for passenger vehicles while reducing emissions to near-zero levels. More specifically,

- By 2015, achieve at least a 17 percent on-highway efficiency of directly converting engine waste heat to electricity which will increase passenger and commercial vehicle fuel economy by 10 percent.
- By 2015, reduce by at least 30 percent, the fuel use to maintain occupant comfort through the use of thermoelectric heaters/air conditioner (TE HVAC) systems.

This activity also supports the overall engine efficiency goals of the FreedomCAR and Fuel Partnership, and 21st CTP. The technical targets for Solid State Energy Conversion are shown in Table 2.3-4.

Table 2.3-4 Solid State Energy Conversion Technical Targets

Characteristics	Fiscal Year			
	2003 Status	2008	2010	2015
Thermoelectric Devices				
Efficiency, % • modified bulk semiconductor	5–7	>10	>12	20
Projected cost/output, $/kW (250,000 production volume) installed	--	1200	1000	500
Passenger Vehicle Application				
Fuel economy improvement, %	<4	>5	>7	>10
Power, kW	<0.5	>0.5	>0.75	>1.0
Projected component life, hours	<10	>10,000	>100,000	150,000
Commercial Vehicle Application				
Fuel economy improvement, %	<3	>5	>10	
Power, kW	<10	>18	>20	
Projected component life, hours	<10	>15,000	>20,000	

Challenges and Barriers

A. ***Cost.*** Thermoelectric devices/systems must be cost-competitive with currently used technologies and be produced on the scale needed for vehicle mass production.

B. ***Scale-up to a practical thermoelectric device.*** Several types of high efficiency thermoelectrics are emerging including low-dimensional materials (nano-scale materials), and bulk materials such as cage structure materials (skutterudites, clathrates) and prototypical narrow gap semiconductors (Half Heusler alloys) that could be modified to enhance their performance. This entails dramatically increasing the size of the laboratory-developed specimens and doing so cost-effectively. In addition, techniques for measuring key parameters for these advanced thermoelectric materials need to be further developed. New technologies for heat transfer to and from the thermoelectric devices need to be explored.

C. ***Thermoelectric device/system packaging.*** Thermoelectric generators and thermoelectric heating/cooling systems must be designed to be integrated with the vehicle architecture. System components include, in addition to the thermoelectric device(s), hot and cold side heat exchangers and an electrical power conditioning and interface subsystem to match the power output of the thermoelectric generator to the vehicle electrical system, or to charge an electric energy storage unit (a battery or battery pack, or ultracapacitor). All these components need to be packaged and integrated into the vehicle architecture.

D. ***Component/system durability.*** Thermoelectric generators and thermoelectric heating/cooling systems must meet specific durability requirements for passenger and commercial vehicle applications. For instance, they will have to survive vibrations encountered in highway driving. Maintaining the integrity of the coupling and interaction between the thermoelectric device and the heat exchangers is critical to the system performance. Initial testing suggests thermoelectric elements should be coated to prevent high temperature oxidation.

Approach for Overcoming Barriers/Challenges

Sources of engine waste heat (the radiator, lubricating oil sump, exhaust gas, exhaust gas recirculation loop, turbocharger air discharge, and brakes) all represent opportunities for direct conversion of heat to electricity and will be investigated.

The overall improvement in vehicle fuel economy is the result of reduced engine load through the use of generated electricity to drive auxiliary load and accessories, as well as through more energy-efficient passenger comfort conditioning afforded by dispersed or zonal thermoelectric heating/cooling. Thermoelectric thermal control of the lube oil and transmission fluid viscosity could provide an additional 2 percent improvement in fuel economy.

The Solid State Energy Conversion activity will focus on developing and integrating the thermoelectric system(s) with the vehicle system architecture and design. While the development of innovative high Figure-of-Merit[2] thermoelectric materials is necessary for the success of thermoelectric devices, it does not guarantee that materials so developed can easily translate into practical designs that can be installed in production vehicles. For thermoelectric devices, like all innovative technologies, the transition from a research design to large-scale practical automotive applications faces unique challenges. This activity will address those challenges.

The development of solid state thermoelectric energy conversion devices for passenger and commercial vehicle applications would be facilitated by a team which will include: a) vehicle and engine OEMs (original equipment manufacturers) who would design, fabricate, integrate, and determine the commercial viability of thermoelectric devices in their products; b) thermoelectric materials researchers with expertise in developing high ZT materials; c) manufacturers of thermoelectric devices who would scale up thermoelectric materials from the laboratory for production and to develop high efficiency thermoelectric modules suitable for vehicle applications; and d) national laboratories or R&D laboratories with expertise in materials R&D, discovery and/or development, synthesis and processing, and characterization of advanced thermoelectric materials.

The technical approach to developing commercially competitive thermoelectrics[3] for vehicular applications is first to validate that bulk semiconductor-based thermoelectric devices/systems of a specific power output could be designed and integrated into a production vehicle. The emphasis is in verifying the extent to which the 1st generation thermoelectric materials can perform power generation and heating/cooling for vehicular applications within the cost criteria for commercial production. Thermoelectric materials researchers will coordinate their work with the assembly manufacturers who will address issues of scale up for production. The coordinated effort could be overseen by the automotive and truck OEMs who will design the thermoelectric device subsystem (thermoelectric device and the ancillary equipment) to be integrated with the vehicle system. Multiple teams would focus on a specific thermoelectric device application (either a thermoelectric generator and/or a thermoelectric heating/cooling system) for either passenger vehicles (cars and light trucks such as pickup trucks, minivans, and sport utility vehicles) or commercial vehicles (e.g., Class 7 and 8 heavy-duty diesel trucks).

Work will be coordinated with the Propulsion Materials Technology activity to address the current thermoelectric materials issues. In addition, the Propulsion Materials Technology activity will undertake or support development of advanced high ZT thermoelectric materials, evaluate the suitability of these materials for automotive applications, and address materials-related issues with the new high ZT thermoelectric materials. As integrated thermoelectric devices/systems become available, they will be tested and evaluated through the Vehicle and Systems Simulation and Testing (VSST) Subprogram.

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[2] The Figure of Merit, ZT, is the performance measure of thermoelectric materials. The thermal-to-electric conversion efficiency is dependent on the value of ZT, which is directly proportional to the Seebeck coefficient, electrical conductivity, and absolute temperature, and inversely proportional to the thermal conductivity.

[3] Proceedings of the *2009 Thermoelectrics Applications Workshop*, sponsored by the Vehicle Technologies Program, U.S. Department of Energy, held in San Diego, CA on September 29 to October 1, 2009.

Success with the single thermoelectric generator in the engine exhaust stream would lead to a follow on project(s) wherein thermoelectric generators would use other sources of engine waste heat (the radiator, lubricating oil sump, exhaust gas, exhaust gas recirculation loop, turbocharger air discharge, and brakes) to achieve engine efficiency improvement goals. This would require the thermoelectrically generated electricity to go into power conditioning and then be integrated with such concepts as the "beltless engine" or "more electric engine" where all the engine accessories are electrically driven (e.g., the 2007 BMW 5 series car has an electric water pump). Thermoelectric generators could also be used with the integrated motor/alternator/starter, which could absorb the electrical energy and reduce engine drag. The 2nd generation thermoelectric generator will replace the alternator. Success with the current 10 percent fuel economy improvement project will be evaluated through the VSST Subprogram simulation, modeling, and testing tools that will provide the basis for an accurate projection of timeframe, cost, and market penetration of thermoelectric devices for vehicle applications.

Additional vehicular opportunities for thermoelectrics are the thermal management of the engine lube oil and transmission fluid at optimized viscosity especially with starting cars in winter. Battery pack performance and service life is affected by temperature. Thermoelectric systems could maintain batteries within their thermal "sweet spot". This thermal management of batteries is a 24/7 requirement. Thermoelectrics may also provide a means of cooling the higher temperature power electronics needed for vehicle electrification. Due to the high reliability of thermoelectrics, they are already used for thermal managements of collision-avoidance radar. Thermoelectric cooling or heating of beverage holders is available on some upscale vehicles.

The ultimate goal is to develop vehicular thermoelectric generators that could produce power for electrical loads of the thermoelectric heating, and air conditioning (TE HVAC) systems as well as additional electricity to the vehicle's system. First Generation TE HVAC will initially downsize the air-conditioners that use compressed R-134a refrigerant gas and the Second Generation TE HVAC will replace the air conditioners. If thermoelectric efficiency of directly converting heat to electricity were to reach 30 percent, TEG's could replace the vehicle's internal combustion engine. These TEG's would use a simple combustor as the heat source that burned virtually any liquid, gaseous or solid particulate (corn, coal, wood etc.). The tasks for the Solid State Energy Conversion Activity are summarized in Table 2.3-5.

Table 2.3-5 Tasks for Solid State Energy Conversion

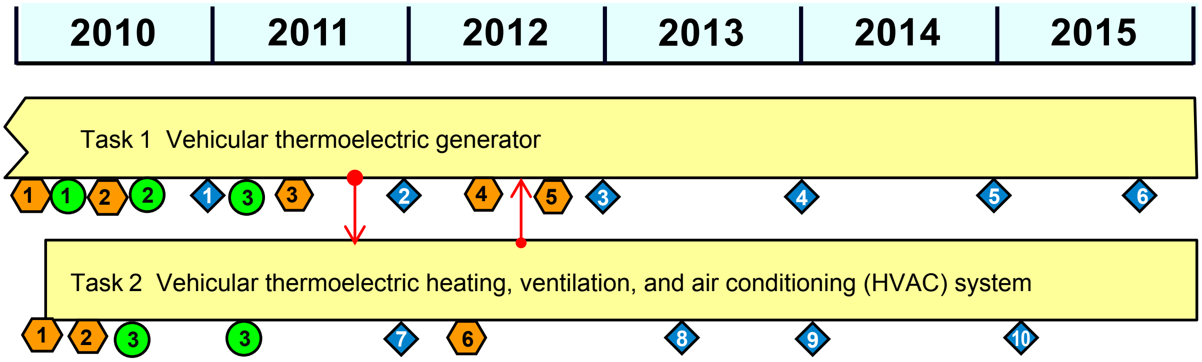
Task	Title	Barriers Addressed
1	***Thermoelectric Generators*** • Develop first generation thermoelectric generators (TEGs) using commercially-viable bulk materials. • Design and integrate TEGs into specific vehicle architecture. • Validate 10 percent fuel economy improvement with a thermoelectric generator for both passenger vehicles (autos and light trucks) and commercial vehicles (Class 7 and 8 trucks). • Based on a successful 10% thermoelectric generator, extend to thermoelectric generators on radiator, lube oil viscosity control, EGR loop, turbocharger discharge air, and brakes, which when integrated with the beltless engine would produce a nominal 55% efficient diesel engine. • Fabricate 2nd generation high efficiency thermoelectric device with at least 20% efficiency and validate fuel economy improvement.	A, B, C, D

Table 2.3-5 Tasks for Solid State Energy Conversion

Task	Title	Barriers Addressed
2	***Thermoelectric Heating, Ventilation, and Air Conditioning (TE HVAC)*** • Develop TE vehicular heating/cooling modules for a dispersed or zonal system to augment or replace current mobile air conditioning system. • Design and integrate into a demonstrator vehicle, dispersed TE heating/cooling system and verify performance and energy savings benefits. • Validate potential efficiency improvements with next generation thermoelectrics.	A, B, C, D

Milestones and Decision Points

Solid State Energy Conversion R&D



◆ **Milestone**

1. Complete fabrication and test of prototype 1st generation thermoelectric generator (TEG) to validate 5% conversion efficiency
2. Validate at least a 5% fuel economy improvement with 1st gen. TEG installed in selected passenger vehicle model
3. Validate at least a 14% on-highway TEG efficiency and at least a 10% fuel economy improvement
4. Validate that module/device fabrication can be scaled up to large volume production
5. Complete selection of TE materials for design and fabrication of 2nd generation TEG
6. Scale up of thermoelectric generator system to over 1 kW output

◆ **Milestone**

7. Complete design of dispersed TE HVAC system and integrate into vehicular HVAC to validate potential reduction of energy use
8. Validate in demonstrator vehicle, performance and energy savings benefit of zonal, dispersed TE heating/cooling
9. Design and integrate a totally TE HVAC into selected passenger vehicle
10. Validate at least 30% reduction in energy use for with totally TE heating/cooling for passenger comfort

⬢ **Technology Program Output**

1. Technical data/information to industry.
2. Technical data/information to Vehicle and Systems Simulation and Testing Subprogram
3. Technical data to Combustion and Emission Control R&D
4. Technical data to DOE EERE/Industrial Technologies Program/Waste Heat Minimization and Recovery activity.
5. Coordination with DoD Programs
6. Technical data to DOE/EERE/ Building Technologies Program

● **Supporting Input**

1. Input from Combustion and Emission Control R&D
2. Input from DARPA/ONR high efficiency thermoelectric materials university research
3. Input from DOE/VT Materials Technology Subprogram.

2.4 Fuels Technology

The Fuels Technology subprogram supports the mission of the Vehicle Technologies Program (VTP) to develop more energy-efficient and environmentally friendly highway transportation vehicles that enable the U.S. to use less petroleum. This will be achieved through R&D that will provide vehicle users with cost-competitive fuel options that enable high vehicle fuel economy with low emissions, and contribute to petroleum displacement.

Fuels and lubricants are complex mixtures of thousands of chemical compounds. It is anticipated that future refinery feedstocks for production of fuels are likely to be increasingly derived from non-conventional sources such as heavy crude, oil sands, shale oil, and coal, as well as renewable resources such as biomass, vegetable oils, and waste animal fats. The impact of changes in refinery feedstocks on finished fuels is an area of relatively new concern to engine manufacturers, regulators and users. Different fuels already in the market that meet the same specifications can have a widely varying impact on the performance and emissions of current engines. Advanced engine technologies are more sensitive to variations in fuel composition than earlier engines were, and are facing tightening emissions standards. The balance of refinery feedstocks also has to be considered to ensure that the slate of refining products matches end-use needs and is efficiently accommodated. There are technology barriers associated with increased use of biomass-based fuels as blendstocks with conventional fuels.

The Fuels Technology subprogram R&D activities are undertaken in close coordination with the Advanced Combustion Engine R&D subprogram.

2.4.1. Fuels and Lubricant Technologies

The Fuels and Lubricant Technologies activity formulates and evaluates non-petroleum-based fuels and lubricants that can be used as neat (pure) alternative fuels or as primary constituents of transportation fuels. A non-petroleum-based fuel consists of components derived primarily from non-crude oil, preferably renewable sources, such as agricultural products or other biomass. Emphasis of R&D is on biomass-based renewable fuels and bio-synthetic fuels.

This activity is undertaken: (1) to enable advanced combustion regime engines and emission control systems to be more efficient while meeting future emission standards; and (2) to reduce reliance on petroleum-based fuels through direct fuel substitution by non-petroleum-based fuels. Of primary concern are the impacts of fuel and lubricant properties on the efficiency, performance, and emissions of current engines as well as the determination of fuel properties and characteristics that will enable emerging advanced internal combustion engines. The NPBFL activity represents the harmonization of the fuel requirements of advanced engine and vehicle manufacturers with the product specifications of future refineries. In addition, the NPBFL activity will provide nonpetroleum-based blendstock specifications to enable both high fuel economy and direct displacement of petroleum fuels.

Goals

The primary goal of the Fuels and Lubricant Technologies activity is to identify fuel formulations with increasingly significant use of non-petroleum fuel components that will enable emerging advanced combustion engines to be more energy efficient while meeting future emissions standards. More specific goals include the following:

- By 2013, identify fuel formulations optimized for use in light-duty advanced combustion regime engines that provide high efficiencies and very low emissions, which incorporate use of non-petroleum based blending components with the potential to achieve at least a 10 percent replacement of petroleum fuels by 2025.

- By 2015, identify fuel formulations using non-petroleum based blending components that are optimized for use in high efficiency heavy truck engines (those with at least a 50 percent thermal efficiency) while meeting prevailing EPA emissions standards, with the potential to achieve at least a 15 percent replacement of petroleum fuels by 2030.

Table 2.4-1 lists the fuels-specific technical targets that support crosscut targets with the Advanced Combustion Engine R&D subprogram (shown in italics), as well as direct petroleum fuel replacement targets.

