QUADRENNIAL TECHNOLOGY REVIEW

AN ASSESSMENT OF ENERGY TECHNOLOGIES AND RESEARCH OPPORTUNITIES

Chapter 8: Advancing Clean Transportation and Vehicle Systems and Technologies
September 2015

Issues and RDD&D Opportunities

- Transportation accounts for 10% of U.S. gross domestic product and provides essential services throughout the economy and for quality of life. It also represents 70% of all U.S. petroleum use and 27% of U.S. greenhouse gas (GHG) emissions.
- Research opportunities to reduce the sector's petroleum use and GHG emissions include the following:
  - **Combustion efficiency**: Significant opportunities exist for improving internal combustion engines, which dominate today's vehicle fleet. Improving internal combustion engines requires research in simulation, sensors, controls, materials, and engine waste heat recovery, as well as new combustion strategies.
  - **Co-optimization of fuels and engines:** Current fuels constrain engine design due to knock performance. New high-performance, low-carbon fuels that are co-optimized (designed in tandem) with engines could improve both performance and efficiency.
  - **Lightweighting:** Reduced vehicle weight improves vehicle efficiency and range. Research focuses on new materials such as advanced, high-strength steel, aluminum, magnesium alloys, and carbon fiber polymer matrix composites.
  - **Plug-in electric vehicles (PEVs):** PEVs have efficient drivetrains and allow for petroleum-free and lower-carbon fueling options, but need further improvements that will require research in new battery designs and chemistries to reduce cost and recharge time while improving energy density, power electronics and motors, and system design.
  - **Fuel cell electric vehicles (FCEVs):** FCEVs can be refueled in minutes, meet a wide range of performance requirements, achieve a better than 300-mile driving range, and have zero emissions from the tailpipe, while offering large potential petroleum and GHG reductions. Key issues are fuel cell cost and durability, and on-board hydrogen storage.
  - **Other modes:** Projected activity growth in off-road transportation (e.g., air, rail, and marine) will make efficiency of these modes increasingly important.
  - **Connected and automated vehicles:** Vehicle connectivity and automation present a variety of potential energy benefits and risks. Research opportunities include supporting technologies (sensors, computation, communications, and control) as well as system research to improve energy outcomes.
  - **Transportation systems:** A systems perspective on transportation, incorporating the interactions between (for example) vehicles, infrastructure, information technology, and human behavior, will enable future investment to optimize energy use through smarter transportation systems and technologies.

8 Advancing Clean Transportation and Vehicle Systems and Technologies

8.1 Introduction

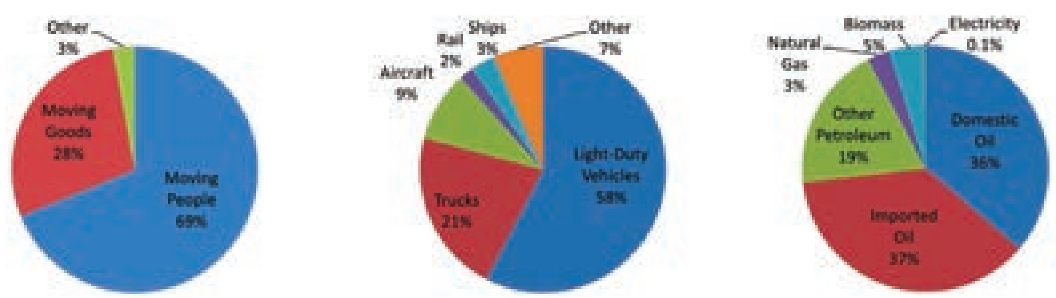
Transportation provides essential services for the economy, but also produces significant negative impacts, including economic costs and risks of dependence on oil, environmental impacts on air quality and health, and greenhouse gas (GHG) emissions. A wide range of technologies at various stages in the research and development pipeline offer the potential to mitigate these impacts. This chapter evaluates these technologies based on their potential for impact. The technology portfolio evaluated here could, if successfully developed and deployed by the market, dramatically reduce transportation impacts.

The Problem

Transportation is a complex system composed of light-duty, medium-duty, and heavy-duty ground support, and material handling vehicles; rail; aircraft; and ships used for personal transport, movement of goods, construction, agriculture, and mining as well as associated infrastructure. Vehicle operations may include very different duty cycles, even for similar vehicles. For example, trucks are operated in short- or long-haul contexts and passenger cars for personal or various commercial uses, for many hours a day or much less. Transportation is approximately 10% of gross domestic product (GDP) and depends on significant public sector investment for development and maintenance of roads, traffic management, transit, airports, ports, and waterways. In 2007 (the latest data available), federal and local governments spent $255.1 billion dollars on transportation infrastructure—1.7% of all GDP.[1]

Overall, the United States uses 21% of the world's oil supply and produces 11% of the world's oil, but it has just 2% of the world's proven oil reserves.[2] Transportation uses 25 quadrillion British thermal units (Btu) of petroleum annually, representing 70% of all U.S. petroleum use, and 93% of energy for transportation is from petroleum, which means that any strategy to improve our economic and energy security by reducing our dependence on petroleum must include transportation. Transportation energy use by purpose, mode, and energy source is shown in Figure 8.1.

Figure 8.1 Composition of 2014 Energy Use in Transportation[3]



Transportation in the United States produces 1.8 gigatons of carbon dioxide (CO_2)-equivalent GHG emissions (27% of U.S. totals)[4] and is a significant source of criteria pollutants, particularly nitrogen oxide (NO_x), carbon monoxide, and particulate matter (PM). Emissions have fallen steadily, however, over the last four decades due to emission control requirements. Despite this progress, significant additional changes will be needed to enable a transportation system that contributes to the economy-wide reductions in GHGs called for in long-term goals.[5] Other systemic costs include loss of time due to traffic congestion, loss of life and property damage from accidents, noise, harm to habitat, and the other opportunity costs such as real estate used for parking lots rather than economically productive use or shared open space. Transportation fuel accounts for the majority of average household energy costs—nearly $4,000 per household in 2014.

Petroleum use and emissions by mode are given in Table 8.1. Transportation also represents 54% of all carbon monoxide emissions, 59% of NO_x emissions, and 23% of volatile organic compound emissions.[6]

Table 8.1 Annual Petroleum Use and Emissions by Mode (2012)[7]

Mode	Petroleum use (quads)	Emissions (million metric tonnes CO_2)
Light-duty vehicles	15.3	1,065
Medium-duty vehicles*	1.5	88
Heavy-duty vehicle	4.5	320
Off-road**	2.1	Not estimated
Rail	0.6	44
Marine	1.2	37
Aviation	2.1	145
Total	**27.3**	

* Includes buses
** Includes industrial, mining, and agricultural equipment (often counted in the industrial sector)

The Opportunity

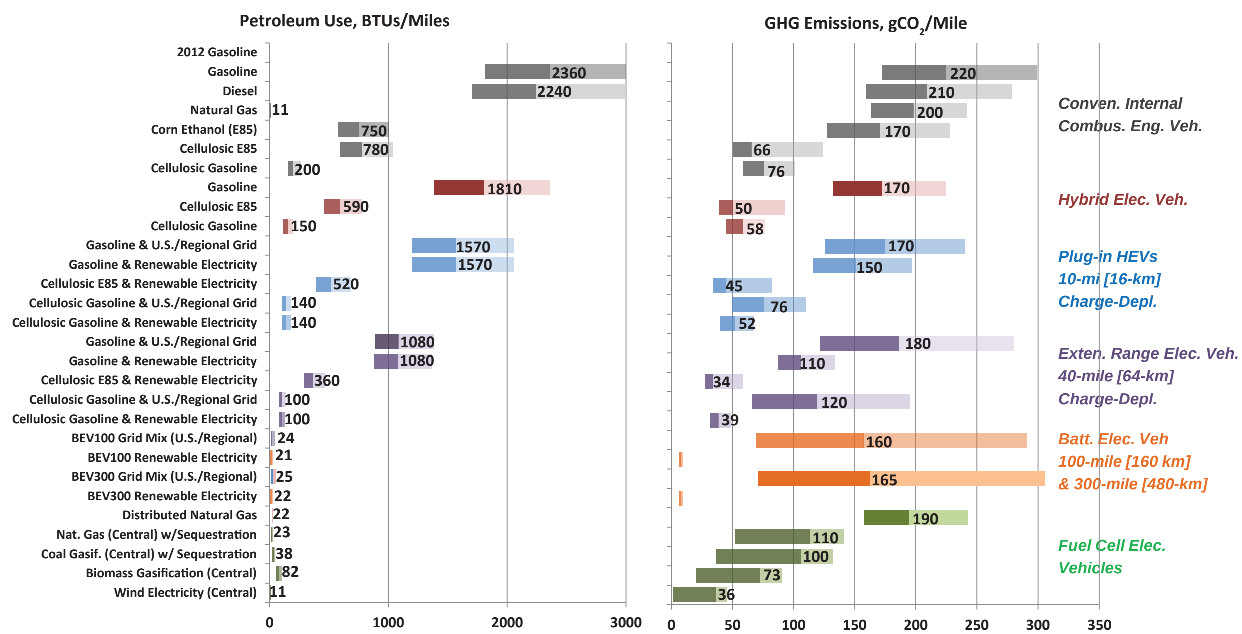
The need for a safe, fuel-efficient, operationally efficient, low-emission, and flexible transportation system can be addressed by advanced technology throughout the transportation system. The need to address energy security concerns and oil import costs has long been a national priority driving DOE transportation technology research on efficient vehicle drivetrains, including efficient combustion vehicles, plug-in electric vehicles, and fuel cell vehicles. Future personal vehicle markets—in which these efficient vehicle technologies compete—may be transformed, and perhaps reduced in size, by information technologies as well as by social and demographic trends. Under the right circumstances, information technology can offer a less costly and less energy-intensive alternative to vehicular transportation. Low or zero tailpipe emissions technologies, including plug-in electric vehicles and fuel cell vehicles, address the need for cleaner transportation to improve air quality, especially in busy metropolitan areas and ports. Technologies, including plug-in electric vehicles and fuel cell vehicles, offer the potential for greater integration between energy systems for transportation, electricity, and building, which could be pursued to improve overall efficiency and reduce emissions.

Technological change in the transportation sector can offer opportunities across a variety of dimensions, from improvements in transportation services to reduction in environmental impacts. One key environmental metric, GHG reduction, illustrates how technological change can produce the desired effect through different parts of the system, including energy intensity of vehicles, carbon intensity of fuels, and demand and system-use intensity. These strategies often correspond to different parts of the transportation system, though many technologies and systems can affect more than one factor. For example, electric drivetrain vehicles improve efficiency while simultaneously providing the opportunity to use lower-carbon fuels and other sources to generate the electricity.

