American Energy Innovation Council

CASE STUDIES ON THE GOVERNMENT'S ROLE IN ENERGY TECHNOLOGY INNOVATION

Public-Private Partnerships in Vehicle Technologies

By David Garman | April 2014

Petroleum is currently the major source of energy in the United States, producing about 35 quadrillion BTUs of the 97 quadrillion BTUs used in the U.S. economy.[1] Moreover, the transportation sector is overwhelmingly dependent on liquid fuels derived from petroleum. More than 93 percent of the energy used for transportation in the United States comes from oil.[2]

U.S. dependence on foreign sources of oil has been detrimental to the U.S. foreign trade imbalance, has subjected American consumers to the market manipulation of a global oil cartel, and has required the deployment of military assets to protect commercial shipments of petroleum. It is therefore no surprise that every American president since Richard Nixon has made reducing U.S. dependence on foreign oil, if not outright independence from it, a core energy policy.

Recent increases in domestic oil and gas liquids production from shale formations, increasing vehicle efficiency, expanded use of biofuels, and other economic factors have lowered demand for oil and reduced U.S. dependency on foreign oil every year since 2005. However, since oil is a global commodity whose price is determined by global supply, demand, and other factors, American consumers cannot be insulated from volatile oil prices in the future. America's continuing dependence on oil for the foreseeable future is virtually assured by existing investments in more than 156,000 gasoline/diesel fueling stations,[3] approximately 250 million petroleum-fueled motor vehicles,[4] and well-established oil-dependent air and rail transportation networks. This level of investment in existing vehicles and refueling infrastructure is inherently resistant to change.

Roughly 71 percent of U.S. oil consumption is used for transportation, so it follows that much of the U.S. government's research, development, demonstration, and deployment activities to reduce oil dependence has focused on making vehicles more efficient and developing alternatives to oil, such as biofuels, natural gas, propane, electricity, and hydrogen to fuel them. The focus of this particular case study is the light-duty vehicle-technology and hydrogen fuel cell programs of DOE, paying particular attention to the broad collaborative R&D partnerships among the U.S. government and U.S. automakers, and later, fuel providers.

The first such high-profile public-private partnership was the Partnership for a New Generation of Vehicles, begun in 1993. It evolved into the FreedomCAR[5] Partnership in 2002, which was modified to the FreedomCAR and Fuel Partnership in 2003. In May 2011, the partnership became known as U.S. DRIVE.[6] These partnerships will be described in greater detail, including their membership and methods of operation while exploring their evolution and focus. Though not all of the light-duty vehicle work of the DOE Vehicle Technologies and Hydrogen R&D programs after 1992 was conducted in association with these partnerships, it is fair to say that any work that was not conducted under the partnership was certainly influenced by it, since partnership activities greatly influence DOE R&D program managers as they plan R&D programs, map activities, and evaluate progress.

It can also be argued that, since the business of personal mobility and fuels, like most energy services, are private-sector activities, a collaborative structure that facilitates input from relevant private-sector partners in government-funded research planning is important to ensure the "market relevance" of government R&D efforts. Some claim that such efforts constitute "corporate welfare," arguing that the government is funding R&D that the private sector should be undertaking by itself. Others counter:

- Reducing petroleum consumption, automotive emissions, and the environmental and geopolitical implications of petroleum are public benefits that are strong candidates for government investment;
- Government investments help address the "market failure" of private-sector underinvestment in basic and pre-commercial applied R&D;
- Government has an unique capacity to convene relevant private-sector partners in collaborative pre-commercial research activities; and
- Government can leverage basic research capabilities and unique scientific tools and instruments at the national labs that even the largest private-sector partners cannot duplicate.

Noting that both Democratic and Republican administrations have embraced transportation-related public-private partnerships (with some distinctions that will be highlighted), it could be argued that these kinds of partnerships and broader government R&D activities are likely to persist, regardless of the political party in power. However, given the pressures on discretionary federal spending, the continuation or expansion of programs, even those with historical bipartisan support, cannot be taken for granted. Therefore, it is useful to evaluate how various R&D programs have performed. To that end, this case study will explore the following questions:

- Have the vehicle-technology and hydrogen activities at DOE and their associated public-private partnerships (Partnership for a New Generation of Vehicles, FreedomCAR, and U.S. DRIVE) been successful? How have these partnerships contributed to the research, development, and commercialization of new vehicle technologies, and how have they evolved with time?
- What improvements have been made in the partnerships and the DOE vehicle-technology programs, and what others might be considered?
- Are there lessons with respect to these transportation-related public-private partnerships that can be applied to other areas of federal energy R&D?

This case study will begin with the "Origins of the DOE Vehicle Technologies Program," a review of the origins of the DOE Vehicle Technologies Programs that began prior to the passage of the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 and have expanded significantly in the decades since. In "The Nature of DOE's Vehicle Technology R&D from 1992 to Today," the study will evaluate the key areas of spending and emphasis during the period 1992–present using an analysis of congressional funding appropriated for key technology areas. While this case focuses on the DOE Vehicle Technologies Program, this analysis also embodies the activities and spending of the automotive-related portions of the Hydrogen Fuel Cell technology program established as a stand-alone program during the administration of George W. Bush. Complicating this analysis was the fact that, during the period from 1992-present, major programs changed names, subprogram activities moved back and forth among different major programs, and budget justification document formats shifted in line with changing Office of Management and Budget (OMB) guidelines, DOE directives, or even the desires of appropriations subcommittee chairs. To avoid confusion, this study tracks spending and activities within DOE's Office of Energy Efficiency and Renewable Energy in four broad areas: (1) Electric and Hybrid Drive, Batteries, and Power Electronics; (2) Internal Combustion Engine R&D; (3) Fuel Cells and Hydrogen R&D; and (4) Materials R&D, irrespective of the program, subprogram, or funding line that carried the work.

In the following section, "The Evolution of the Partnerships," the case looks more closely at the Partnership for a New Generation of Vehicles (PNGV) and the FreedomCAR, FreedomCAR and Fuel, and U.S. DRIVE partnerships which evolved from PNGV, with attention to how and why those evolutions or re-brandings occurred, as well as the findings of the National Academy of Sciences (NAS) panels convened to evaluate the partnerships and the DOE Vehicle Technologies Program activities they helped guide.

Finally, in "Discussion and Conclusions," the case presents conclusions about the efficacy and worth of these partnerships as well as some of the key aspects highlighted by the case study itself. These conclusions are particularly important in the context of calls to maintain or even expand federal spending in key energy-technology areas during times of severe constraints on discretionary federal spending.

Origins of the DOE Vehicle Technologies Program

In his Special Message to Congress on Environmental Quality,[7] President Nixon outlined a 37-point plan to improve the environment. As part of his plan, Nixon ordered the newly formed Council on Environmental Quality to "marshal both government and private research with the goal of producing an unconventionally-powered, virtually pollution free automobile within five years." The federal government had been regulating carbon-monoxide and hydrocarbons emissions from vehicles since 1968, and new federal standards for nitrogen oxides and particulates were in development. The Arab Oil Embargo of 1973 gave added emphasis to the "unconventionally-powered" aspect of the goal, and Congress eventually responded with the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976.[8]

This 1976 Act directed the Energy Research and Development Administration (ERDA), a DOE predecessor organization, to undertake a program of research, development, and demonstration designed to promote electric and hybrid vehicle technologies.[9] The bill also called for the development and federal purchase or lease of up to 7,500 demonstration electric and/or hybrid electric vehicles and a loan guarantee program to assist in the market introduction of such vehicles. President Ford, however, vetoed the bill. His veto message stated that:

> **[T]echnological breakthroughs in battery research are necessary before the electric vehicle can become a viable option. It is simply premature and wasteful for the federal government to engage in a massive demonstration program—such as that intended by the bill—before the required improvements in batteries for such vehicles are developed.[10]**

But Congress promptly overrode the veto, enacting the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 into law.

In retrospect, President Ford was arguably correct that such a demonstration program in the absence of technological progress was premature. Only 1,100 vehicles were ultimately purchased under the authority of the 1976 Act, mainly from four small business manufacturers, with loan guarantees for two of those companies.[11] This can hardly be termed a success when evaluated against the technology demonstration goals originally expressed by Congress for the program.

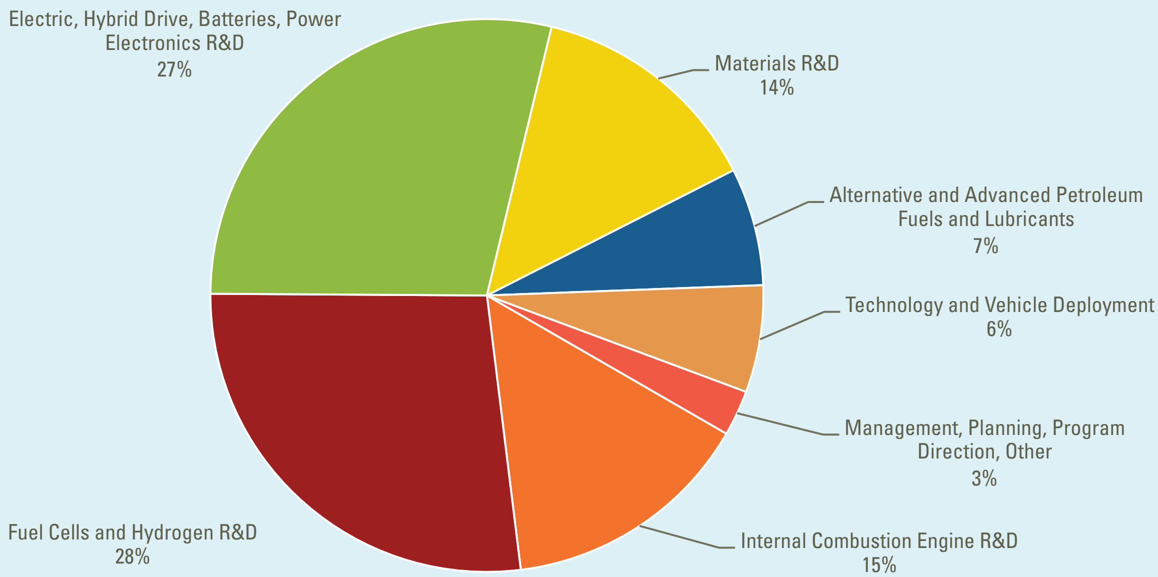
But the goals of pollution prevention and reduction in petroleum demand were sufficiently compelling to bipartisan majorities of Congress that vehicle technology R&D remained a high-profile activity among the applied R&D programs at ERDA and, later, DOE.

The Nature of DOE's Vehicle Technology R&D from 1992 to Today

It is an almost universally held—and incorrect—view that the DOE Vehicle Technologies Program has been narrowly focused on the vehicles and chosen technologies favored by various administrations. For example, the PNGV program of the Clinton administration is almost exclusively regarded as a diesel-hybrid vehicle program. The Bush administration's FreedomCAR Program is often regarded solely as a hydrogen fuel cell vehicle program. The Obama administration's U.S. DRIVE Program is chiefly regarded as a battery electric and plug-in hybrid vehicle program. Senator Jeff Bingaman (D-NM), former chairman of the Senate Energy Committee, notably observed that each administration tends to "focus … on advocating a particular technological solution, instead of solving an energy problem," which resulted in what he called "Technology Attention Deficit Disorder."[12]

While there is some truth that each of the partnerships have had a particular emphasis, a budgetary analysis of the DOE vehicle and hydrogen fuel cell activities from FY 1991–FY 2012 reveals that the actual spending under three different administrations has been largely and fairly consistently directed toward four primary technology areas: Electric and Hybrid Drive, Batteries, and Power Electronics; Internal Combustion Engine R&D; Fuel Cells and Hydrogen R&D; and Materials R&D. Indeed, 86 percent of the spending over the course of these 22 years was focused on these four areas (See Figure 1).

Figure 1: **DOE Vehicle Technology Investment by Major Category, FY 1991-FY 2012**



Electric, Hybrid Drive, Batteries, Power Electronics R&D

The work in this area is focused on the electrification of light-duty battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and extended-range electric vehicles (EREVs). In addition, much of the work is also applicable to fuel cell electric vehicles and fuel cell hybrid electric vehicles (FCEVs and FCHEVs). Past and current work in this area has included:

- *Battery and ultracapacitor R&D.* The different vehicles outlined above (BEVs, HEVs, PHEVs, FCHEVs) have different electrochemical storage needs. A gasoline, diesel-electric, or fuel cell hybrid vehicle can generate some or all of the electric power it needs to operate, so it will generally employ a smaller, lower *energy* battery with comparatively shallow charge/discharge cycles. On the other hand, a BEV must have a high-power/high-energy battery, typically employing deep charge/discharge cycles, to deliver performance and range.[13] Deep cycles usually have adverse implications for battery life. Finding combinations of battery chemistries and architectures for a range of vehicle needs, with acceptable cost, durability, and safety remains a continuing challenge and a focus of this work.

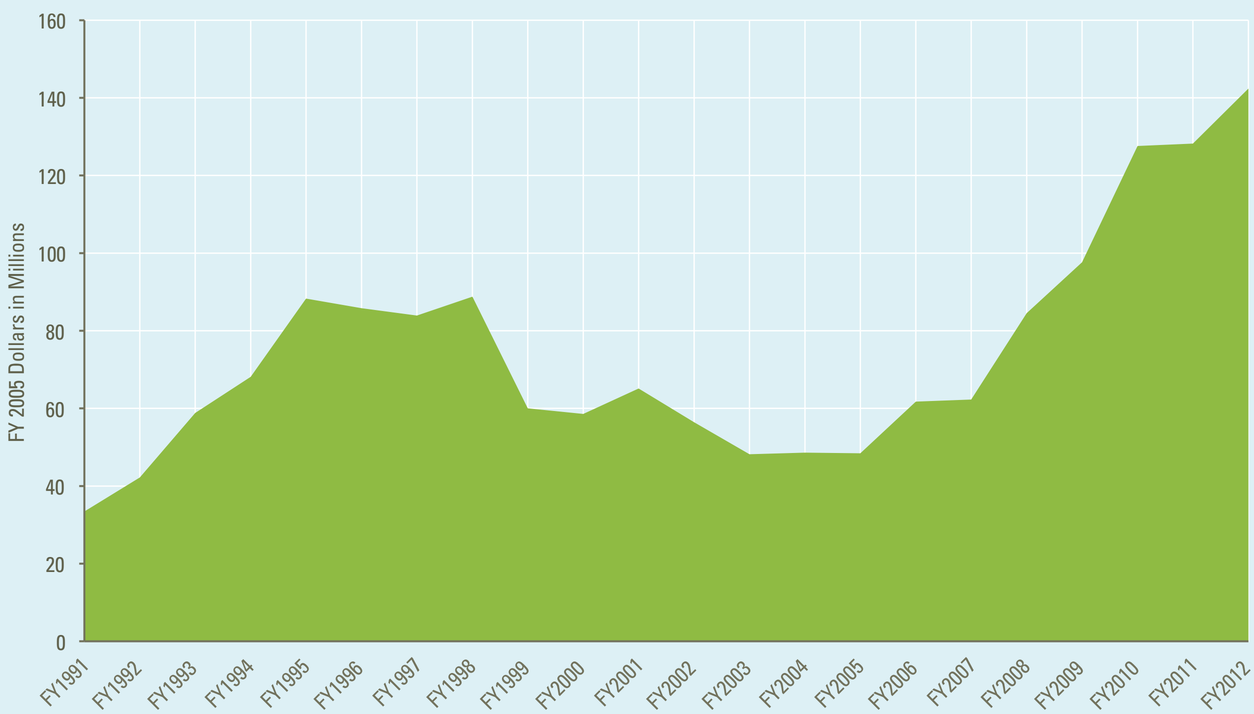
- *Power electronics R&D.* Power electronics, including the inverters that convert the direct current from the fuel cell, the battery, or the engine-driven generator into alternating current needed to power the electric motors to drive the wheels are critical components in electric-drive vehicles. Efforts continue to reduce the size, weight, and cost of the power electronics.

- *Electric Motor R&D.* Many of the electric motors used in advanced vehicles are permanent magnet motors utilizing neodymium iron boron (NdFeB) magnets, an expensive rare-earth material largely controlled by China. Alternatives include induction motors, which are used by Tesla and BMW, but there are trade-offs in size and efficiency. Additional options, such as switched reluctance motors, are also being investigated.[14]

- *Thermal management.* Both batteries and power electronics require thermal management (cooling and/or heating). New materials and strategies are being investigated for this purpose.