Table 2.4-1 Technical Targets for Fuels and Lubricant Technologies Activity

Characteristics	2010	2015	2018
Cross-Cut Targets with ACE R&D			
Light-duty vehicles			
Engine Efficiency Goal			
Peak thermal efficiency, %	*45*		
Vehicle level goals			
Durability, hrs	*5,000*	*5,000*	
Thermal efficiency penalty due to emission control devices, %	*<1*	*<1*	
Fuel economy Improvement, % (gasoline/diesel)		*25/40*	
Emissions, gm/mile		*Tier2, Bin 5*	
Heavy-duty vehicles			
Engine Thermal Efficiency, %		*50*	*55*
NOx emissions, g/bhp-hr		*<0.20*	*<0.20*
PM emissions, g/bhp-hr		*<0.01*	*<0.01*
Stage of development		*prototype*	*prototype*
Fuels and Lubricant Technologies Targets			
Fuel sulfur level (available fuel), ppm	15	15	15
Fuel sulfur level (w/on-board or fuel-station based removal), ppm	<3	<5	<5
Emission control penalty reduction, %	>50	>50	50
Potential for replacement of petroleum, %	<5	At least 5	>5
Compatibility with infrastructure	Validated		
Health effects Unregulated toxics and ultra-fine PM Health and safety of fuel, by analysis	No significant increase in composite risk compared with conventional fuels		
Life-cycle greenhouse and criteria emissions, by analysis	Reduced		

Challenges and Barriers

A. ***Infrastructure.*** The lack of a fuel quality specification is a major barrier for any non-petroleum based liquid fuel component that is not compatible with all current systems. This barrier, as well as distribution and fueling infrastructure, must be addressed to significantly reduce the transportation sector's dependence on petroleum-based fuels using non-petroleum based fuels.

B. ***Cost.*** Public data on refinery economics and processing strategies are not sufficient to enable cost comparison of options for advanced combustion engine fuels. Also inadequate is the knowledge base on the technical and economic impacts of non-petroleum fuel components on the distribution, storage, and fueling infrastructure, as well as data and information on the health, safety, and regulatory issues associated with most non-petroleum fuel components that might be used to replace petroleum-based fuels.

C. ***Inadequate data and predictive tools for fuel property effects on combustion and engine efficiency 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. Models 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 on the ability to operate in low-emission, low-temperature combustion (LTC) regimes. Also, the impact of the variability of refinery stream (blendstock) composition on the efficiency, performance, and emissions of engines appears to be significant but is poorly understood.

D. ***Inadequate data and predictive tools for fuel effects on emissions and emission control system impacts.*** There is inadequate data to determine the extent to which petroleum fuel and non-petroleum fuel components contribute to toxic emissions. Data must be improved in order to optimize engine and aftertreatment systems for fuel economy. 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 to generate this knowledge base are not available.

E. ***Inadequate data on long-term impact of fuel and lubricants on engines and emission control systems.*** The knowledge base is inadequate for determining the effect of fuel properties on the deterioration rates and durability of engine fuel system and emission control system devices and components. The effects of lubricating oil on engine emissions and emission control devices are not clearly understood, nor are the effects of non-petroleum based fuels on lubricating oil performance. Improved understanding is needed in developing approaches that mitigate any deleterious effects caused by fuel and lube oil components. Furthermore, new fuel formulations could require corresponding new lube oil formulations.

Approach for Overcoming Barriers/Challenges

The Fuels and Lubricant Technologies activity supports studies of the effects of physical and chemical property variation in synthetic and renewable fuels on the performance and emissions of advanced combustion engines, and potential impacts of increasing levels of non-petroleum fuel blendstocks in finished fuels. This activity is undertaken in coordination with the Advanced Combustion Engine R&D subprogram.

The Fuels for Advanced Combustion Engines task seeks to identify and exploit fuel properties that can enable advanced combustion engines to operate in the highest-efficiency mode while meeting future emissions standards and to expand the operating conditions at which maximum efficiency is achievable. Research and development are conducted to determine the effects of variations in the physical and chemical properties of petroleum-based fuels blended with non-petroleum based fuels, at varying levels, on the performance and emissions of advanced combustion engines, specifically: 1) to identify fuel-property requirements to fully exploit post-2010 advanced internal combustion engines; and 2) to expand the kinetic modeling of base fuel properties that affect operation of these engines. Issues of concern include: combustion characteristics; effects on engine components; effects on emissions; lubricity or lubrication requirements; blending limitations; and greenhouse gas (GHG) emissions.

The Petroleum Displacement Fuels task will formulate and evaluate non-petroleum-based fuels and lubricants that can be used as neat (pure) alternative fuels or as blendstocks in fuels for passenger and commercial vehicles. Work includes identifying fuels and fuel-blending components that are suitable for advanced-combustion-regime engines and at the same time, have the potential to reduce dependence on imported petroleum. These fuels will likely come from non-fossil sources such as biomass, vegetable oils, and waste animal fats, as well as from fossil sources other than light, sweet crude oil, for example, oil sands, oil shale, and synthetic fuels from natural gas or coal. With a primary focus on biomass-based renewable and synthetic fuels, specific areas being investigated include fuel quality and stability; detailed chemical composition and its relationship to fuel bulk properties; the effect of physical and chemical properties on engine performance and emissions; and safety associated with storage, handling, and toxicity.

A wide variety of fuels will be tested and evaluated to develop a better understanding of the relationships between fuel properties, engine efficiency, system durability, and emissions. Key deliverables from these 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 subprogram.

Guidance on the fuels to be tested and other tasks will be provided by representatives from the automotive, energy, and engine companies; renewable- and non-petroleum-based fuel manufacturers; industry associations; and national laboratories. Government/industry technical and supporting groups will make specific recommendations for tasks, data analyses, and overall direction. Through the use of roundtable discussions, government-industry workshops, peer reviews, participation in the Coordinating Research Council, and through other forums, this activity has obtained what is believed to be a good understanding of the inadequacies of predictive tools and fuel property data necessary to identify fuel property requirements for fuels for advanced combustion engines.

Fuels, engines, and emission control devices are being addressed in the context of complete, integrated engine power systems. Technical task descriptions are provided in Table 2.4-2.

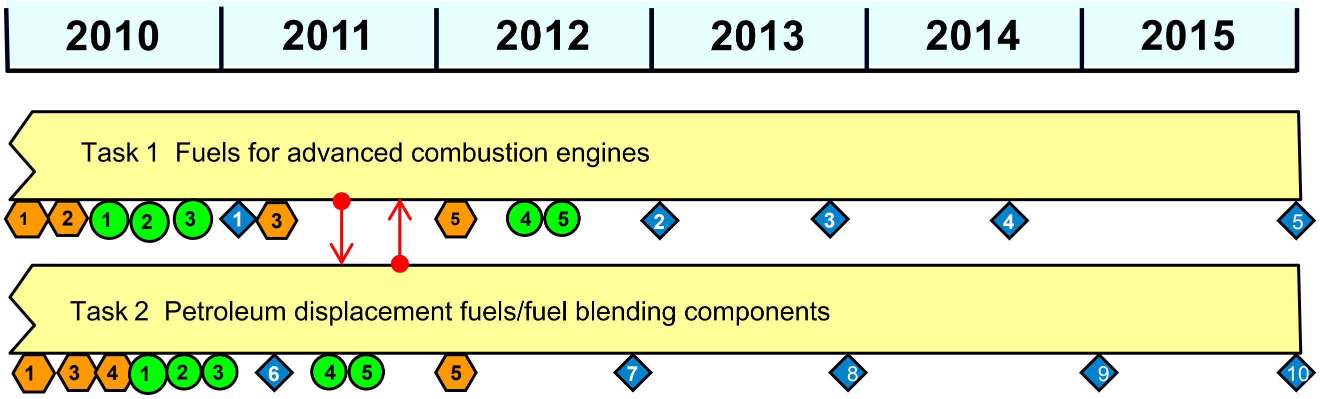
Table 2.4-2 Tasks for the Fuels Technology/NPBFL Activity

Task	Title	Barriers Addressed
1	Fuels for Advanced Combustion Engines • Develop fundamental understanding of fuel effects on in-cylinder combustion and emissions formation processes in advanced combustion regimes through experimental and modeling approaches • Develop predictive tools that relate molecular structure to ignition behavior and heat release for fuels used in advanced combustion engines • Evaluate new fuels and fuel blends for efficiency, emissions, and operating stability with advanced combustion regimes • Evaluate the potential of reforming small amounts of fuel to generate additives that can be used to achieve fast control in low temperature combustion (LTC) modes • Evaluate the performance of traditional lubricant formulations in engines using advanced combustion regimes and identify any performance deficiencies	A, B, C, D, E
2	Petroleum displacement fuels/fuel blending components • Study combustion and emissions-formation processes of non-petroleum based fuels and blending components using experimental and modeling approaches • Identify renewable and synthetic fuel blending components that provide enhanced efficiency, performance, and emissions characteristics • Quantify the potential for improving engine and/or vehicle fuel economy through the use of renewable biolubricants	A, B, C, D, E

Task	Title	Barriers Addressed
	• Evaluate long-term degradation and loss of effectiveness of emission control devices for light- and heavy-duty engines using 15-ppm-sulfur diesel fuel and renewable blending components such as biodiesel • Investigate options for optimizing engine and emission control systems for both emissions and performance when switching between conventional fuel and non-petroleum-based fuels • Identify fuel properties other than sulfur that are critical to improving the efficiency, performance, and emissions of diesel engine and aftertreatment systems • Perform RD&D to support appropriate codes and standards to increase the availability of petroleum displacement fuels	

Milestones and Decision Points

Fuels Technology



◆ **Milestone**

1. Complete identification of fuel and lubricant characteristics that are critical to operation in advanced combustion regimes
2. Validate that fuel formulation used in advanced combustion engine results in reducing emission control penalty by 50% and meets useful life requirement
3. Complete identification of fuel and lubricant formulation for advanced combustion engines needed to achieve 50% engine efficiency, power density >20 bar bmep, and emissions compliance
4. Validate that advanced fuel formulation can enable >50% engine efficiency with full in-cylinder emission reduction eliminating the need for exhaust aftertreatment
5. Complete identification of fuel formulations optimized for use in advanced combustion engines that provide high efficiency and very low emissions

◆ **Milestone**

6. Determine maximum blending with ethanol without deleterious consequences to engine performance
7. Identify potential performance impacts of liquefied natural gas on current heavy-duty engines
8. Determine adequacy of codes and standards for fuels with non-petroleum and synthetic blending components
9. Validate >5% petroleum fuel displacement using renewable and synthetic fuel blending components without efficiency reduction while meeting prevailing EPA standards
10. Validate >10% petroleum fuel displacement

⬢ **Technology Program Output**

1. Technical data/information to industry.
2. Advanced petroleum-base fuels property and characteristics data to Advanced Combustion Engine (ACE) R&D subprogram
3. Fuel-derived reductant for emission control to ACE R&D subprogram
4. Non-petroleum based fuel formulation(s) with potential to enable efficient combustion with very low emissions to ACE R&D subprogram
5. Technical data/information to refereed journals for wide public dissemination.

● **Supporting Input**

1. Input from industry.
2. Input from Advanced Combustion Engine R&D subprogram
3. Fuel property requirements for HCCI and LTC from ACE R&D Subprogram.
4. Fuel-derived reductant requirement for for emission control use, from ACE R&D Subprogram
5. Technical results and feedback from ACE R&D .

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2.5. Materials Technology

The Materials Technology subprogram supports the development of cost-effective lightweight materials and materials manufacturing processes that can contribute to fuel-efficient passenger and commercial vehicles. This subprogram contributes to concepts developed throughout the VT Program. The Materials Technology subprogram contributes to the VT Program goal by developing higher performing, more cost-effective materials that will make lighter vehicle structures and more efficient power systems. Lighter vehicles require less energy to operate and thus reduce both greenhouse gases and fuel consumption. Likewise, better propulsion materials can enable more efficient power systems that will contribute to a vehicle's reduced energy consumption. The subprogram consists of three activities: Lightweight Materials Technology, Propulsion Materials Technology, and the High Temperature Materials Laboratory (HTML).

The Materials Technology subprogram is further refining the focus on demonstration projects and technology transfer by reaching out to suppliers directly through the competitive solicitation process. Depending on the nature of the project, suppliers and OEMs may partner to validate technologies through demonstration. This approach augments the growing emphasis on ensuring that successful technology is commercialized.

2.5.1. Lightweight Materials Technology

The Lightweight Materials Technology activity supports R&D on advanced concepts to reduce the weight of vehicles, accomplished primarily by substitution of lower density and stronger materials for current materials or by designing components and structures around the unique and superior performance characteristics of new materials. Since cost-effectiveness is the major challenge in the use of new materials, this activity supports research, development and validation of materials needed to meet the goal of a weight reduction of 50 percent for the body and chassis, as well as demonstration projects involving the designing, manufacturing, and testing/validation of assemblies from these materials. Lightweight materials include magnesium, aluminum, advanced high-strength steels, titanium as well as polymer-matrix composites reinforced with glass and carbon fibers. A list of the lightweight materials and their potential for weight reduction are shown in Table 2.5-1.

Table 2.5-1 Potential Vehicle Materials Substitution

Lightweight Material	Material Replaced	Mass Reduction (%)	Relative Cost (per part)*
High Strength Steel	Mild Steel	10	1
Aluminum	Steel, Cast Iron	40 - 60	1.3 - 2
Magnesium	Steel or Cast Iron	60 - 75	1.5 – 2.5
Magnesium	Aluminum	25 - 35	1 – 1.5
Glass Fiber Reinforced Polymer (FRP) Composites	Steel	25 - 35	1 – 1.5
Graphite FRP Composites	Steel	50 - 60	2 – 10+
Aluminum Metal Matrix Composite	Steel or Cast Iron	50 - 65	1.5 – 3+
Titanium	Alloy Steel	40 - 55	1.5 – 10+
Stainless Steel	Carbon Steel	20 - 45	1.2 – 1.7

*Includes both materials and manufacturing

Reference: William F. Powers, "Automotive Materials in the 21st Century," *Advanced Materials & Processes*, May 2000, pp. 38 – 41.

Goals

The Automotive Lightweighting Materials activity focuses on structural materials for applications in the body and chassis that can significantly reduce the weight of passenger vehicles without compromising lifecycle cost, performance, safety or recyclability. The specific goals of the Automotive Lightweighting Materials activity are:

- By 2015, validate (to within 10 percent uncertainty) the cost-effective reduction of the weight of passenger vehicle body and chassis systems by 50 percent with recyclability comparable to 2002 vehicles;
- By 2015, have an industry lead performer design, build and validate a prototype vehicle that is 50 percent lighter weight compared to a 2002 vehicle. The results of this validation will result in early commercialization of the technical success and help identify remaining technical gaps in lightweighting that still need to be addressed.

There are a number of materials and measures involved in these goals. The materials with the highest potential for weight reduction by over 50 percent, magnesium (Mg) and carbon fiber polymer composites have the highest priority for development efforts. Thus this area focuses on:

- the development of magnesium and its alloys to provide a clean and low cost solution to lightweighting that may also enable recycling, low cost joining, and corrosion resistance;
- the design, build and validation of a multi-material vehicle that contains magnesium; and
- the development of low cost carbon fiber that most likely utilizes non petroleum feedstock and does not duplicate prior work with lignin

For example, lowering of the cost of carbon fiber to approximately $5 per pound is a priority. American Recovery and Reinvestment Act (ARRA) funds will significantly augment research on low cost carbon fiber by enabling the building of a prototype line to validate the manufacturing of carbon fiber made from low cost starting materials using innovative manufacturing processes.

Challenges and Barriers

A. ***Cost.*** Prohibitively high cost of finished materials is the greatest single barrier to the market viability of advanced lightweight materials for automotive and commercial vehicle applications.

B. ***Manufacturability.*** Methods for the cost-competitive production of automotive assemblies from advanced lightweight materials need development to realize the full potential of lightweight materials for both automotive vehicle and the heavy vehicle industry. Advanced materials, by virtue of their unique or different physical and mechanical properties, are often difficult to manufacture with current technology in production quantities and with the required precision and reproducibility.

C. ***Performance.*** Low cost materials needed to achieve the performance objectives (strong, durable, easily formed and joined into assemblies and components, sufficiently well-characterized) for demanding applications may not exist today.

D. ***Predictive modeling tools.*** Adequate predictive tools that will enable the low cost manufacturing of lightweight structures would reduce the risk of developing new materials for vehicular applications.

E. ***Tooling and prototyping.*** The cost of tooling for forming components made with lightweight materials is too high for the volumes typical of the heavy vehicle industry. The development and fabrication time required for prototyping components needs to be shortened.

F. ***Joining and assembly.*** High-volume, high-yield joining technologies for lightweight and dissimilar materials needs further improvement. Non-destructive techniques for the evaluation of the integrity of joints need further development

G. ***Inadequate supply base.*** The manufacturing and materials supply base does not currently exist to support even modest deployment, especially for carbon fiber polymer composites and magnesium. The materials supply chain and production industry needs to expand with a viable product. For example, an inexpensive and clean domestic source of magnesium would support the development of lighter weight assemblies that will help contribute to reduction in green house gases, in fuel consumption and enable Mg recycling.