There are broadly two types of metrics that are used to evaluate technology and system options: 1) viability metrics that assess how competitive a technology can be; and 2) impact metrics that estimate the benefits of successful research, demonstration, and deployment. Impact metrics include reduced GHG emissions (Figure 8.2), reduced petroleum use (Figure 8.2), improved energy efficiency, and economic benefits, as well as more systematic effects such as air quality, safety, and land use. Viability metrics include cost of driving (or total cost of ownership), vehicle performance and desirability, and infrastructure availability and compatibility. Targets for viability metrics are developed through technology roadmapping based on market needs and engineering-based analysis.

In assessing the research, development, demonstration, and deployment (RDD&D) opportunities among vehicle technologies, it is important to evaluate the costs and benefits of the different vehicle technologies using a number of analytical tools, such as techno-economic analysis, return on investment analysis (including financial, petroleum savings, and reduced GHGs), life-cycle assessments, and sustainability analysis (which encompasses diverse criteria and quantifiable evaluation metrics). These analyses are vital for identifying RDD&D options and establishing priorities for addressing near-term technology "choke points" as well as

Figure 8.2 Well-to-Wheels Petroleum Use and GHG Emissions for 2035 Mid-Size Cars



Diverse technology options exist to reduce transportation petroleum use and GHG emissions. The only options that achieve very high petroleum reductions and very low carbon emissions combine electric drive with low-carbon fuels. Contributions of vehicle cycle, fuel production, and vehicle operations are given in the Technology Assessments.[11]

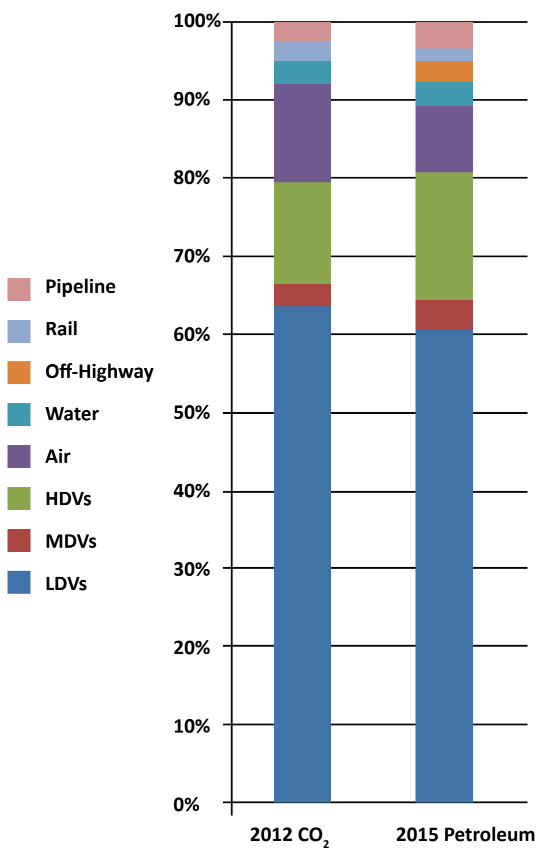
longer-term step-changing innovations. Basic science research is needed that links effectively with applied RDD&D conducted with strong industry engagement. A number of groups in industry, government, and academia have adopted similar analytical approaches for emphasizing the RDD&D needs in vehicle technology, including federal advisory groups such as the National Petroleum Council,[8] the Secretary of Energy Advisory Board,[9] and the National Academy of Sciences/National Academy of Engineering.[10]

Particular attention is given to early-stage innovations and technologies, where the social benefit may be very high and yet the incentives for companies to invest in many of these research and development (R&D) activities are lower than in later-stage technologies that are being commercialized anyway.

Overall Impact Potential

Throughout this chapter, technology system analyses include assessments of the impact of successful deployment of those technologies. In aggregate, the technologies evaluated here could have a very significant effect on the petroleum use and GHG emissions of light-duty vehicle (LDV) and heavy-duty vehicles (HDVs), as shown in Figure 8.3. The combined impacts of technologies evaluated here could have a long-term reduction

Figure 8.3 Potential Benefits of Advanced Transportation Technologies



HDV	GHG Benefit	Petroleum Benefit	Timing
Combustion	→25%	→25%	near
Systems	→20%	→20%	near

LDV	GHG Benefit	Petroleum Benefit	Timing
Combustion	→25%	→25%	near
LDV Systems	→20%	→20%	near
Advanced Materials	→20%	→20%	mid
Electrification	→80%	→99%	mid
Fuel Cell	→80%	→99%	long

Improved LDV and HDV systems have the potential for significant reductions in transportation petroleum use and GHG emissions. These figures are aggregated from the technology sections. Each estimate is calculated as the per-vehicle impacts times the total opportunity for the affected mode(s). This is intended only as a reference point and not a goal or forecast. Estimates cannot be combined directly with other impact potentials in this chapter due to double counting. (Source: DOE) in LDV GHG emissions and petroleum use of more than 80%, and a long-term reduction in HDV GHG emissions and petroleum use of approximately 50%. Impacts for other modes and from automation are a newer area of study and are not included here due to higher uncertainty. Technology analysis evaluates a wide range of possible impacts due to technology and market factors; upper values are provided here for simplicity.

The total size of the potential to reduce the negative impacts of transportation through technology has been a subject of significant study. Several studies have identified technology options for greater than 80% reduction in emissions and petroleum use. A recent National Academies study[12] found that several pathways exist to reduce petroleum use and emissions for light-duty vehicles, and a DOE study, *Transportation Energy Futures,*[13] found that there is potential—through a combination of system, vehicle, and fuel improvements—to reduce transportation petroleum use and emissions by more than 80% overall. Each study noted that a portfolio of technologies and a systems perspective is likely to be pivotal for successful transformation of the transportation system.

The Challenge

Despite the size of the opportunity to impact petroleum usage and GHG emissions, transportation poses a key challenge due to the long fleet life, complex customer needs, and the entrenched nature of petroleum fuels and combustion engine vehicles. For example, advanced technologies in light-duty vehicles have often taken fifteen years or more to be incorporated into all vehicles sold, and vehicles will often remain on the road for fifteen years or more after purchase.

Because of the high price of petroleum products relative to other energy forms, the transportation sector is relatively insensitive to a carbon pricing mechanism compared to, for example, the electricity sector, indicating that transportation may be more challenging to transition to a low-carbon future unless multiple strategies are taken. For example, based on 2014 average gasoline prices, a $38 per ton carbon price[14] would lead to only approximately a 9% increase in the direct cost of fuel.

8.1.1 Technology Approach

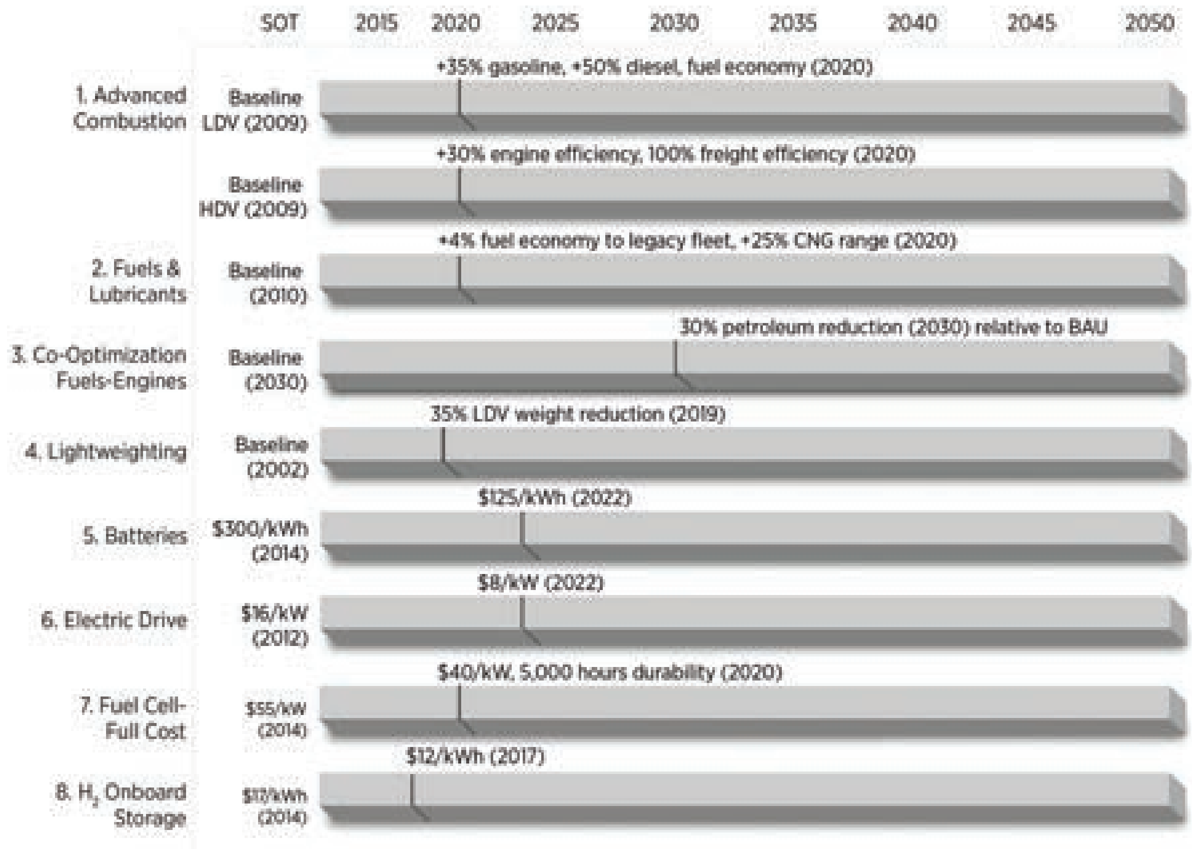
In this chapter, technologies are evaluated on the basis of their current state of technology and engineering-based projections of improvements (referred to in this chapter as "targets") that may be achieved, over a variety of time frames, through RDD&D activities. Figure 8.4 shows an overview of key transportation technologies which will be discussed in this chapter.