During the time period of this case study, DOE funding for Electric/Hybrid Drive, Batteries and Power Electronics–related R&D has ranged from approximately $33–142 million annually, or a total of approximately $1.6 billion (in FY 2005 dollars). It should be noted, however, that $2.4 billion (FY 2005 dollars) in funding for advanced battery manufacturing and transportation electrification contained in the American Recovery and Reinvestment Act of 2009 (also known as ARRA or the Recovery Act) was not included in this analysis. As described in "Appendix D" on the methodology of the budget analysis used in this case study, the ARRA funding was a very large and anomalous appropriation directed at manufacturing facilities to deploy existing technology rather than R&D to develop new technology. It was not integrated into, or informed by the usual collaborative partnership planning process. Job creation was the primary focus rather than the promotion of technology innovation. Had the ARRA spending on electrification been included here, this category of spending would have exceeded the sum total of all others combined (See Figure 2).

Figure 2: **Direct Federal Investment in Electric, Hybrid Drive, Batteries, Power Electronics R&D**



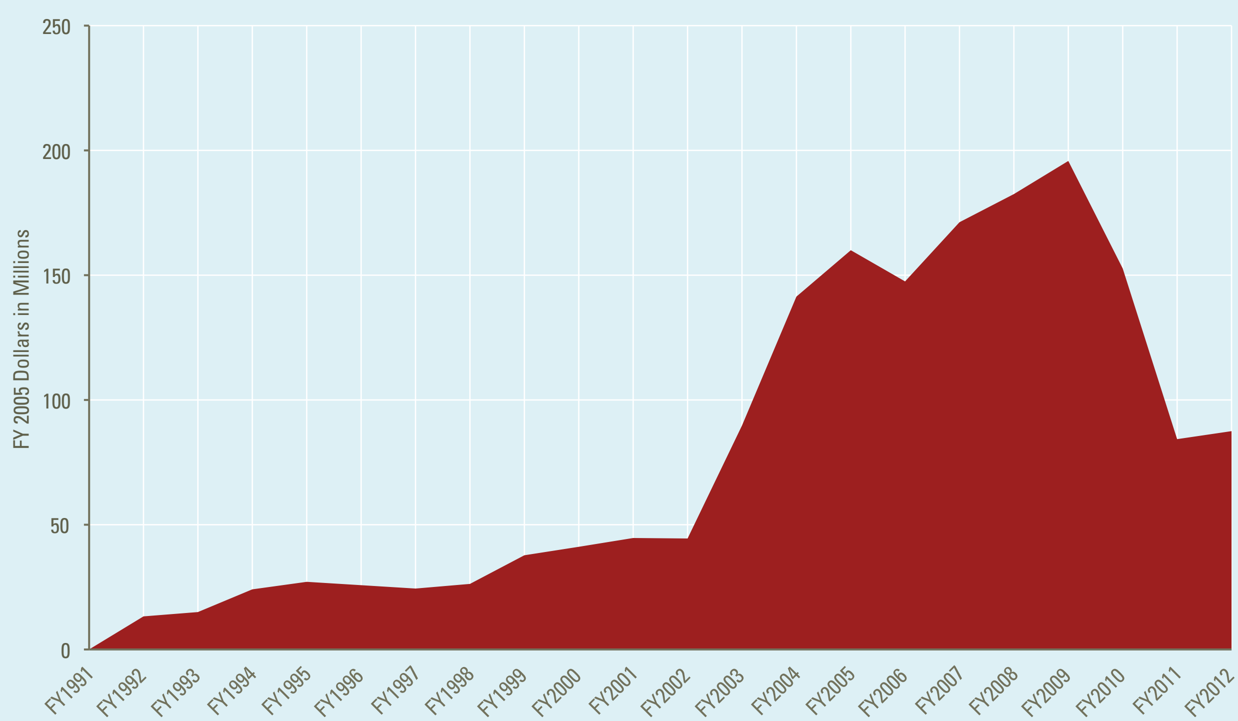
Fuel Cell and Hydrogen R&D

Fuel cell vehicles powered by hydrogen have the attributes of electric drive, with the additional advantage of quick refueling, requiring several minutes, as opposed to recharging times for battery electric vehicles, generally measured in hours.[15] Like battery electric vehicles, fuel cell vehicles have zero harmful emissions at the vehicle, although the full life-cycle (upstream) emissions resulting from hydrogen production must be considered, just as the life-cycle emissions of electricity generation must be considered in the case of battery electric vehicles. DOE's work in this area included in this analysis encompasses a variety of activities, such as:

- Reducing the cost and improving the durability of fuel cells, mainly through efforts to identify and evaluate new formulations and materials for fuel cell stack catalysts and membranes;
- Exploring new methods for hydrogen storage aboard the vehicle. Current designs that can deliver a 300-plus-mile range depend on bulky, high-pressure tanks constructed of expensive materials. Other alternatives that have been explored include solid-state chemical storage on metal hydrides and other chemical sorbents;
- The exploration of various methods of hydrogen production, delivery, storage, and fueling, as well as the vehicle interface with the refueling infrastructure;
- Real-world testing and data analysis of on-the-road hydrogen fuel cell vehicles; and
- Work on related codes and standards.

During the time period of this case study, funding for applicable fuel-cell- and hydrogen-related R&D began in FY 1992 at approximately $13 million, peaking in FY 2009 at $196 million before declining to roughly $87 million in FY 2012, for a total expenditure of approximately $1.7 billion (all expressed in FY 2005 dollars) (See Figure 3).

Figure 3: **Direct Federal Investment In Automotive Fuel Cell and Hydrogen R&D**



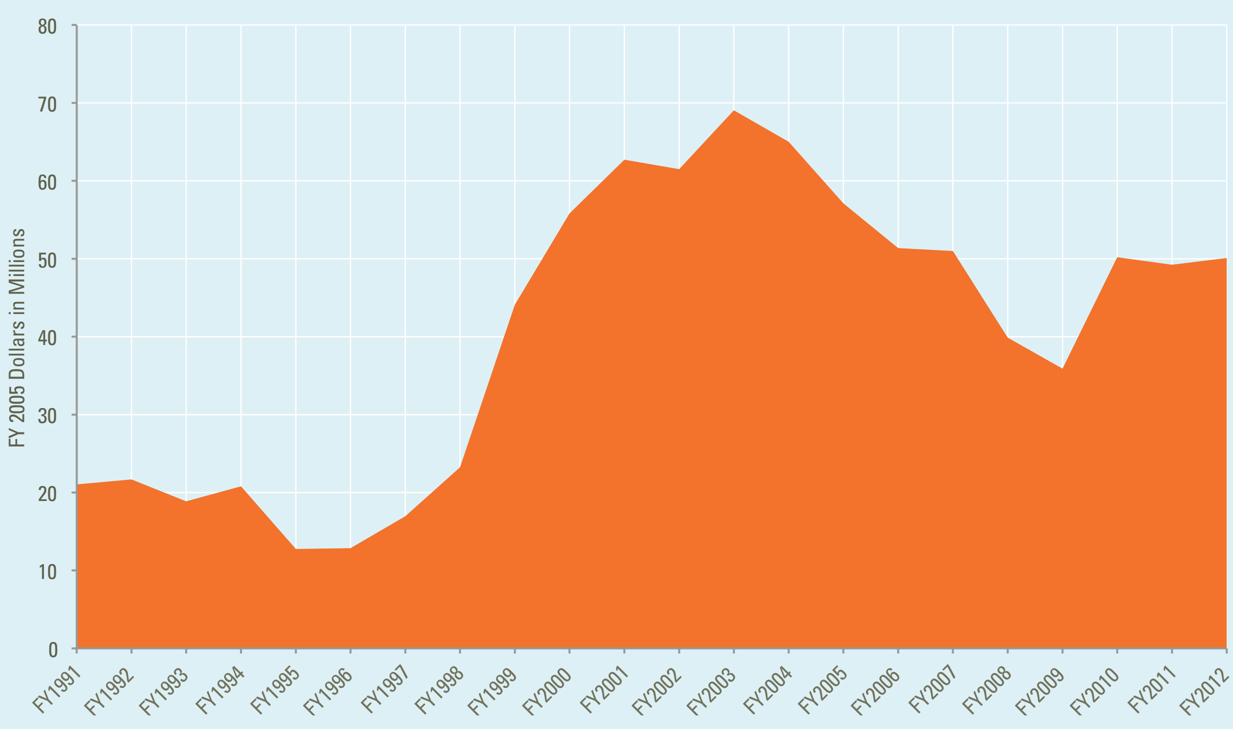
Internal Combustion Engine R&D

Much of the work in internal combustion R&D is applicable to both light-duty and heavy-duty transportation, with heavy-duty generally regarded to be less amenable to electrification and likely to rely on internal combustion engines for many decades to come. Past accomplishments include advancements in light-duty clean diesel engines that are now in the marketplace. Current work in internal combustion R&D encompasses a variety of activities, including:

- Advanced combustion and emissions controls to promote greater efficiency *and* lower emissions. Simultaneously achieving greater efficiency with lower emissions can be challenging since many emissions-reducing technologies impose an energy penalty, requiring additional fuel use;
- The development and support of computational fluid dynamics (CFD) models and laboratory tools to better understand combustion dynamics across a wide variety of engine operating regimes. For example, a better understanding of engine combustion dynamics could aid in the development of a low-temperature, high-efficiency diesel that might avoid the formation of nitrogen oxides altogether, reducing the need for costly, energy-robbing emissions treatment devices;
- The continued development and advancement of lean-burn, direct-injection engines, and low-temperature combustion options for vehicles fueled by diesel, gasoline, biofuels, natural gas, and hydrogen; and
- Waste heat recovery, sensors, fuel injector design, and emissions treatment catalysts.

During the time period of this case study, funding for internal combustion engine and related R&D has ranged from approximately \$12–\$70 million annually, with a total cost of approximately \$891 million (all expressed in FY 2005 dollars) (See Figure 4).

Figure 4: **Direct Federal Investment in Internal Combustion Engine R&D**



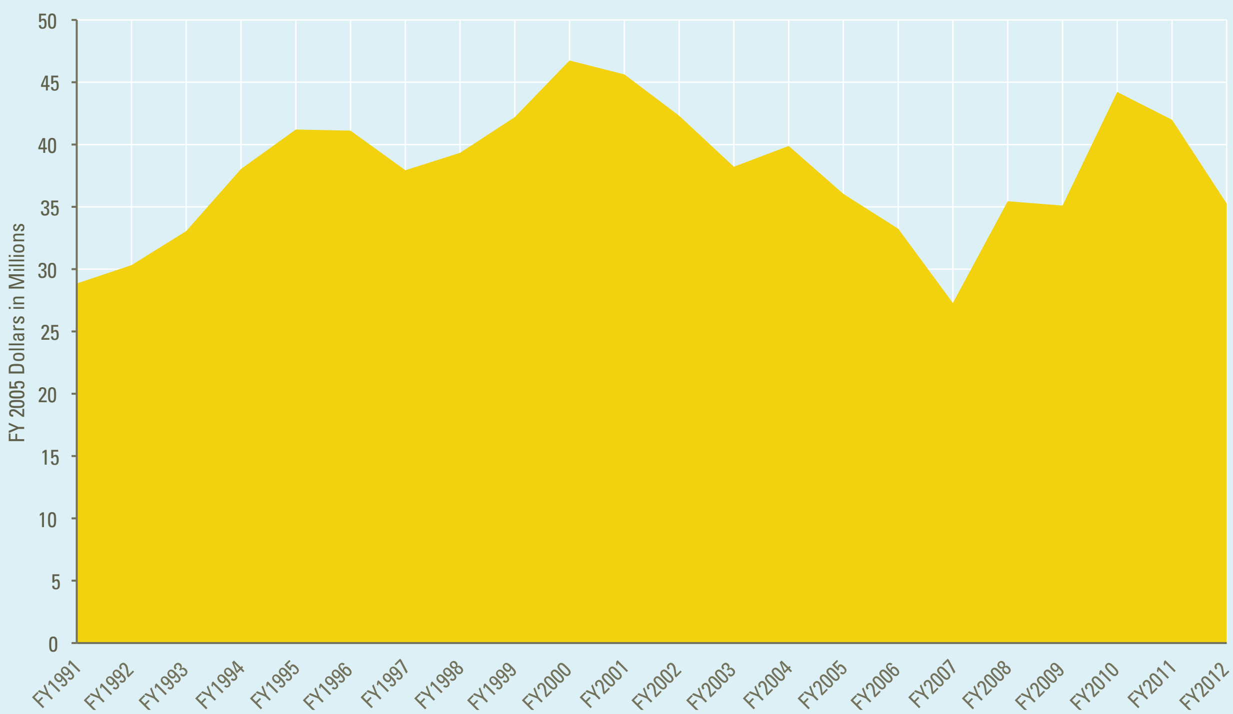
Materials R&D

There are a variety of different materials challenges inherent in light-duty transportation. Most of the materials effort centers on strategies to reduce vehicle weight (improving fuel economy) without adding substantial cost or degrading the crash worthiness of the vehicle. Indeed, a lighter vehicle benefits from the phenomenon known as "mass decompounding," where a lighter vehicle structure requires lighter suspension, brakes, and powertrain components, including a smaller engine. Past and current work in this area has included:

- Development and use of aluminum, high-strength steels, and fiber-reinforced composites as well as the welding/joining technologies needed to incorporate these materials; and
- Development of new methods to manufacture and recycle materials such as carbon fiber.

During the time period of this case study, funding for materials related R&D has ranged from approximately \$29–\$47 million annually, with a total cost of approximately \$833 million (all expressed in FY 2005 dollars) (See Figure 5).

Figure 5: **Direct Federal Investment in Automotive Materials R&D**

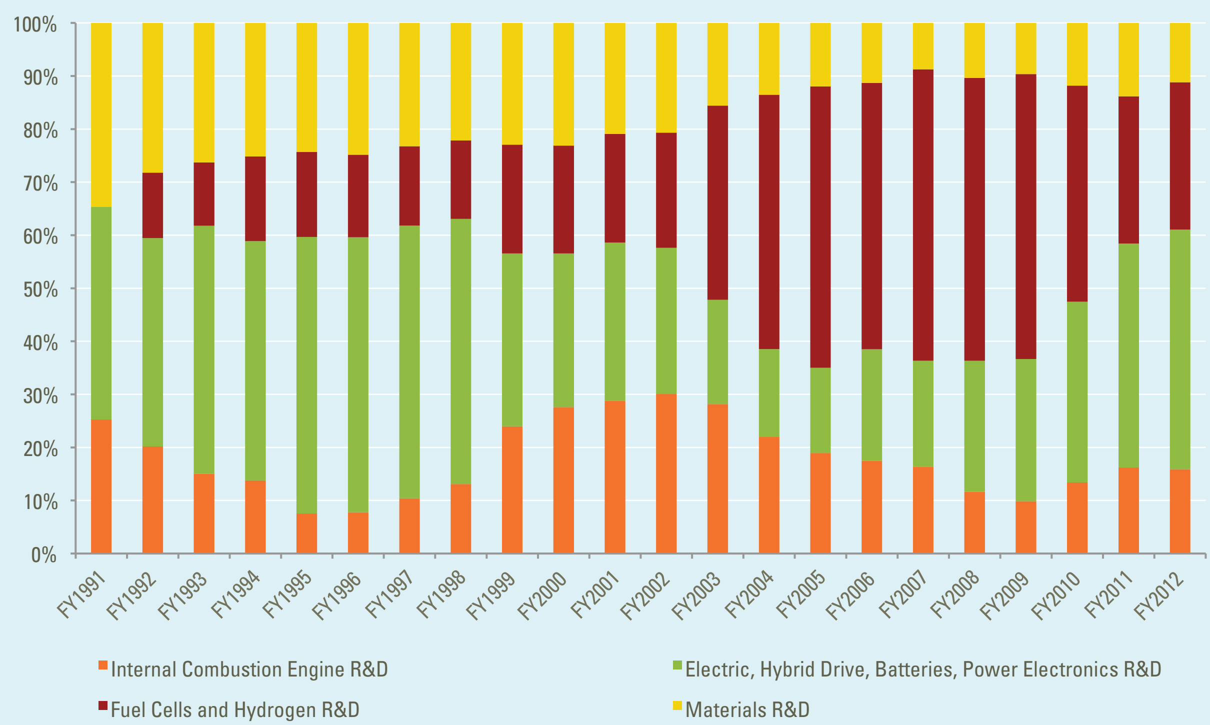


Relative Share of Four Primary Technology Areas

While there have been areas of strong emphasis and funding shifts, particularly with respect to hydrogen and fuel cell funding, it is noteworthy that every administration has directed investment in *all* of these categories every year since FY 1992. In other words, the vehicle-technology R&D programs have arguably been more diversified than it may have appeared at the time to critics of a particular administration's approach. Figure 6 portrays the relative share of spending in the four major categories during the time frame of this case study. The chart illustrates that the Bush administration, with a greater emphasis on the long term, directed a larger share of resources toward longer-term technology (hydrogen fuel cells); while the Clinton and Obama administrations each directed a larger share of resources toward nearer-term technologies (hybrids and battery electric vehicles).