H. ***Maintenance, repair and recycling.*** Technologies for cost-effective recovery of high-value materials from end-of-life vehicles and, maintenance and repair of advanced materials need substantial research and development.

Approach for Overcoming Barriers/Challenges

Cost. Technologies will be pursued that can reduce the cost of materials, and the cost of manufacturing of lighter-weight structural components. These technologies include:

- *Carbon fiber*—Research will continue to explore and develop new classes of low cost precursor for manufacturing carbon fibers. These new precursors will augment current reliance on aerospace grade, pitch and polyacrylonitrile derived carbon fibers that carry a cost premium. This effort will also continue the development and validation of methods of processing that have the potential to significantly reduce the cost of producing carbon fiber. These methods of processing and manufacturing innovations include microwave carbonization, radiation stabilization, plasma oxidation, and improvements in line speed and reduction in production downtime. With the availability of ARRA funds, a pilot line will be constructed by FY2013 and be available thereafter to validate promising technology(ies). This effort is synergistic with EERE's Industrial Technologies Program and this office will be appraised of efforts and progress in this area.
- *Primary metal production*—Focus will be on processing technology(ies) that could enable the cost-effective and clean production of magnesium. Current production of magnesium relies on energy-intensive and more costly technologies. This effort will focus on key technical barriers that limit research success and will identify opportunities for optimizing these technologies to achieve efficiency improvements that will result in lower-cost primary metals. This activity is synergistic with EERE's Industrial Technologies Program and this office will be appraised of efforts and progress in this area.
- *Magnesium alloys*—Identify alloys of magnesium that provide the desired properties without the addition of rare earth elements. The best candidates will be alloyed, validated, and used for future demonstration projects, the performance goals of which will be dictated by the target component or assembly systems and the appropriate manufacturing process to realize these goals..

Performance. Higher performance and lighter weight materials will be pursued as needed. Fundamental work with NSF on third generation advanced high strength steel has been fruitful. The continuation of this collaborative effort will proceed along the needs of both agencies. Current ideas include workshops to identify needs in computational tools as well as advancing magnesium and its alloys.

Predictive Modeling Tools. To best take advantage of the properties of polymer composite and lightweight metals in 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 involved in crash events. The following research areas address these problems:

- *Predictive modeling of long carbon fiber injection molded thermoplastic composites* – Work on the validation of predictive models for the injection molding of long carbon fiber thermoplastic composites will involve first larger plaques, and second will involve predictions for a complex 3-D large part. This work is under development with both the resin suppliers as well as a key developer of commercial code for prediction of the flow of resin during the manufacturing of parts. Future plans include validation of both the predictive tool as well as low cost carbon fiber with industrial manufacturers through a future BAA.
- *Crash energy management testing and models*—This effort will continue to support the development and validation of theoretical and computational models for predicting the energy absorption and dissipation in automotive composite components and assemblies 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.
- *Integrated Computational Materials Engineering* – This approach to materials engineering problems uses hierarchal computational materials models (i.e. models of material behavior from the atomic scale up to component levels) and databases to dramatically shorten the R&D cycle for developing new materials and applications. Continued work is planned for developing new models, improving database usability, and demonstrating ICME principles to solve automotive lightweighting problems.

Tooling and Prototyping. The introduction of advanced polymer-based composite and lightweight material manufacturing processes to vehicle manufacturers and their supplier base is severely impacted by the high cost of tooling and long development times. The development of low-cost tooling technologies for lightweight materials will enable the use of these light weight materials. The priority for the type of tooling and prototyping pursued will be dictated by the needs of demonstration projects that design, build and validate lightweight assemblies.

Joining and Assembly. Joining unlike materials continues to be a challenge. 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 development of robust and reliable joining and assembly technologies for lightweight materials will enable the increased use of these light weight materials. The priority for the type of joining and assembly of the specific materials pursued will be dictated by the needs of demonstration projects that design, build and validate lightweight assemblies.

Inadequate Supply Base. DOE will work directly with suppliers through the BAA process to develop their capabilities in the manufacturing of magnesium and low-cost carbon fiber. This subprogram will also engage the suppliers to develop experience in the design and manufacture of new light weight assemblies which, if successfully validated will continue development that leads to commercialization.

Maintenance, and Recycling. Work will be conducted in conjunction with industrial consortia and other organizations as appropriate. Work on recycling of polymers has been successfully demonstrated and commercialized. Future work on the recycling of lightweight metals will be considered after successful demonstration projects validate that sufficiently higher content of such materials can be included in the vehicle manufacturing to warrant this investment. Possible recycling capability of magnesium may be enabled by the development of magnesium manufacturing technologies.

Tasks

A summary of some of the tasks being carried out by the Lightweight Materials Technology activity along with the technical barriers addressed are provided in Table 2.5-2.

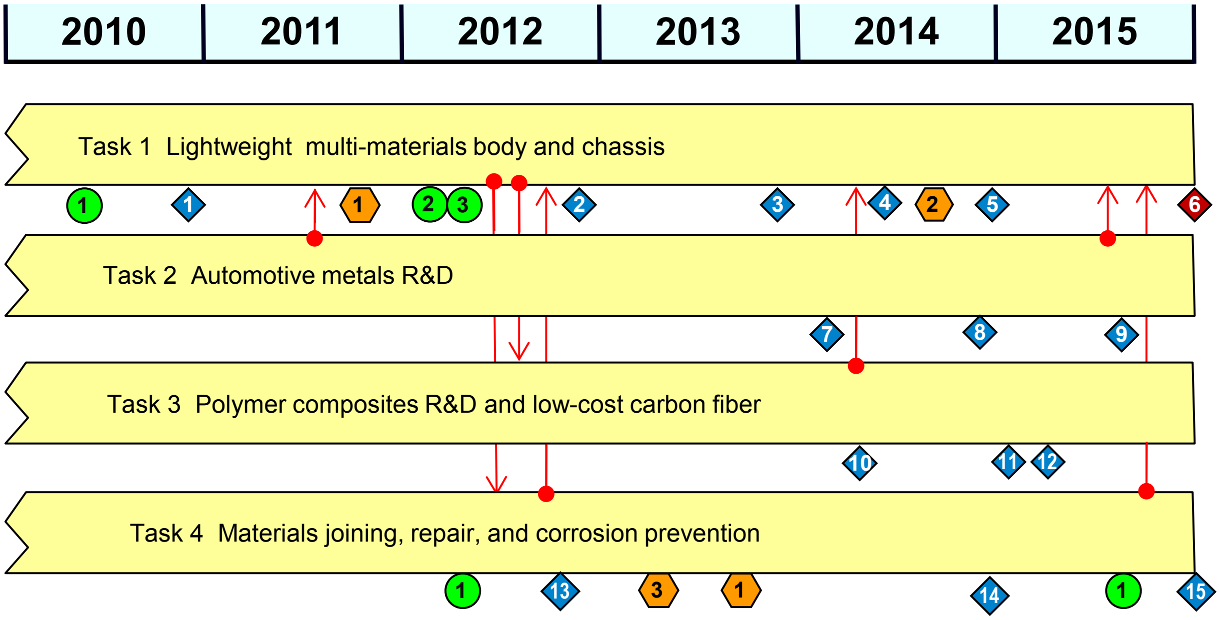
Table 2.5-2 Tasks for Lightweight Materials Technology

Task	Title	Barriers Addressed
1	Lightweight Multi-Materials Vehicle • Develop detailed design and cost model for a multi-materials vehicle for validation assessments of cost-effective weight reduction. • Validate cost of weight reduction targets with substitution of cost-effective materials. • Through the BAA process, have industrial lead design, build, and validate a multi-material vehicle that is 50% lighter than a standard 2002 vehicle.	A, B, C, D, E, F
2	Automotive Metals R&D • Pursue overcoming technical challenges of magnesium production that has the potential to provide low cost and clean magnesium from a domestic source. • Research alloys of magnesium that have the potential to produce desired properties for both performance and processing without the use of rare earth elements. • Research low cost advanced high strength steel that achieves 1,200 MPa tensile strength and 25% uniform elongation at a cost penalty of less than 25% compared to HSLA steel.	A, B, C, D, E, G
3	Polymer Matrix Composites and Low-Cost Carbon Fiber R&D • Continue advanced processing technology to lower the cost to manufacture carbon fibers. • Investigate at pilot-scale, processing technologies for cost-effective carbon-fiber to validate the cost models. • Through the BAA process, initiate demonstration project to validate low cost carbon fiber in a polymer composite component or assembly to result in a structure that meets mechanical and cost targets while also providing the ability to reduce the weight of the vehicle. • The demonstration project may also include that validation of the predictive modeling tool of injection molding of long carbon fiber thermoplastic composites is the process of choice for the target structure.	A, B, C, D, E, G
4	Materials Joining, Repair, and Corrosion Prevention • Characterize mechanisms of interaction and properties of an interface or joint formed between two lightweighting materials. • Conduct investigations on low cost joining dissimilar materials. • Investigate corrosion prevention issues of magnesium with muti-material vehicle structures.	H

Milestones and Decision Points

The milestones and decision points for the Lightweight Materials Technology activity are shown in the next figure.

Lightweight Materials Technology



◆ **Milestone**

1. Detailed design and cost models for multi-materials vehicle.
2. Validate cost-effective 25% weight reduction potential of multi-materials vehicle.
3. Validate cost-effective 40% reduction in weight of multi-materials vehicle.
4. Design, build, and validate multi-material vehicle that is 50% lighter than standard 2002 vehicle (BAA procured effort).
5. Validate cost-effective 50% reduction in weight of multi-materials vehicle.
6. Validate cost-effective weight reduction of passenger vehicle body and chassis by at least 50% comparable to 2002 vehicles. (Go/no-go decision)
7. Through BAA, identify and validate technical feasibility at bench scale, of at least one (1) promising low-cost process for manufacturing magnesium (Mg) domestically.

◆ **Milestone**

8. Develop at least one candidate steel alloy with 1,200 MPa tensile strength and 25% uniform elongation at a cost penalty of less than 25% compared to HSLA steel.
9. Through use of integrated computational materials engineering, identify at least one (1) candidate Mg alloy that has potential to provide required properties without relying on use of rare earth elements.
10. Develop, demonstrate, and validate technical feasibility of low-cost carbon fiber.
11. Demonstrate technical and economic feasibility of producing low-cost carbon fibers, validated in a demonstration project for use in automotive.
12. Validate to within 10% of prediction, stiffness and strength of injection molded long carbon fiber composite in complex 3-D part through demonstration project to validate predictive engineering tool and low cost carbon fiber.

◆ **Milestone**

13. Conduct investigations on low-cost joining of dissimilar materials.
14. Investigate corrosion prevention issues of magnesium with multi-material vehicle structures.
15. Validate best candidates for low-cost Mg corrosion prevention.

⬢ **Technology Program Output**

1. Baseline multi-materials concept vehicle body and chassis with USAMP.
2. Revised program priorities to include remaining technology gaps identified after validation of milestone 4.
3. Technical data to USAMP.

● **Supporting Input**

1. USAMP data for vehicle body and chassis to baseline targets for multi-materials vehicle body.
2. Revised roadmap for materials lightweighting for heavy vehicles
3. Revised roadmap for materials lightweighting for light-duty vehicles

2.5.2. Propulsion Materials Technology

The Propulsion Materials Technology activity supports the energy security and reduction of greenhouse emissions goals of the Vehicle Technologies (VT) Program by developing advanced materials that enable development of higher efficiency power trains for ground transportation. Propulsion Materials works closely with the other disciplines within the VT Program to identify the material properties essential for the development of cost effective, highly efficient, and environmentally friendly next generation heavy and light duty power trains. The technical approaches available to enhance propulsion systems focus on improvements in both vehicle efficiency and fuel substitution, both of which must overcome performance limitations of materials currently in use. The Propulsion Materials Technology activity works with National Laboratories, industry experts, and VT Program teams on strategies to overcome materials limitations in powertrain performance. The technical maturity of projects funded range from basic science to subsystem prototype validation.

Goals

The Propulsion Materials Technology activity focuses on key technical deficiencies in materials performance that limit expanded capabilities of advanced combustion engines, electric-drive systems, and fuels and lubricants. It provides materials R&D expertise and enabling advanced materials that support the goals of the following VT subprograms discussed in the previous sections: Advanced Combustion Engine R&D (Section 2.3); Batteries and Electric Drive Technology (Section 2.1); and Fuels Technologies (Section 2.4). The Propulsion Materials Technology activity has identified specific key near- and long-term enabling materials goals in support of these VT subprograms.

In support of the Advanced Combustion Engine R&D subprogram:

- By 2015, develop materials and materials processing techniques to enable the development of fuel injection systems with pressures of over 2800 Bar.
- By 2015, develop materials and materials processing techniques to enable the development of prototype turbochargers with at least a 10 percent improvement in performance and at least a 20 percent reduction in weight relative to 2008 baseline.
- By 2015, develop materials, coatings, and materials processing techniques to improve the durability of prototype heavy duty engine exhaust gas recirculation (EGR) systems by at least 25 percent compared to the 2008 baseline.
- By 2015, develop materials, materials processing, and filter regeneration techniques that reduce the fuel economy penalty of particle filter regeneration by at least 25 percent relative to the 2008 baseline.
- By 2013, develop NOx sensor materials and prototypic NOx sensors that meet the sensitivity requirements identified by industry for emissions control in light duty diesel engines.
- By 2015, expand the commercialization potential of thermoelectric devices through characterization, modeling, and synthesis of thermoelectric materials and development of test protocols that will provide a basis for commercial acceptance of new materials in thermoelectric devices.

In support of the Fuels Technology subprogram:

- By 2013, provide materials for fuel injection systems on high efficiency prototypical engines operating on non-petroleum based gaseous fuels.
- By 2014, examine the impact of at least one non-petroleum based fuel formulation on key light-duty internal combustion engine components.
- By 2015, evaluate the impact of at least one renewable fuel blend on at least one heavy-duty emission after-treatment device.

In support of the Batteries and Electric Drive Technology subprogram:

- By 2013, develop materials (capacitors, solder joint connections, and integrated circuit substrates) necessary for development of highly efficient, high-temperature (105°C), power electronic control devices for applications in advanced hybrid and electric vehicles.

Challenges and Barriers

A. ***Changing internal combustion engine combustion regimes:*** As the combustion régimes of heavy and light-duty engines change the material properties of the engine cylinder block, cylinder heads, intake and exhaust valves, and fuel injection systems will need to change to accommodate the changes in peak cylinder pressure, exhaust temperatures, fuel injection pressures, and fuel formulations.

B. ***Long lead times for materials commercialization:*** Before new materials can be included in commercial vehicle designs, their properties need to be thoroughly characterized and validated to industry standards. The time from material concept to commercialization typically takes about 15 years. Materials research needs to address new engine requirements long before the engine goes into commercial production.

C. ***Many advanced vehicle technologies rely on materials with limited domestic supplies:*** many of the advanced vehicle technology concepts rely on electric motors or very lightweight cast alloys; these technologies in turn may rely on rare earth magnetic materials or lightweight alloys such as magnesium with limited domestic supplies. From an energy security perspective materials research needs to be conducted to ensure that the next generation of advanced technology vehicles can be produced domestically.

D. ***Need to reduce the weight in advanced technology vehicles***: Weight will be a critical issue in the next generation of advanced technology vehicles; it has been shown that a 10% reduction in vehicle weight results in a 6% improvement in fuel efficiency. It has also been shown that as the weight of the vehicle declines the size of the internal combustion engine, hybrid electric drive system, and battery pack for a given set of performance parameters also declines. Thus the weight of the propulsion system must be reduced even as the combustion régimes place higher strength requirements on the engine components.

E. ***Cost.*** The vehicle industry is very cost sensitive, light-duty vehicles are extremely sensitive to upfront costs and heavy-duty vehicles are extremely sensitive to lifecycle costs. Therefore any new materials technology will have to meet stringent cost targets to achieve commercial success.

Approach for Overcoming Barriers and Challenges

The Propulsion Materials Technology activity utilizes a team approach to accelerate materials technology development from component requirements, to basic understanding of materials properties, to component development, leading to component commercialization. Teams typically consist of materials researchers at the national laboratories and industry partner technologists and engineers with additional guidance provided by pertinent VT Technology Development Managers. Materials researchers at the national laboratories provide key links to Basic Energy Sciences researchers, physicists, and innovative research being conducted in support of other DOE programs which are dominated by similar physics, crystalline behavior, or material property requirements. Technologists and engineers from the industry partner provide an understanding of the component technical requirements and provide a mechanism for rapid industry acceptance and commercialization of new technologies. This combined with the guidance from the Vehicle Technologies Program to ensure that the research is in alignment with DOE goals helps to maximize the effectiveness of the program.

A. ***Changing internal combustion engine combustion regimes.*** The Propulsion Materials Technology team works closely with the Advanced Combustion Engine team and the Fuels Technology team to identify the characteristics of new combustion régimes and the materials properties that will be necessary to commercialize these technologies. This collaboration allows the Propulsion Materials team to anticipate future materials requirements.