8.1.2 Mapping the Opportunity Space: A Chapter Guide

This chapter is primarily organized around technology opportunities as they relate to the transportation modes. Several sections of the chapter update and evaluate the technology opportunities in core research areas for DOE, while others explore new opportunities. The combustion vehicle efficiency Section 8.2 addresses light-, medium-, and heavy-duty vehicle efficiency, including engine efficiency, advanced combustion, eBoost supercharging, and reduction of parasitic losses from emissions controls. The lightweighting Section 8.3 focuses on materials that include advanced high strength steels, aluminum alloys, magnesium alloys, carbon fiber and other composites, and mixed materials including material joining. The plug-in electric vehicles Section 8.4 addresses batteries and energy storage, power electronics and motors, and system and vehicle design. The hydrogen fuel cell vehicles Section 8.5 covers automotive fuel cells, onboard hydrogen storage, system and vehicle design, and fuel cells as auxillary power units.

This chapter also addresses technology areas in transportation that are not currently a major investment area for DOE. The non-LDV modes Section 8.6 includes the efficiency potential in aircraft, marine, pipeline, rail, and off-road. The vehicle automation Section 8.7 examines the potential energy impacts of connected and automated vehicles, sensor development, infrastructure technologies, and automation outside the LDV sector.

Figure 8.4 Overview of Key Transportation Technologies and Performance Targets Based on DOE Assessment of Current RDD&D Activities. Key research areas for each technology are listed in the lower box and are discussed in the main text.



1 Low-temperature combustion strategies to achieve higher engine efficiencies; more efficient, lower-cost approaches for reducing NOx, HC, and PM in low-temperature exhaust; system-level technologies to improve vehicle fuel economy through a combination of combustion strategies, emission control, fuel injection, air handling, waste heat recovery, and control systems; advanced materials to address limitations for advanced combustion regimes and engines

2 Alternative and renewable fuels; unique, non-conventional fuel properties to improve efficiency; lubricant technologies that can reduce friction losses in new and legacy vehicles

3 High-performance, low carbon fuels for high-efficiency engines; integration into production, distribution, and dispensing infrastructure

4 All vehicle systems (body, chassis, powertrain, closures, tires, bumpers) using advanced high-strength steels, aluminum and magnesium alloys, carbon fiber composites, and mixed material systems

5 High-voltage, high-capacity cathodes; advanced metal alloy and composite anodes; electrolytes; separators; surface films; cell fabrication, pack integration

6 Cost, performance, reliability, efficiency, packaging, weight, manufacturing of electric motors and power electronics, wide bandgap semiconductors, high-temp passive devices, interfaces, interconnects, laminations, windings, packaging, capacitors, magnetic materials, reduced rare earth materials

7 Lower-cost, more durable, non-platinum group metal catalysts and membrane electrode assemblies

8 Lower-cost, spatially/volumetrically efficient storage

The chapter concludes with a discussion of transportation system effects (see Section 8.8). This perspective can be more challenging to use when evaluating sector opportunities, but is potentially very useful for long-term R&D planning and is an emerging research need.

8.2 Vehicle Efficiency and Combustion Technologies

Improving fuel economy with advanced combustion engines and more energy efficient vehicle systems offers a significant potential to reduce the overall fuel consumption of the vehicle fleet. Table 8.2 outlines the estimated impacts from the technologies in this section if successfully deployed fleet wide.[15]

Table 8.2 Combustion and Vehicle Efficiency Impact Summary (DOE calculations)

Technology system	R&D time frame	Per vehicle impacts		Long-term impact potential	
		GHG reduction	Petroleum reduction	Annual GHG reduction	Petroleum reduction
LDV combustion	To 2020	Up to 25%	Up to 25%	266 MMT	4.3 quads
LDV systems	To 2020	Up to 20%	Up to 20%	213 MMT	3.4 quads
HDV combustion	To 2020	Up to 25%	Up to 25%	80 MMT	1.2 quads
HDV systems	To 2020	Up to 20%	Up to 20%	64 MMT	0.9 quads

8.2.1 Internal Combustion Engines

Increasing the efficiency of internal combustion engines (ICEs) is one of the most promising and cost-effective approaches to dramatically improving the fuel economy of the on-road vehicle fleet in the near to mid term. Currently, ICEs power more than 99% of the vehicle fleet and provide motive service to more than 240 million on-road passenger vehicles, and for the foreseeable future, most vehicles will still be ICE-powered. The recently revised Corporate Average Fuel Economy (CAFE) standards[16] and the upcoming more stringent emissions regulations (e.g., Tier 3 Vehicle Emission and Fuel Standards Program,[17] Low Emission Vehicle [LEV-III] Program[18]) are expected to accelerate deployment of engine efficiency improving technologies.

Current ICEs already offer outstanding drivability and reliability, still have the potential to become substantially more efficient and have the capability to use alternative fuels. Engine efficiency improvements alone can potentially increase passenger vehicle fuel economy by 35%–50%, and commercial vehicle fuel economy by 30%–40%, both compared to the baselines shown in Figure 8.4, with accompanying carbon dioxide emissions reduction.[19] These improvements offer direct fuel cost savings to the consumer and do not require any changes to consumer driving behavior.

Accurate simulation of fundamental in-cylinder combustion/emission-formation processes and the effects of fuel composition will enable increased engine efficiency. Advances in engine technologies, sensors, and onboard computing are enabling unprecedented opportunities in high-speed engine controls for the real-world implementations of advanced high-efficiency clean combustion strategies and improved integration with emissions controls and engine waste heat recovery.

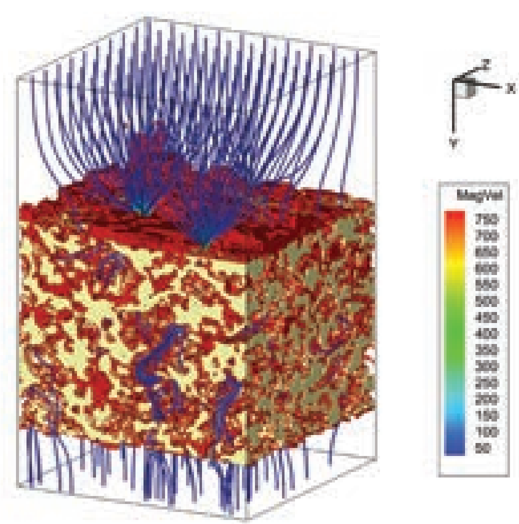
R&D addresses the following technological barriers to the development of more efficient ICEs:[20]

- Inadequate understanding of fundamentals of in-cylinder combustion/emission-formation processes and inadequate capability to accurately simulate them, as well as incomplete understanding and predictive capability for exploiting or accommodating the effects of fuel composition

- Lack of cost-effective emission control to meet standards for oxides of nitrogen and particulate matter emissions with a smaller penalty in fuel economy
- Incomplete fundamental understanding of, and insufficient practical experience with, new low-temperature catalyst materials and processes for lean-burn engine emission control
- Lack of integrated computational models that span engine and emission control processes with vehicle loads to predict vehicle fuel economy improvements
- Lack of effective engine controls to maintain robust and clean lean-burn combustion for boosted, down-sized engines
- Lack of understanding of issues such as energy demand, conversion efficiency, durability, and cost of new emission control systems for engines operating in novel combustion regimes that need to perform effectively for 150,000 miles in passenger vehicles and 435,000 miles for heavy-duty engines
- Higher cost of more efficient ICE technologies (advanced engines are expected to be more expensive than conventional gasoline engines and additional cost must be offset by benefits)

Research and development focuses on increasing the efficiency beyond current state-of-the-art engines and reducing engine-out emissions of NO_x and PM to near-zero levels. Research is being conducted on three major combustion strategies that have the potential to increase fuel economy in the near to mid term:[21] a) low-temperature combustion, including homogeneous charge compression ignition, pre-mixed charge compression ignition, and reactivity controlled compression ignition; b) lean-burn (or dilute) gasoline combustion; and c) clean-diesel combustion. In parallel, research can increase emission control system efficiency and durability to comply with emissions regulations at an acceptable cost and with reduced dependence on precious metals. Due to the low exhaust temperatures (150°C) of lean-burn engine technologies, emissions of NO_x and PM are a significant challenge. Modeling and simulation of air flow through a catalyzed soot filter (Figure 8.5) provides understanding of the placement of the catalyst on the substrate to maximize soot removal and minimize back pressure increase.

Figure 8.5 Catalyzed Particulate Filter Air Flow Modeling[22]



A critical issue for future R&D will be achieving the maximum theoretical ICE fuel conversion efficiency of about 60%, which is considerably higher than the mid-40% peak values seen today.[24] High irreversibility in traditional premixed or diffusion flames limits achievable efficiencies. Other contributing factors are heat losses during combustion/expansion, structural limits that constrain peak cylinder pressures, untapped exhaust energy, and mechanical friction. R&D opportunities include operating the engine near peak efficiency over real-world driving cycles. For spark ignition engines, this means reducing the throttling losses with technologies such as lean-burn, high-dilution, and variable compression ratio. Exhaust losses can be reduced with compound compression and expansion cycles made possible by variable valve timing, use of turbine expanders, and regenerative heat recovery. R&D can enable engine hardware changes needed to implement advanced combustion strategies, including variable fuel injection geometries, turbo- and super-charging to produce very high manifold pressures, compound compression and expansion cycles, and improved sensors and control methods. Larger reductions in combustion irreversibilities may be possible through approaches that are a substantial departure from today's processes.[25]

Advancing engine technologies to improve automobile fuel economy will require industry to accelerate its product development cycles even as it explores innovative designs. Design processes that over-rely on "build and test" prototype engineering are slow. The challenge of accelerating product design and speeding up market introduction of advanced combustion engines presents a unique opportunity to marshal U.S. leadership in science-based simulation to develop new capabilities in predictive computational design, such as simulating the complex in-cylinder air flow during the intake stroke (Figure 8.6) to enhance engine performance. Predictive computational design and simulation tools will shrink engine development timescales, reduce development costs, and accelerate time to market of more efficient, emission-compliant ICEs.

Figure 8.6 Complex In-cylinder Flow During Intake Stroke in Diesel Engine[23]

8.2.2 Fuel-Vehicle Co-optimization

Significant improvements in engine efficiency and GHG emissions are possible through co-optimization of fuels and engines that are designed in tandem to enable maximum performance. Additional GHG reductions are possible through leveraging the lowest carbon pathways to create fuels with desired properties (discussed in detail in Chapter 7). Higher compression ratios in engines can allow higher maximum efficiency, but in SI engines, compression ratios are limited by the tendency of gasoline to autoignite, or "knock." Increasing the octane of liquid fuels would enable design of engines with higher compression ratios without experiencing knock. A high-octane fuel from a renewable source can have the additional benefit of reducing life-cycle GHG emissions. Currently, the only renewable high-octane fuel available at large scale is ethanol, which makes up 10% of gasoline sold by volume. Increasing this percentage of ethanol can dramatically increase the octane

8

Table 8.3 Fuel-Vehicle Co-optimization Impact Summary (DOE calculations)

Technology system	R&D time frame	Per vehicle impacts		Long-term impact potential	
		GHG reduction	Petroleum reduction	Annual GHG reduction	Petroleum reduction
LDV combustion	2025–2030	9%–14%	Up to 30%	96–149 MMT	5.2 quads

rating of the finished gasoline/ethanol fuel blend, with most of the benefit being realized around 25%–40% ethanol by volume. Other renewable components (e.g., bio-derived isobutanol) also have high octane ratings. Higher-octane fuel would enable downsizing, downspeeding, and charge air boosting of the engine to improve the fuel economy of vehicles. Understanding what additional physical fuel properties, such as heat of vaporization, impact engine performance and how fuel with desirable properties can be produced using the lowest-carbon pathways is a key area requiring research.