But the fact remains that all three administrations maintained a fairly diverse R&D portfolio, allocating funding to each of the four major funding categories. It is also important to appreciate that there are synergies in much of this spending. For example, materials research leading to vehicle weight reduction benefits all vehicle types. Technology that improves electric motors and power electronics, or that reduces the size and weight of batteries, is beneficial to battery electric vehicles, gasoline/diesel electric hybrid vehicles, plug-in hybrid vehicles, and fuel cell vehicles because they are all electric drive vehicles that employ these components.[16] Therefore, while there could be variations in emphasis and approach as administrations changed, there was actually a common body of work focused on key technologies and systems (See Figure 6).

Figure 6: **Relative Shares of Direct Federal Investment in Four Key Vehicle Technolgy Areas**



The Evolution of the Partnerships

It must first be appreciated that the relationship between automakers and government is one that has often been strained, if not antagonistic—with the government working to impose tightening safety, emissions, and vehicle-efficiency standards on an economically important, politically powerful industry with the clout to delay or, in some cases, roll back regulatory initiatives. The concept of such a government-industry partnership was a fairly new one at the time that the Partnership for a New Generation of Vehicles was first considered. As one government official put it, "[Through PNGV] we are trying to replace lawyers with engineers."[17] And by nearly all accounts, most notably the NAS program reviews that have assessed the performance of PNGV as well as FreedomCAR and U.S. DRIVE, the partnerships have succeeded in creating a sustained, functional relationship that has enhanced communication and understanding among all of the parties that has continued from 1993 to the present.

In the 1960s, there was a private technology partnership solely among the U.S. automakers focused on pollution-control technologies. According to a 1969 antitrust suit brought by the U.S. Justice Department, the purpose of this partnership was to facilitate collusion to delay the development and diffusion of vehicle anti-smog technologies rather than to advance the technologies themselves. A sealed settlement and consent decree ultimately disbanded the partnership, and U.S. automotive companies avoided technical collaborative efforts until Congress passed the Cooperative Research Act of 1984 to limit the antitrust liability of joint research and development ventures. U.S. automakers launched the Automotive Composites Consortium (ACC) in 1988 to foster collaborative, pre-commercial R&D on lightweight materials. In 1991, the U.S. Advanced Battery Consortium (USABC)—a pre-commercial research collaboration focused on electrochemical storage R&D involving GM, Ford, Chrysler, and DOE—was formed. In 1992, the United States Council for Automotive Research, or USCAR, was created. USCAR has since been the industry's focal point for PNGV, FreedomCAR, and U.S. DRIVE.

Early critics of the public-private automotive partnerships ranged across the political spectrum. Those on the right feared "industrial policy," those on the left regarded the partnership as a "scam to keep regulation at bay,"[18] and both sides claimed the program constituted "corporate welfare." These voices have become less pronounced over the years, since the regulation of all facets of the automotive industry has continued, the most pronounced "industrial policy" aspects of the partnership have been abandoned, and various analyses of the spending directed under the DOE Vehicle Technologies Program has shown that the largest recipients of DOE automotive technology funding are not automakers, but the National Laboratories.[19] Indeed, under FreedomCAR and U.S. DRIVE, USCAR members receive no federal funding whatsoever via the partnership structure, although they may compete for DOE funding through competitive solicitations like any other entity.

It is also important to recognize that the partnerships, particularly in the later years, have been aimed at collaborative, *pre-commercial* applied research—the kind of research focused on overcoming more fundamental engineering challenges. Automakers and automotive suppliers then carry any results forward with their own proprietary R&D to bring new technology to the market. For example, engineers from Ford, GM, and Chrysler (and their suppliers) worked collaboratively with researchers at Oak Ridge National Laboratory's Power Electronics and Electrical Power Systems Research Center to explore different approaches to decrease the size and weight of DC-AC inverters needed for electric and hybrid-electric vehicles. But then they would take what was learned collaboratively behind their own "proprietary curtain" to develop the actual inverter that would ultimately be installed in their vehicle. While there was collaboration to develop a common understanding of the best general approach, there was also competition to develop the best proprietary technology. This collaboration/competition model is arguably the best way to understand how these partnerships actually functioned as they matured.

But perhaps the most important aspect to recognize is that PNGV, FreedomCAR, and U.S. DRIVE are not, in fact, three different partnership approaches. Instead, they are re-brandings accompanying shifts in emphasis and evolutionary changes in what is, in reality, a single expanding partnership that has existed continuously since 1993. This study will explore each of the three phases of this partnership, their technical successes and failures, and consider how and why the changes in emphasis and evolutionary changes took place.

Partnership for a New Generation of Vehicles (PNGV)

President Clinton officially launched PNGV in September 1993 as a cooperative R&D program between the U.S. government and USCAR, whose members were the Chrysler Corporation, the Ford Motor Company, and General Motors Corporation (GM).[20]

PNGV, unlike FreedomCAR and U.S. DRIVE, was led by the U.S. Department of Commerce. The Departments of Energy, Transportation, Defense, the Interior, the Environmental Protection Agency, the National Science Foundation, and the National Aeronautics and Space Administration (NASA) were officially part of the partnership, although the formal participation of the Department of Defense and NASA was limited in practice since these agencies lacked specific statutory authorization for such activities.[21]

The explicit goals of PNGV were:

- *Goal 1: Significantly improve national competitiveness in manufacturing for future generations of vehicles.* Improve the productivity of the U.S. manufacturing base by significantly upgrading U.S. manufacturing technology, including the adoption of agile and flexible manufacturing and the reduction of cost and lead times, while reducing the environmental impact and/or improving product quality.

- *Goal 2: Implement commercially viable innovations from ongoing research on conventional vehicles.* Pursue technology advances that can lead to improvements in the fuel efficiency and reductions in the emissions of standard vehicle designs, while pursuing advances to maintain safety performance. Research will focus on technologies that reduce the demand for energy from the engine and drivetrain. Throughout the research program, the industry has pledged to apply those commercially viable technologies resulting from this research that would be expected to significantly increase vehicle fuel efficiency and improve emissions.

- *Goal 3: Develop a vehicle with up to three times the fuel economy of comparable 1994 family sedans.* Increase vehicle fuel efficiency to up to three times that of the average 1994 Concord/Taurus/Lumina automobiles with equivalent cost of ownership adjusted for economics.[22]

At the time of PNGV's creation, there was widespread alarm over the loss of global market share by the "Big Three" U.S. automakers, driven mainly by competition from offshore automakers, particularly the Japanese. Consequently, the goal of improving "national competitiveness in manufacturing" was a key driver behind the partnership, constituting the first goal. Indeed, when the Toyota Motor Company expressed a potential interest in joining the partnership through USCAR, they were reportedly rebuffed with the argument that Toyota did not at the time have major powertrain R&D facilities in the United States and could not therefore participate.[23]

But the goal that is most generally associated with PNGV was the goal to develop a family sedan with up to triple the fuel efficiency of the automakers' 1994 offerings—roughly 80 miles per gallon—that could meet safety and emissions standards as well as customer expectations, all at a competitive price point. In pursuit of that goal, the PNGV partners adopted milestones to select a technology approach by 1997, to reveal concept vehicles in 2000, and to produce prototype vehicles in 2004.

Ultimately, a technology approach (diesel-hybrid electric) was selected by each of the automotive partners; and concept vehicles were revealed in 2000.[24] However, it soon became clear that the vehicles could not be successful for three reasons: the diesel technology at the time could not meet evolving emissions standards, the market trends were moving from family sedans to sport utility vehicles and crossovers, and the vehicles envisioned could not be offered at a competitive market price.

At roughly the same time that the PNGV concept vehicles were revealed, Honda and Toyota introduced *mass production* gasoline electric hybrid vehicles into the U.S. market in 1999 and 2000 respectively. The Toyota Prius has since become the world's best-selling hybrid electric vehicle with more than five million units sold globally.

Since the PNGV program did not result in an affordable family sedan that could approach 80 MPG by 2004, could it be termed a success?

The NAS panel tasked to evaluate the program tackled that question, concluding that:

> **The PNGV program has overcome many challenges and has forged a useful and productive partnership of industry and government participants. In addition to the cooperative program, *substantial proprietary industry R&D activity has been generated.* Teams of industry and government representatives have addressed formidable technical issues and made significant progress on many of them despite the complexity of managing an inter-disciplinary program involving three competing companies, several government agencies, and significant government budget constraints. The program concept cars introduced in January and February of 2000 are important evidence of these activities, but the ongoing R&D program, much of which is summarized in the following sections [of the NAS Review], is equally significant.[25] [Emphasis added.]**

Indeed, some of the work funded by the DOE Vehicle Technologies Program, with input from the PNGV partnership structure and coordinated with the closely related U.S. Advanced Battery Consortium (USABC), resulted in substantial technical progress and, ultimately, commercial application. A prime example is the nickel-metal hydride battery designed for hybrid vehicle applications. One of the DOE-supported design approaches funded through USABC ultimately led to a commercially available nickel-metal hydride battery from a U.S. manufacturer, ECD Ovonics, which ultimately licensed the technology to Panasonic and Sanyo, suppliers to Toyota and Honda. In other words, the Japanese automakers may have beaten the U.S. automakers to market with their hybrid vehicles, but they did so using some key U.S. technology that was funded by DOE and guided by the PNGV and USABC partnerships.

There was another impact of the PNGV program that is worth mentioning—the external impact of the program on non-participating automakers such as Toyota. According to Takeshi Uchiyamada, who was responsible for development of the first-generation Toyota Prius and who today serves as the vice chairman of Toyota Motor Company, the PNGV program, and its focus on hybrid vehicles was a significant factor in Toyota's pursuit of hybrid vehicles.[26] Indeed, some observers noted that PNGV resulted in a "boomerang effect," where "apprehensive foreign competitors responded to the program with aggressive efforts of their own, which in turn sparked an acceleration of the U.S. efforts."[27]

Despite these positive impacts, the headline goal of the PNGV—an affordable 80 MPG family sedan—was clearly not achieved. In addition, a 2001 NAS report reviewing the progress of the PNGV[28] concluded that there was "a need to update the program goals and technical targets in the context of current and prospective markets" and that it was "inappropriate to include the process of building production prototypes in a precompetitive, cooperative industry-government program." The Academy report also argued that the "timing and construction of such vehicles is too intimately tied to the proprietary aspects of each company's core business to have this work scheduled and conducted as part of a joint, public activity." Rather than a focus on a single car, the report suggested that the focus be on component technologies and systems that can be applied to all types of vehicles to have the maximum impact on total fleet fuel consumption.

The incoming administration of George W. Bush wished to revise and refocus the partnership, move past the failures of the PNGV program, and focus the program goals on longer-term, pre-commercial activities focused on drivetrain component technologies rather than flagship or prototype vehicles. The Bush administration was also cognizant of the Academy report's discussion of the progress that had been made in fuel cell vehicles, noting the report's assertion that "[n]o other energy converter appears to have a better potential for combined low-emission, high-energy conversion efficiency than fuel cells." This ultimately led to the next evolution of the partnership: FreedomCAR.

FreedomCAR and the FreedomCAR and Fuel Partnership

During the months following the 2001 NAS report, the Bush administration DOE and representatives of USCAR worked to develop a new framework to guide the next phase of the partnership. The general approach was to focus on systems and components that could result in "a full spectrum of vehicles that can operate free of petroleum and harmful emissions while sustaining the driving public's freedom of mobility and freedom of vehicle choice."[29]

Specific engineering targets and milestones pertaining to system/component performance were developed and agreed upon, and are included as "Appendix A." In January 2002, FreedomCAR was launched at the North American Auto Show in Detroit.

FreedomCAR's long-term emphasis was on hydrogen fuel cell vehicles. President Bush, in his 2003 State of the Union speech, suggested the possibility that, "the first car driven by a child born today could be powered by hydrogen and pollution-free." And yet, the partnership targets also included specific cost and technical goals for internal combustion engine efficiency, performance and cost goals for batteries and electric motors, power electronics, and other components that would be used for hybrid electric vehicles, battery electric vehicles, and even advanced internal combustion engine vehicles that would be in the marketplace until and even after the introduction of fuel cell vehicles. Perhaps most importantly, the overarching FreedomCAR goal for the hydrogen fuel cell vehicle was not a specific concept vehicle, prototype vehicle, or production vehicle by a date certain, but rather, a *commercialization decision* by the year 2015. In other words, the focus would be on achievement of specific cost and engineering goals for key technologies and systems, ranging from internal combustion engines to batteries to fuel cells. Once those targets were achieved, it would be up to the automakers to determine how these systems and components could best be utilized and packaged in a vehicle to appeal to the mass market.

This was an evolutionary development that was consistent with the expected thinking of a Republican administration; namely, shift more of the focus to longer-term research that is more appropriate for government support (i.e., fuel cells) while avoiding what some might regard as "industrial policy" to pursue national competitiveness goals or produce specific vehicle types in specified time frames, leaving the ultimate decision of marketability to the private sector. Moreover, with the focus toward the achievement of specific technical and engineering goals (rather than the national competitiveness/advanced manufacturing goals of PNGV), the lead agency would no longer be the Department of Commerce. Instead, DOE would be the sole federal agency in the partnership.

As FreedomCAR continued to evolve and the challenges of hydrogen and electric power fueling infrastructure came into focus, the partnership was expanded to include fuel providers, including the major oil companies in 2003 and electricity providers in 2008. After 2003, the partnership was officially referred to as the FreedomCAR and Fuel Partnership, recognizing that success in advancing automotive technologies did not depend on vehicle technology alone, but in the refueling/repowering infrastructure and interface as well, regardless of whether the fuel was a petroleum derivative, electricity, or hydrogen.

The FreedomCAR and Fuel Partnership also institutionalized a collaborative but independent approach to pre-commercial research. Research priorities, roadmaps, goals, and milestones were collaboratively established and joint government-industry technical teams frequently met to monitor and evaluate progress, but the partners would independently undertake their own research activities. It was expressly stated in the partnership plan that:

> **DOE intends to fund R&D activities at the national laboratories, traditional and non-traditional automotive suppliers, universities, small businesses, and other research institutions. *It is expected that direct funding by DOE to partner companies or consortia will be limited.* In general, DOE research projects will be selected competitively, and DOE R&D funding decisions are made independently.[30] [Emphasis added.]**

The 2010 NAS review[31] of the program found that "the Partnership is effective in progressing toward its goals. There is evidence of solid progress in essentially all areas, even though substantial barriers remain."[32] Other highlights of the review included:

- With respect to *advanced internal combustion engines and emissions controls*, the report found that "all aspects of ICE [internal combustion engine] operation are being pursued, and good progress is being made."[33]

- With respect to work related to *hydrogen fuel cells*, the report found that "progress has been significant, with continuing increases in performance and decreases in projected costs essentially every year. However, in spite of the significant progress, no single fuel cell technology has attained the combination of performance and projected costs to be competitive with conventional systems." The review went on to elaborate that "most performance targets have been met in various demonstrations, but not with a single technology."[34]

- With regard to work on *batteries and ultracapacitors* for use in plug-in hybrid and battery electric vehicles, the review found that "at present, none of the [lithium-ion] battery chemistries meets the combination of performance, life and cost goals for 2012 PHEV requirements. Although significant progress has been recorded in the Li-ion battery performance, durability, and safety, there has been no significant reduction in the projected cost of batteries. … Battery cost will play an even bigger role in the eventual success of the PHEV and BEV applications because much larger batteries are required."[35]

- With regard to *materials R&D*, the review found that the partnership's goal of reducing vehicle weight by 50 percent without cost penalty to be "unrealistic."[36] The committee noted that "the materials needed to make the required weight reductions—high-strength steels, aluminum, titanium, magnesium, and fiber-reinforced composites—are available. The key issue is not improving their performance but getting the weight reductions needed at an acceptable cost," and recommended that "the materials technical team should develop a systems analysis methodology to determine the currently most cost-effective way for achieving a 50 percent weight reduction for hybrid and fuel cell vehicles."[37]

The 2010 review was a positive one, but it did make some important recommendations, particularly with respect to hydrogen fuel cells. The review had bridged the 2009 change of administrations. The new Obama administration, emphasizing near-term vehicle electrification, had attempted to zero-out all hydrogen fuel R&D activities while promoting the expenditure of $2.7 billion for advanced battery manufacturing, public recharging stations, and similar technology deployment activities through the American Recovery and Reinvestment Act of 2009 (ARRA)—funding that was not conducted with FreedomCAR partnership input. The NAS review noted the shift toward nearer-term activities but warned that:

> **The fuel cell/hydrogen R&D is viewed by the committee as long-term, high-risk, high-payoff R&D that the committee considers not only to be appropriate, but also to be of the type that much of it probably would not get done without government support.[38] … In light of the prior funding of this [hydrogen fuel cell] program as reported in this review period (2007–2009) and the advancements reported to the committee, at the time of this assessment the success of the program could have been put in jeopardy as a result of the zeroing of the primary budget line items related to the fuel cell development activities (in the FY 2010 administration's budget request). If vehicle fuel cell development is to continue, such funding must remain intact and must be directed at the R&D that can help enable OEMs to develop the complete vehicle fuel cell power-generation subsystem.[39]**

Congress kept the hydrogen program alive, but at a reduced level of funding as noted earlier. In subsequent years, the Obama administration acquiesced to the view of NAS and the Congress that hydrogen-related R&D needed to be continued in the portfolio of activities conducted under the partnership, and for fiscal year 2014 sought $100 million for hydrogen and fuel cell activities in the Office of Energy Efficiency and Renewable Energy, plus some additional funding for basic hydrogen-relevant research in the Office of Science. Notably, this work has arguably continued to yield results. In the 2013 NAS partnership review, the committee noted that:

> **Statements by automotive companies in this country as well as by companies in other countries have indicated that vehicles in limited quantities will be placed in predetermined locations, partly gated by the availability of hydrogen refueling facilities, in the 2014–2016 time frame. This activity coincides with the timing of the original technology roadmap of the FreedomCAR and Fuel Partnership whereby in 2015 there would be a commercialization readiness decision. Considering the economic downturn and the budget constraints of late, the vehicle engineering accomplishments attest to the commitment of automotive manufacturers to fuel cell vehicles and thus to the importance of the Partnership's enabling R&D. The onset of HFCV deployment is impressive.[40]**

Toward the end of 2010, Obama administration officials determined that it was time to re-brand the partnership and refresh the partnership goals in keeping with the administration's emphasis on nearer-term technologies as well as selected recommendations from the NAS review committee. After deliberation with the partnership participants, the next iteration of the partnership—U.S. DRIVE—was launched.