B. Long lead times for materials commercialization: Most of the projects of the Propulsion Materials Technology activity include an industry partner who can assist in the commercialization of any new technologies being developed within the activity. When an industry partner has foreknowledge of new materials that may be available for inclusion in their design, there is a greater likelihood that the industry partner will utilize these new material properties, thereby accelerating the commercialization process.

C. Many advanced vehicle technologies rely on materials with limited domestic supplies. The Propulsion Materials team works with the various technology development teams within the Vehicle Technologies Program to identify any critical materials issues that may be of strategic importance to the Program. Once critical materials issues are identified, Propulsion Materials identifies approaches to mitigate these issues using a Material- by-Design approach involving materials characterization, modeling, and material synthesis to address the issue. These activities usually include a strong collaborative effort among multiple teams in the Vehicle Technologies Program.

D. Need to reduce the weight in advanced technology vehicles. Most improvements to power train efficiency can lead to vehicle weight reduction. As propulsion system efficiency increases, the size or displacement requirements of the power train decreases for a given level of performance. In light-duty applications this can result in a positive feedback, as the vehicle gets lighter the power requirements are reduced and minimizing the power requirements of advanced vehicle systems can help to minimize the incremental system cost.

E. Cost. The involvement of industry in Propulsion Materials projects provides leveraging to reduce the cost of the research. Further, having industry involved helps researchers remain focused on the cost target aspects of the materials research. Industry is quick to point out that technically viable solutions may not always be economically viable. Having the National Laboratories involved in materials research projects provides industry access to instruments, expertise, and equipment that would be economically prohibitive without government involvement.

Tasks

A summary of some of the tasks of the Propulsion Systems Material activity along with the technical barriers addressed are provided in Table 2.5-3.

Table 2.5-3. Tasks for Propulsion Materials Technology

Task	Title	Barriers Addressed
1	Materials for Combustion Systems/High Efficiency Engines • Evaluate and develop materials for cylinder liners, pistons, piston rings, and valve seats for low temperature combustion engines • Develop materials for advanced turbochargers for low temperature combustion engines • Evaluate and characterize emerging materials for application in advanced high-efficiency heavy truck engines	A, B, C, D

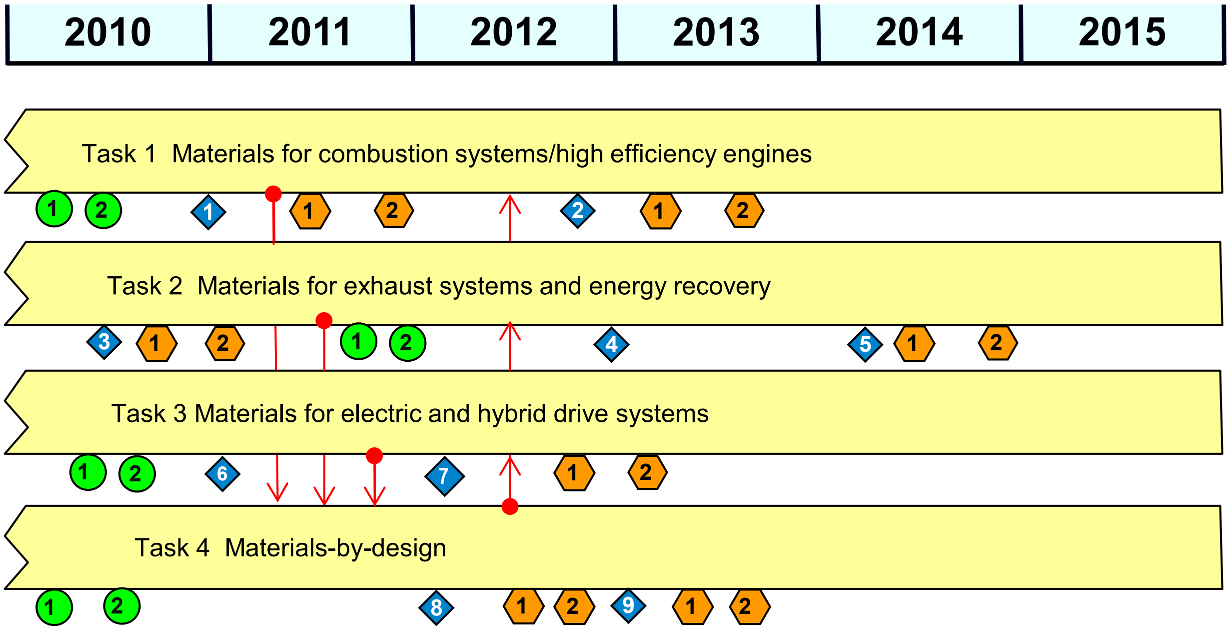
Table 2.5-3. Tasks for Propulsion Materials Technology

Task	Title	Barriers Addressed
2	Materials for Exhaust Systems and Energy Recovery • Collaborate with VT industry partners and technical teams to determine and characterize materials-related life-limiting mechanisms and failure modes of engine system components	A, B, C, D
3	Materials for Electric and Hybrid Drive Systems • Identify and characterize mechanisms for improving the figure of merit (ZT) of advanced thermoelectric materials • Identify and characterize mechanisms for improving energy storage capacity, energy and power densities, durability, and cycle life	A, B, C, D
4	Materials-by-Design • Establish nanoscience foundation (theory, processing, characterization) of catalyst performance and durability in heavy-duty engine applications • Develop capability for discovery of new and improved materials from first principles • Effectively use computational theory to guide direction of experimental effort accelerate discovery and development of new and improved materials for clean and efficient commercial vehicles	A, B, C, D

Milestones and Decision Points

The milestones and decision points for the Propulsion Materials Technology activity are shown in the figure that follows.

Propulsion Materials Technology



◆ Milestone

1. Complete evaluation/development of materials for cylinder liners, pistons, piston rings, and valve seats for low temperature combustion engines
2. Complete evaluation of mechanical behavior of emerging materials for application in advanced high-efficiency diesel engines
3. Complete development of materials to enable advanced turbocharger for low-temperature combustion engines
4. Complete evaluation of mechanical behavior of advanced materials to facilitate reduction of thermal energy to engine coolant by 50%

◆ Milestone

5. Evaluate performance of advanced bulk high ZT material for the next generation thermoelectric devices
6. Evaluate performance of materials developed for high-temperature electronic devices
7. Identify compositions for non-rare earth magnet for further optimization
8. Apply modeling, simulation, and experimentation to develop high-ZT thermoelectric material without rare earth elements
9. Establish nanoscience foundation of catalyst performance and durability for heavy-duty engine applications

⬢ Technology Program Output

1. Technical data and information to VT technology development teams
2. Technical data and information to peer reviewed journals
3. User project report to all partners.

● Supporting Input

1. Materials related issues identified by VT technology development teams
2. Materials related issues identified by industry partners

2.5.3. High Temperature Materials Laboratory

The High Temperature Materials Laboratory (HTML) is an advanced materials characterization R&D facility located at the Oak Ridge National Laboratory. As a nationally designated user facility sponsored by the EERE Vehicle Technologies (VT) Program, the HTML provides a skilled staff and numerous sophisticated, often one-of-a-kind, materials characterization tools and equipment, and a professional staff having the knowledge needed for solving complex materials engineering problems. The HTML strives to maintain world-class, state-of-the-art advanced materials characterization capabilities not available elsewhere in the U.S. and through the HTML User Program, make these capabilities readily accessible to users as varied as industrial scientists and engineers, university materials researchers, and national laboratories and ORNL researchers.

The HTML supports the transportation materials development activities of the VT Program, other EERE materials development efforts, other transportation materials-relevant R&D, and training of materials technologists. Experience has shown that technologies needed to enhance vehicle fuel economy, enable the efficient use of alternative fuels, and energy efficiency are often limited by the properties, performance, and cost of the materials used. The HTML professional staff develops cutting-edge analytical techniques to develop innovative materials for use in transportation applications. Activities include the investigation and determination of the composition, structure, physical and chemical properties and performance characteristics of metals, alloys, ceramics, composites, and novel nano-phase materials under development for vehicle applications.

The HTML procures, maintains, and provides unique and sophisticated state-of-the-art materials research equipment and also provides the expertise to operate the equipment and interpret the results. By providing timely access to these capabilities, the HTML assists industry, academic and national laboratory partners in realizing the VT Program goals as well as the goals of the FreedomCAR and Fuels Partnership, and the 21st Century Truck Partnership.

Goals

The goal of the HTML is to provide world-leading materials characterization instrumentation and capabilities to resolve materials-related barriers impeding the success of VT research. More specific goals directly supporting the VT Program are:

- Provide materials-related solutions that will enable the development of energy efficient technologies capable of using alternative fuels and that will improve the fuel economy of and reduce emissions from engine/vehicle systems being developed by VT and its industry partners.
- Through the HTML user centers, assure broad application of materials science and tools that are developed in support of VT and other EERE programs.

Challenges and Barriers

A. ***Lack of knowledge of advanced materials properties and performance characteristics.*** A primary barrier to adoption of advanced materials in vehicles by the U.S. automakers is the lack of understanding of the characteristics and capabilities of these materials to perform under real world vehicle operating conditions.

B. ***Uncertainties (risk).*** Inherent risks to employing advanced materials, such as risk of failure, must be better understood to be mitigated. HTML equipment aids in understanding failure modes of materials.

C. ***Cost.*** New materials must be cost competitive and available in sufficient supply.

D. ***Processing and Manufacturability.*** Parts and components made from advanced material(s), will need to be produced in quantity and rates consistent with the mass production of vehicles. Processes to produce the desired properties in new materials must be understood to produce materials which are reliable and cost competitive.

Approach for Overcoming Barriers/Challenges

The HTML will continue to maintain and provide state-of-the-art materials characterization facilities and equipment, operated by skilled technical staff. VT R&D programs, its partners in industry, academia, and other government agencies are provided ready access to HTML facilities to address and overcome materials-related barriers and challenges to achieving VT goals. Characterization of advanced materials is focused on four major materials research areas: energy storage and catalysis; propulsion materials; thermoelectric materials; and lightweighting and high-strength weight reduction materials.

In situ characterization of materials and processes will be utilized to investigate operable mechanisms at the atomic/molecular levels and advance the understanding of material composition and structures needed to address materials-related barriers to the development of long life, high performance, and cost-competitive vehicle components and systems. Real-time characterization at the atomic level would provide knowledge of how catalytic nanoparticles behave at high temperatures, or how the microstructure of lithium-ion battery electrodes changes during charging-discharging cycles to provide understanding of the mechanisms that limit the durability and life of the battery.

The HTML facilities and equipment are typically either one-of-a-kind instruments or a collection of characterization instrumentation located together in one facility, unavailable elsewhere in the world. The HTML will continue to procure/acquire new capabilities as needed and as funding allows. New analytical capabilities at the HTML to be utilized include: instruments to characterize the properties and performance of new high efficiency thermoelectric materials, deployment of an intense neutron flux diffractometer, VULCAN, enabling research on chemical reactions occurring in the solid state and rapidly occurring changes in materials subjected to stresses. In addition, the HTML has a special purpose scanning transmission electron microscope (STEM) modified for *in-situ* characterization of catalysts, advanced battery, thermoelectric materials, and lightweight materials. Novel experiments using *in situ* neutron scattering are used to characterize Li-ion cells, providing data on internal volume and temperature changes, and distribution of active materials during charging and discharging. These enhanced capabilities will also help companies solve materials problems occurring from recent changes in fuel composition, such as the addition of ethanol to gasoline and the removal of sulfur from diesel fuel.

The HTML User Program will continue to fund pre-competitive non-proprietary materials research projects submitted by U.S. companies, universities, and national laboratories for the advancement of high efficiency vehicle technologies aligned with the VT goals. Users shoulder the cost of travel to ORNL and the cost of making and preparing the samples used in the research. Typically, 50 to 75 projects are completed each year, with results published in peer reviewed journals, industry presentations, and trade press.

Tasks

A summary of some of the tasks being carried out at the HTML along with the technical barriers addressed are provided in the Table 2.5-4.

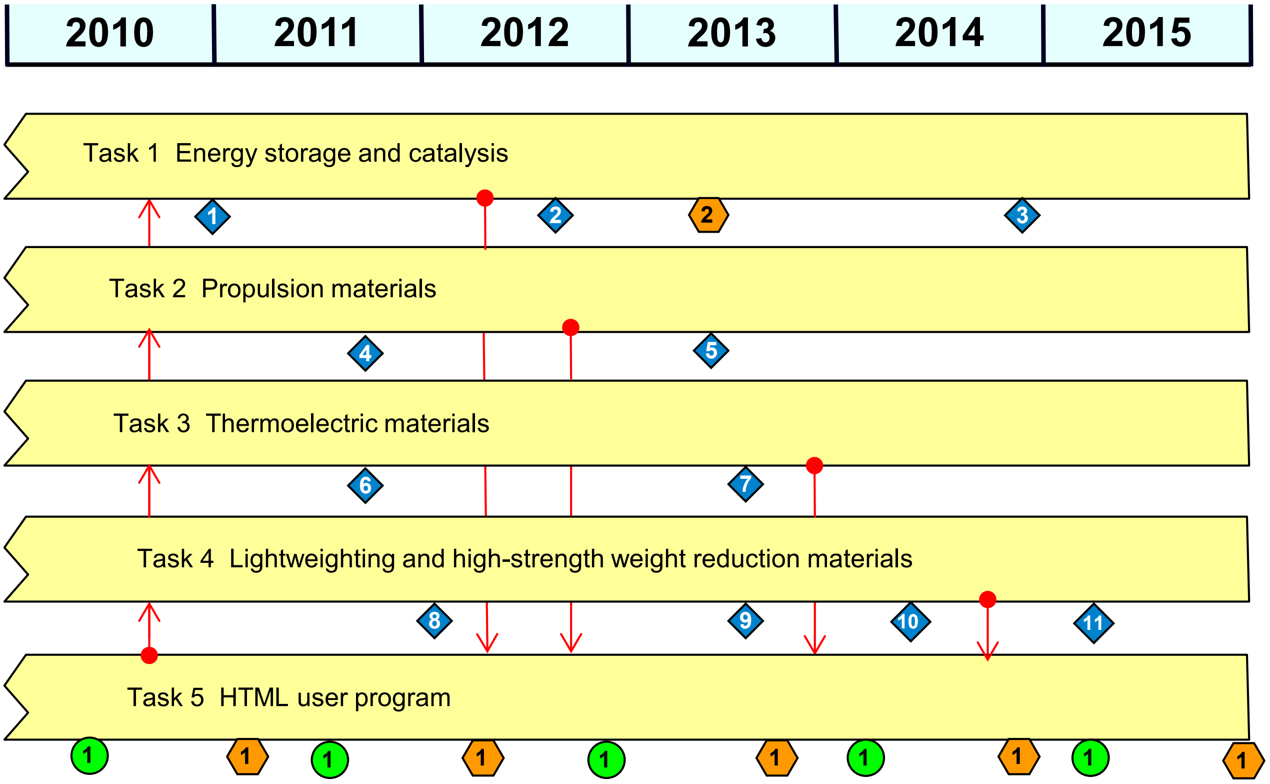
Table 2.5-4. Tasks for HTML

Task	Title	Barriers Addressed
1	Energy Storage and Catalysis • Identify and characterize mechanisms for improving energy storage capacity, energy and power densities, durability, and cycle life • Identify and characterize mechanisms of functioning and degradation of lean-burn engine emission control catalysts • Assist VT industrial and academic partners in developing advanced materials and processes for emissions reduction components	A, B, C, D
2	Propulsion Materials • Collaborate with VT industry partners and technical teams to determine and characterize materials-related life-limiting mechanisms and failure modes of engine system components	A, B, C, D
3	Thermoelectric Materials • Identify and characterize mechanisms for improving the figure of merit (ZT) of advanced thermoelectric materials	A, B, C, D
4	Lightweighting and High-Strength Weight Reduction Materials • Characterize the mechanisms of interaction and the properties of an interface or joint formed between two lightweighting materials • Characterize the effect of loading rate on the mechanical properties of lightweight alloys and fiber-reinforced composites • Characterize the microstructural evolution of carbon fibers during carbonization and graphitization of low-cost precursors	A, B, C, D
5	Develop and Maintain HTML Capability and User Center Utilization • Develop and maintain state-of-the-art materials characterization instrumentation and expertise on advanced materials of interest to VT, its partners, and other EERE programs • Support a robust user community of automotive and heavy–vehicle manufacturers and materials and component suppliers	A, B, C, D

Milestones and Decision Points

The milestones and decision points for the High Temperature Materials Laboratory activity are shown in the figure that follows.