Similarly, fuel properties optimal for advanced compression ignition engines (i.e., diesel engines) and advanced combustion regime engines (e.g., low temperature combustion) will be sought via renewable routes. Advanced combustion regime engines present a particular challenge because they are less well understood than conventional spark ignition and compression ignition engines. Much of the data space, including determination of desirable properties for fuels, remains to be populated. Many versions of advanced combustion exist and each has fuel property requirements associated with it that do not always match those for other versions (or current fuel specifications). As advanced combustion engines come into the market over the next few decades, we have a unique opportunity to design the performance specifications of commercially available fuels for the future to match the appetite of whatever version of advanced combustion regime engine emerges as dominant in the market.

The following technological barriers to the co-development of fuels and engines require R&D:

- A high volume of candidate fuel and an expensive and cumbersome engine-based test are currently required to compare candidate fuels to a baseline.
- The decades-old octane tests (Reasearch Octane Number and Motor Octane Number) were designed to detect auto-ignition for petroleum-derived fuels. As bio-derived feedstocks diversify the blending streams for gasoline fuels, some of the knock-resistant fuel properties are not adequately measured (such as heat of vaporization). Moving forward, it is essential to ensure that fuel standards tests measure all of the relevant fuel properties under relevant engine conditions for current and evolving combustion regimes.
- There is a lack of information on current biochemical and thermochemical routes for biofuels, as well as a need to develop a library of pathways and proposed end products, and how these relate to and can be co-optimized with engine performance.
- There is no database of fuel properties for candidate low-carbon fuels and biofuels.

Because end-to-end, market-driven solutions are required to bring any new fuel to market, R&D should consider production, distribution, and dispensing of fuels into the retail market including required technology and infrastructure compatibility, topics that are discussed in detail in Chapter 7.

8.2.3 Efficient Light-Duty Vehicle Systems

A system engineering approach to more conventional powertrains can provide potential fuel savings beyond what is possible at the component level. Vehicle level attributes, accessory load management, powertrain systems optimizations, and driver feedback are areas that present opportunities to improve the system efficiency of the light-duty vehicle fleet.

Vehicle mass, aerodynamics, and rolling resistance define the energy required to move a vehicle on a given speed profile. Light weighting while maintaining crashworthiness is addressed through materials research detailed in Section 8.3. Tire technology has to balance dynamic requirements such as braking and lateral grip and provide low rolling resistance of tires to reduce the powertrain losses. Research to quantify the tires losses impact on the overall powertrain efficiency across different operating conditions (temperatures and pressures) can lead to opportunities to improve the overall powertrain efficiency. Gearing losses in the vehicle driveline (i.e., transmission, differential, constant-velocity joints, bearings) can be mitigated through research in tribology on lubricants and surface treatment at a range of thermal conditions. Aerodynamic considerations are especially important for highway travel. Although aerodynamics and body design for vehicles are compromises in the hands of individual manufacturers, active aerodynamics devices deserve attention. Addressing these vehicle level attributes from a vehicle system perspective can result in a reduction in energy consumption.

The majority of fuel energy is translated to vehicle motion along with engine and driveline losses, but a notable amount of energy is absorbed by accessories that enable the powertrain to operate other loads, such as pumps, fans, and controllers; or provide service to the driver such as climate control, power steering, radio, and headlights. These devices may be operated through mechanical linkages to the engine. The electrification of typical mechanical components, such as fans, power steering, and pumps enables these systems to operate in optimized conditions rather than depend on engine speed. The industry has already migrated toward accessory electrification but there are still opportunities to optimize these loads. Other opportunities include advanced lighting, higher efficiency 12V (volt) power generation, and the active management of that generation (system control research).

The largest accessory load in a vehicle is related to the climate control system for the cabin, especially the air conditioning compressor. In a light-duty vehicle, five kilowatts (kW) of mechanical power (up to 30 kW of fuel power) can be consumed by the air conditioning system for initial cooling and 1–2 kW of mechanical power for temperature maintenance. The ventilation fans can also consume considerable energy. R&D can reduce the energy needed for cooling through cabin pre-conditioning (for example, ventilation before the driver gets in the car or thermal energy storage such as phase change materials), reducing heat loads on vehicles (for example, spectrally reflective windshield and window coatings to reflect near-infrared radiation), and through focused cooling on the driver rather than the whole cabin. Although conventional vehicles use waste heat for cabin heating, laboratory testing has shown that a conventional vehicle with the heater on consumed more fuel then the same vehicle with the heater off. This shows value in further powertrain and cabin thermal management research.

The efficiency technologies discussed in Section 8.2.1 enable other systems fuel saving strategies. For example, advanced combustion systems can allow deceleration fuel cut off. Idle stop technology (also called "start-stop" technology), which shuts the engine off while the vehicle is stopped, provides another avenue to save fuel in city driving. The idle stop feature utilization rate is reduced by climate control needs and cold start powertrain requirements. Further system work could regain the start stop functionality by using phase change material to maintain cool cabin air even if the compressor is off while the engine is off. The cold start operation may also be improved through thermal heat redistribution or engine thermal insulation enabling a faster warm up period.

Vehicles with a 48V electrical system (rather than a conventional 12V system) enable new fuel saving opportunities at a relatively low system cost. A 48V electrical system enables more efficient power transfer and higher power levels, allowing expanded electrification of accessories such as air conditioning. In addition, a 48V system enhances start-stop technology through faster engine restart, and creates opportunities for further efficiency through mild hybridization (e.g., electric torque addition to powertrain, engine load leveling, and regenerative braking). While electrical systems at voltages higher than 48V could increase efficiency further, they are significantly more expensive.

A research focus that has significant potential in fuel saving is at the interface between the powertrain and the driver. The driver's driving style can influence a vehicle's fuel consumption by up to 20%.[26] Therefore, methods to encourage more efficient driving behaviors can enable large fuel savings.

Much of the research addressed in this section will also translate to applications in hybrid electric vehicles (HEV) and plug-in electric vehicles (PEV). Furthermore, a smaller subset of technologies in this section could be options to improve fuel efficiency in the current legacy fleet.

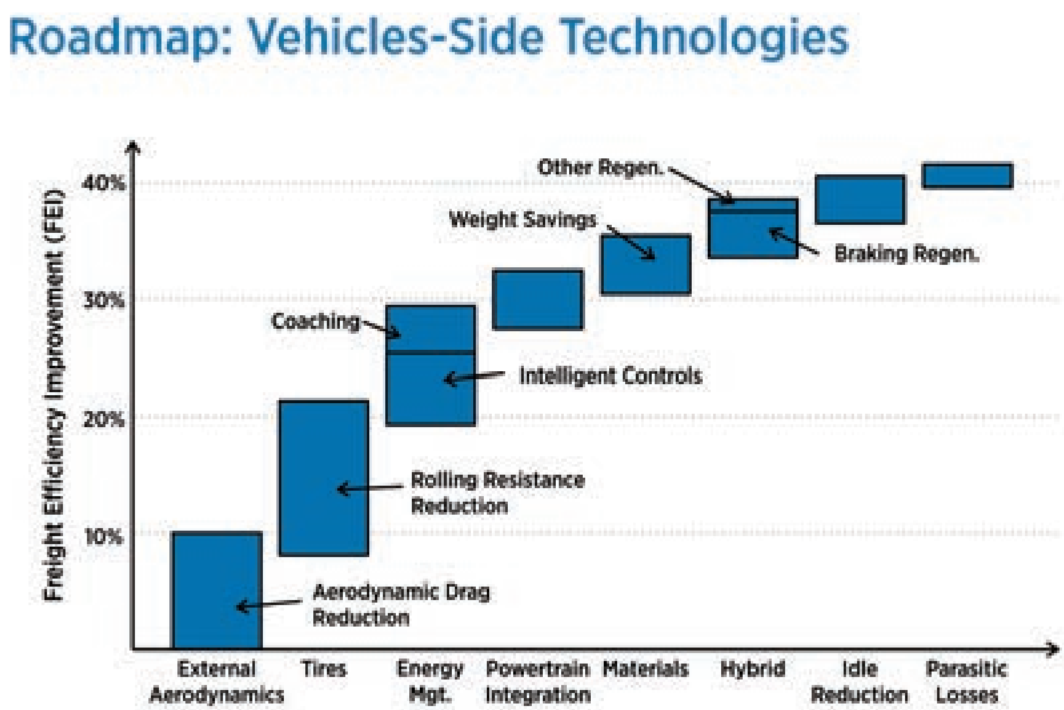
8.2.4 Heavy-Duty Vehicle Engine and Systems

Heavy-duty vehicles, which include trucks of all classes, are a mainstay for trade, commerce, and economic growth in the United States. Long-haul Class 8 trucks represent 4% of the heavy-duty vehicles on the road but consume about 18% of the fuel used by all on-road vehicles.[27] Class 8 trucks, mostly diesel-powered, move 73% of freight by value, and 49% by ton-mileage of freight travel. Improving the efficiency of heavy-duty vehicles is a particularly important strategy, where drivetrain electrification is less practical in the medium term.

The modern heavy-duty vehicle is a complex and carefully designed vehicle. Complementing recent progress in key components like engines and tires, some of the most promising future efficiency gains will be attained through system synergies (i.e., the tractor-trailer combination of over-the-road, long-haul Class 8 trucks). Technology areas relevant to heavy-duty vehicles system include aerodynamics (including advanced wind tunnel testing and air flow modeling), hybridization (advanced modeling and simulation to speed development), transportation electrification (with specific applications for heavy vehicles), thermal management (climate control and efficiency solutions), friction and wear (advanced lubricants), and data collection and modeling (including real-world operational data). The systems viewpoint extends to the operation of the vehicle as well, with technology improvements to help drivers operate the vehicle more efficiently.