U.S. DRIVE (U.S. Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability)

In May 2011, U.S. DRIVE was launched, comprising all of the existing partners from the FreedomCAR and Fuel Partnership in addition to two new partners: the Electric Power Research Institute (EPRI) and Tesla Motors.[41]

U.S. DRIVE carried forward the organizational structure and approach of the FreedomCAR and Fuel Partnership—including a focus on pre-commercial research (with no proprietary information being introduced into the process), a focus on components and systems rather than individual vehicle types, and decision-making by consensus—with the primary work undertaken by industry-government technical teams. The key technical goals of U.S. DRIVE appear in "Appendix B."

The 12 key focus areas of U.S. DRIVE, each represented by a technical team, are:

- Advanced Combustion and Emission Control;
- Electrical/Electronics (electric drive);
- Electrochemical Energy Storage;
- Fuel Cells;
- Materials;
- Vehicle Systems and Analysis;
- Grid Interaction;
- Fuel Pathway Integration;
- Hydrogen Production;
- Hydrogen Delivery;
- Hydrogen Storage; and
- Hydrogen Codes and Standards.

The U.S. DRIVE focus areas/technical teams were identical to the technical teams constituted under the FreedomCAR and Fuel Partnership. However, one new innovation of U.S. DRIVE was the inclusion of "Associate Members" at the technical-team level representing non-partner organizations with the goal of providing "additional experts with diverse perspectives, including technical knowledge uniquely relevant to a specific technical area."[42]

U.S. DRIVE is too new to assess independently; the most recent NAS review of the partnership was completed prior to the finalization of the U.S. DRIVE technical and cost targets, so the review could only make general comments with respect to the technical progress, structure, and management of the partnership. Nevertheless, the NAS review was a generally favorable one. The committee found that while "technical progress since the previous NAS review has been steady,"[43] continued government R&D efforts were necessary since neither battery electric or hydrogen fuel cell vehicles yet have "the performance attributes and cost to dominate the market and to meet the goal of the large-scale replacement of petroleum use and the reduction of emissions. Therefore, it is appropriate to continue investing resources on the most impactful research and not to let resources dwindle so far as to be unable to sustain a critical mass required to support a robust decision on any technology."[44] In essence, the committee was stressing the importance of maintaining a diverse portfolio of government-supported R&D that included advanced combustion engines, hybrid and battery electric vehicles, and hydrogen fuel cell vehicles in the partnership portfolio—something the Obama administration now appears more inclined to do.

The NAS committee also singled out the "exemplary" work of the technical teams, but noted a potential leadership vacuum at the level of the Executive Steering Group, composed of the assistant secretary for energy efficiency and renewable energy and industry vice presidents, as well as the need for a portfolio strategy based on rigorous systems analyses with respect to both vehicle systems and fuels. Put another way, the technical-team arrangement is excellent, but systems-level and strategic guidance from above could be improved.[45] DOE and the industry partners have, by all accounts, every intention of addressing this observation of the NAS committee, mindful that future NAS reviews will be forthcoming. Also by all accounts, DOE and the expanding list of partners and associate members remain enthusiastically committed to this enduring and evolving partnership.

Discussion and Conclusions

A review of the history and evolution from the partnerships leads to several initial conclusions:

- While PNGV, the FreedomCAR/FreedomCAR and Fuel Partnership, and U.S. DRIVE are popularly thought of as three discrete efforts undertaken by different presidential administrations, they are more accurately a single, evolving, and expanding partnership. Not only have the original partners judged the partnership to be worthy of their continued participation, additional partners have joined as well.

- While the earliest phase of the PNGV/FreedomCAR/U.S. DRIVE partnership did not meet its headline goal of an 80 MPG family sedan by 2004, the partnership contributed to steady and significant technical progress in key technologies according to a continuous series of reviews by panels convened by the NAS. Moreover, the partnership did so while fostering a healthy collaborative partnership between the government and automakers—in spite of a preexisting relationship that had been fairly antagonistic. Also, the partnership arguably increased aggressive, competitive technology development by foreign competitors that have ultimately been beneficial to American consumers and to the environment.

- The partnership now balances collaboration and competition in a successful manner—the automakers and government researchers work collaboratively to solve fundamental challenges with new and novel approaches, but then build upon that work with proprietary research and development that can ultimately result in new vehicle technologies reaching the marketplace. This collaborative/competitive model helps address the frequently heard criticisms that government R&D is often irrelevant and rarely fosters new technology that actually makes it to market, because any new and novel approach developed in the government lab is available to automakers and suppliers.

- Despite the different approaches emphasized by different presidential administrations, much of the work was focused on key areas, including materials, power electronics, electric motors, fuel cell technology, and energy storage that were beneficial to hybrid vehicles (the emphasis of the Clinton administration); hydrogen fuel cell vehicles (the long-term emphasis of the Bush administration); and plug-in battery electric vehicles (the emphasis of the Obama administration). While there has been some disruption in funding for hydrogen as a consequence of the Obama administration's nearer-term focus on battery electric vehicles, prompting a warning from the NAS review panel about the importance of a diversified portfolio, the hydrogen program has continued to perform fairly well nevertheless.

- In addition to undertaking technical collaborations under the umbrella of the PNGV, FreedomCAR, and U.S. DRIVE public-private partnership, automakers are increasingly entering into new technical partnerships, manufacturing alliances, and equity arrangements with each another. According to a 2012 study by Lux Research,[46] General Motors and Ford, as well as Toyota, BMW, and Volkswagen, are increasingly partnering with other automakers to share technologies like alternative fuels, electric vehicles, and advanced composites. While it can't be proven that the collaborative relationships developed under public-private partnerships such as FreedomCAR helped pave the way for these private partnerships, it seems likely that the associations and relationships developed at the technical-team and executive levels under the public-private partnership could be a contributing factor.

Yet the question at the heart of this case study remains: have the vehicle-technology and hydrogen activities at DOE and the closely associated public-private partnership (Partnership for a New Generation of Vehicles, FreedomCAR, and U.S. DRIVE) been successful when judged against the public investment? Has it been worth it? These are challenging questions to definitively answer for several reasons:

- Because the focus of the partnership is on pre-commercial activities, and because DOE investments in key technology areas are generally early-stage investment that is carried forward in proprietary research, the "direct genealogy" of a given innovation is often difficult to prove. Having said that, various studies and peer reviews that have performed patent-tracking and expert interviews with industry insiders strongly conclude that DOE work has been a key contributor in energy storage (batteries and ultracapicators), hydrogen and fuel cells, materials R&D, and advanced combustion engines.[47]

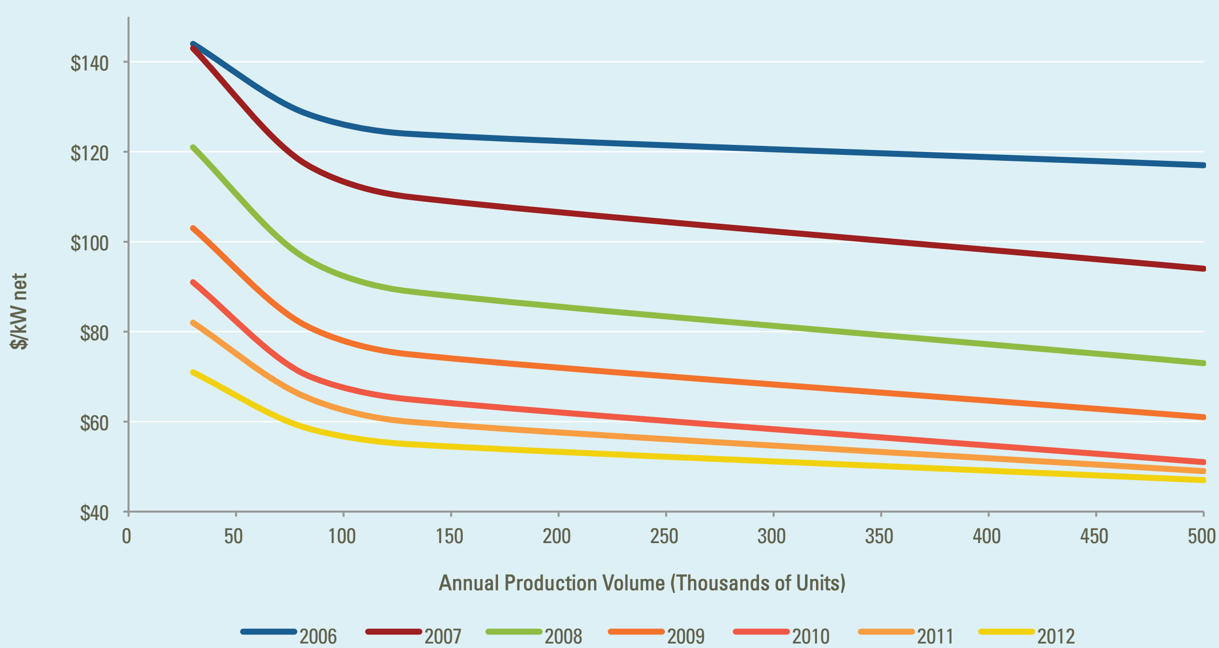
- Many of the long-term pre-commercial technologies that have been the focus of this work are still in development. The petroleum savings or emissions reductions attributable to technologies that have been significantly advanced, but are not yet deployed in vehicles cannot be quantified. Moreover, research cannot provide insight into the specifics of vehicle development and marketing plans by the private partners, as these are closely held corporate secrets. Several major automakers, for example, are planning to offer hydrogen fuel cell vehicles in the 2015–2020 time frame, but the numbers of vehicles that will be offered or sold are unknown. Corporate Average Fuel Economy requirements going forward will accelerate the incorporation of materials, advanced internal combustion, and other technologies advanced under the partnership, but the impact is not yet quantifiable.

- The PNGV/FreedomCAR/U.S. DRIVE partnership helps to *guide* automotive-related DOE research, but it doesn't *direct* DOE research. More importantly, there are many other players in the private and public sector operating around the world who are also engaged in this work, including many who are also linked to DOE and the partnership in some manner. Given the number of players and the complexity of the "innovation ecosystem," attributing or quantifying the specific level of contribution of DOE and the PNGV/FreedomCAR/U.S. DRIVE partnership to advances in energy-storage technology is simply not possible. The old adage, "Success has many fathers, but failure is an orphan," arguably holds true.

Despite the difficulties in quantifying or measuring success, a number of important observations can be made:

- The United States is seeing a steady increase in the technological accomplishments claimed by the partnership. "Appendix C" lists several hundred leading technological accomplishments of the FreedomCAR and U.S. DRIVE partnership as identified by the partnership's technical-review teams.
- The NAS program reviews have reinforced these claims, stating that the partnership has exhibited steady progress toward performance, reliability, and cost targets for batteries, fuel cells, and other key enabling technologies for advanced light-duty vehicles, including the "impressive" anticipated deployment of fuel cell vehicles that is consistent with the some of the original goals of the FreedomCAR partnership.
- The DOE hydrogen fuel cell program, in the pursuit of goals originally established and updated through the partnership process, which has been successful in lowering the cost of fuel cell systems is illustrated in Figure 7.[48]

Figure 7: **Automotive Fuel Cell System Cost Estimates, by Production Volume** [49]



- In addition, the hydrogen fuel cell program claims 363 resulting patents, including 183 fuel cell patents, 131 production/delivery patents, and 49 storage patents—more than 200 of which have been issued after 2005. Of these patents, 16 are currently used in commercial products, 60 are part of research now taking place on emerging technologies, and 183 are being utilized via continuing research and/or active attempts to license the patent. Moreover, 36 commercial fuel cell technologies have entered the market, of which 35 are still commercially available.[50]
- The DOE Vehicle Technologies Program and the partnership, in pursuit of technical goals developed under the partnership umbrella, have contributed to a 50 percent cost reduction for automotive lithium-ion batteries between 2008 and 2012. According to proprietary data submitted by battery companies participating in the U.S. Advanced Battery Consortium (USABC), the cost of high-energy, high-power batteries in mass production has been reduced from $1,200/kWh in 2008 to $500/kWh in 2012. The DOE Vehicle Technologies Program also claims to have supported the development of the Johnson Controls–SAFT and Compact Power/LG Chem lithium-ion battery packs that are today in production in hybrid and plug-in hybrid vehicles.[51]
- The DOE partnerships have also successfully evaluated technology approaches to determine which would ultimately be unsuitable for commercial application, including flywheels in battery electric vehicles and onboard hydrogen reforming from liquid fuels in the case of hydrogen fuel cell vehicles. In this manner, scarce public and private R&D funding could be directed more productively.

The value of the partnerships from the perspective of the automotive partners is clear, not only from their continuous association since 1993, but from the public pronouncements of industry executives:

"Having started from nearly nothing almost 15 years ago (under the Partnership for a New Generation of Vehicles), the FreedomCAR and Fuel Partnership vision is on track to changing the DNA of transportation in the United States. It's not just a few patents; we've seen a leap of generations, and each of us—energy companies, the Department of Energy, the auto companies—all share a common understanding of energy diversity."

—Larry Burns, USCAR council member and GM's vice president of research and strategic planning, All Tech Team Meeting 2007

"While we work with our partners to achieve our goals, we are realizing accomplishment and successes that have both near- and long-term benefits for consumers and society. Our precompetitive learnings provide a solid foundation for the application of new and better technologies in the competitive marketplace, which ultimately benefit consumers and the environment."

—Gerhard Schmidt, chief technical officer and vice president for research and advanced engineering, Ford, March 2008

And yet, those looking for dramatic, silver-bullet solutions to energy challenges may find even these accomplishments and the hundreds more listed in "Appendix C" to be underwhelming. The premise of the Vehicle Technologies Partnership and related activities conforms to the often stated adage that there are no silver bullets in energy, only "silver buckshot."