High Temperature Materials Laboratory



◆ **Milestone**

1. Use aberration corrected microscope (ACEM) in study of experimental NO_X trap material, showing imaging capabilities not possible with present-day microscopy capability at ORNL.
2. Characterize candidate battery materials for high energy and high power densities
3. Study 2 experimental diesel NOX-reduction materials using a combination of HTML's ex situ catalyst reactor for TEM specimens, and the imaging and spectroscopy capabilities of ACEM.
4. Complete evaluation of industrial residual stress sectioning technique using neutron diffraction techniques.
5. Evaluate materials in realistic reciprocating engine environments.

◆ **Milestone**

6. Characterize advanced bulk high ZT material for next generation thermoelectric devices.
7. Elucidate effect of modifications on ZT of bulk thermoelectric materials.
8. Characterize effect of loading rate on vehicle structure component made of magnesium.
9. Characterize in real time, the microstructural evolution in lightweight alloys at high temperature using novel high-resolution microscopy *in situ* tools.
10. Characterize the evolution of carbon fiber microstructure from low-cost precursors during carbonization and graphitization using *in situ* X-ray diffraction.

◆ **Milestone**

11. Apply VULCAN* to establish grain boundary behavior and changes as a function of loading, fatigue, and temperature.

⬢ **Technology Program Output**

1. User project report to all partners.
2. Material characterization and technology related to atomic level understanding of energy storage materials available to industry

● **Supporting Input**

1. Research project proposals from potential users

*VULCAN is a new neutron spectrometer installed on a port (beamline) of the high intensity spallation neutron source.

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2.6. Outreach, Deployment, and Analysis

- The Outreach, Deployment, and Analysis subprogram focuses on activities that will accelerate the adoption and use of alternative fuels and advanced technology vehicles to help meet national energy and environmental goals. Widespread introduction and deployment of these fuels and vehicles would contribute to the reduction in the consumption of petroleum-based fuels and reduction in greenhouse gas emissions. This subprogram consists of the following activities which logically follow and complement successful research by industry and government:Vehicle Technologies Deployment
- Legislative and Rulemaking
- Graduate Automotive Technology Education (GATE) and Advanced Vehicle Competitions

Primary functions are in support of the Energy Policy Acts of 1992 and 2005, EPAct 1992 (P.L. 102-486) and EPAct 2005 (P.L. 109-58), respectively, which mandate alternative fuel and fleet activities, voluntary community-based partnerships to promote deployment of vehicle technologies and alternative fuels that can reduce petroleum consumption and greenhouse gas emissions. In addition, educational opportunities are provided for university students to learn and use real-world engineering skills while demonstrating the performance of new vehicle technologies.

2.6.1. Vehicle Technologies Deployment

The Vehicle Technologies Deployment activity promotes the voluntary adoption and use of petroleum reduction technologies and practices by working with locally based coalitions and their stakeholders, industry partners, fuel providers, and end-users such as fleet operators. Technology focus areas include: alternative fuel vehicles (AFVs), alternative fuel infrastructure development, idling reduction for commercial trucks and buses, expanded use of non-petroleum and renewable fuel blends, hybrid vehicles, and driving practices and engine/vehicle technologies that maximize fuel economy. Outreach, training, and technical assistance related to each technology focus area are provided by technology experts at DOE headquarters and national laboratories. Also provided are technical assistance for early adaptors of technologies, and training and workshops to coalitions, public safety officials, and stakeholders related to infrastructure development and targeted niche market opportunities that include transit, refuse trucks, school bus, delivery trucks, and municipal fleets. Provided as well is public information on the benefits and costs of the use of alternative fuels in vehicles.

Goals

The overall goal of the Vehicle Technologies Deployment activity is to support DOE’s strategic goal of protecting the U.S. national and economic security by reducing imports and promoting a diverse supply of reliable, affordable, and environmentally sound energy. More specifically:

- By 2020, to achieve a petroleum reduction of over 2.5 billion gallons per year through voluntary adoption of alternative fuel vehicles and infrastructure.

This goal will be achieved by: a) reduction in petroleum consumption through vehicle efficiency technologies; b) replacement of petroleum fuels with alternative fuels, non-petroleum fuel blends, and electric drive technology vehicles; and c) further reduction in petroleum consumption through idle reduction technologies, and potentially through reduction in personal vehicle miles traveled or other means.

Other specific goals of the Vehicle Technologies Deployment activity are:

- To ease market introduction of alternative fuels and new electric drive vehicle technologies through voluntary efforts in partnership with local communities; and

- To provide technical and educational assistance to support local communities and partnerships that promote better understanding of the benefits of these new technologies.

Challenges and Barriers

The challenges and barriers addressed are as follows:

A. ***Availability of alternative fuels and electric charging station infrastructure.*** Most of the alternative fuels face challenges in availability of supply, production capacity, and the lack of fueling infrastructure to compete with the fully mature conventional petroleum-based gasoline and diesel fuels. For example, although auto manufacturers have sold millions of flexible fuel vehicles (FFVs) that can utilize E85 (and have stated commitments to sell even more), there are only 2,000 E85 outlets in the U.S. (versus around 167,000 gasoline stations[1]), which limits the ability of flexible fuel vehicle owners to use E85 fuel even if they want to do so. Other alternative fuels (such as natural gas and hydrogen) have similar barriers. In addition, prices in comparison to gasoline and diesel fuel prices tend to vary regionally, affecting the ability of the consumer to achieve the cost savings that make the alternative fuel choice more attractive. For instance, biofuels have tended to be cheaper and more readily available in the Midwest, while gaseous fuels have tended to be somewhat more competitively priced and available on the coasts and in the South. Certification of the equipment used in alternative fuel dispensers has been a barrier as well. The change by Underwriters Laboratories from component-level listing to dispenser system-level listings for UL certification for ethanol fuel dispensers has resulted in delays in some communities in permitting and construction of a number of ethanol stations over the past several years. Currently there are very few electric charging stations needed for the coming plug-in hybrid electric vehicles (PHEVs) and fully electric vehicles (EVs).

B. ***Availability of AFVs and electric drive vehicles.*** Of the AFVs, only the FFVs which can use E85 are available in large numbers (currently over 1 million every year, in sedan and light-truck models) and at virtually no incremental cost. This is still small in comparison to the total vehicle sales per year (which range from 10 to 15 million per year, depending on economic conditions). Major vehicle manufacturers have ceased production of their own OEM gaseous fuel (natural gas and propane) light-duty vehicles, with one exception (a CNG compact sedan). Conversions of existing vehicles to use alternative fuels (especially propane and natural gas) have seen renewed interest because of this, but such conversions are subject to rigorous government testing and approvals. For this reason, the availability of conversion kits is limited to a few vehicle models, and the cost of the testing required can increase the price of these kits. In addition, some fleets are unwilling to consider conversion kits for alternative fuels because of warranty concerns or previous unfavorable experiences. Sales of many alternative fuel vehicles have been hampered particularly by being more expensive to purchase than conventional gasoline vehicles. Natural gas engines are available for heavy-duty fleet vehicles, especially for intra-city use with a central fueling station where long-term fuel purchase contracts can lower the price of the fuel to ensure a robust business case for these vehicles. Other advanced technology vehicles (such as plug-in hybrids, electric vehicles, and hybrid vehicles) have similar supply and cost issues. The cost issue is particularly acute for plug-in hybrid and electric vehicles whose energy storage needs require relatively high-cost batteries. Several models will, however, be entering the market over the next few years.

C. ***Consumer reluctance to purchase new technologies.*** Most vehicle buyers try to make the most out of their purchases and use their vehicles for as long as they can. Hence, they tend to be reluctant to purchase vehicles with new technologies that could potentially be made obsolete sooner, have possibly lower resale value, be different or more difficult to maintain, offer unknown reliability, and for which fuel availability is uncertain. Manufacturers are

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[1] American Petroleum Institute, The Economics of Gasoline Retailing, 2003, http://www.api.org/aboutoilgas/upload/Economics_of_Gas_Retail.pdf.

averse to assuming the risk required for the production, promotion, and distribution of advanced energy-efficient vehicle technologies that consumers might be reluctant to purchase.

D. Lack of technical experience with new fuels and vehicle technologies. As with most new technologies, early technical expertise and assistance needs to be made available to users. Also, user experience with the new technologies would be helpful to making other potential users to be more amenable to adapting the new technologies. In addition, technical issues identified need to be addressed.

E. Maintenance of local coalition effectiveness. The Vehicle Technologies Deployment activity has built a network of almost 90 coalitions to promote the goals of the program at the local level. The effectiveness of these local coalitions is critical to meeting the overall goals of the activity, and it varies by coalition area (some are very successful, others less so). Effectiveness can be limited by a number of factors, including coordinator personnel turnover, unfamiliarity with the broad portfolio of technologies, or limitations on activities and/or personnel availability imposed by a host organization.

Approach for Overcoming Barriers/Challenges

The Vehicle Technologies Deployment activity, through the *Clean Cities*[2] network, will continue building national and regional alliances to promote petroleum reduction strategies, increase public awareness and consumer acceptance and/or adoption of alternative fuels, and to showcase advanced vehicle technologies being developed through the VTP R&D activities. The primary focus is to achieve petroleum reduction by implementing next steps when R&D is completed. Deployment efforts include:

- Direct support of *Clean Cities* activities, public events, training for coalitions and key community decision makers, and deployment project coordination
- Development of targeted industry, end-user, university, and stakeholder partnership(s)
- Consumer information, outreach, and education through web-based consumer tools (Fuel economy guide, AFDC) and others. targeted workforce and end-user education
- Technical and problem solving assistance such as addressing market barriers, safety issues, technology shortfalls
- Financial assistance such as through funding to facilitate infrastructure development and vehicle deployment
- ARRA-funded training of new technology vehicle maintenance technicians through the community and technical colleges in all regions throughout the U.S.

Specific strategies and approaches include partnering with states and local organizations, providing outreach, education, and information resources, facilitating infrastructure development, coordinating efforts with EPAct-regulated fleets, and providing technical and financial assistance. Critical tools and information are provided via the internet (mainly through the Alternative Fuel and Advanced Vehicle Data Center website), telephone hotline, publications, and direct interaction with experts. Additionally, the activity supports the development and promotes the use of the legislatively-mandated Fuel Economy Guide and its associated website, www.fueleconomy.gov. *Clean Cities* is also tied to fleet regulatory programs for Federal fleets (managed by the EERE FEMP Program), as well as state and fuel provider fleets (managed by the Vehicle Technologies Program). *Clean Cities* helps regulated fleets meet their requirements and maximize their petroleum reduction benefits. These regulated fleets also serve as anchor fleets for many coalitions, providing identifiable demand for alternative fuels to support infrastructure development.

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[2] *Clean Cities* (http://www1.eere.energy.gov/cleancities/) is a network of about 90 locally based coalitions under which government agencies and private companies have voluntarily come together in partnerships to promote alternative fuels and advanced vehicles, fuel blends, fuel economy, hybrid vehicles, and idle reduction. All parties identify mutual interests and agree to meet the objectives of reducing the use of imported oil, developing regional economic opportunities, and improving air quality.

The American Recovery and Reinvestment Act (ARRA) of 2009 (P.L. 111-5) provided funding for *Clean Cities* to accelerate the transformation of the Nation's vehicle fleet through a range of energy efficient and advanced vehicle technologies, as well as refueling infrastructure for various alternative fuel vehicles, and public education and training initiatives. Over 2,000 alternative fuel and electric charging stations will be built or upgraded, over 9,000 alternative fuel and advanced technology vehicles will be deployed, leading to local and community development, and creation of jobs. Several consortia of technical universities and colleges will establish programs to educate and train the workforce needed to design, manufacture, and service/maintain advanced electric vehicles and associated infrastructure. These consortia throughout all regions of the U.S. will develop curricula and offer certificates and associate degrees for training technicians for the maintenance and repair of electric drive vehicles, B.S. and M.S. degree programs for design and manufacturing engineers for electric vehicle industry, and certificate programs in electric vehicle safety for emergency responders.

Tasks

A summary of some of the tasks being carried out by the Vehicle Technologies Deployment activity along with the technical barriers addressed is provided in Table 2.6-1.

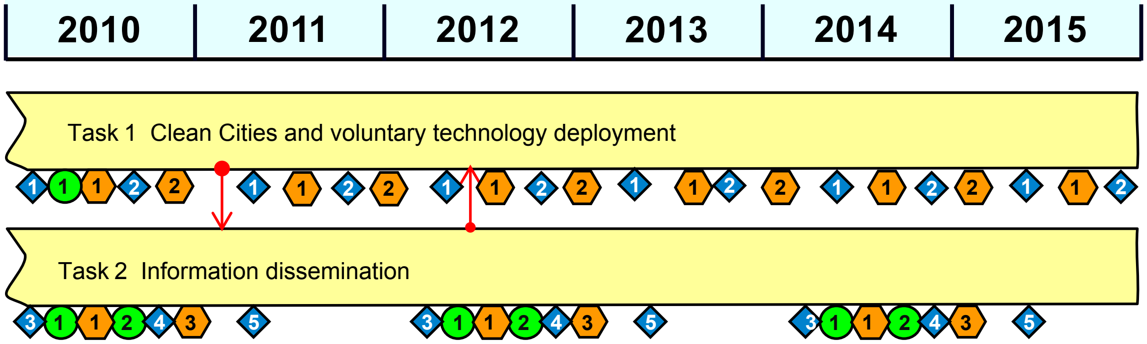
Table 2.6-1. Tasks for Vehicle Technologies Deployment

Task	Title	Barriers Addressed
1	Clean Cities and voluntary deployment • Build national awareness and brand recognition for Clean Cities • Maximize effectiveness of Clean Cities in deploying its portfolio of technologies by strengthening the leadership and instituting mentoring programs to enhance communication capabilities within the coalitions • Develop national partner program(s) to encourage major national corporations to participate in local efforts • Promote technologies initially in niche markets and develop, as needed, strategies for more widespread deployment	A, B, C, D, E
2	Information dissemination • Update data and information in the Alternative Fuels Data Center website (www.afdc.energy.gov) • Develop fuel economy guide annually and post links on the VT website (www.fueleconomy.gov) • Maintain expertise for providing timely response to technology-specific queries (e.g., hotline: 1-800-EERE-INF (1-877-337-3463)	A, B, C, D, E

Milestones and Decision Points

The Vehicle Technologies Deployment activity milestones are shown in the following chart.

Vehicle Technologies Deployment



◆ **Milestone**

1. Initiate planning for Clean Cities meetings at selected localities.
2. Conduct networking meetings to strengthen Clean Cities coalitions through technical training .
3. Identify technical data/information needed to promote selected alternative fuels and advanced vehicle technologies.
4. Collect data and develop information packages.
5. Disseminate data/information via selected information transfer mechanisms.

⬢ **Activity Output**

1. Technical data/information for wide public dissemination.
2. Technical data/information needs to VT R&D activities.
3. Fuel economy information on www.fueleconomy.gov

● **Supporting Input**

1. Alternative fuels and advanced vehicle technologies data and information from VT R&D activities.
2. Input from industry on model year vehicle technical information

2.6.2. Legislative and Rulemaking

The fleet provisions of the Energy Policy Act (EPAct) of 1992, as amended by later Congressional enactments, including most recently Section 133 of the Energy Independence and Security Act of 2007 (EISA), and as implemented through DOE’s implementing regulations (10 CFR Part 490), seek to reduce our nation’s dependence on petroleum by increasing the presence of alternative fuel capable vehicles (AFVs) and thereby promoting the use of alternative fuels and other replacement fuels. Consistent with these provisions, State government and alternative fuel provider fleets located in major metropolitan areas must ensure that AFVs comprise 75 and 90 percent, respectively, of their fleets’ annual light-duty vehicle acquisitions or, in lieu of AFV acquisitions, achieve annual petroleum fuel use reductions.

To date, DOE’s State and Alternative Fuel Provider (S&FP) Program has resulted in the acquisition of nearly 140,000 AFVs. Alternative or replacement fuel now comprises approximately 3 percent of U.S. motor fuel[3].

Goals

The Legislative and Rulemaking activities focus on three primary goals:

- Promoting the replacement of petroleum motor fuels with replacement fuels “to the maximum extent practicable,” with a national goal of replacing 30 percent of U.S. motor fuel consumption with replacement fuels by the year 2030.
- Integrating and coordinating with the Federal fleet and DOE’s *Clean Cities* network in an effort to enhance the opportunities for nationwide deployment of AFVs, development of the necessary alternative fuel infrastructure, and introduction of advanced vehicle technologies as they become market-ready.
- Implementing legislative and regulatory modifications to the S&FP Program.

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[3] Transportation Energy Data Book, Edition 28.