Energy-efficient technologies, if cost-effective, are very often adopted quickly by commercial heavy truck fleets, where profit margins are small and fuel represents the largest operating cost. Vehicles in this sector can accumulate more than 150,000 miles per year, so small percentage improvements in fuel economy can represent large annual cost savings. R&D can serve a key role in demonstrating to industry stakeholders, fleets, and the general public that real-world fuel efficiency gains can be attained with technologies that are practical and usable in customer drive cycles. In addition, the heavy truck market is now subject to federal fuel efficiency and greenhouse gas standards, the first phase of which was completed in 2011 to take effect for the 2014 to 2018

Figure 8.7 Vehicle-level Technology Contributions to Efficiency.[28] Freight efficiency represents decreased energy use per ton-mile.



model years, and the second phase in 2015 for the 2021 and 2027 model years. These new standards are also driving considerable interest in fuel saving technologies, particularly in the long haul (Class 8) truck market. R&D can address technology needs in the development and deployment of system efficiency technologies into the heavy truck market.

Government-industry RDD&D collaborations have demonstrated 40%–75% gains in on-road freight efficiency of long-haul Class 8 tractor-trailer combination trucks as a function of various truck system-level combinations of advanced engine packages, waste heat recovery, improved lubrication, advanced transmissions, aerodynamics, predictive cruise control, lithium-ion battery auxiliary power for idle management and/or a parallel hybrid system, low rolling resistance tires, and lightweight materials. For an example, see Figure 8.7.

Due to increased availability of natural gas, significant new interest has focused on using natural gas in heavy trucks. In current vehicles, use of natural gas in either a spark-ignition engine or mixed with diesel in a bi-fuel engine decreases efficiency. R&D in a purpose-designed engine optimized around natural gas could potentially reduce that efficiency gap. Natural gas vehicles generally produce lower emissions of hydrocarbons, carbon monoxide, and particulate matter than analogous diesel vehicles, but higher emissions of nitrogen oxides. Newer natural gas engines, however, operate at higher fuel/air ratios with water-cooled exhaust recirculation and a three-way catalyst to reduce NO_x emissions.[29]

Vehicle systems R&D, using a combination of simulation, lab testing, and real-world operations, develops system-level solutions and evaluates their performance, efficiency, costs, and benefits. Heavy-duty engines and vehicle systems have made great advances in the state-of-the-art for the Class 8 truck market, but still may be difficult to commercialize due to policy or regulatory issues. For example, some aerodynamic technologies may affect the operation of safety-critical systems such as lighting or rear under-ride guards on trailers.

8.3 Lightweighting

Reducing the vehicle weight can significantly reduce a vehicle's fuel consumption at all vehicle speeds by reducing rolling resistance and power required for acceleration. For vehicles using conventional internal combustion engines, a 10% reduction in vehicle weight will improve fuel economy between 6% and 8%[30] when the vehicle systems, including the engine, are resized to maintain equal performance. Comparable savings in vehicle energy demand with weight reduction occur in all vehicle classes. For example, reducing the weight of heavy-duty vehicles improves both fuel and freight efficiency. Table 8.4 outlines the integrated impacts from the technologies in this section if successfully deployed fleet wide.

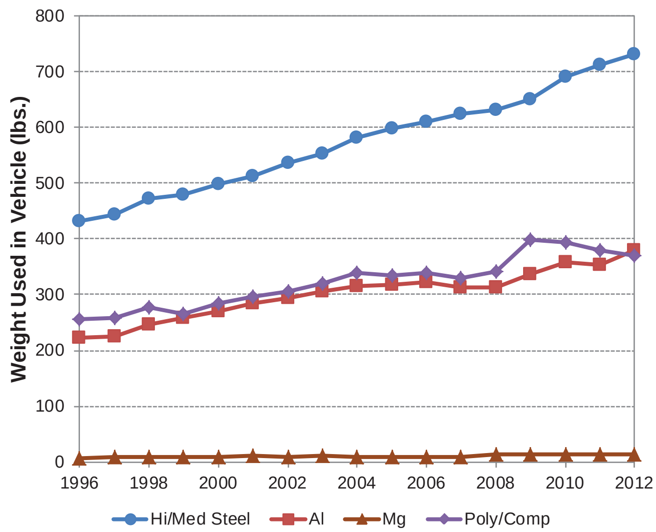
Table 8.4 Fuel-vehicle Co-optimization Impact Summary (DOE calculations)

Technology system	R&D time frame	Per vehicle impacts		Long-term impact potential	
		GHG reduction	Petroleum reduction	Annual GHG reduction	Petroleum reduction
Lightweighting	to 2019	20%	20%	213 MMT	3.4 quads

Today's average passenger vehicle weighs 3,350 pounds without passengers or cargo, and consists of the following materials as a percentage of total vehicle mass: 54% iron or mild steel; 10% first generation high-strength steel; 9% aluminum; 7% plastic; 4% glass; 1% magnesium; and the remaining 15% a mixture of copper, paint, carpeting, padding, insulation, and rubber. The amount of high-strength steel, aluminum, plastic, and magnesium has been steadily increasing, as shown in Figure 8.8. Since 1996, lighter-weight materials have shown significant increased use in production vehicles. Aluminum has increased by 70%, magnesium has increased by 64%, medium- and high-strength steel has increased by 70%, and the use of composites

8

Figure 8.8 Trends of Lightweight Materials Use in Vehicles[31]



has increased by 45%. In today's car, the use of these materials represents a 10% weight reduction and a 7% improvement in fuel economy.

Despite this increased use of lightweight materials, vehicle weight increased throughout this period until 2004, probably due to offsetting weight increases from other content changes, such as increased safety system requirements, increased vehicle size, greater consumer content (such as entertainment, speakers, etc.), and higher-output drivetrains.

There are a number of new materials under development that may have application in vehicle lightweighting—if technical, performance, manufacturing, and cost improvements can be achieved. These materials include next generation high-strength steel (sheet), high-performance cast steel/iron, sheet magnesium, high-performance cast magnesium, high-performance cast aluminum, low-cost automotive grade carbon fiber, hybrid carbon/

Table 8.5 Materials Properties, Cost, and Lightweighting Potential Relative to Mild Steel[32]

Material	Density (g/cm^3)	Comparison to steel			
		Strength/density	Modulus/density	Cost	Mass reduction potential
Mild steel	7.87	1	1	1	0%
High-strength steel	7.87	1.86	1	0.9–1.2	10%
Adv high-strength steel	7.87	3	1	0.8–1.5	10%–28%
Gen 3 high-strength steel	7.87	7	1	1.0–2.0	15%–30%
Ceramics	3.9	0.7	3.05	1.5–3.0	10%–30%
Sheet molding compound	1.1–1.9	4.39	1.16	0.5–1.5	20%–30%
Glass fiber composites	1.4–2.4	4.74	5.75	0.9–1.5	25%–35%
Plastics	0.9–1.5	0.82	0.08	0.7–3.0	20%–50%
Aluminum	2.7	3.95	1.02	1.3–2.0	30%–60%
Titanium	4.51	4.73	0.98	1.5–10	40%–55%
Metal matrix composites	1.9–2.7	5.41	35.28	1.5–3.0	50%–65%
Magnesium	1.74	3.66	1.02	1.5–2.5	30%–70%
Carbon fiber composites	1.0–1.6	20.9	5.41	1.5–5.0	50%–70%

glass fiber composites, and low-cost titanium. Most of these new materials are being tailored to automotive requirements and have cost targets up to 50% less than commercially available aircraft grade materials, as shown in Table 8.5. Still, cost of the base material remains a challenge.

Quantifying vehicle-level weight reduction potential is complex because the answers will vary with vehicle platform, performance requirements, and commercial limitations in the supply chain and manufacturing infrastructure. While weight reduction through material substitution is a promising pathway for body and structure and chassis components, Table 8.6 indicates that about 32% of vehicle weight is due to non-structural systems such as the powertrain, heating, ventilation, and air conditioning (HVAC), and electrical.

Table 8.6 Vehicle Weight in a Typical Mid-size Passenger Car Without Passengers or Cargo. Weight is distributed across different subsystems in the vehicle (DOE calculations)

System	Baseline weight (lbs.)	Percent of total
Body and structure	1,591	47%
Chassis	696	21%
Powertrain	645	19%
HVAC and electrical	158	5%
Other	268	8%
Total	**3,358**	

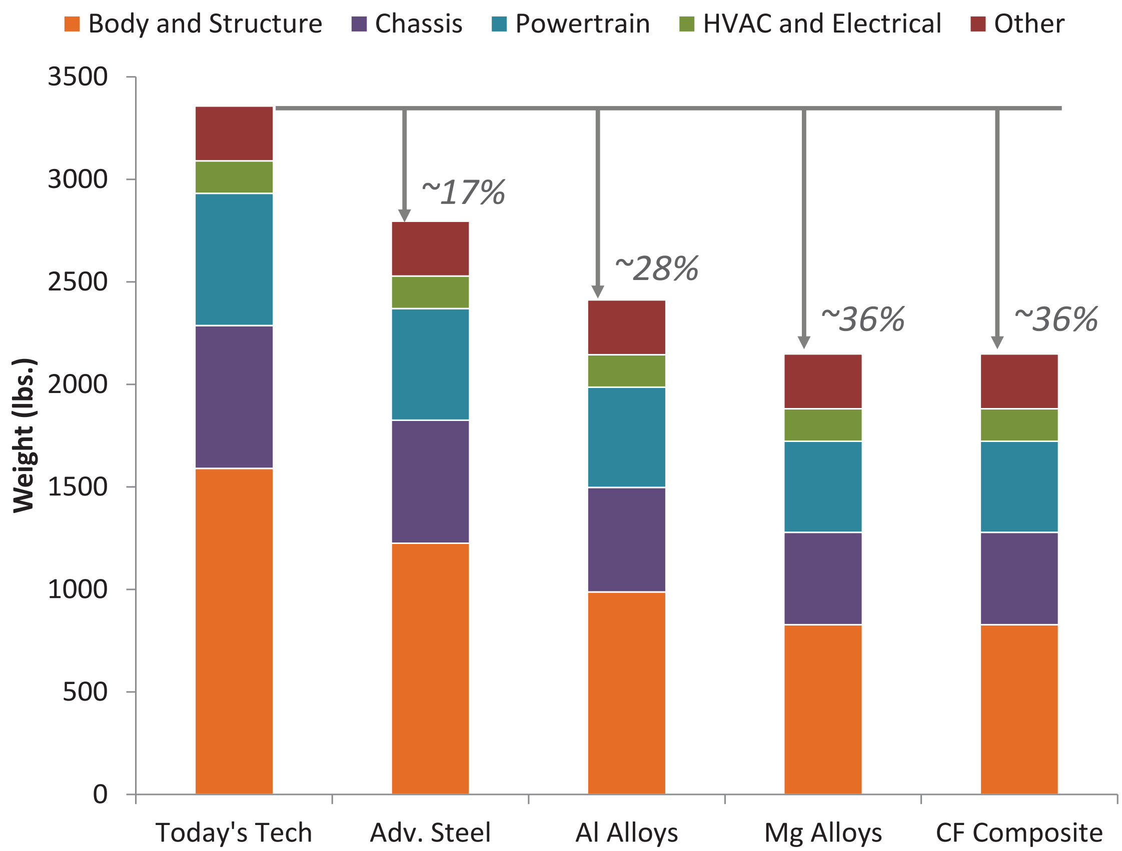
Weight reduction in the powertrain and in certain parts of the chassis is achieved mostly through mass decompounding—for example, by reducing the size of the engine and brakes to accommodate a lighter-body structure—rather than through direct savings. Finally, the weight reduction potential for many systems, such as the HVAC or many electrical components, is negligible. The weight reduction potentials for vehicles that make the greatest reasonable use of each material system discussed here are shown in Figure 8.9.