It is clear, however, that new car offerings in the United States have demonstrated gains in average vehicle efficiency while offering greater average horsepower, quicker average acceleration, and larger average interior volume as illustrated by Figures 8-10[52]

Figure 8: **Mileage and Horsepower of U.S. Light-Duty Vehicles**

Figure 9: **Mileage and Acceleration of U.S. Light-Duty Vehicles**

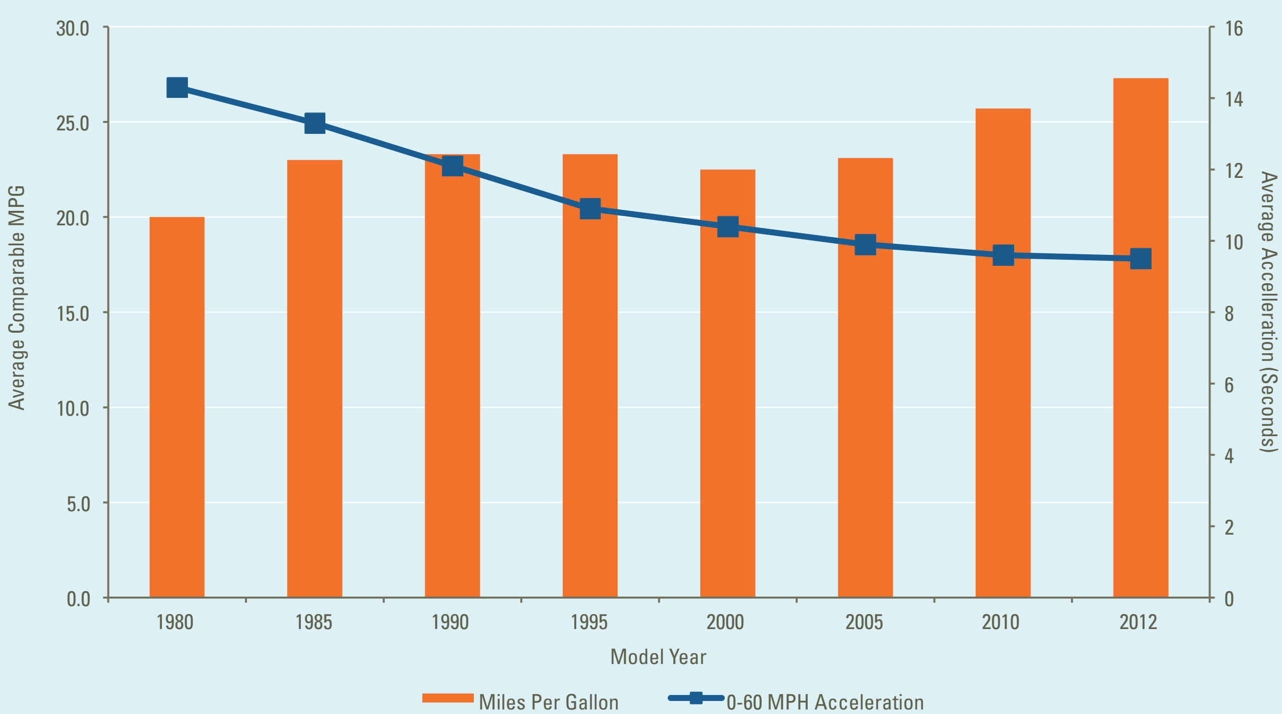
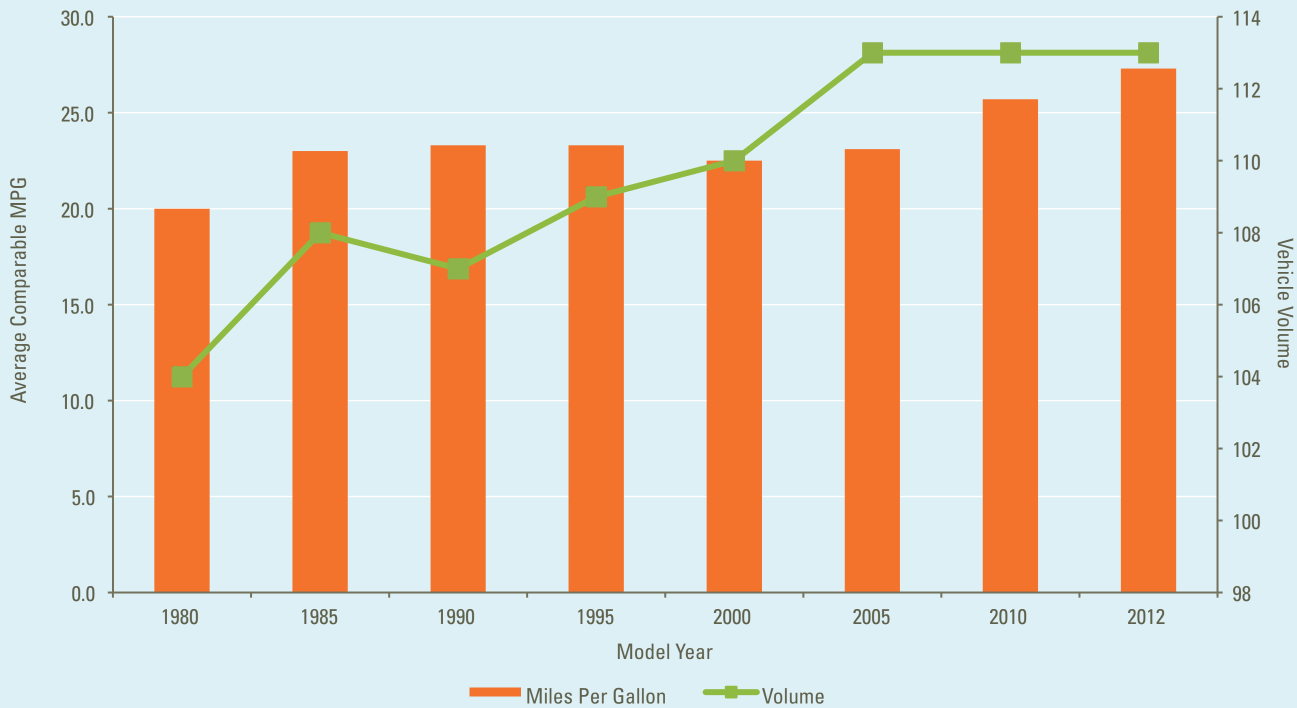


Figure 10: **Mileage and Volume of U.S. Light-Duty Vehicles**

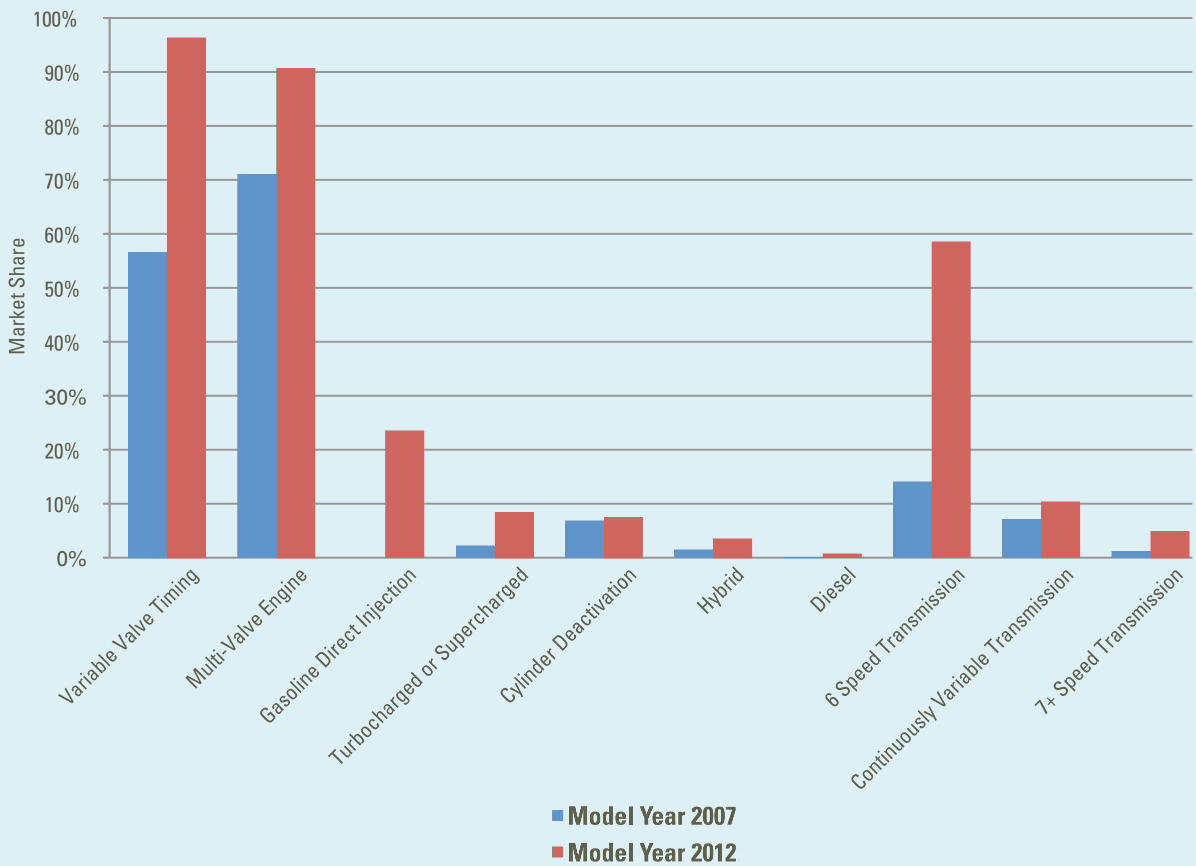


These improvements did not occur as a sole consequence of the DOE-automaker partnerships or the broader DOE Vehicle Technologies Program. Indeed, the regulatory requirements promulgated by the Department of Transportation (DOT), the Environmental Protection Agency (EPA), and in many cases the California Air Resources Board (CARB) have been and will remain important forcing mechanisms that require automakers to go well beyond the pre-commercial activities performed under the partnership with far greater amounts of funding and proprietary effort of their own.

Ultimately, automakers must offer affordable products that are responsive to regulatory requirements and consumer tastes, and the fiercely competitive automotive market is a relentless and unforgiving judge. While it may be possible to build even cleaner, more efficient vehicles with current technology than are offered in the marketplace today, automakers must deal with the fact that their market offerings must appeal to consumer demands while meeting market price expectations. After all, the cleanest, most efficient vehicles imaginable will not deliver environmental and other public benefits if nobody buys them. It is noteworthy that even though Ford offers a vehicle, the 2013 Ford Focus Electric, which has an EPA rating of 105 miles per gallon of gas equivalent, the top-selling vehicle in the United States remains the Ford F-series pickup truck with a top EPA combined rating of around 19 MPG. Sport utility vehicles and crossovers also remain very popular. But today, such vehicles are increasingly offered with light-duty, low-emissions diesel and direct-injection gasoline engines, as well as turbocharged 6 cylinder engines that are delivering the power and torque of the 8 cylinder engines of the past, with greater fuel economy.

No one is suggesting that these technologies would not have emerged in the absence of the DOE public-private automotive partnerships, but the participation of automakers and their supplier teams in collaborative R&D activities with government-funded and -led R&D has both helped to inform government regulators about the progress, prospects, and cost of candidate technologies while assisting automakers in the exploration of new approaches. The "innovation ecosystem," which includes these partnerships as well as the work carried on beyond them, has demonstrably increased the use of advanced technologies in the light-duty fleet as illustrated in Figure 11, drawn from a recent EPA report illustrating technology penetration between model years 2007 and 2012.[53]

Figure 11: **Light Duty Vehicle Technology Penetration Share, by Model Year**

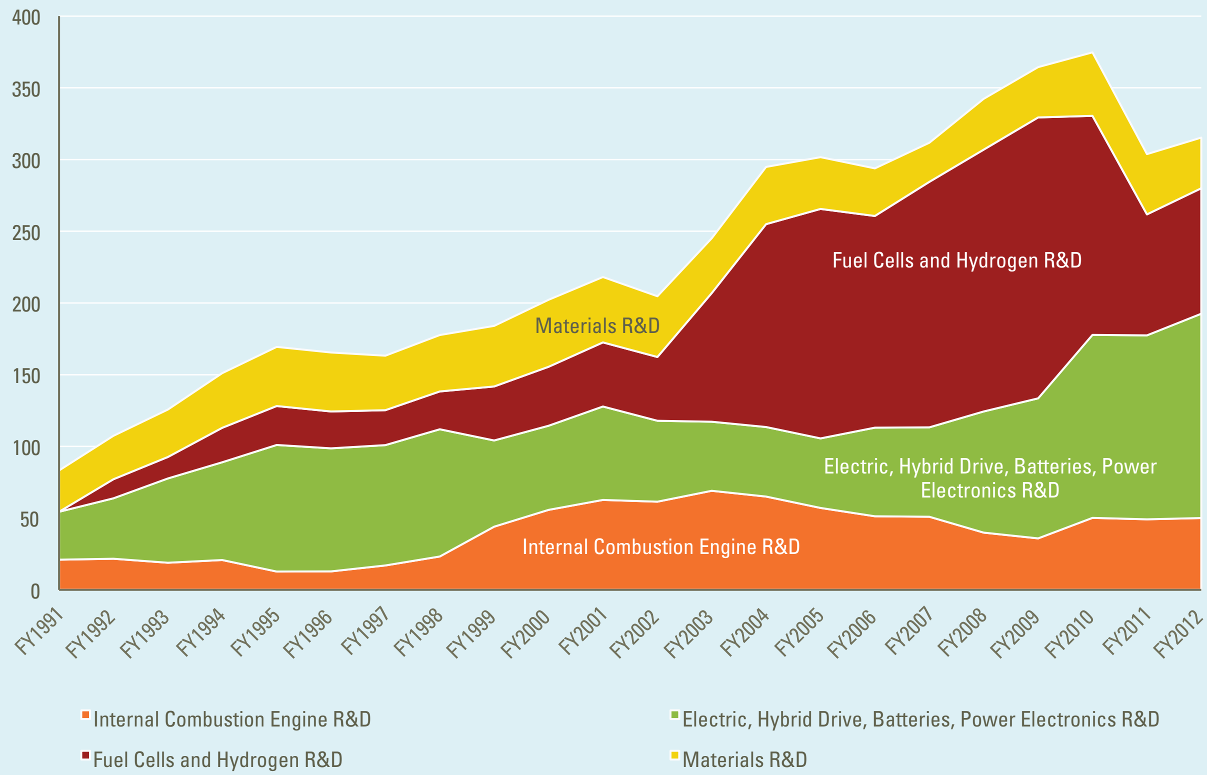


Given the critical nature of consumer choice, the shift from the PNGV's focus on a singular "supercar" family sedan to FreedomCAR and U.S. DRIVE's focus on systems and components that can be applied across a variety of vehicle platforms seems particularly wise and market relevant. The decisive shift that FreedomCAR made toward longer-term research also helped to assure that taxpayer contributions would be focused on longer-term, pre-commercial activities rather than proprietary product development. This is arguably a more comfortable place for automakers since they are fiercely competitive and ultimately unwilling to share their best technology in any forum that includes their competitors. This is a factor that would tend to keep the partnerships focused on pre-commercial research.

Another measure, albeit an implicit one, of the fundamental success of the program is the reaction of Congress to it, as expressed in appropriations for the four primary technology areas at the heart of the partnership's work. Figure 12 illustrates appropriated funding (in consistent 2005 dollars, *excluding ARRA spending*) during fiscal years 1991–2012 in the four key technology areas. The general trend would argue that the overall reaction of Congress has been favorable.

In sum, the generally favorable NAS reviews, the increasing appropriations by Congress, the implementation of technologies in actual vehicles in the marketplace, and the participation of a growing number of increasingly diverse partners in each iteration of what is, in reality, a continuous but evolving and expanding public-partnership (PNGV to FreedomCAR to Freedom CAR and Fuel to U.S. DRIVE), constitute explicit and implicit confirmations of the efficacy of the work of the DOE Vehicle Technologies Program and the public-private partnerships that help to guide it. For

Figure 12: **Direct Federal Investment in the Four Key Vehicle Technology Areas**



these reasons, and in light of the major achievements as listed in "Appendix C," the program is successful and worthy of continued support. It is by no means faultless, and there remains room for further improvement. For example, as suggested by the NAS in their 2010 review, greater attention to strategic and portfolio analysis is needed. Nevertheless, this evolving partnership has grown into a model of private-sector consultation and participation in the planning and evaluation of research and development and provides important lessons for other areas of DOE's portfolio of pre-commercial energy research involving buildings, lighting, appliances, and power generation.

APPENDIX A: Key Technical Goals of the FreedomCAR and Fuel Partnership

(From the March 2006 Partnership Plan)

Technology-Specific 2010 and 2015 Research Goals (Note: Cost references based on CY 2001 dollar values. Where power (kW) targets are specified, those targets are to ensure that technology challenges that would occur in a range of light-duty vehicle types would have to be addressed.)

To ensure reliable systems for future fuel cell powertrains with costs comparable to conventional internal combustion engine/automatic transmission systems, the goals are:

- Electric Propulsion System with a 15-year life capable of delivering at least 55kW for 18 seconds, and 30kW continuous at a system cost of $12/kW peak; and
- 60 percent peak energy-efficient, durable fuel cell power system (including hydrogen storage) that achieves a 325 W/kg power density and 220 W/L operating on hydrogen. Cost targets are at $45/kW by 2010 ($30/kW by 2015) (note: does not include vehicle traction electronics).

To enable clean, energy-efficient vehicles operating on clean, hydrocarbon-based fuels powered by internal-combustion powertrains, the goal is:

- Internal combustion engine powertrain systems costing $30/kW, having a peak brake engine efficiency of 45 percent, and that meet or exceed emissions standards.

To enable reliable hybrid electric vehicles that are durable and affordable, the goal is:

- Electric drivetrain energy storage with 15-year life at 300 Whr per vehicle with discharge power of 25 kW for 18 seconds and $20/kW.