Specific goals for the Legislative and Rulemaking activities are as follows:

- Maximizing replacement fuel use through S&FP fleets' deployment of AFVs and use in those vehicles of the appropriate alternative fuel;
- Encouraging S&FP fleets to consider pursuing petroleum consumption reductions in lieu of annual AFV acquisitions; and
- Maximizing compliance with the legislative and regulatory requirements.

Challenges and Barriers

The challenges and barriers addressed are as follows:

A. ***Availability of alternative fuels and electric charging station infrastructure.*** This is the most prominent market challenge facing the Legislative and Rulemaking activities. Ethanol and biodiesel continue to be the most viable alternative fuels for most S&FP fleets. However, there are only approximately 2,000 ethanol fueling stations in the U.S., with more than half of those located in the Midwest.[4] California and Texas, the most populous states in the country, together have a total of 87 ethanol fueling stations. With respect to biodiesel, there are fewer than 700 fueling stations nationwide that offer neat biodiesel or a biodiesel blend, although some of those blends are at levels below the 20 percent blend level required for credit under the S&FP Program.[5] Presently there are very few electric charging stations needed for the coming PHEVs/EVs.

B. ***Limited regulatory authority.*** While EPAct 1992 requires alternative fuel provider fleets to use alternative fuel in their AFVs (except when the vehicles are operating in an area where the appropriate fuel is unavailable), such a requirement was not imposed on State government fleets. As a result, State government fleets, while needing to meet AFV-acquisition requirements, do not have to use alternative fuel in those AFVs, thus minimizing the potential impact of the S&FP Program. Similarly, the EPAct 1992 fleet program for S&FP fleets was limited to light-duty vehicles only and because the legislation was enacted in the 1990s there was no provision concerning electric drive vehicles. Medium- and heavy-duty vehicles typically use several times the annual amount of fuel of a light-duty vehicle, and therefore could have increased significantly the petroleum displacement potential of this activity. In addition, given that alternative fuel infrastructure and electric charging stations remain key barriers, commercial vehicles may have been much more important due to the fact they are more likely to be parked in a central location when not in use, and their increased fuel demand means that fewer vehicles are needed to support a single fueling location. The S&FP Program also was limited to larger fleets in major urban areas, thereby limiting the pool of vehicles from which petroleum displacement might occur.

Approach for Overcoming Challenges/Barriers

The Legislative and Rulemaking activities are focused on several key strategies for accomplishing its performance goals. These strategies include:

- Implementing legislative modifications to the S&FP Program's credit scheme by allocating credits for the acquisition of various electric drive vehicles;
- Making other S&FP Program improvements;
- Continuing to work with fleets to maximize compliance;
- Working with fuel providers/suppliers to communicate fleet needs;
- Reviewing, analyzing, and responding to proposed legislation affecting the S&FP Program;

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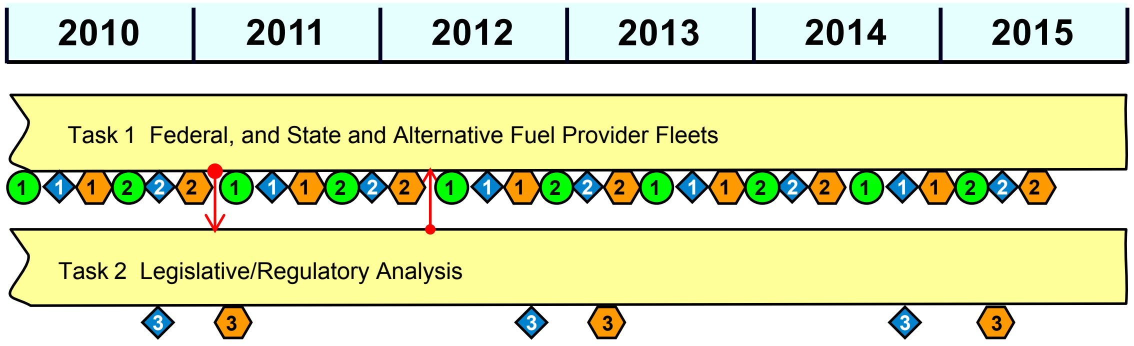
[4] DOE Alternative Fuels & Advanced Vehicles Data Center's Alternative Fueling Station Locator (http://www.afdc.energy.gov/afdc/fuels/stations_counts.html).
[5] DOE Alternative Fuels & Advanced Vehicles Data Center's Alternative Fueling Station Locator (http://www.afdc.energy.gov/afdc/fuels/stations_counts.html).

- Conducting necessary education and coordination activities; and
- Identifying technical barriers and working with other programs to overcome those barriers.

Milestones and Decision Points

The Legislative and Rulemaking activities have the key milestones shown in the following chart.

Legislative and Rulemaking Activities



◆ Milestone

1. Report on Federal Fleets
2. Report on compliance of State and Alternative Fuel Provider Fleets
3. Review of replacement fuel goal(s) and assessment of activities

⬢ Activity Output

1. Report to Congress on Federal Fleets.
2. Document on status of compliance of State and Fuel Provider Fleets.
3. Report on analysis of goal(s) and assessments.

● Supporting Input

1. Data and information from Federal Fleets
2. Data and information from State and Alternative Fuel Provider Fleets .

2.6.3. Graduate Automotive Technology Education (GATE) and Advanced Vehicle Competition

A significant barrier to the accelerated commercial introduction of new vehicle technologies is the limited base of personnel trained specifically in the new areas. Furthermore, there is a general lack of educational curricula to train the needed experts. The continual demand from the competitive technology, conventional vehicles, and the shift of many technology development activities from auto manufacturers to Tier 1 and 2 suppliers has created a significant, growing need for specialized training of engineers and scientists with knowledge of the key new technology areas. In the past, automotive engineers were thought of “mechanical,” “electrical” or “chemical” Engineers. The vehicle of the future will be designed and built by engineers who are “all of the above” and work as vehicle integrators to make sure that these complex systems work together to provide more efficient and clean transportation.

In developing innovative technologies and transferring them to industry, DOE is addressing the growing need for people trained in non-traditional, emerging vehicle technologies. The advanced technologies being developed by the DOE/VTP and the automotive industry require a knowledgeable and experienced workforce to carry them forward into production. To respond to this growing need, VTP has advanced two college-level education efforts to engage some of the best engineering minds in advanced transportation research: GATE and Advanced Vehicle Competitions.

The first vehicle competitions, beginning in 1987, were focused on the use of alternative fuels and were executed as the Methanol, Natural Gas, and Ethanol Challenges. Subsequent competitions, Future Car and Future Truck, evolved to greater focus on attaining the total vehicle efficiency goals. The latter challenge was implemented over a five-year period and concluded in FY 2004. The Advanced Vehicle Competition was called ChallengeX: Crossover to Sustainable Mobility. Challenge X was a four-year collegiate engineering competition sponsored by the VTP and General Motors Corporation. It was conducted from 2004 through 2008 and offered college engineering students the opportunity to experience hands-on R&D with leading-edge automotive propulsion, fuels, materials, and emissions control technologies. Teams imitated the GM real-world process to model, design, build and integrate vehicles with cutting-edge advanced automotive technologies and alternative fuels that minimize total environmental impact and help build a sustainable transportation future. EcoCAR is the successor to Challenge X and is a three-year engineering competition headlined and sponsored by the Vehicle Technologies Program and General Motors (GM). EcoCAR was started in 2008 and will end in 2011. It challenges students to re-engineer a 2009 Saturn Vue to reduce fuel consumption and lower emissions by using advanced vehicle technologies, such as: hydrogen fuel cells, plug-in hybrid technology, hybrid technology, diesel technology and other advanced fueling technologies. EcoCAR also is introducing hardware-in-the-loop (HiL) and software-in-the-loop (SiL) training for its competition students. This is state-of-the-art training and allows students to mirror the real-world development process used by GM and other auto manufacturers from around the world.

The growing need for the specialized, new workforce coupled with earlier success of the vehicle competitions led DOE to establish the Graduate Automotive Technology Education (GATE) effort in 1998. GATE provides a new generation of engineers and scientists with cross-disciplinary (broader than mechanical or electrical) knowledge and skills in advanced automotive technologies. It supports universities to establish centers in special technology areas with new curricula development, and it provides support for relevant research fellowships. In 1998, the DOE funded 10 proposals to establish GATE centers of excellence at nine universities. These Centers addressed the following key technology areas: fuel cells, hybrid electric vehicle drivetrains and control systems, lightweight materials, direct-injection engines and advanced energy storage. In 2005, the DOE re-competed the GATE effort, which resulted in funding eight proposals to establish or expand centers in the following key technology areas: fuel cells, hybrid electric vehicle drivetrains and control systems, lightweight materials, advanced energy storage and biofuels. GATE is being recompeted in 2011.

Goals

The overall goal of GATE and the Advanced Vehicle Competitions is to contribute to the acceleration of advanced petroleum saving vehicle technologies into the marketplace.

The specific goals are the following:

- Tap the technical and human resources of U.S. colleges and universities in a comprehensive and integrated manner aiming for involvement of over 120 faculty members by 2011.
- Build a solid foundation of research knowledge and engineering experience including creation of over 40 interdisciplinary courses specializing in advanced automotive technology needs by 2011.
- Accelerate the development of technologies necessary for cost-effective manufacture of highly fuel-efficient, low-emission vehicles with involvement of 125 industry partners by 2011.
- Develop a new workforce of talented, trained individuals who will be instrumental in building our country’s future automotive industry with more than 400 students participating in the specialized programs by 2010.
- Provide hands-on experience for teams of students with advanced vehicle system technologies at over 26 universities by 2011.

Challenges and Barriers

A. ***Lack of trained engineers and scientists.*** There is not a sufficient body of engineers and scientists trained in key areas of the advanced energy efficient technologies being developed by the VT Program to allow optimal accelerated introduction of these technologies.

B. ***Lack of advanced technology curricula.*** Teaching curricula specific to the advanced technologies in the VT Program is not available at a sufficient number of universities to sustain a specialized workforce.

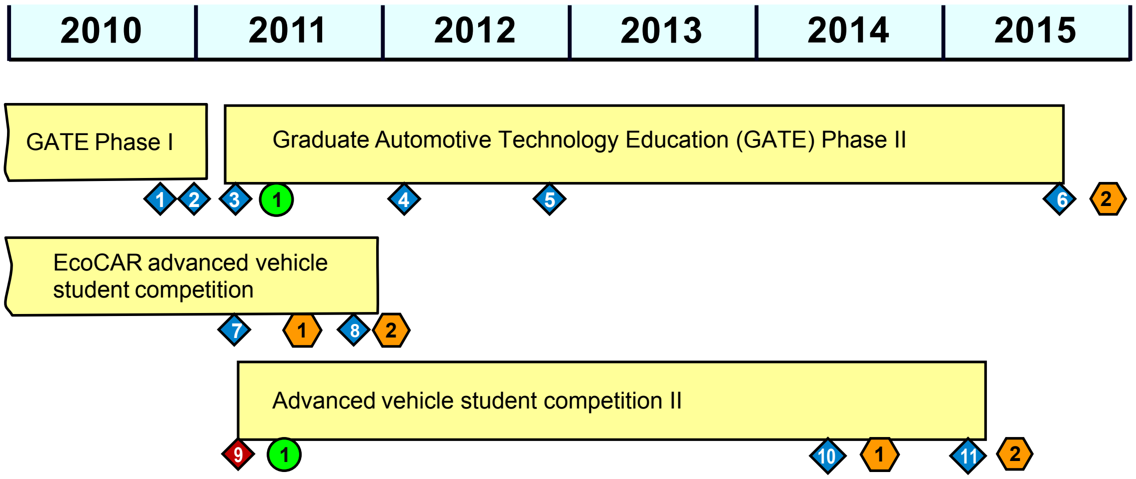
Approach for Overcoming Barriers/Challenges

The GATE and Advanced Vehicle Competition efforts are aimed at overcoming barriers A and B to accelerated commercialization of the VT technologies due to the lack of an optimum workforce of specifically trained engineers and scientists. Primary focus of these two efforts is the sustainable production of the necessary new generation of engineers and scientists. This is accomplished through several means. GATE sponsors the establishment of university centers of excellence specializing in areas of the advanced vehicle technologies. These centers develop new, unique curricula to add to existing subjects to train students in new disciplines. Sometimes as needed there is the addition of faculty to the university. Partnerships between the university and industry or government are formed to identify critical research needs and students undertake the research with the partners. The partners provide resources also and the university moves toward sustainability eventually without VT support. Under the competitions effort, teams of students are formed at competitively selected universities to develop full vehicle systems incorporating energy savings technology. VT partners with industry and other agencies to provide resources and close technical support to maximize the benefit of the experience for the students.

Milestones and Decision Points

The milestones for GATE and Advanced Vehicle Competitions are shown in the following chart.

GATE and Vehicle Competition



◆ **Milestone**

1. Complete curricula development
2. Complete summary evaluation
3. Competitively solicit and award new GATE centers of excellence
4. Complete curricula development of new GATE centers of excellence.
5. Progress reports on student interest and enrolment.
6. Centers of excellence graduate next batch of automotive engineers.

◆ **Milestone**

7. Complete evaluation of student-designed vehicles.
8. Student competition winner awards.
9. Go/No-go Decision. Decision on next competition; key criterion is success in partnering for sponsorship.
10. Complete evaluation of student-designed vehicles.
11. Student competition winner awards.

⬢ **Technology Program Output**

1. Competition vehicles performance data to Vehicle and Systems Simulation and Testing (VSST) subprogram for evaluation.
2. Trained engineers to industry.

● **Supporting Input**

1. Partner resources.

2.6.4. Analysis – Approaches for Improving Efficiency of Personal Transport Legacy Vehicles

The Vehicle Technologies Program (VTP) conducts R&D related to improving the efficiency of a wide variety of vehicles through development of advanced technologies such as hybridization and electrification, and incorporating renewable fuel sources wherever possible. This research conducted by VTP will have a significant effect on the efficiency technologies being planned by major manufacturers for the future. When fully implemented, advanced technologies being developed by VTP such as hybrids, plug-in vehicles, advanced combustion engines, and vehicle lightweighting will represent a major shift in the architecture and performance of the automobile in the future. However, because many of these technologies will be applied only to new vehicles because of the fundamental changes they often represent, they will have little effect on the existing fleet of vehicles currently on the road.

The current U.S. fleet of vehicles on the road numbers over 250 million, and improvements in quality and reliability over the last several decades mean that these vehicles will remain in use for well over ten years. This slows the natural turnover of the fleet, and lengthens the time in which the more-efficient advanced vehicles of tomorrow will become the majority of the fleet. The median age of vehicles between 1999 and 2008 shows this trend toward longer vehicle lifetimes: in 1999, the median age for cars was 8.3 years, while in 2008 it reached a new record high of 9.4 years.[6] Vehicle scrappage rates have dropped consistently over the past several decades as well: almost 10 percent of the total vehicle population in 1970 was scrapped during that year, but in 2008 that figure was around 5 percent.

Because of these considerations, the Department of Energy is supplementing its research efforts for new vehicles with initiatives designed to address the legacy vehicle fleet. These efforts will be designed to enable incremental improvements in the efficiency of the existing vehicle fleet with simple, inexpensive retrofit technologies that can easily be added to most vehicles to provide effective efficiency improvements.

Driver Fuel Economy Performance Feedback

Driver habits in how they operate their vehicles have a significant effect on the overall fuel economy of the vehicles. Hard accelerations, high speeds, and other operating characteristics that place high power demands on the vehicle powertrain will decrease fuel economy: this effect is especially pronounced in today's hybrid vehicles. In many cases, the effect of this kind of operation is not visible to the driver until he or she refuels the vehicle and calculates the fuel economy achieved on that tank of fuel. In many cases, vehicle owners do not make these fundamental calculations of vehicle performance and thus do not have any information on how their vehicle is performing with respect to fuel economy.

To address this concern, many new vehicles have dash-mounted readouts (either through vehicle navigation systems or through dedicated instrument cluster displays) that provide the driver with feedback on average fuel economy (and in some cases, instantaneous fuel economy). Other systems provide the driver with simple readouts of when the vehicle is operating in an "eco-friendly" or efficient mode. Systems vary in the information provided, from very simple color-based feedback to show "good" or "bad" fuel economy, while others provide more complex displays of instantaneous and average fuel economy, and time histories of fuel economy performance. Still others provide a qualitative view of a driver's fuel economy performance through graphical displays of "eco-performance" with leaves or other such conceptual elements. A focus group study conducted by the U.S. Department of Transportation (NHTSA)[7] examined driver opinions about a wide variety of these driver fuel economy feedback devices and found that more complex displays and devices appealed to drivers who were existing drivers of hybrid vehicles or vehicles with fuel economy displays: the average

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[6] R.L. Polk and Company, "U.S. Vehicle Median Age Increased in 2008, According to Polk," http://usa.polk.com/News/LatestNews/2009_0303_vehicle_median_age.htm.