R&D has focused on developing these most promising materials and the technology needed to overcome barriers to use in automotive structural applications, while continuing to evaluate other material options as new information becomes available. These research and development activities can be partitioned into three broad areas:

- **Properties and manufacturing:** Reducing the cost of raw materials and processing, while improving the performance and manufacturability.
- **Multimaterial enabling:** Evaluation and development of multimaterial joints and structures, taking best advantage of the properties of each of the materials.
- **Modeling and simulation:** The development of commercially available design tools and predictive models, which incorporate validated data and computational processes for lightweight material options, and making the validation data available to the community.

Lightweight materials also face non-technical considerations from consumers, manufacturers, and suppliers. From the consumer perspective, substituting lighter-weight materials for steel in vehicle structures can increase production cost and vehicle price. From the manufacturer's perspective, vehicle weight reduction involves risk, such as uncertainty in structural performance and repair concerns. While there are supply chain capacity concerns with the lighter-weight material options, material supply is of particular concern with magnesium and carbon fiber, where minor increases in use of these materials across a wide section of the automobile fleet would overwhelm the current available supply.

Figure 8.9 Weight Reduction Opportunities if the Indicated Material was Applied to the Greatest Extent Possible. Each bar is the weight allocation after replacement with advanced materials. Percentage reductions are shown for the whole vehicle (DOE calculations).



8.4 Plug-in Electric Vehicles

PEVs draw their energy partially or entirely from an external electric source by storing the energy in an on-board battery and using that energy to run the vehicle on electric motors. In plug-in hybrid electric vehicles (PHEV), the battery provides the primary power source for a number of "all-electric" miles, after which the vehicles operate in HEV mode. The inherent efficiency of electric drive and recapture of braking energy allows very high vehicle efficiencies. Additionally, electricity in the United States uses almost no petroleum and can be significantly decarbonized (see Chapter 4); as such, shifting mobile sources like vehicles to electricity can provide large GHG and petroleum reductions. Electrification is most viable in the light-duty vehicle fleet, as onboard energy storage becomes an increasing challenge with higher power and total energy storage requirements. Opportunities in this section include improved batteries, better electric drive technologies, and systems-level research. The overarching technical goals are to achieve PEV cost parity with conventional vehicles for a wide variety of consumers. Table 8.7 outlines the integrated impacts from the technologies in this section if successfully deployed fleet wide.

8.4.1 Batteries

An important step for the electrification of the nation's light duty transportation sector is the development of more cost-effective, long-lasting, and abuse-tolerant batteries. Lower-cost, abuse-tolerant batteries with higher energy density, higher power, better low-temperature operation, and longer lifetimes are needed for

Table 8.7 Plug-in Electric Vehicle Impact Summary (DOE calculations)

Technology system	R&D time frame	Per vehicle impacts		Long-term impact potential	
		GHG reduction	Petroleum reduction	Annual GHG reduction	Petroleum reduction
PEVs	To 2022	Up to 80%	Up to 99%	852 million metric tons	17 quads

the development of the next-generation of HEVs, PHEVs, and electric vehicles (EV) to expand commercial markets. Lithium-based batteries offer the potential to meet the requirements of all three applications, and ultra-capacitors may offer a more cost-effective solution for low-energy, high-power micro- and start/stop HEVs. Technology projections and market analysis show that more cost-effective, longer-lasting, and more abuse-tolerant PEV batteries are necessary for enabling PEVs to be as convenient and affordable as today's gasoline vehicles by 2022, as shown in Figure 8.10.

R&D efforts, including pack design optimization and simplification, manufacturing improvements at the cell and pack level, materials production cost reduction, and novel thermal management technologies, can also contribute to battery cost reduction. Achieving the battery power density target (2,000 watts per kilogram) is important to assure that technology breakthroughs meet the discharge power requirements for a wide range of PEV architectures and to enable the battery to be rapidly charged. Fast charging may be important for consumer adoption of certain PEVs. Battery R&D includes research to reduce cost, weight, and volume, improve performance, efficiency and reliability, develop innovative modular and scalable designs, improve manufacturability, and accelerate commercialization.

Figure 8.10 Battery Performance Advancements that are Needed to Enable a Large Market Penetration of PEVs[33]

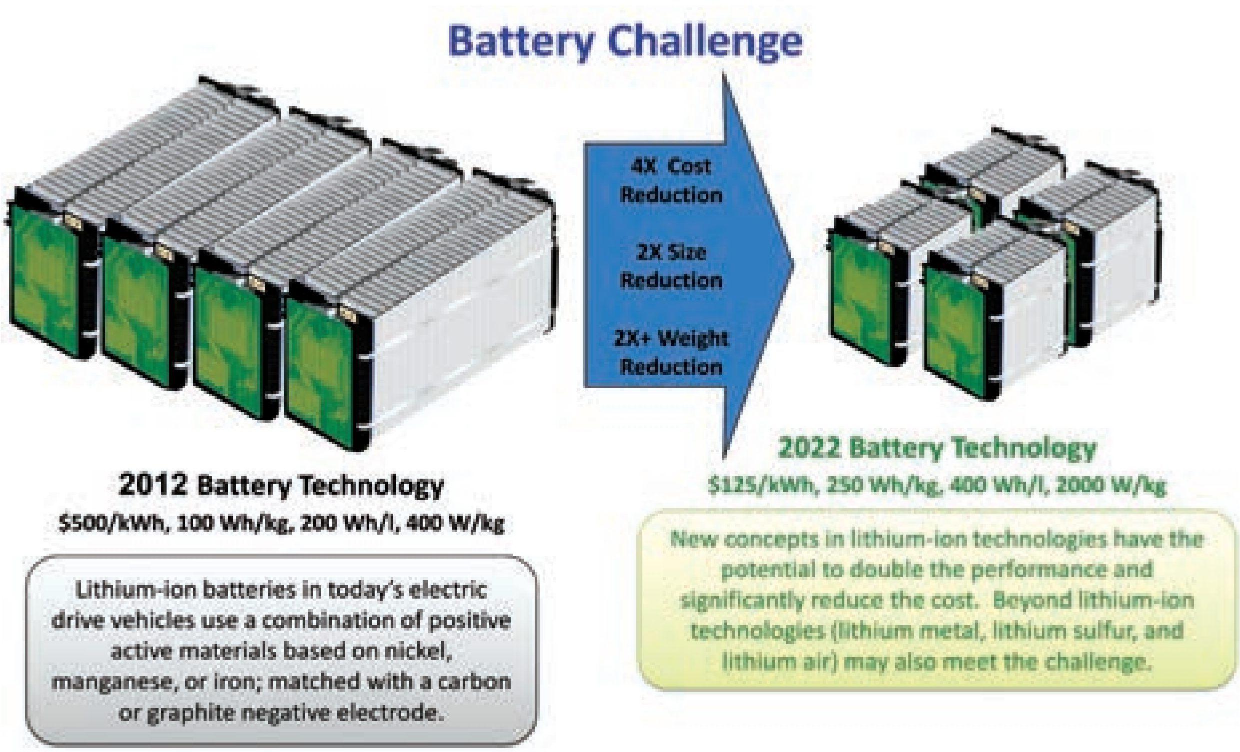


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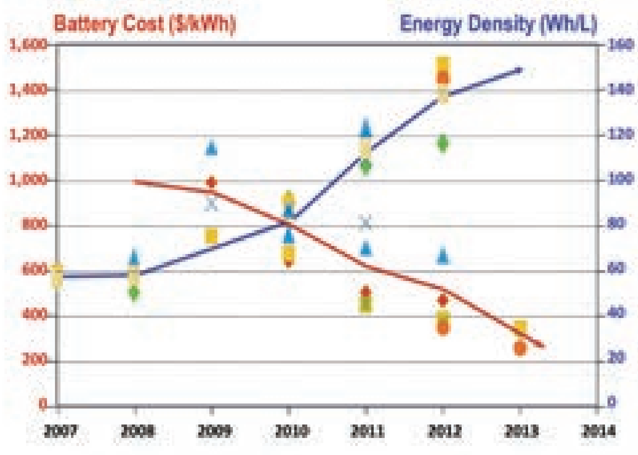
Figure 8.11 Modeled Cost and Energy Density of PEV Batteries Developed and Tested[35]



R&D has made significant progress, reducing the cost of lithium-ion batteries by nearly 70% and improved their energy density by 60% during the last five years. As shown in Figure 8.11, the modeled cost of PHEV batteries under development has been reduced from $1,000 per kilowatt-hour (kWh) of useable energy in 2008, to a cost of $289 per kilowatt-hour in 2014 if mass produced at the rate of 100,000 units per year. Market prices have also fallen significantly.[34] Battery development projects focus on advanced cathodes, processing improvements, cell design, and pack optimization, using standard electrolytes and graphite anodes.

Concurrently, the size and weight of PEV battery packs have also been reduced by more than 60%. The battery pack energy density has increased from 60 watt-hours (Wh) per liter in 2008, to more than 150 Wh/liter in 2014.