To enable the transition to a hydrogen economy, ensure widespread availability of hydrogen fuels, and retain the functional characteristics of current vehicles, the goals are:

- Demonstrated hydrogen refueling with developed commercial codes and standards, and diverse renewable and non-renewable energy sources with a cost of energy from hydrogen equivalent to gasoline at market price, assumed to be $2.00–$3.00 per gallon gasoline equivalent produced and delivered to the consumer independent of pathway by 2015 (note: based on lower heating value of hydrogen; allows more than 300-mile range);
- Onboard Hydrogen Storage Systems demonstrating specific energy of 2.0 kWh/kg (6 weight percent hydrogen), and energy density of 1.5 kWh/liter at a cost of $4/kWh by 2010, and specific energy of 3.0 kWh/kg (9 weight percent hydrogen), 2.7 kWh/liter, and $2.00/kWh by 2015; and
- Internal combustion engine powertrain systems operating on hydrogen with a cost target of $45/kW by 2010 and $30/kW in 2015, having a peak brake engine efficiency of 45 percent, and that meet or exceed emissions standards.

To enable lightweight vehicle structures and systems, the goal is:

- Material and manufacturing technologies for high-volume production vehicles that enable/support the simultaneous attainment of:
    - 50 percent reduction in weight of vehicle structure and subsystems;
    - Affordability; and
    - Increased use of recyclable/renewable materials.

APPENDIX B: Key Technical Goals of the U.S. DRIVE Partnership

(From the March 2013 Partnership Plan)

Partnership Goal (1): Enable reliable hybrid electric, plug-in hybrid, and range-extended electric, and battery electric vehicles with performance, safety, and costs comparable to or better than advanced conventional vehicle technologies, supported by charging technologies that can enable the widespread availability of electric charging infrastructure.

2020 Partnership Research Targets:

- An electric vehicle battery at a cost of $125/kWh[1]; and
- An electric traction drive system at a cost of $8/kW.

Partnership Goal (2): Enable reliable fuel cell electric vehicles with performance, safety, and costs comparable to or better than advanced conventional vehicle technologies, supported by viable hydrogen storage and hydrogen production and delivery pathways that can enable the widespread availability of hydrogen fuel.

2020 Partnership Research Targets:

- An automotive fuel cell system at a cost of $40/kW; and
- An onboard hydrogen storage system at a cost of $10/kWh.

Partnership Goal (3): Significantly improve the efficiency of vehicles (including hybrids) powered by advanced internal combustion powertrains and vehicle fuel systems while protecting the environment.

2020 Partnership Research Target:

- *A 20 percent improvement in engine efficiency, compared with a 2010 baseline; engine concepts shall be commercially viable and meet 2020 emissions standards.*

Partnership Goal (4): Improve the efficiency of all vehicle types by using lightweight materials to reduce vehicle mass.

2020 Partnership Research Target:

- *An 18 percent glider[2] mass reduction, relative to comparable 2012 vehicles, at cost of $5.00/lb saved.*

1 Cost-related partnership research targets are expressed in 2012 dollars.

2 For this purpose, a glider is defined as the total vehicle minus the propulsion system, fuel/energy storage, wheels and tires.

APPENDIX C: Technical Accomplishments of the FreedomCAR and U.S. DRIVE Partnerships

Each year since 2002, the technical teams of the partnership select and describe "Highlights of Technical Accomplishments" from the many DOE-funded projects focused on advanced automotive and related infrastructure technologies.

The reports and one-page descriptions for each of the accomplishments listed below may be found at: http://www1.eere.energy.gov/vehiclesandfuels/about/partnerships/roadmaps-other_docs.html.

2002

Advanced Combustion & Emissions Control
- After-Treatment Subsystem Development Program
- Soot Formation in Diesel Fuel Sprays
- Swirl-Supported Diesel Combustion

Electrical & Electronics
- Automotive Integrated Power Module Development

Electrochemical Energy Storage
- Accelerated Life Test Protocol
- Lithium-Ion Battery System

Fuel Cells
- Advanced Membrane-Electrode Assemblies
- Carbon Composite Bipolar Plates
- Fuel Cell Neutron Imaging
- Low Platinum-Loading Electrode
- Microchannel Fuel Processor Development
- Quick Starting of Fuel Processors

Hydrogen Storage & Vehicle Interface
- Standardized Testing Program for Emergent Chemical Hydride and Carbon-Storage Technologies

Materials
- Commodity-Grade PAN Precursors for Low-Cost Carbon Fiber
- High-Strength Steel Stamping
- Low-Cost Cast Aluminum Metal Matrix Composite
- Magnesium Powertrain Cast Components
- Structural Composites Focal Project

Systems Engineering & Analysis
- Hardware-in-the-Loop Vehicle Emulation Test Facility

2003

Advanced Combustion & Emissions Control
- Charge Stratification to Improve Homogeneous-Charge Compression-Ignition (HCCI) Combustion Efficiency
- Lower-Temperature Diesel Combustion
- Sensors for Closed-Loop Diesel Engine Control

Electrical & Electronics
- High-Voltage Power Module Hits Performance & Cost Targets

Electrochemical Energy Storage
- 42V Battery Test Manual Issued
- Abuse Tolerant Lithium-Ion Cathode
- Lithium-Ion Battery Thermal Runaway Mechanism
- Lithium-Ion Electrolyte Model for Low Temperatures
- Lithium-Ion HEV Battery Cost Reduced

Fuel Cells
- Advanced Fuel Cell Membrane Electrolyte
- Benchmarking of High-Temperature Fuel Cell Membranes & Catalysts
- Durability Gains in Fuel Cell Membranes
- Durable, Low-Cost Fuel Cell Catalysts
- Fuel Cell Water Flow for Start-Up Diagnostics
- Offset Impact of Air Impurities on Fuel Cells 17

Hydrogen Storage
- Hydrogen Storage: Cryo-Compressed Tank
- Hydrogen Storage: High-Capacity Metal Hydrides
- Hydrogen Storage: Higher-Pressure Tanks

Materials
- Lightweight Aluminum Metal Matrix Composite Casting Hits Performance & Cost Targets
- Lightweight Magnesium Cast in Structural Application
- Faster Qualification of Lightweight Polymer Composites
- Test Machine for Automotive Crashworthiness

2004

Advanced Combustion & Emissions Control
- Fast-Throughput Methods Used to Discover New, NOx-Reducing Catalytic Materials

- Real-Time Measurement of Particulate Material
- Response Maps Developed for Lean NOx Traps
- X-Ray Measurements Reveal Structure of Diesel Spray Core

Codes & Standards
- International Agreement on Hydrogen Fuel Quality Specifications
- Predictive Capability Developed for H2 Radiation Heat Transfer
- Prevention of Premature Codes and Standards Setting

Electrical & Electronics
- System-on-a-Chip (SoC) Motor Controller

Electrochemical Energy Storage
- Analysis of Battery Thermal Performance
- Increased Calendar Life for Lithium-Ion HEV Battery
- Lithium-Ion HEV Battery Separator Cost Reduction
- Ultracapacitor Test Manual

Fuel Cells
- Air-Compressor Design Meets Performance, Weight, and Volume Targets
- Identification of Fundamental Materials Changes Associated with Fuel Cell Aging
- Low-Platinum and No-Platinum Cathode Catalysts
- More Durable Membranes for Fuel Cells
- Pt-Alloy Catalysts with Cycling Durability Better than that of Pure Platinum
- Structure/Performance Relationships in Fresh and Aged Fuel Cells
- Ternary Pt-Alloy Electrocatalysts: Approaching Activity Goal of 4x 19 Platinum
- Unique Nanostructured Thin Film Catalyst Demonstrates Improved Durability

Hydrogen Storage
- Hydrogen Storage System Pre-Prototype Using NaAIH4 Complex Hydrides
- Hydrogen Storage: Establishment of Standardized Testing Facility
- Regenerable Off-Board Chemical Hydrogen Storage
- Research & Development of High-Capacity Onboard Reversible Materials: Low-Temperature Reversible Amides/Imides

Materials
- Lightweight Front-End Structure
- Lightweight Magnesium-Intensive Engine Developments
- Low-Cost Titanium Process Feasibility
- Lower-Cost Carbon Fiber for Automotive Structures
- Recycling Automotive Materials
- Vehicle Systems Engineering & Analysis
- Benchmarking Advanced HEV Technology with 4WD Dynamometer Facility
- Powertrain System Analysis Toolkit (PSAT)

2005

Advanced Combustion & Emissions Control
- Extension of High-Load Limit of HCCI Engines by Combustion-Timing Retardation Explained
- Effect of EGR on Soot Formation
- Low-Temperature Combustion Used for More Efficient Lean NOx Trap Regeneration
- New Algorithm for Efficient Analysis of Partially Stratified Combustion Regimes
- Protocol Developed to Determine Kinetics of Regeneration in Lean NOx Traps

Electrical & Electronics
- Z-Source Inverter Reduces Cost and Complexity of Drive System in Fuel Cell Vehicles

Electrochemical Energy Storage
- Cost and Cell Performance Batteries for Hybrid Electric Vehicles
- Low-Cost Lithium-Ion HEV Battery Separators
- Manufacturing and Cost Model Developed for Lithium-Ion Batteries
- Viability of New High-Power Lithium-Ion Cell Chemistry Demonstrated

Fuel Cells
- Achieving Higher Fuel Cell Catalyst Activity with Less Platinum
- Dynamic Model of Fuel Cell Startup from Subfreezing Conditions
- Effects of Subfreezing Temperatures on Fuel Cells
- Fundamental Mechanisms Tied to Fuel Cell Durability Issues
- Improved Facilities for Imaging Water in Operating Fuel Cells
- Membranes Resistant to Mechanical and Chemical Degradation

- Microstructural Characterization of Fuel Cell Membrane-Electrode Assemblies
- Non-Platinum Cathode Catalyst Layer with Improved Mass Transport
- Reclaiming/Recycling of Used Platinum Membrane-Electrode Assemblies
- State-of-the-Art Cathode Mass Activity in a Durable Electrode Structure

Onboard Hydrogen Storage

- Hydrogen Storage Systems Engineering Facility Enables Measurement and Analysis
- Improved Hydrogen Release from High-Density Metal Hydride, AlH3
- Nanostructured Scaffolds Improve Ammonia Borane Hydrogen Storage Characteristics
- Novel Liquid-Phase Hydrogen Carrier

Materials

- Advanced Binder Control for Robust Stamping
- Cost of Wrought Magnesium Sheet Assessed
- Durability-Driven Design Guidelines for Carbon-Fiber-Based Composite Systems
- Feasibility of Low-Cost Titanium Process Established
- Structural Cast Magnesium Development

Vehicle Systems Engineering and Analysis

- AVTA Collects Hybrid Vehicle Performance
- Benchmarking Advanced HEV Technology with 4WD Dynamometer Facility

Fuel-Pathway Integration

- H2A Cost-Modeling Tool

Hydrogen Delivery

- H2A Hydrogen Delivery Models

Hydrogen Production

- Natural Gas Distributed Reforming Technology Assessment by Independent Review Panel
- Outcomes Maps Development

Codes & Standards

- Technical Reference for Hydrogen Compatibility of Engineering Materials

DOE Demonstration and Validation Project

- DOE Hydrogen Learning Demonstration

DOE Hydrogen Safety Panel

- DOE Hydrogen Safety Panel Review

2006

Advanced Combustion & Emissions Control

- Model of 3D Diesel Particulate Filter Shows Location Where Soot Collects
- High-Efficiency, Low-Emission Combustion Achieved at Modal Test Conditions Relevant for Small-Car FTP
- KIVA Enhanced for Faster Computations and HCCI Combustion
- Durability of a DOC-UREA SCT-DPF System for a Light-Duty Truck Studied for 120,000 Miles

Electrical & Electronics

- DC/DC Converter for Fuel Cell and Hybrid Vehicles
- Silicon-Silicon Carbide Hybrid Inverter

Electrochemical Energy Storage

- New High-Power Cell Chemistry Identified
- Gap-Analysis Software Developed
- Lithium-Ion Cells with Enhanced Abuse Tolerance
- Performance Enhancements and Cost Reduction
- Calendar Life/Cell Performance Improved

Fuel Cells

- Identified Method to Recover Fuel Cell Performance Loss Caused by Sulfur Poisoning
- Durability of Low-Cost Membrane is Improved
- Improved Platinum Alloy Catalyst Activity Could Dramatically Reduce Fuel Cell Cost
- A Platinum Catalyst Degradation Mechanism Is Identified
- New Membrane Demonstrates Improved Durability with No Loss in Performance

Onboard Hydrogen Storage

- Increasing Hydrogen Storage in Metal Organic Frameworks
- Predicting the Thermodynamics of Complex Hydrogen Storage Mixtures via Atomistic Modeling
- Hydrogen Storage Systems Analysis
- Second-Generation Cryo-Compressed H_2 Tank
- Improved Hydrogen Release from High-Density Chemical Hydride, NH3BH3

Materials

- Auto/Steel Partnership Future Generation Passenger Compartment
- Composite Intensive Body Structure (ACC Focal Project III)
- Ultra-Large Castings for Lightweight Vehicle Structures
- Friction Stir-Spot Welding of Advanced High-Strength Steels
- Warm Forming of Aluminum

Vehicle Systems Engineering and Analysis

- Hybrid Performance Testing Collaboration Reveals Consistent Performance over Life
- Control Strategy for Plug-In Hybrid Vehicles

Fuel Pathway Integration

- Pathway Components Model

Hydrogen Delivery

- Hydrogen Compression R&D: Feasibility Design for a Hydrogen Centrifugal Compressor for Hydrogen Pipeline Delivery

Hydrogen Production

- Development of a Turnkey Hydrogen Fueling Station
- Wind-Powered Electrolysis

Codes & Standards

- Hydrogen Behavior and Interface Information
- National Codes and Standards Template and National Hydrogen Fuel Cell Codes and Standards Coordinating Committee
- DOE Hydrogen Safety Databases

Hydrogen Analysis Resource Center (HyARC)

- Hydrogen Analysis Resource Database

2007

Advanced Combustion & Emissions Control

- Injection Timing Strongly Impacts H2—Air Mixing in a Direct-Injection Hydrogen Engine
- Demonstrated 2007 Engine Efficiency Milestone of 42% Peak Brake Thermal Efficiency
- Kinetic Mechanism for Diesel Lean NOx Trap Regeneration
- Studies of Lean NOx Trap Aftertreatment Contribute to Diesel Vehicle Commercialization

Electrical & Electronics

- Floating Loop Inverter
- Sintered Die Attachment
- Thermal Systems Analysis for Advanced Vehicle Power Electronics
- High-Temperature DC Bus Capacitors

Electrochemical Energy Storage

- Next-Generation Lithium-Ion Cell Pilot Production Line Completion
- Calendar/Cell Performance Improvements
- Performance Improvements of Lithium-Ion Cells with new Li4Ti5O12 Anodes
- Novel High-Capacity Tin-Carbon Composite Anode Synthesized Using a Microwave Technique
- Battery-Life Prediction Model and Software
- Stabilizing Interfaces with Electrolyte Additives
- More Stable Lithium-Ion Layered Cathode Materials

Fuel Cells

- Identification of Water Transport-Related Failure Modes in Gas Diffusion Media
- Multi-Block Copolymers Show Potential for Low-Cost, High-Temperature Membranes
- Microstructural Characterization of PEM Fuel Cell Membrane-Electrode Assemblies (MEAs)

Onboard Hydrogen Storage

- Theory Guiding Experimental Efforts: The Story of Calcium Borohydride
- Chemical Hydride: Improved Hydrogen Release from Aminoborane with Additives
- Hydrogen Storage Sodium Borohydride Go/No-Go Decision
- Aerogels Improve Performance of Complex Hydrides
- Systems-Level Analysis of Different Hydrogen Storage Options
- Room-Temperature Hydrogen Storage in Spillover Materials

Materials

- Development of a Tool to Quantify the Severity of Bond-Line Read-Through
- Recycling End-of-Life Vehicles of the Future
- Lignin-Based Precursors for Lower-Cost Carbon Fibers
- Mass Compounding
- High-Integrity Magnesium Automotive Castings

Vehicle Systems Engineering and Analysis
- Hybrid Electric Vehicle (HEV) Fuel Economy Over a Wide Range of Battery Temperatures
- Energy Storage System Requirements for PHEVs

Fuel Pathway Integration
- Well-to-Wheels and Resource Analysis

Hydrogen Delivery
- Carriers for Hydrogen Delivery
- H2A Hydrogen Delivery Models

Hydrogen Production
- Distributed Hydrogen Production from Natural Gas through Advanced Reforming
- Distributed Hydrogen Production from Bio-Derived Liquids through Aqueous Phase Reforming

Codes & Standards
- Hydrogen Safety Best Practices Manual
- Hydrogen Fuel Quality—PEMFC Road Vehicles
- Hydrogen Fueling Station Permitting Compendium

Other
- DOE Hydrogen Learning Demonstration

2008

Advanced Combustion & Emissions Control
- Hydrogen Engine Achieves 45% Efficiency
- A Detailed Picture of Exhaust Gas Recirculation Effects on HCCI Operation Developed
- A Predictive Model Developed for Spark-Assisted HCCI Combustion
- Understanding Lean NOx Trap (LNT) Sulfur Tolerance