[7] U.S. Department of Transportation, National Highway Traffic Safety Administration, "Fuel Economy Driver Interfaces: Designed Range and Driver Opinions," August 2009, report DOT HS 811 092.

driver in this study was more likely to prefer simpler interfaces that indicated simply whether the vehicle was being operated inefficiently.

Information about the fuel savings effect of such systems is limited, but some studies have found that providing drivers with feedback on their fuel efficiency performance can improve fuel economy by 10% or more.[8] Qualitative studies have shown that vehicle owners respond to these systems and alter their behavior based on the feedback provided.[9] Other studies[10] are underway to provide more quantitative analysis of the benefits which are generally believed to be present.[11]

Most of these systems work by gathering information from the vehicle's onboard data collection and communication equipment and sensors, through the CAN bus (the information communication network present on many newer vehicles). The systems translate information about the quantity of fuel flowing to the engine, engine speed, throttle position, and other factors into a miles-per-gallon number that is then displayed and averaged.

Aftermarket systems that tap into the vehicle's communication network are beginning to be developed that can provide this feedback tool to cars and trucks that did not originally come equipped with such devices. Some of these devices typically plug into a diagnostic port that is mounted under the steering wheel (or elsewhere in the passenger compartment) to access the vehicle communication network to collect fuel use information.[12] Some portable GPS units[13] provide feedback and efficient route guidance simply through user entry of the vehicle's city and highway fuel economy and fuel costs (i.e., no direct connection to the vehicle's onboard systems): this provides the user with some estimates of fuel costs and fuel use for various routes, and can provide some feedback to the driver on efficient driving. Also, in a recent study it was noted that use of GPS routing can guide drivers toward shorter trips with less distance, thus improving fuel efficiency by up to 12%.[14] Real-time traffic information (to help drivers avoid congestion) also improved fuel efficiency of the drivers in this study.

VTP's role in expanding the use of these feedback devices will be to encourage their adoption and use (likely through the Clean Cities information dissemination network) for the legacy vehicle fleet through education and outreach efforts within the Clean Cities activity that complement the fuel efficiency tips provided through the Fuel Economy Guide. VTP will work with its Clean Cities partners to assist in these outreach efforts, using their network of local coalitions to bring information about the benefits of these devices to local communities throughout the U.S. VTP will also work with its National Laboratory partners and the Environmental Protection Agency to collect existing information about the effects of these devices on fuel economy performance of legacy vehicles and summarize that information in an easily-understandable form for use in the outreach efforts. If necessary, laboratory testing of selected devices to supplement existing information will be performed.

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[8] Driving Change, an Internet-based vehicle greenhouse gas management system that provided real-time measurement of several driving behaviors that impact fuel economy, found in a pilot test of its feedback system that improved fuel efficiency in the City of Denver's fleet by 15%.

[9] University of California-Davis, "Impact of in-car instruments on driver behavior," http://www.internationaltransportforum.org/Proceedings/ecodriving/4-02Kurani.pdf

[10] Transportation Research Board, "Studies in Consumers and Automotive Fuel Economy: A Qualitative Field Test of the Effects of Driver Feedback on Automotive Fuel Consumption," http://rip.trb.org/browse/dproject.asp?n=13141.

[11] David Greene, Oak Ridge National Laboratory, "Near Term Options to Increase Fuel Economy and Decrease Petroleum Demand," testimony to the U.S. Senate Committee on Energy and Natural Resources, http://www-cta.ornl.gov/cta/Publications/Reports/Testimony_NearTermOptionsforFuelEconomy_Greene%20.pdf.

[12] See, for example, the ScanGauge II (http://www.scangauge.com/).

[13] See, for example, the Garmin ecoRoute system (http://www8.garmin.com/buzz/ecoroute/). This system provides fuel use, carbon footprint, and fuel cost for a given trip or route. It also provides a "driving challenge" that keeps a running score on the driver's habits.

[14] NAVTEQ study, http://www.navteq.com/webapps/NewsUserServlet?action=NewsDetail&newsId=724&lang=en&englishonly=false.

Tires for Improved Fuel Efficiency

Another area of potential improvement for legacy vehicles is in low rolling resistance tire technology. Tires are an area in which retrofits can easily be done, and an existing vehicle may require several sets of tires over its lifetime. Several manufacturers are already selling low rolling resistance tires into the aftermarket and highlighting their ability to save fuel (in some cases, rolling resistance is reduced by around 25-30%, resulting in improvement in fuel mileage of up to 4%).[15] Estimates for the California Energy Commission have indicated that about 1.5% to 4.5% of gasoline use could be saved if all replacement tires in the U.S. (about 237 million per year) were low rolling resistance tires.[16] Low rolling resistance tires can also be cost-effective in many cases, paying for their additional cost in fuel savings over the lifetime of the tires.[17]

VTP's role in expanding the use of low rolling resistance tires in the legacy fleet will be to encourage their adoption and use through education and outreach efforts (likely through the Clean Cities network) that will provide consumers with information about the benefits and availability of these tire technologies, and their ability to provide cost savings to some consumers. VTP will also work with its National Laboratories and the tire manufacturers on gathering current information on the benefits of these tire technologies to present to consumers in an objective and factual manner.

High Efficiency Lubricants

Lubricants for a vehicle's engine and drivetrain can have an effect on the overall fuel consumption of the vehicle because of their contribution to the overall drivetrain energy losses. New lubricant formulations are being developed that maintain lubricating properties while reducing the overall friction within the engine and drivetrain. In some cases, these new lubricants can be used in existing vehicles to meet lubrication requirements without damage to the vehicle, but still providing a fuel economy benefit. EPA has stated that low viscosity lubricants can improve fuel efficiency by about 3% for heavy trucks.[18] Care must be taken in using these lubricants, however, to ensure that their use will not void manufacturer warranties.

VTP's role in high efficiency lubricants for legacy vehicles will be to work closely with lubricant manufacturers as well as engine and vehicle OEMs to explore the potential for enhancing vehicle efficiency while maintaining adequate lubrication. This will by necessity include some collaboration with vehicle maintenance and repair organizations (both dealers and independent repair shops) to ensure that they are aware of the benefits and potential drawbacks to use of these products. VTP will summarize current information available about these lubricant products to provide the consumer with information about the most efficient lubricant choices for their vehicle.

Engine Block Heaters

An engine block heater is a simple resistance heating device that is used to warm an engine's coolant or lubricating oil to speed the warm-up cycle for an engine in colder weather. Devices range from simple oil dipstick replacements with heating elements to more complex circulating pump designs that pump warmed engine coolant through the radiator and engine block. These devices are often found in colder climates to decrease the warm-up time so heat can be provided to the passenger compartment faster.

Block heaters can reduce fuel consumption by lowering the amount of fuel necessary to start the engine and shortening the amount of time and fuel necessary to bring the engine up to operating temperature. Testing by Environment Canada

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[15] Goodyear Assurance FuelMax tires, http://www.goodyear.com/cfmx/web/corporate/media/news/story.cfm?a_id=90.
[16] Green Seal, http://www.greenseal.org/resources/reports/CGR_tire_rollingresistance.pdf.
[17] U.S. Department of Energy Alternative Fuel Data Center, http://www.afdc.energy.gov/afdc/vehicles/fuel_economy_tires_light.html.
[18] EPA SmartWay Transport Partnership, http://www.epa.gov/smartway/documents/lowviscositylubes.pdf.

showed that using a block heater to warm the engine of a vehicle sitting in a -25°C environment reduced fuel consumption by 25% over an urban driving cycle relative to cold-starting the vehicle and driving it over the same cycle.[19] Testing has also shown that use of a timer to turn the heater on several hours prior to driving the vehicle is preferable to leaving the heater turned on constantly. The heater will take around 2-4 hours to bring the coolant up to a stable temperature, and additional time will not increase the temperature any further, and will use additional electricity unnecessarily.[20] It should be noted that, for vehicles still under warranty, block heaters not installed by an authorized OEM dealership may void the vehicle manufacturer's warranty.

The VTP role relative to engine block heaters will be to encourage their use through education and outreach efforts demonstrating their energy benefits, especially in cold-weather states. VTP will work with its National Laboratory partners and vehicle OEM partners to collect up-to-date information on the benefits of these devices to provide the consumer with the best available data.

Efficient Driving and Maintenance Techniques

Educating consumers on ways to operate their current vehicle more efficiently and how to maintain that vehicle for maximum efficiency will also be beneficial for the legacy vehicle fleet. The Department of Energy maintains an extensive list of driving and maintenance tips on its Fuel Economy website. VTP is in the process of reviewing and verifying the accuracy of these tips (some of which have been part of the accepted wisdom for more than two decades) to ensure that they are still relevant to today's vehicles and provide the maximum benefit to the consumer.

Improved Strategy for Natural Gas as a Transportation Fuel

Natural gas has been used for a number of years as a fuel for internal combustion engines both here in the U.S. and overseas. Its popularity has been cyclical, driven by fuel cost and availability questions. Vehicles using natural gas typically carry an incremental cost versus similar conventional fuel vehicles, a cost that can be paid back through fuel cost savings in operation (the magnitude of which depends on the relative cost of natural gas and its conventional fuel competition as well as the relative fuel efficiency of the natural gas and conventional vehicles). Because of these cost challenges and the relative lack of infrastructure to refuel vehicles, the total population of natural gas vehicles in the U.S. has remained relatively small, although natural gas has been very popular in certain fleet applications.

From a domestic energy security standpoint, natural gas appears to be a reasonable alternative to conventional petroleum fuels. Due to recent discoveries of natural gas and new drilling technologies for recovering gas from extensive shale deposits[21] in the U.S., future availability of natural gas is good. Full fuel cycle greenhouse gas emissions from natural gas vehicles are roughly 30% lower than for conventional gasoline or diesel vehicles, making them an attractive short-term bridge for achieving transportation carbon reduction goals.

VTP will be undertaking new research and development efforts designed to increase the use of natural gas in transportation applications through improvements in engine efficiency, and natural gas refueling infrastructure.

Natural Gas Engine Efficiency

In general, natural gas engines have been developed as modifications of existing gasoline or diesel engines, using as many standard production components as possible to keep overall engine costs competitive given the low production volumes

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[19] Environment Canada, Envirozine Issue 40, http://www.ec.gc.ca/EnviroZine/english/issues/40/any_questions_e.cfm.
[20] Natural Resources Canada, http://oee.nrcan.gc.ca/transportation/idling/warm-up.cfm?attr=8.
[21] EIA estimates that there are almost 33 trillion cubic feet of natural gas in U.S. shale deposits, http://tonto.eia.doe.gov/dnav/ng/ng_enr_shalegas_s1_a.htm.

expected. For this reason, these engines often do not take full advantage of the unique properties of natural gas to maximize power or efficiency. This is an especially critical problem for natural gas engine competitiveness in the heavy-duty market, where these engines (typically spark-ignited) are competing against more efficient and lower cost diesel engines. This makes the value proposition for natural gas for most heavy-duty fleets unfavorable, even given the generally lower cost for natural gas as a vehicle fuel relative to diesel.

Past research efforts at the Department of Energy have focused on improving the efficiency of the natural gas engine through the use of advanced technologies and design concepts. These research efforts have culminated in the development and sale of advanced natural gas engines (chiefly in the heavy-duty market) by the industrial partners who participated in the program.

Future research effort in this arena will continue to focus on increasing the efficiency of the natural gas engine to improve its competitiveness, particularly in the heavy-duty market. This will involve collaborative research and development efforts among industrial partners and the National Laboratories to explore new combustion concepts, advanced air handling equipment, diesel-like cycles, and other technologies necessary to improve the thermal efficiency of the natural gas engine. The brake thermal efficiency of current commercially available heavy-duty natural gas engines have been reported to be from about 70% to 90% that of current diesel engines at the rated conditions.

Natural Gas Storage for Vehicles

Storage of natural gas onboard a vehicle has been an issue for manufacturers from a design and packaging standpoint. Natural gas can be stored on a vehicle in compressed form at pressures of 3,000 to 3,600 psi: this requires high-pressure tanks specifically designed for this purpose which are usually bulky and difficult to package. Storage densities are typically low, as well, affecting vehicle driving range (or, if more tanks are purchased, increasing incremental costs). Liquefied natural gas offers higher volumetric energy storage, allowing more fuel to be stored onboard the vehicle, but these tanks are also special-purpose cryogenic vessels to store the liquefied fuel at very low temperatures. These tanks are quite costly, and also difficult to package in a vehicle.

Education and Outreach

Part of the difficulty in expanding the use of natural gas as a transportation fuel is the lack of knowledge among prospective consumers about the benefits and costs of this fuel choice. Objective information about available vehicle products and fueling infrastructure, potential cost savings, and potential environmental benefits is difficult to find and sometimes contradictory.

VTP will use its *Clean Cities* network to provide educational information about the technology advances achieved under this program to consumers and fleets. This information will allow them to make more informed decisions regarding the choice of natural gas as a fuel and the benefits available from the latest technology.

3.0. Program Portfolio Management

This section describes how the Vehicle Technologies Program develops and manages its portfolio of research, development, and deployment (RD&D) activities. It includes the portfolio management process, program analysis, and performance assessment.

3.1. Program Portfolio Management Process

All planning is based on overarching DOE and EERE program and policy guidance. The EERE vision, mission, and strategic goals serve as starting points, as well as reference points, by which to guide and evaluate courses of action for VT. For this planning timeframe, the EERE Strategic Technologies-for-Energy Plan (STEP) sets the pathways for achieving the Administration's aggressive oil and CO_2 reduction targets for 2030 and 2050. The RD&D portfolio that VT management establishes must have the potential to meet the aggressive goals (see Figure 3-1). With the EIA Annual Energy Outlook (AEO) 2010 as the base case and using the EERE-prescribed STEP tool, the VT RD&D portfolio of existing and new projects was reviewed to ascertain which of the RD&D activities would need to be funded to achieve the minimally acceptable case (MAC) goals. The process is shown in Figure 3-1. Based on the in-depth analysis, the VT management establishes the RD&D portfolio that would be the basis for the budget request. The Multi-Year Program Plan discussion in Section 1.0 outlines the strategies needed to achieve EERE's aggressive goals.

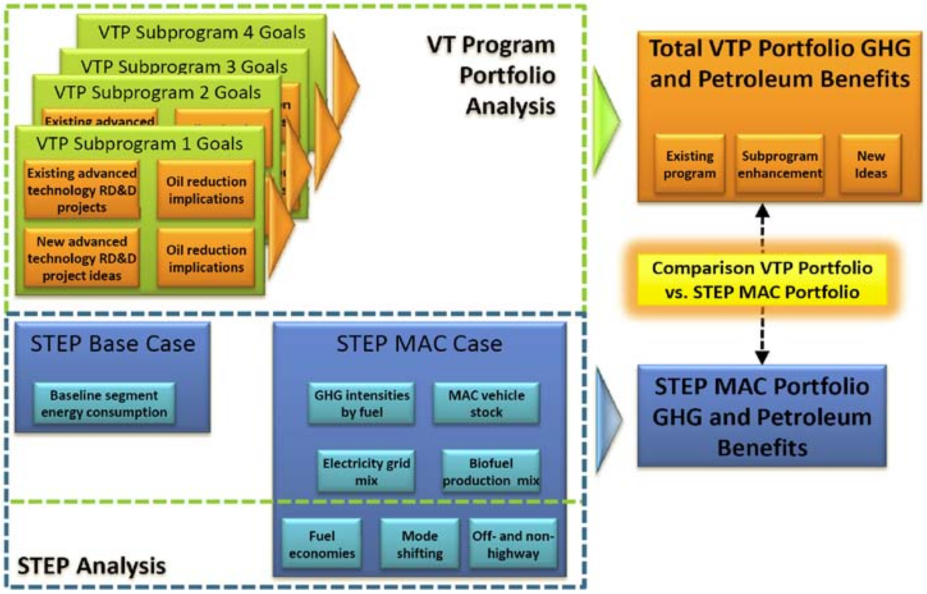

Figure 3-1. Analysis of VT Portfolio vs. EERE Goals

The VT Program RD&D portfolio consists of all projects aimed at achieving VT's goals and is kept on track through the use of established management processes. The RD&D portfolio is continually updated and revised. Technology managers develop ideas for new projects based on their expertise, information obtained from attendance in technical and scientific conferences, such as the Materials Research Society (MRS), Society of Automotive Engineers (SAE), attendance and participation in reviews of fundamental research by the Office of Science, as well as solicit new ideas through Small Business Innovative Research (SBIR) and Broad Agency Announcement (BAA). New ideas for projects must be deemed necessary to meet VT vision, mission, and goals. They are planned, evaluated, and prioritized together with existing projects. The VT RD&D portfolio is comprised of the combination of existing and new projects that at different planned funding levels, is able to closely meet the STEP MAC portfolio oil and greenhouse gas reduction benefits.