Despite recent progress, current battery technology is still far from its theoretical energy density limit. In the next roughly five years, advances in lithium-ion technology could more than double the battery pack energy density from 120 Wh per kilogram to 250 Wh per kilogram through the use of new high-capacity cathode materials, higher voltage electrolytes, and the use of high-capacity silicon or tin-based intermetallic alloys to replace graphite anodes.[36]

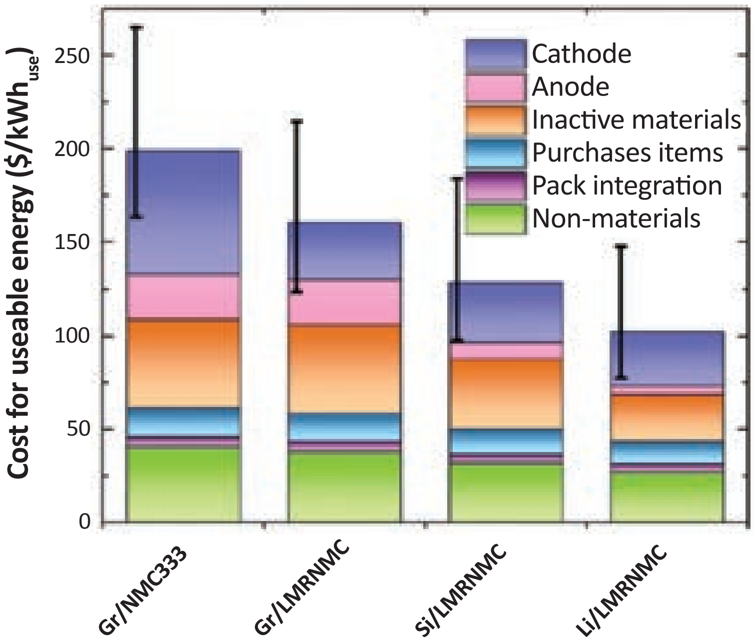
In the next five to fifteen years, "beyond Li-ion" battery chemistries, such as lithium-sulfur, magnesium-ion, zinc-air, and lithium-air, offer the possibility of energy densities that are significantly greater than current lithium-ion batteries, as well as the potential for greatly reduced battery cost.[37] However, major shortcomings in cycle life, power density, energy efficiency, and/or other critical performance parameters currently stand in the way of commercial introduction of state-of-the-art "beyond Li-ion" battery systems. Breakthrough innovation will be required for these new battery technologies to enter the PEV market.

The potential of more advanced lithium-ion materials and "beyond lithium-ion" chemistries to reach the goals has been quantified using the Battery Performance and Cost model developed at Argonne National Laboratory.[38] This model captures the interplay between design, performance, and cost of advanced battery technology. The results show that the combination of lithium- and manganese-rich high-energy cathode (LMRNMC) and silicon alloy anodes can significantly improve battery costs. Batteries with silicon alloy anodes (Si/LMRNMC) and lithium metal batteries (Li/LMRNMC) are estimated to be able to reach a cost of $125/kWh, as shown in Figure 8.12.

R&D can help overcome the major challenges to developing and commercializing batteries for PEVs:

- **Cost:** Primary battery cost drivers are the high cost of raw materials and materials processing, the cost of cell and module packaging, and manufacturing costs. Addressing the cost barrier requires developing and evaluating lower-cost components, including much higher energy active materials, alternate packaging, and processing methods, as well as joint work with U.S. suppliers to implement these low-cost solutions.

Figure 8.12 Advanced Battery Technology Low-cost Pathway[39]



Gr/NMC333: Graphite anode coupled with nickel-manganese-cobalt cathode

Gr/LMRNMC: Graphite anode coupled with manganese-rich layered cathode

Si/LMRNMC: Silicon alloy composite anode coupled with manganese-rich layered cathode

Li/LMRNMC: Lithium metal anode coupled with manganese-rich layered cathode

Estimated cost for a 100 kWh use PEV battery using advanced technology and produced at 100,000 packs per year. *(Courtesy of Argonne National Laboratory, Joint Center for Energy Storage Research, supported by DOE Office of Science, Basic Energy Sciences.)*

- **Performance:** Higher energy densities are needed to meet both volume and weight targets for PHEV and EV applications, and improvements in low-temperature performance are particularly critical when the battery is the sole power source.
- **Abuse tolerance, reliability, and ruggedness:** Many lithium batteries are not intrinsically tolerant of certain abusive conditions that can occur during vehicle operation, particularly large format lithium cells. In addition, current thermal control technologies, although adequate to dissipate heat in today's systems, are expensive and add significant weight and volume.
- **Life:** For high-energy batteries in a PEV application, a combination of energy and power fade over life are challenging issues as the battery must provide significant energy over the life of the vehicle and either provide full vehicle power (for an EV) or high-power HEV pulses (for a PHEV) near the bottom of its state-of-charge window. Today, batteries designed for HEVs can deliver 300,000 shallow discharges. However, batteries with a higher energy density have difficulty meeting the 5,000 deep discharge cycle requirement for PHEVs.

Battery technology R&D includes multiple activities, from focused fundamental materials research, generally spearheaded by the national laboratories and universities, to battery cell and pack development and testing, mainly by commercial developers and national laboratories.

Joint Center for Energy Storage Research

The Batteries and Energy Storage Hub: Beyond Lithium-ion for Next-generation Energy Storage Technologies

The Joint Center for Energy Storage Research (JCESR), headquartered at Argonne National Laboratory and managed by the DOE Office of Basic Energy Sciences (BES), brings together many of the world's leading battery researchers around a common objective of overcoming fundamental scientific challenges and enabling next-generation, beyond lithium-ion, energy storage systems for both transportation and the electrical grid. Funded at approximately $120 million over five years, the JCESR mission is to pursue advanced scientific research to understand electrochemical materials and phenomena at the atomic and molecular scale, and to use this fundamental knowledge to discover and design new approaches for next-generation energy storage. The enhanced understanding of materials and chemical processes at a fundamental level will enable exploration of new technologies. The overarching goal of JCESR is, within five years, to produce prototypes for both transportation and grid-level storage that will scale up to store at least five times more energy than the baseline 2011 batteries at one-fifth of the cost. JCESR is coordinating its efforts with the DOE BES Energy Frontier Research Centers and DOE technology offices including the Office of Energy Efficiency & Renewable Energy (EERE), the Office of Electricity Delivery and Energy Reliability (OE) and the Advanced Research Projects Agency - Energy (ARPA-E). JCESR's industrial partners help guide the Hub's efforts to ensure that the research leads toward practical solutions that are competitive in marketplaces such as transportation, electric utilities, construction, electronics, medicine, aerospace, and defense.

JCESR focuses exclusively on beyond lithium-ion batteries, a wide, rich and relatively unexplored research space. JCESR carries out its research through collaborative teams that span discovery science, battery design, research prototyping, and manufacturing collaboration; these teams interact across the R&D spectrum. The effort is organized around three broad research directions, each containing multiple battery chemistries: multivalent intercalation, chemical transformation, and non-aqueous redox flow. In addition, computational chemistry research is introducing a genomic approach to evaluate thousands of materials by theory and computer modeling before selecting the most promising candidates for laboratory synthesis. For materials characterization, JCESR is leveraging the unique capabilities of the DOE laboratory system to explore structure-function relationships at the atomic and molecular level. For systems-level assessments, techno-economic modeling translates these materials discoveries to systems level operation, projecting the performance and cost of candidate battery systems before they are prototyped.

8.4.2 Electric Drive Technologies

Electric drive technologies (EDT), encompassing power electronics and electric motors (see Figure 8.13; EDT components are in green), are critical components for electric drive vehicles. Power electronics, traction motor(s), and controls add several thousand dollars to the vehicle cost. Without innovation and cost reduction in these additional components, the cost of electric vehicles will continue to exceed that of conventional vehicles.

EDT R&D opportunities are based on several key system needs:

- Reducing cost, weight, and volume
- Improving performance, efficiency, and reliability
- Developing innovative modular and scalable designs
- Improving manufacturability and accelerating commercialization

Specific opportunities for cost reduction and performance improvement lie in the following research areas:

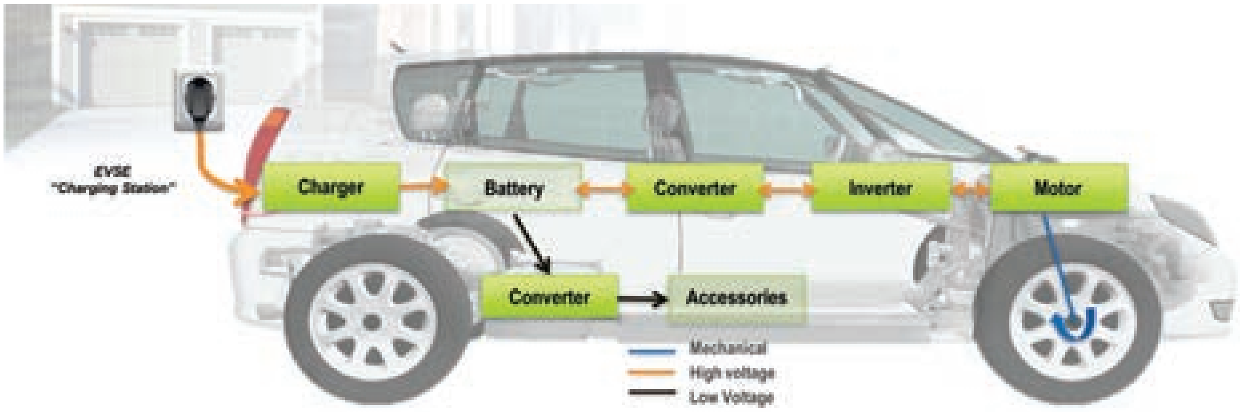
- Wide bandgap (WBG) devices for power electronics
- Advanced motor designs to reduce or eliminate rare earth materials
- Novel packaging for power electronics and electric motors
- Improvements in thermal management and reliability
- Integration of power electronics functions

Four key metrics for opportunities to improve the traction drive system (combined power electronics and motors) are cost, power density, specific power, and efficiency. EDT R&D opportunities have been identified in four different research areas: power electronics; motors; packaging technologies and design; and benchmarking, testing, and analysis. Packaging technologies and design, and benchmarking, testing, and analysis are supporting activities to electric motors and power electronics R&D. Therefore, they are included in the more detailed description of these two research areas below.

Power Electronics

EDT research activity in power electronics primarily focuses on improving inverters, as they have the biggest impact on power electronic targets. Researchers are working to reduce inverter volume by a third, reduce part count by integrating functionality, and reduce cost. Today's vehicle power electronics utilize silicon-based

Figure 8.13 Schematic Diagram of a PEV



semiconductors. However, WBG semiconductors are more efficient and can withstand higher temperatures than silicon components and have a significant potential to improve EDT performance, but need further research.[40] The two most commonly used WBG materials are silicon carbide (SiC) and gallium nitride (GaN). The ability to operate at higher temperatures can also decrease system costs by reducing thermal management requirements.