Electrical & Electronics
- Direct Back-Side Cooling of Power Electronics
- High-Temperature SOI Gate Driver
- Advanced DC to DC Converter
- High-Temperature Polymer DC Bus Capacitors

Electrochemical Energy Storage
- NCA-Based Lithium-Ion Battery Packs Delivered
- Airless Spray Deposited Ceramic Separator
- Life and Safety Improvements of Lithium-Ion Polymer Battery
- A Lithium-Ion Battery Using Stable Nano-Lithium Iron-Phosphate Cathode Development of a Lithium-Ion Battery for Plug-In Hybrids with Life and Safety Improvements

Fuel Cells
- New Ionomer Achieves Low-Temperature Conductivity Target
- Exceeded 7,300 Hours Durability with MEA Under Load Cycling
- Improved Fuel Cell Cathode Electrocatalysis: Pt Monolayer on Core-Shell Nanoparticle
- Demonstrated High Conductivity at Low RH with Two Polymer Systems Using Rigid Rod Architecture
- A Membrane with More Than Twice the Conductivity of Nafion and Reduced In-Plane Swelling
- Impurity Migration in Fuel Cells
- Improved Methods for Imaging Water in Operating Fuel Cells
- Microstructural Characterization of PEM Fuel Cell Membrane-Electrode Assemblies

Onboard Hydrogen Storage
- Systems Analysis of Hydrogen Storage Options
- Identifying Areas for Storage System Cost Reduction
- $MB_{12}H_{12}$ Effects on Borohydride Reversibility
- Chemical Hydrogen Storage Materials Down Select
- Alane Regeneration Via Adduct
- Metal Hydrides Materials Down Selected
- Improved Ammonia Borane Regeneration Efficiencies and Yields
- Higher Hydrogen Binding Energy on Adsorbents
- Improved Hydride Kinetics via Carbon Aerogel Scaffolds

Materials
- Development of Textile-Based Carbon-Fiber Precursor
- Lightweight (Rear) Chassis Structures
- Magnesium Front-End Design and Development
- Engineering Property Tools for Tailored Polymer Composite Structures
- Development of a Structural Composites Underbody

Vehicle Systems Engineering and Analysis
- Fuel-Efficiency Improvements for Hydrogen Internal Combustion Engine-Powered Vehicles
- Renewable Fuel Vehicle Modeling and Analysis
- Cold-Temperature Performance of a PHEV Battery

Fuel Pathway Integration
- Infrastructure Materials Availability Analysis

- Resource Availability Analysis
- Well-to-Wheels Analysis Refinement

Hydrogen Delivery
- Inexpensive Delivery of Cold Hydrogen in Glass Fiber Composite Pressure Vessels
- Fiber-Reinforced Polymer Materials for Hydrogen Pipelines

Hydrogen Production

- Hydrogen Production from Sunlight-Powered Biological Water Splitting
- Hydrogen Production from Water Electrolysis

Codes & Standards
- Hydrogen Fuel Station Permitting Compendium
- Hydrogen Component Standards
- Fuel Quality Round-Robin Testing
- Technical Basis Established for NFPA 55 Separation Distances

2009

Advanced Combustion & Emissions Control
- High Efficiency Clean Combustion (HECC) Shows Potential to Reduce Fuel Penalty for Diesel Particulate Control by 25%
- Ethanol-85 Engine Achieves Greater Torque and Similar Fuel Economy Compared with a Larger Diesel Engine
- Simulations Provide New Insight into the Potential Benefits and Limitations of Compression Ignition Engines in Hybrid Vehicles
- Understanding of Lean NOx Trap Chemistry Enables Improved Onboard Diagnostics
- Fuel Injector Motion Linked to Structure of Spray
- Boosted Gasoline HCCI Achieves 2x Load Increase over Previous Best

Electrical & Electronics
- Current Source Inverter for HEVs and FCVs
- Active Filter Approach to Reducing the Traction Inverter Capacitor
- Wide Bandgap Characterization
- Characterization of Thermal Interface Material Performance
- Rapid Parametric Modeling Process for Thermal Management and Electronics Packaging Technologies
- High-Efficiency Soft-Switching Inverter

Electrochemical Energy Storage
- Advanced Separators for HEV/PHEV Applications
- New High-Voltage High-Capacity Composite-Structure Cathode Is Being Commercialized
- Six Amp-Hour HEV Prismatic Cell
- 19 Amp-Hour Prismatic Cell
- Life Improvements for PHEV Lithium-Ion Battery
- Development of a Lithium-Ion Cell for Plug-In Hybrid Vehicles with Improved Life and Safety Characteristics
- First-Principles Calculation Leads to Extremely High Rate $LiFePO_4$
- USABC Lower-Energy, Energy-Storage Systems Requirements for Power Assist HEVs
- Smart Battery Status Monitor
- Technology Life Verification Testing
- A Molecular Dynamics Model of Charge Transfer across a Solid-Liquid Interface

Fuel Cells
- Membrane Conductivity Interim Target Met with Functional Composite System
- Dimensionally Stable Membranes
- NanoCapillary Network Proton Conducting Membranes for High-Temperature Hydrogen/Air Fuel Cells
- Platinum Loading Targets Achieved with NSTF-Containing MEA
- Eightfold Improvement in Activity of Non-Precious Metal Catalyst
- New Water Transport and GDL Characterization Techniques Developed
- Development of Angström-Scale Analysis for Composition and Structure of Catalyst Particles
- Effects of Fuel and Air Impurities on PEM Fuel Cell Performance
- Mass Production Cost Estimation for H2 Fuel Cell Systems for Automotive Applications 32

Materials
- Development of a Lightweight Composite Seat
- Lightweight Magnesium-Intensive Engine
- Full-Scale Recycling Validation Plant for Recovering Polymers Starts Operation
- Future Generation Passenger Compartment—Validation
- Infrared Inspection of Resistance Spot Welds Non-Destructive Inspection
- Low-Cost Titanium Materials for Suspension Applications

Vehicle Systems Analysis
- PHEV and HEV Fleet Testing
- Cost-Effective Vehicle Electrification
- Plug-In Hybrid Engine Thermal State and Resulting Efficiency

Fuel Pathway Integration
- Well-to-Wheels Analysis
- Analysis of Hydrogen Integration in Non-Transportation Sectors
- Geologic Hydrogen Storage Issues

Hydrogen Delivery
- H2A Hydrogen Delivery Scenario Analysis Model

Hydrogen Production
- Maximizing Sunlight Utilization Efficiency and Productivity in Photosynthesis
- Hydrogen Production in Programmatic Advances
- Scale-Up of Hydrogen Transport Membranes for IGCC and FutureGen Plants

Crosscutting Technologies

Codes & Standards
- Separation Distance—Code Unification
- NFPA 2 Hydrogen Technologies Code

Onboard Hydrogen Storage
- Alane Regenerated at Low Pressure
- Low-Cost Pathway to Production and Regeneration of Ammonia Borane
- Characterization of Hydrogen Adsorption by NMR
- Chemical Hydrogen Storage Center of Excellence Progress in Amino Borohydrides
- Best Practices for Characterizing Hydrogen Storage Properties of Materials
- Neutron Characterization of Hydrogen Storage Materials
- Development of Metal Hydrides for Reversible Onboard Hydrogen Storage
- Robust Computational Methods to Predict Metal Hydrides for Reversible Hydrogen Storage
- Hydrogen Storage Media Through Nanostructured Polymeric Materials
- Fundamental Calculations to Advance Chemical Hydrogen Storage
- Improved Hydrogen Release from Amineborane with Additives

2010

Advanced Combustion & Emissions Control
- Dual-Fuel (Gasoline + Diesel) RCCI Offers High Efficiency and Low Emissions in Engines
- Turbocharger Technology to Deliver Better Performance and Reduced Fuel Consumption
- Late Intake Valve Closing Improves Trade-Off Between Diesel-Engine Smoke and NOx Emissions
- Modeling of Lean NOx Trap Chemistry
- Neutron Radiography Non-Destructive Image of EGR Cooler and DPF Buildups
- Accurate Detailed Chemical Kinetic Surrogate Model for Gasoline
- Sources of Inefficiency Identified in Light-Duty, Low-Temperature Diesel Combustion
- 2010 FreedomCAR Engine Milestone for 45% Brake Thermal Efficiency Met

Electrical & Electronics
- Novel Power Semiconductor Packaging Reduces Die Area, Volume, Weight, and Cost
- Direct Water-Cooled Power-Electronics Packaging Concept Reduces Size and Weight
- Segmented Drive Inverter Topology Enables Smaller and Lower-Cost DC Bus Capacitor
- Effect of Enhanced Surfaces on Single and Two-Phase Heat Transfer is Quantified
- Reduced-Cost Permanent Magnets for High-Speed Interior Permanent Magnet Motors
- Compact Bidirectional Charger for Plug-In Vehicles

Electrochemical Energy Storage
- Novel Battery Thermal Management System Developed
- Nanophosphate Battery Technology for HEVs
- Advanced PHEV Cathode Material Developed
- Design, Build, and Testing of NMC-Prismatic Format Cell and System
- High-Temperature Melt Integrity Separator and Test Suite Developed
- 19 Amp-Hour Prismatic Cell Delivered
- Advanced Separators for HEV/PHEVs
- Surface-Coated, High-Energy Battery Cathode Demonstrates Improved Cycling and Capacity

- Pre-Lithiating Graphite, Silicon, and Tin Anodes Reduces First Cycle Irreversible-Capacity-Loss
- Synthesis of a High-Voltage Cathode Material with Improved Stability
- Improved Performance of High-Energy Battery Anodes
- New Electrolyte Additive for Lithium-Ion and Lithium-Air Batteries
- Improved Thermal Performance Using a Coated Cathode Material
- In Situ NMR Observation of the Formation of Metallic Lithium Microstructures
- Development of High-Rate Anode Using Graphene Building Blocks

Fuel Cells
- Automotive Fuel Cell System Cost Modeling Shows Progress Toward Cost Targets
- New Ultra-Low Platinum Loading Fuel Cell Catalyst has 7X Improved Activity and High Stability
- Systems Analysis Shows Significant Cost Savings Possible by Easing Peak-Power Efficiency Target
- New Composite Membranes Show Improved Durability without Compromising Performance
- Improved Resolution for Imaging Water in Operating Fuel Cells Aids Developers
- Improved Performance and Stability of Non-Precious Metal Cathode Catalysts
- Hollow Platinum Nanoparticles Developed for Stable, High-Activity Fuel Cell Catalysts
- Fuel Cells Can Recover from Ammonia Contamination in Both Fuel and Air Streams
- Better Water Management Improves Transient Performance of Low-Platinum-Loading Catalysts Fuel Cell Membranes Show Promise to Meet High Temperature Operation Targets
- Simultaneous Water Visualization and Resistance Measurements Can Be Used to Develop Fuel Cell Shutdown Strategy
- New Fuel Cell Membranes Show Promise to Meet High-Temperature Operation Targets

Materials
- Advanced High-Strength Steel Matches Aluminum Performance and Lightweight with Reduced Cost
- Minimum-Weight SMC Assemblies Free from Bond-Line Read-Through
- Reliability Tools for Resonance Inspection
- Development of High-Volume Warm Forming of Low-Cost Magnesium Sheet
- Friction Stir and Ultrasonic Solid-State Welding Enable Joining of Magnesium to Steel
- Friction Stir-Spot Welding of Advanced High-Strength Steel
- Stabilization Time of Lignin Precursor Fiber Reduced from Days to Minutes

Vehicle Systems Analysis
- Accelerating Advanced Technology Introduction through Plug-and-Play Architecture Modeling
- Accelerating Control Development Using Hardware in a Virtual System Environment
- Grid-Connected Electric Drive Vehicle and Charging Studies Demonstrate Petroleum Reductions
- A Standard Practice for Testing PHEVs Developed and Balloted
- European Hybrid Vehicle Benchmarked for Fuel Consumption Benefits and Emissions Trade-Offs
- PHEV Bus Reduces Fuel Consumption Up to 50%
- Thermal Preconditioning Restores Range Up to 19%

Fuel Pathway Integration
- Hydrogen Threshold Cost Updated
- Hydrogen Costs from Fuel Cell Combined Heat and Power
- Infrastructure Costs for Coal-Based Hydrogen Production

Hydrogen Delivery
- Development of a Centrifugal Hydrogen Pipeline Gas Compressor

Hydrogen Production
- Hydrogen Selective Membranes as Reactors/Separators for Distributed Hydrogen Production
- New Benchmark Efficiency for Photoelectrochemical Water-Splitting Devices

Codes & Standards
- SAE J2579 TIR and GTR Coordination
- SAE J2601 Hydrogen Fueling Protocol

Onboard Hydrogen Storage
- Cryo-Compressed Tank Exceed 2015 Weight and Volume Targets
- 12 Weight Percent Hydrogen Reversibility Demonstrated for Magnesium Borohydride

- "Optimized" Sorbents Designed and Synthesized for Hydrogen Storage
- New Class of Lightweight Metal Hydrides Show Promise for Hydrogen Storage
- New Techniques for Safe Hydride Containment
- Performance and Cost Analyses Accelerate Development of Hydrogen Storage Technologies

Grid Interaction

- Universal Vehicle Energy-Use Communications Technology Developed
- Compact Low-Cost Revenue-Grade Sub-Meter Demonstrated

2011

Advanced Combustion and Emission Control

- High-Efficiency and Full-Load Range Low-Temperature Combustion—Using Gasoline in a Diesel Engine
- Dual-Fuel Combustion Enables Efficiency Improvement as High as 5% over Diesel Combustion
- Hydrogen Engine Exceeds DOE Efficiency Targets
- New Spray Model Accounts for Nozzle-Flow Effects
- Engine Combustion Network—A Collaboration on Engine Fuel Spray Research
- Order-of-Magnitude Speedup of High-Fidelity Combustion Chemistry Simulation
- HCCI Achieves 48% Indicated Thermal Efficiency
- Optical Engine Research Rapidly Reveals How High-Efficiency RCCI Combustion Controls Burning Rates
- New Understanding of EGR Cooler Fouling Mechanisms Provides Information for Improving Cooler Designs
- Diagnostic Technology for Real-Time Measurement of Fuel in Oil Transferred to Industry
- Spark-Assisted, High-Dilution, Stoichiometric HCCI with Ethanol-85—Potential Path to Higher Efficiency
- 2011 Super-Duty Diesel Truck with NOx Aftertreatment
- Turbocharger Design Improves Engine Efficiency

Electrical and Electronics

- Advanced Integrated Electric-Traction System Meets 2010 Technical Targets
- Computational Prediction and Discovery of New Magnet Materials
- Smaller, Highly Efficient Planar-Bonded Power-Electronics Module
- Advances in Current-Source Technology for Component Minimization and Integration
- Design of Lightweight, Low-Cost, High-Thermal Performance Inverter-Scale Heat Exchanger

Electrochemical Energy Storage

- New Electrode Designs for Ultrahigh Energy Density
- High-Voltage, Single-Ion Conducting Electrolytes
- LiF-Anion Binding Agent Electrolytes for Enhanced Abuse
- Fabrication of High-Energy Si Anodes Suitable for Large Format Lithium-Ion Batteries
- High-Energy Composite Cathode Materials
- Development of $LiCoPO_4$ Cathode and High-Voltage Electrolyte
- Improved Performance of Doped High-Voltage Spinel Cathodes
- Materials Search Engine with Lithium Electrode Explorer
- Improving the Power of High-Energy, Lithium-Rich Cathodes
- In Situ X-Ray Diffraction Development and Diagnostics of Cathode Materials
- Determination of Aging Path Dependence in Batteries
- A New Multi-Scale Model Framework to Help Industry Design Better Lithium-Ion Batteries
- 3M Silicon-Based Anode Exceeds Targets
- Low-Energy Energy-Storage System from Maxwell Technologies
- High-Energy Density Electrode Demonstrated for Electric Vehicle Batteries
- PHEV Cell Projected to Meet USABC Calendar Life Goal
- JCI Develops New Prismatic Cell and System Technology
- Multifunctional Inorganic-Filled Separator for Large-Format Lithium-Ion Batteries

Fuel Cells

- Novel Characterization and Models Advance Understanding of Fuel Cell Performance Limitations
- Fuel Cell System Cost Projected at $49/kW
- "Best in Class" Membrane Electrode Assembly Meets DOE Component Durability Requirements
- 3M High-Temperature Membrane Meets Durability Targets
- Multi-Metallic Nanoparticles with Tailored Composition Reduce Cost, Improve Durability of Fuel Cell Catalyst
- Novel Techniques for Measurement of Key Fuel Cell Transport Parameters
- Two-Dimensional Dynamic Model Developed for Fuel Cell Freeze Start Operation

- Novel Techniques Provide Insight into Fuel Cell Component Degradation
- High Spatial Resolution of Neutron Imaging for Water Management Analysis in Fuel Cells