3.2. Program Analysis

Studies and analyses are conducted by the VT Program to support planning and decision making regarding RD&D options as described in Section 3.1. Modeling and simulation are the primary tools used to investigate advanced technology vehicle systems and assess the potential of technology options to achieve VT goals such as reduce vehicle petroleum consumption, enhance energy security for transportation, and reduce associated carbon dioxide emissions. For example, the Powertrain Systems Analysis Toolkit (PSAT) software enables advanced vehicle component technologies to be assembled into a set of complete advanced technology vehicle computational models capable of simulating vehicle performance over EPA drive cycles. Simulation of vehicle driving performance and fuel consumption for many different vehicle configurations allows VT to quickly narrow the focus on the most fuel-efficient components and configurations. The end result of PSAT modeling simulation is a series of vehicle incremental costs and fuel economies (with low, medium, and high degrees of uncertainty) per advanced vehicle technology type and size class (e.g., compact sedan, mid-size sedan, small SUV, etc.). PSAT will be phased out and replaced by a new “plug and play” software modeling tool named *Autonomie*. The new modeling tool complements the automotive industry’s interests in accelerating the development and introduction of advanced automotive technologies. *Autonomie* allows the virtual simulation of vehicle powertrains and components and their performance without the expense of building the actual hardware.

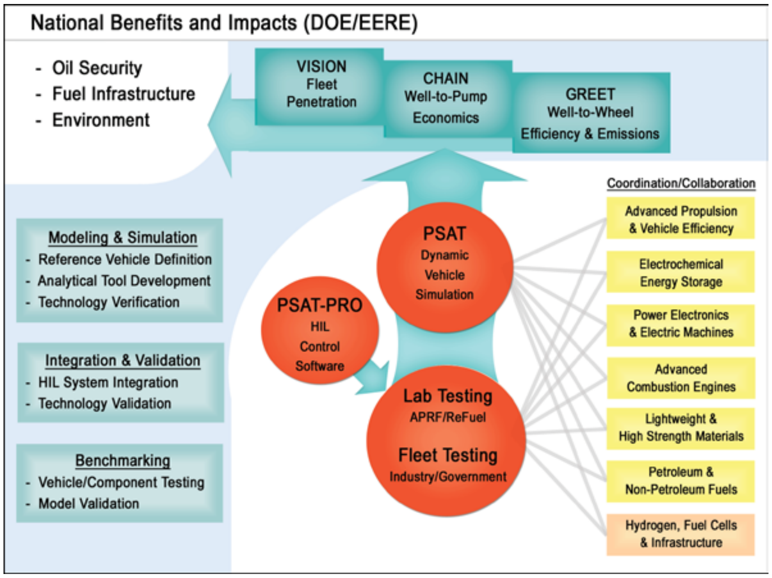

Figure 3-2. Integrated VT Analytical Activities

The low-cost, high fuel economy case is adapted as the closest practical future vehicle that embodies VTP program benefits. Models such as VISION, CHAIN, and GREET are employed to forecast national-level energy and environmental benefits including oil use, infrastructure economics, and greenhouse gas contributions of new technologies. These are compared with Energy Information Administration (EIA) projections using the National Energy Modeling System (NEMS) or MARKAL.

3.3. Performance Assessment

Performance assessment includes all aspects of the reporting, monitoring, and program review process that allows routine evaluation of progress against stated goals, program rationale, process, impact, and cost-benefit.

Performance Assessment Strategy and Plan

The following performance assessment processes are used by all EERE programs, including the VT Program: results-based performance reporting, peer reviews, general program evaluation studies, and technical program reviews.

Results-based Performance Reporting

In conjunction with BA, VT uses accepted RD&D investment criteria to support its budget proposals. DOE has established a Performance Management Measurement (PMM) System In which VT specifies milestones which correspond to its priority goals at the beginning of each fiscal year and then reports on them quarterly. Program performance and progress toward EE Mission Critical Goals (Dashboard Goals) in key technology pathways are tracked quarterly and evaluated annually. Dashboard Goals associated with the FY 2011 Congressional Budget Request are provided in Appendix B.

Peer Reviews

The National Research Council of the National Academy of Sciences conducts biennial reviews, on an alternating basis, of the R&D activities of the FreedomCAR and Fuels Technology Partnership and the 21st Century Truck Partnership. These reviews examine accomplishments, productivity, quality, relevance to goals, management, and provide reports that summarize findings and recommendations.

The VT Program conducts an Annual Merit Review (AMR) and Peer Evaluation of its projects. Various technical experts are utilized to evaluate the projects/activities in VT subprogram areas. Experts are selected by DOE program leads on the basis of their expertise. Each expert is required to sign a conflict of interest form to assure an unbiased review. This type of review allows for a more detailed evaluation of each project.

Project results are also formally peer reviewed through technical papers presented at conferences and meetings such as the Directions in Engine-Efficiency and Emissions Research (DEER) Conference, the Society of Automotive Engineers (SAE) World Congress, and other technical forums. Presentations at these meetings are subjected to a review process prior to being included in the technical program.

Program Evaluation Studies

A variety of program evaluation efforts are conducted in different areas by VT. Prominent among these is the overall cost benefits analysis, which is cycled on a several year basis. This analysis is reviewed annually to support Government Performance and Results Act (GPRA) potential benefit assessments used in future budget formulation and requests. This analysis provides information on the balance of costs and benefits of the Program and is one input for Program improvement. Other studies, such as focus groups examining market forces and other aspects, are conducted on an as-needed basis with the EERE Office of Business Administration (BA). Two such studies are the linkages study[1] and retrospective benefit cost analysis[2]. VT industry partners conduct studies which contribute to the overall evaluation of the Program. One such study, regarding technology successes within the Program, is conducted by USCAR on an annual basis. Sometimes studies are conducted by interested parties who are not funded by DOE. This research also can provide useful data and information to support or change the Program.

Technical Program Reviews

Specific technical areas are reviewed by government-laboratory-industry technical teams formed under the Partnerships. Input is provided to DOE managers on a quarterly and annual basis. Outside activity such as awards from independent groups provide another input, and measure, into the evaluation of the technical program. Each year R&D Magazine awards the top 100 innovations with the R&D 100 Award. Since the early 1990s, VT has received more than 20 R&D 100 Awards.

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[1] *Linkages of DOE's Energy Storage R&D to Batteries and Ultracapacitors for Hybrid, Plug-In Hybrid, and Electric Vehicles*, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.

[2] *Retrospective Benefit-Cost Evaluation of U.S. DOE Vehicle Advanced Combustion Engine R&D Investments: Impacts of a Cluster of Energy Technologies*, prepared for Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, May 2010.

Data Collection to Support Routine and Periodic Performance Assessment

The VT technology development managers assume the primary responsibility for ensuring the availability of adequate data at the appropriate times for project performance assessments. The VT technology development managers are supported by their government-industry-laboratory technical teams and others.

Technology Development Managers and their teams monitor the RD&D for which they are responsible through verbal and written reports, including monthly and quarterly, specific milestone reports, and reports on deliverables. Reports on monitoring and validating planned deliverables are often based on data from tests supported with simulation and modeling. Routine reports are supplemented by direct communication with researchers, onsite reviews (sometimes related to specific decision points), and periodic technical team meetings. Reports cover project milestones, decision points, major deliverables, important test results, project status including costs versus plan, and problems requiring correction. Summary data on progress or problems is supplied by the Technology Development Managers to the Program Manager, to the CPS, and to the PMM reporting system on a quarterly basis.

Annual progress reports covering each technology area are based on data sources already mentioned, but include additional data from annual reports supplied directly by researchers. These annual reports can cover broad areas (usually from a national laboratory with technical oversight) or individual projects such as those collected in conferences.

Peer reviews, for both projects and programs, involve all of the above data collection methods, but often involve specific data collection for the review. For project peer reviews, researchers present up-to-date result for the peers to utilize in their deliberations. Program peer reviews may involve the same data, but include additional data collected and summarized by Technology Development Managers and partnership technical teams specifically for the peer reviewers.

Different kinds of data are collected for broad studies to help guide the overall Program. These may involve data from the EIA in support of GPRA analysis or data from specific interviews designed to support the conduct of risk benefit analyses. As a last example, data collected from ad-hoc focus groups or committees may be included. Other data to guide the Program, even including guidance for project selection, may be collected from selected sources such as the Office of Science or other sources outside the government (such as USCAR or universities) that have data unique to their activities. Selective ad-hoc data collection also supports non-government analyses such as is done for R&D 100 Awards; feedback from these analyses provide input for identifying exceptional achievements of the Program and a measure of how well the Program is doing.

Data collected from all of the above sources contribute to the Technology Development Managers for their inputs to the Program Manager for the annual budget formulation and execution, and the annual Senior Manager Reviews.

APPENDIX A

GLOSSARY

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Acronyms, Abbreviations, and Units of Measure

Acronyms and Abbreviations

21 CTP	21st Century Truck Partnership
ACE	Advanced Combustion Engine R&D
APEEM	Advanced Power Electronics and Electric Motors
ADVISOR	Advanced Vehicle Simulator
AEO	Annual Energy Outlook
AFV	alternative fuel vehicles
AMR	Annual Merit Review
ARRA	American Recovery and Reinvestment Act
APU	auxiliary power unit
Autonomie	A software environment and standard framework for simulating from single vehicle components, subsystems to entire vehicles
AVTA	advanced vehicle testing activity
BAA	Broad Agency Announcement
BEDT	Batteries and Electric Drive Technology
CAD	computer-aided design
CAM	computer-aided manufacturing
CHAIN	a well-to-pump economics model
CNG	compressed natural gas
CPS	Corporate Planning System
DEER	Diesel Engine-Efficiency and Emissions Research
DC	direct current
EISA	Energy Independence and Security Act of 2007
EPAct	Energy Policy Act
EREV	extended range electric vehicle
EV	full or battery electric vehicle
E85	gasoline blend containing 85 percent ethanol by volume
EGR	exhaust gas recirculation
FCV	fuel cell vehicle
FOA	Funding Opportunity Announcement
FRP	fiber-reinforced polymer (composites)
FTP	Federal test procedure
FFV	flexible fuel vehicles
FPA	full power assist
GHG	greenhouse gas
GPRA	Government Performance and Results Act
GATE	Graduate Automotive Technology Education
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
HC	hydrocarbons
HIL	Hardware-In-the-Loop
HTML	High Temperature Materials Laboratory

HCCI	homogeneous-charge compression-ignition
HEV	hybrid-electric vehicle
ICE	internal combustion engine
IGBT	insulated gate bipolar transistors
Li-ion	lithium ion
LPG	liquefied petroleum gas
LTC	low-temperature combustion
MAC	minimally acceptable case scenario (under STEP)
MARKAL	a MARKet ALlocation, data-driven, energy system optimization model (calculates least cost set of technologies over time, subject to various user-defined constraints)
MATT	Mobile Automotive Technology Testbed
MIT	Massachusetts Institute of Technology
M-HEV	medium hybrid electric vehicle
MMC	metal-matrix composites
MMBDOE	million barrels of oil equivalent per day
MMTE	million metric tons of carbon equivalent
MYPP	multi-year program plan
NEMS	National Energy Modeling System
NO_X	oxides of nitrogen
NPBFL	non-petroleum based fuels and lubricants
OEM	original equipment manufacturer
PM	particulate matter
PMM	Performance Management Measurement System
PHEV	plug-in hybrid electric vehicle
PHEV10	plug-in hybrid electric vehicle with 10-mile all-electric range
PHEV40	plug-in hybrid electric vehicle with 40-mile all-electric range
PSAT	Powertrain Systems Analysis Toolkit
PART	Program Assessment Rating Tool
R&D	research and development
RD&D	research, development, and deployment
SCR	selective catalytic reduction
SEI	solid electrolyte interface
SI	spark-ignition
STEP	Strategic Technologies-for-Energy Plan
SUV	sport utility vehicle
VCR	variable compression ratio
VMT	vehicle-miles traveled
VISION	a model used to estimate potential energy and oil use, and carbon emission impacts of advanced light- and heavy-duty vehicle technologies and alternative fuels to 2050
VSST`	Vehicle and Systems Simulation and Testing
WBG	wide band gap semiconductor
ARPA-E	Advanced Research Projects Agency - Energy
BA	Office of Business Administration
BES	Basic Energy Sciences

DARPA	Defense Advanced Research Projects Agency
DOE	Department of Energy
DOT	Department of Transportation
EERE	Office of Energy Efficiency and Renewable Energy
EFRC	Energy Frontier Research Center
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ERDA	Energy Research and Development Administration
FRA	Federal Railroad Administration
MRS	Materials Research Society
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NRC	National Research Council
NSF	National Science Foundation
OE	Office of Electricity Delivery and Energy Reliability
OMB	Office of Management and Budget
SAE	Society of Automotive Engineers
SBIR	Small Business Innovative Research
SC	Office of Science
USABC	U.S. Advanced Battery Consortium
USAMP	U.S. Advanced Materials Partnership
USCAR	U.S. Council for Automotive Research
VTP	Vehicle Technologies Program

Units of Measure

bhp	brake horsepower	kW	kilowatt
bhp-h	brake horsepower-hour	kWh	kilowatt-hour
bmep	brake mean effective pressure	L	liter
g	gram	MMBDOE	million barrels per day of oil equivalent
h	hour	MMTE	million metric tons (CO_2) equivalent
kg	kilogram	rpm	revolutions per minute
lb	pound	s	seconds
ºC	degrees Celsius	V	Volts
ºF	degrees Fahrenheit	W	Watts
%	percent	Wh	Watt-hour

Chemical Elements

Al	aluminum	Mn	manganese
C	carbon	Ni	nickel
Fe	iron	O	oxygen
H	hydrogen	P	phosphorus
HC	hydrocarbon	Si	silicon
Li	lithium	Ti	titanium
Mg	magnesium		

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APPENDIX B

FY 2011 CONGRESSIONAL BUDGET

VEHICLE TECHNOLOGIES PROGRAM

AND

MISSION CRITICAL GOALS

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Vehicle Technologies Program
Funding Profile by Subprogram
(Comparable Structure to the FY 2011 Request)

	FY 2009 Current Appropriation[a]	FY 2009 Current Recovery Act Appropriation	FY 2010 Current Appropriation	FY 2011 Request
Batteries and Electric Drive Technology (Formerly Hybrid Electric Systems)	*101,572*[b]	0	*101,405*	*120,637*
Vehicle and Systems Simulation and Testing	*21,126*	0	*44,328*	*44,328*
Advanced Combustion Engine R&D	39,657	0	57,600	57,600
Materials Technology	38,786	0	50,723	50,723
Fuels Technology	19,560	0	24,095	11,000
Outreach, Deployment & Analysis (Formerly Technology Integration)	*46,442*[c]	0	*33,214*	*41,014*
Commercial Vehicle Integration/X-Prize	0	109,249	0	0
Subtotal, Vehicle Technologies	267,143	109,249	311,365	325,302
Advanced Battery Manufacturing	0	1,990,000	0	0
Transportation Electrification	0	398,000	0	0
Alternative Fueled Vehicles	0	298,500	0	0
Total, Vehicle Technologies	267,143	2,795,749	311,365	325,302

Public Law Authorizations:
P.L. 95-91, "U.S. Department of Energy Organization Act" (1977)
P.L. 102-486, "Energy Policy Act of 1992"
P,L, 109-58, "Energy Policy Act of 2005"
P.L. 110-140, "Energy Independence and Security Act of 2007"

[a] In FY 2009, $5,443,000 was transferred to the SBIR program and $652,000 to the STTR program.

[b] Includes Technology Validation activities previously funded in the HFCT Program in years prior to FY 2009.

[c] Includes Safety and Codes and Standards, and Education activities previously funded in the HFCT Program in years prior to FY 2009.

[d] Technology Validation, Safety and Codes and Standards, and Education were transferred back to the HFCT Program in FY 2010.

Mission Critical Goals (Dashboard Goals)

Program Goal 1: Reduce the cost of electric-drive technologies. Demonstrate through data, simulation and modeling an inverter/motor, when combined, of 1.1 kW per kilogram, 2.7 kW per liter, at a cost of $18 per kW peak. The baseline is a 2005 commercially available motor and inverter combination with 0.85 kW per kilogram, 1.8 kW per liter, at a cost of $35 per kW peak.

Program Goal 2: Improve modeled fuel economy by 10% for passenger and 5% for commercial vehicles through improvements in powertrain efficiency, relative to a 2009 vehicle.

Program Goal 3: Collect and analyze data from 15 million miles of on-road testing of plug-in electric drive vehicles to determine impact on electricity grid and consumer charging behavior.

Program Goal 4: Reduce the cost of energy storage for PHEVs to $700 per kW hour based on modeling assuming high-volume (100,000 units) production. A modeled high volume production battery cost was $1,000/kWh in 2009.

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Vehicle Technologies Program

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