Materials
- Development of the Ablation Casting Process for High-Volume Production
- Friction Stir-Spot Welding of Advanced High-Strength Steels II
- Lower-Cost Carbon Fiber from Textile-Based Precursors
- Enhanced Formability of Aluminum at Room Temperature Through Pulse-Pressure Forming
- Ultrafine-Grain Magnesium Foil and Sheet by Large-Strain Extrusion Machining
- Direct Compounding of Structural Engineering Composite Lightweight Sealed Steel Fuel Tanks for Advanced Hybrid Electric Vehicles
- Reliability Tools for Resonance Inspection

Vehicle Systems Analysis
- Thermal Research to Improve Electric Vehicles
- Idle Stop Vehicle Fuel Consumption Benefits Based on a Comprehensive Dynamometer Study
- Electric Drive Vehicle Advanced Battery and Component Test Bed

Grid Interaction
- National Permit Template Can Help Make Homes Electric Vehicle-Ready
- Auto-REM Module Developed for Effective Vehicle-Grid Communication
- Electric Vehicle Measurement Device Developed for End-Use Metering
- Vehicle-Grid Interoperability (SAE J2931) Demo

Codes and Standards
- Science-Based, Data-Driven International Standard for Fuel Quality Published

Hydrogen Storage
- Selection of Ammonia Borane Hydrogen Storage System Concept
- Reduced Size Improves Performance of Hydrogen Storage Materials
- Alane: Improved Hydrogen Release and Regeneration
- Development of Integrated System Model for the Evaluation of Hydrogen Storage Technologies

Fuel Pathway Integration
- Hydrogen Threshold Cost Apportionment
- Infrastructure Costs for Biomass-Based Hydrogen Production
- Hydrogen Fuel Station Cost Analysis for Early Transition

Hydrogen Delivery
- Electrochemical Hydrogen Compressor Development

Hydrogen Production
- Reforming of Bio-Oil for Production of Hydrogen
- Significant Cost Reductions in Capital Costs of Electrolyzer Stacks

2012

Advanced Combustion and Emission Control
- Multi-Mode RCCI Engine Map Used to Demonstrate Potential Improvements in Modeled Fuel Economy
- Newly Developed Conceptual Model Describes In-Cylinder Processes of Low-Temperature Combustion
- Gasoline Compression Ignition Demonstrated over a Significant Light-Duty Engine Operating Range
- Surrogate Fuels Match Properties of Real-World Gasoline and Diesel Fuels
- Gasoline with 20% Ethanol Extends High-Load Limit of HCCI to 20 B $IMEP_g$
- In-Cylinder Mixture Formation Quantified for Low-Temperature, Light-Duty Diesel Combustion
- New Aging Protocol Enables More Rapid Laboratory Assessment of Useful Life for Urea SCR/DOC Aftertreatment Systems
- "Passive SCR" Demonstrates Lower-Cost Emission Control to Enable Fuel-Efficient Lean Gasoline Engines
- Fuel Penalty Reduction of 50% Using Electrically Heated Diesel Particulate Filter Technology

Electrical and Electronics
- Motor Efficiency Improvements
- Improved High-Temperature Polymer Film Capacitor Fabrication
- Electric Motor Thermal Management
- New Understanding of Alnico Magnets Helps Design Improvements to Boost Properties for Drive Motors

Electrochemical Energy Storage

- High-Energy Lithium-Ion Batteries for EVs
- GenII Prismatic Cell Development
- EV Technology Assessment Program
- A High, Specific-Energy PHEV Battery Pack with a Robust Thermal System
- Scale-Up and Production of Low-Cost Nickel/Manganese/Cobalt Cathode Material
- Modeling and Understanding Lithium-Ion Battery Performance and Cost
- Computer-Aided Analysis Methods for Lithium-Ion Battery Design Developed and Deployed
- Cell Fabrication Using Advanced Battery Materials
- AutoLionTM: A Thermally Coupled Lithium-Ion Battery Model
- Investigation and Improvement of High-Voltage Cathode Material
- A New Synthesis Approach to High-Energy Manganese-Rich Cathodes
- Lithium-Ion Electrolytes with Wide Operating Temperature Ranges
- Scale-Up of Promising Overcharge Shuttle for Industry Evaluation
- High-Capacity Hollow Silicon Nanofiber Anodes
- Single Crystal Diagnostics Leads to Improved Material Performance
- Technologies for Improved Safety of Lithium-Ion Batteries
- Use of Atomic Layer Deposition Coatings to Stabilize High-Voltage, High-Energy Cathode Materials

Fuel Cells

- Model Validates Performance and Cost Projections
- Model Prediction of Performance for Low-Platinum Use
- Designing Durable Fuel Cell Catalysts
- Investigation of Micro- and Macro-Scale Transport Processes for Improved Fuel Cell Performance
- Novel Non-Platinum Group Metal Electrocatalysts for Fuel Cell Applications Synthesized

Materials

- Optimization of High-Volume Warm Forming For Lightweight Sheet Alloys
- Integrated Computational Materials Engineering of Magnesium
- Magnesium Front-End Research and Development
- Establishment of Quality Mapping for Ductility in Magnesium Casting
- Non-Rare-Earth Containing Wrought Magnesium Development
- Advanced Plasma Oxidation

Vehicle Systems and Analysis

- New Air-Conditioning Model Validated and Released
- Accelerating EV Development with New Test Standards
- Vehicle Mass: Road Load and Energy Consumption Impact
- Wireless Power Transfer: Stationary Charging

Codes and Standard

- Optimizing Materials Testing for Hydrogen Service
- Publication of Harmonized SAE J2719 Hydrogen Fuel Quality for Fuel Cell Vehicles

Onboard Hydrogen Storage

- Material Requirements for Viable Onboard Hydrogen Storage Using Metal Hydrides
- Systematic Analysis and Avoidance of Material-Based Hydrogen Storage System Failure Modes
- Best Practices Reference Document Released
- Validation of Hydrogen Storage Using Weak Chemisorption

Grid Interaction

- Enabling Technologies for Vehicle-Grid Communication

Fuel Pathway Integration

- Well-to-Wheel Analysis

Hydrogen Delivery

- Increased Tube Trailer Capacity

Hydrogen Production

- Improved Hydrogen Evolution in Recombinant Cyanobacteria
- Updates to the Hydrogen Production Analysis Model

APPENDIX D: Budget Analysis Methodology Used for this Case Study

The budget analysis for this case study was conducted by reviewing the detailed budget justification materials provided to Congress for vehicle-technology R&D spending (including activities in the DOE Vehicle Technologies Program and relevant activities in the Hydrogen and Fuel Cell programs in DOE's Office of Energy Efficiency and Renewable Energy) from FY 1993 to FY 2014. Because an appropriation can be subjected to various types of reductions—including rescissions and SBIR/STTR[54] reductions after appropriations are first made—the study looked back two years for a "final" number in any given fiscal year. For example, final FY 2003 spending levels were derived from FY 2005 budget justification materials; thus the study analyzed information from FY 1991 to FY 2012.

And again, as stated earlier, while not all of the work of the DOE Vehicle Technologies R&D programs after 1992 was wholly conducted under the umbrella of the Partnership for a New Generation of Vehicle, FreedomCAR, and U.S. DRIVE, it is fair to say that any work that was not conducted under the partnership was greatly influenced by it—since partnership activities greatly impacted DOE R&D program managers as they planned R&D programs and evaluated progress.

The study does *not* include the $2.7 billion for vehicle-technology-related activities contained in the American Recovery and Reinvestment Act of 2009, which made supplemental appropriations mainly for advanced battery manufacturing, transportation electrification, alternative fueled vehicle infrastructure, and similar deployment activities. Not only was this a very large and anomalous appropriation largely directed at deploying existing technology rather than developing new technology, but program managers were directed to spend it quickly. It was not integrated into, or informed by, the usual collaborative partnership planning process.

The study does, however, include congressional earmarks, including those that arguably contributed little to the R&D goals established by the programs. The available budget information did not consistently identify earmarks, nor did it prospectively or retrospectively value the earmarked projects' contributions to the R&D goals.

It is also important to note that DOE's categories/descriptions of activities often changed as different Appropriations Subcommittees, DOE financial officers, and program heads would require budget information to be prospectively or retrospectively presented in different formats. Also, various activities were shifted between budget table categories or even program offices from year to year. For example, the "Clean Cities" program, which funds a variety of vehicle-technology deployment programs, shifted from the Vehicle Technologies Office to the Office of Weatherization and Intergovernmental Programs in FY 2003 before returning to the Vehicle Technologies Office in FY 2007. Nevertheless, the study tracked it as a technology-deployment activity regardless of its host office. Similarly, in some years, fuel cell vehicle demonstration activities were listed in the Vehicle Technologies Program budget, while in other years, it was detailed under the Hydrogen and Fuel Cell technologies program budget. Again, it was tracked as a hydrogen and fuel cell activity regardless of host office or budget presentation listing.

Taking these shifts and changes into account, the study worked to categorize work activities within a manageable number of general categories. Exact precision in this process was not possible, as there were some subjective judgments that had to be made. For instance, if a fuel cell-related project was oriented to stationary (generally solid oxide) fuel cells, the study did not include it since it was not directly relevant to vehicle technologies. For these reasons, the budget category totals here often differ from the DOE budget tables or other analyses.

The study also converted all spending totals to FY 2005 dollars, employing Office of Management and Budget (OMB) tables and methodologies recommended by OMB for R&D spending. In doing so, this study presents the best apples-to-apples comparison available for this purpose.

With these caveats in mind, the vehicle-technology spending from fiscal year 1991 to fiscal year 2012 is categorized as such:

- Internal Combustion Engine R&D;
- Electric and Hybrid Drive, Batteries, and Power Electronics;
- Fuel Cells and Hydrogen R&D;
- Materials R&D;

- Alternative and Advanced Petroleum Fuels and Lubricants;
- Technology/Vehicle Deployment; and
- Management, Planning, Program Direction, Other Miscellaneous.

Of those seven categories, the ones most relevant to the public-private partnerships and this case study were the first four, which was thus the study's focus.

Endnotes

1 Energy Information Administration (2012) *Annual Energy Review 2011*, U.S. Department of Energy: DOE/EIA-0384(2011), September.

2 Energy Flows 2010: Lawrence Livermore National Lab based on EIA data.

3 National Petroleum News Survey, 2013.

4 U.S. Census Bureau, Statistical Abstract of the United States, 2012.

5 CAR in FreedomCAR is an acronym for Cooperative Automotive Research.

6 DRIVE is an acronym for Driving Research and Innovation for Vehicle efficiency and Energy sustainability.

7 February 10, 1970.

8 Public Law 94-413, September 17, 1976.

9 The Act defined an electric vehicle as "a vehicle which is powered by an electric motor drawing current from rechargeable storage batteries, fuel cells, or other portable sources of electrical current, and which may include a nonelectrical source of power designed to charge batteries and components thereof." The Act defined a hybrid vehicle as "a vehicle propelled by a combination of an electric motor and an internal combustion engine or other power source and components thereof."

10 Comments of President Gerald R. Ford to the House of Representatives, September 13, 1976.

11 Byrne, John; and Rich, Daniel (Ed.s) (1986) *The Politics of Energy Research and Development*.

12 *The Albuquerque Journal* (2008) "U.S. Energy Policy Lacks a Conductor," March 30.

13 The energy density (watt hours/kilogram) of a battery is a measure of how much energy a battery can hold. Energy density is very important for vehicle range in a BEV or for ultra-high-mileage in a PHEV or HEV. The power density (watts/kilogram) of a battery is an indicator of how much power a battery can deliver on demand. High-power density is needed to accelerate a BEV to highway speeds; it is less important in the case of a hybrid that can rely on its engine or fuel cell power plant for most or all of its acceleration needs.

14 National Research Council (2013) In: The Fourth Report, *Review of the Research Program of the U.S. DRIVE Partnership*, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences.

15 There are "quick charge" technologies being developed and deployed that offer 80 percent recharge rates in 20 –30 minutes.

16 Many fuel cell electric vehicles also have a storage battery for the purpose of operating the vehicle during fuel cell start-up, smoothing power flow or maximizing driving range and reducing fuel consumption through the use of regenerative braking.

17 Matthew Wald (1993) "Government Dream Car: Washington and Detroit Pool Resources to Devise a New Approach to Technology," *The New York Times*, September 30, p. D-7.

18 *Sierra* (1999) "Why Detroit's Going Green," July/August 84(4): p. 38.

19 For example, see: Sperling, Daniel (2002) "Updating Automotive Research," *Issues in Science and Technology* Spring 18(3): pp. 85-89.

20 USCAR had previously been formed in 1992 to facilitate collaborative research in pre-commercial technologies.

21 Trinkle, David S. (2009) "A Vehicle for Change: PNGV, an Expiriment in Government-Industry Cooperation," A Dissertation, The Pardee Rand Graduate School, December.

22 Adapted from: National Research Council (2001) In: The Seventh Report, *Review of the Research Program of the Partnership for a New Generation of Vehicles*, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences, Transportation Research Board.

23 Toyota has since built and opened major powertrain R&D facilities through Toyota Motor Engineering & Manufacturing North America, with major operations in Arizona, California, Kentucky, and Michigan. Interestingly, Toyota has not since sought to join USCAR.

24 The concept vehicles were as follows: The GM Precept was expected to achieve 80 MPG using a 1.3 liter 3-cylinder diesel, hybrid electric drive employing a nickel-metal hydride or lithium polymer battery and the extensive use of aluminum materials. The Ford Prodigy was expected to achieve 72 MPG using a 1.4 liter 4-cylinder diesel, hybrid electric drive employing a nickel-metal hydride battery and the extensive use of aluminum materials. The DaimlerChrysler ESX3 was expected to achieve 72 MPG using a 1.5 liter 3-cylinder diesel, hybrid electric drive employing a lithium-ion battery and the extensive use of thermoplastic materials.

25 National Research Council (2001) In: The Seventh Report, *Review of the Research Program of the Partnership for a New Generation of Vehicles*, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences, Transportation Research Board.

26 Author's conversation with Takeshi Uchiyamada at the 2004 North American (Detroit) Auto Show.

27 Sperling, Daniel (2002) "Updating Automotive Research," *Issues in Science and Technology* Spring 18(3): pp. 85-89.

28 National Research Council (2001) In: The Seventh Report, *Review of the Research Program of the Partnership for a New Generation of Vehicles*, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences, Transportation Research Board.

29 Available at: http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/introduction.pdf.

30 Freedom CAR and Fuel Partnership Plan (2006) March, p. 8.

31 National Research Council (2010) In: The Third Report, *Review of the Research Program of the FreedomCAR and Fuel Partnership*, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences.

32 Ibid., p. 3.

33 Ibid., p. 4.

34 Ibid., p. 4.

35 Ibid., p. 7.

36 Ibid., p. 9.

37 Ibid., p. 108.

38 Ibid., p. 4.

39 Ibid., pp. 66-67.

40 Ibid., p. 7.

41 The electric utilities DTE and Southern California Edison also joined in 2009.

42 U.S. DRIVE Partnership Plan (2013) March.

43 National Research Council (2013) In: The Fourth Report, *Review of the Research Program of the U.S. DRIVE Partnership*, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences, p. 4.

44 Ibid., p. 3.

45 Ibid., pp. 4-5.

46 Lux Research (2012) "Under the Hood: Mapping Automotive Innovations to Megatrends," June.

47 Examples of these studies can be found at: http://www1.eere.energy.gov/analysis/pe_plans_reports.html#vehicle.

48 Brian D. James (Primary Contact), Kevin Baum, Andrew B. Spisak, Whitney G. Colella (2012) "Mass-Production Cost Estimation for Automotive Fuel Cell Systems," 2012 Progress Report, Strategic Analysis, Inc. Contract Number: DE-EE0005236.

49 James, Brian (2012) "Fuel Cell Transportation Cost Analysis, Preliminary Results," prepared for DOE Fuel Cell Technologies Program, available at: http://www.hydrogen.energy.gov/pdfs/review12/fc018_james_2012_o.pdf. See also DOE Fuel Cell Technologies Program Record 12020, available at: http://www.hydrogen.energy.gov/pdfs/12020_fuel_cell_system_cost_2012.pdf. Values in figure are the result of a fuel cell model developed by Argonne National Laboratories and continuously updated with technology development.

50 Pacific Northwest National Laboratory (2012) "Pathways to Commercial Success: Technologies and Products Supported by the Fuel Cell Technologies Program," prepared for the U.S. Department of Energy Fuel Cell Technologies Program, September.

51 Vehicle Technologies Program: Goals, Strategies and Top Accomplishments (2010) Fact Sheet, December.

52 Data from *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2012*, EPA-420-R-13-001, March 2013.

53 Ibid., page iv.

54 Small Business Innovation Research/Small Business Technology Transfer.

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