Achieving the identified improvement opportunities for power electronics will require achieving advances in several areas, including device packaging, innovative power module designs, high-temperature capacitors, and new inverter architectures. Device packaging and innovative power module designs can eliminate existing interface layers and provide cooling at or very near the heat sources. Improved capacitors can reduce inverter cost and volume, and enable higher-temperature operation. New inverter architectures can reduce part counts and enable modular, scalable components.

Electric Motors

EDT research activity is supporting research to improve electric motors, with a particular focus on reducing the use of rare earth materials inside the rotor magnet since the magnets account for the largest portion of the motor costs and their supply is limited.[41] This activity's primary goal is to decrease the electric motor's cost, volume, and weight while maintaining or increasing performance, efficiency, and reliability.

8.4.3 Electrified Vehicles Systems

Electric-drive vehicle systems are complex and involve many technologies. Various opportunities for system integration exist among batteries, electric-drive technologies, the powertrain, and passenger's cabin experience (including electrically powered amenities). A more integrated hardware and software approach could yield better overall system efficiencies. The high operating efficiencies of electric drive powertrains increase the need for a vehicle system optimization. Reducing system losses (i.e., friction losses, tire rolling resistance, auxiliary loads), enhancing performances of components (i.e., battery capacity, electric drive efficiencies) and optimizing the vehicle characteristics (i.e., lightweighting, aerodynamics) has proportionately greater benefits for electric drive vehicles than conventional technology vehicles. PHEVs offer special opportunity for systems optimization, since the presence of both mechanical and electrical powertrains offers trade-offs between fuel and electricity, both for mobility and for other aspects of the driving experience (i.e., warming up the powertrain and cabin at freezing temperatures).

Optimizing the balance across technologies within electric-drive vehicles is an opportunity and a challenge. A key research opportunity is the system level tradeoffs between electric-drive system components. For example, a larger battery capacity increases the electric range but increases cost, mass, and packaging complexity. Hardware experiments and software tools can quantify these powertrain trade-offs and opportunities. The possible combinations of powertrain architectures are abundant and the control opportunities are substantial.

Minimizing accessory loads (powertrain support systems, climate control system, driver comfort features) are also a primary research area. For example, a small, all-electric range vehicle may use an average of 4–5 kW to move in the urban driving while an electric heater draws 4–5 kW to warm the cabin in freezing temperatures, which translates to half the electric range. Even smaller loads such as headlights or fans can affect the electric range significantly. Therefore, vehicle system R&D targets ways to minimize the system loads and increase the system efficiencies.

PEV charging interactions with the grid is another key system opportunity because charging convenience and reliability are essential enablers for PEVs. Home charging and work place charging will cover most daily use cases, but further research to understand charging behaviors is important.[42] Ensuring that any PEV can be charged at any charging station will require development of codes and standards related to charging, which address the physical interfaces, power flow, communications, test procedures, and installation and permitting processes. Vehicle systems R&D includes several level of charging speeds and efficiencies up to direct current fast charging and future wireless charging technologies. The battery capacity of PEVs can also provide grid services, which are discussed in Chapter 3.

Advanced vehicle testing generates data necessary to identify research opportunities to improve vehicle technologies and systems. This includes fleet testing as well as laboratory testing of the newest powertrains, ranging from prototypes to production vehicles. The data serve to develop and validate modeling and simulation software, which itself enables a fast and methodical exploration of the design space and its potential opportunities. Testing can identify surprising systems benefits; for example, Chevrolet Volt owners thus far drive more than 70% of their daily miles on electricity,[43] higher than theoretical estimates using standard methodologies based on vehicle characteristics and assumptions of driving behavior (defined by standards SAE J1711 and SAE J2841).[44]

Vehicle system R&D can help integrate other technology progress to accelerate market penetration of advanced vehicles and systems with several objectives:

- Evaluate technology performance targets of components and systems
- Accelerate efficient designs via tools, analysis, and procedures
- Provide stakeholders with data and analysis on vehicle performance and consumer behavior to support decision making on future R&D priorities
- Accelerate codes and standards development for electric vehicles

Specific R&D opportunities to address these objectives include the following:

- Rapid evaluation of new powertrain/propulsion technologies through virtual design and analysis in a math-based simulation environment
- Laboratory and field evaluations of automotive technologies to benchmark automotive technology progress (e.g., using structured and repeatable testing methods in both laboratory and real-world fleet testing to provide unbiased, independent, public, quality data on advanced technologies; quantifying performance targets; and developing and validating simulation models)
- Research to enable informed decision making to support the development and adoption of PEV codes and standards, including communications, interoperability, security, safety, and performance of PEVs and electric vehicle supply equipment
- Investigating systems optimization strategies to enhance vehicle efficiency, robustness, and emissions performance, such as aerodynamic drag reduction, friction and wear reduction, thermal control and auxiliary load reduction, fast wireless charging, and smart grid integration

8.5 Hydrogen Fuel Cell Vehicles

Fuel cell electric vehicles (FCEVs) are powered by hydrogen through use of a fuel cell, which generates electricity by converting hydrogen and atmospheric oxygen to water. FCEVs are thus hybrid electric vehicles and have much in common with other electric drivetrain technologies, including motors, batteries, and regenerative braking. FCEVs can be refueled in a few minutes, can be used for a wide range of vehicle sizes and performance requirements, and can achieve a driving range of more than 300 miles. FCEVs offer large potential petroleum reductions and, especially when fueled with hydrogen from low-carbon sources, greenhouse gas reductions. Table 8.8 outlines the integrated impacts from the technologies in this section if successfully deployed fleet wide.

Table 8.8 Fuel Cell Electric Vehicle Impact Summary (DOE calculations)

Technology system	R&D time frame	Per vehicle impacts		Long-term impact potential	
		GHG reduction	Petroleum reduction	Annual GHG reduction	Petroleum reduction
FCEVs	2020+	More than 80%	Up to 99%	>1,000 MMT	17 quads

This section addresses only the technologies specific to FCEVs, but advances in batteries and electric drive technologies can be beneficial to FCEVs as well. While using renewables to generate hydrogen can result in more than 80% reductions in total well-to-wheels carbon emissions compared to today's internal combustion gasoline vehicle, using natural gas-derived hydrogen—the dominant method today, without carbon sequestration—can yield a 50% reduction in carbon emissions compared to today's gasoline vehicle baseline.[45] The opportunities and challenges related to hydrogen production and infrastructure are discussed in detail in Chapter 7.

Although hydrogen and fuel cells face technological, economic, and institutional challenges, FCEVs have significant long-term potential. R&D has already reduced automotive fuel cell cost from $124/kW in 2006 to $55/kW today, based on high-volume manufacturing projections.[46] Nevertheless, further progress is needed for significant market penetration and R&D is required to address the following:

- **Cost:** Automotive fuel cell systems must cost $30/kW or less ($40/kW by 2020) to be competitive with gasoline internal combustion engines.
- **Efficiency and durability:** Fuel cell systems should operate at 65% efficiency (ultimate target is 70%) and be durable for 5,000 hours (equivalent to about 150,000 miles).[47]
- **Hydrogen storage:** On-board hydrogen storage should provide a driving range of more than 300 miles at a cost of $8/kWh or less, without reducing performance or interior space.

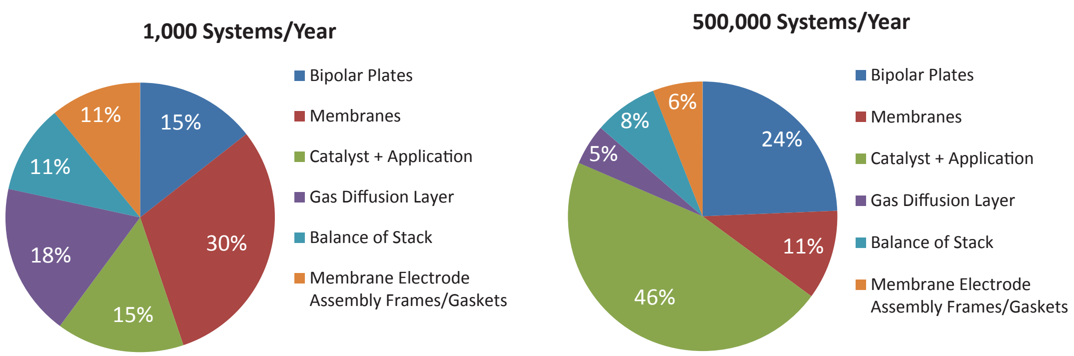
8.5.1 Fuel Cells

Fuel cells[48] convert the chemical energy in fuels such as hydrogen directly into electricity. Unlike heat engines, which are limited by Carnot efficiency, fuel cells can theoretically achieve efficiency over 90%. Current fuel cell technology can exceed 60% efficiency, and R&D is underway to reach 70% efficiency or higher. When using hydrogen as a fuel, fuel cells emit only water.

Fuel cell technology has matured enough that initial commercialization of fuel cell vehicles is already underway, but several technological barriers remain that impede commercialization and require research:[49]

- **Cost:** Primary fuel cell costs are a result of the high costs of materials and components as well as manufacturing processes (see Figure 8.14). Addressing the cost barrier requires developing lower-cost components such as catalysts and membranes, as well as manufacturing methods.
- **Performance:** Higher performance enables production of power at a higher efficiency from a smaller fuel cell system, leading directly to cost reductions and improved fuel economy. This implies overcoming the following barriers:
  - Sub-optimal utilization of platinum group metals (PGM) content in current catalysts
  - Low performance of current catalysts and electrodes, which require pressurized operation to achieve sufficient power output
  - Low performance of membranes under the hot and dry conditions that occur when operating near the peak power point without humidification
  - Lack of understanding of the role of electrode composition and microstructure on fuel cell performance and durability

Figure 8.14 Breakdown of the 2014 Projected Fuel Cell Stack Cost at 1,000 and 500,000 Systems Per Year[50]



- **Durability:** Fuel cell systems must perform adequately more than 5,000 hours of vehicle operation, which requires overcoming the following barriers:
  - Low durability of current catalysts and electrodes, which are not yet capable of 5,000 hours of durable operation at low PGM loading
  - Low durability of current ultrathin membranes, which are not yet capable of withstanding 5,000 hours of operation with humidity cycling and exposure to contaminants
  - Tolerance of fuel cells to a range of fuel quality conditions as well as automotive cycling such as start-stop conditions

R&D on materials, stack components, balance-of-plant subsystems, and integrated fuel cell systems, with an emphasis on science and engineering at the cell level could help overcome these barriers. Additional fuel cell innovations will be required to meet cost and durability targets, including development of low-cost, corrosion-resistant metal bipolar plates and development of durable, low-cost balance-of-plant components. Figure 8.15 summarizes major advancements that would enable significant market penetration.

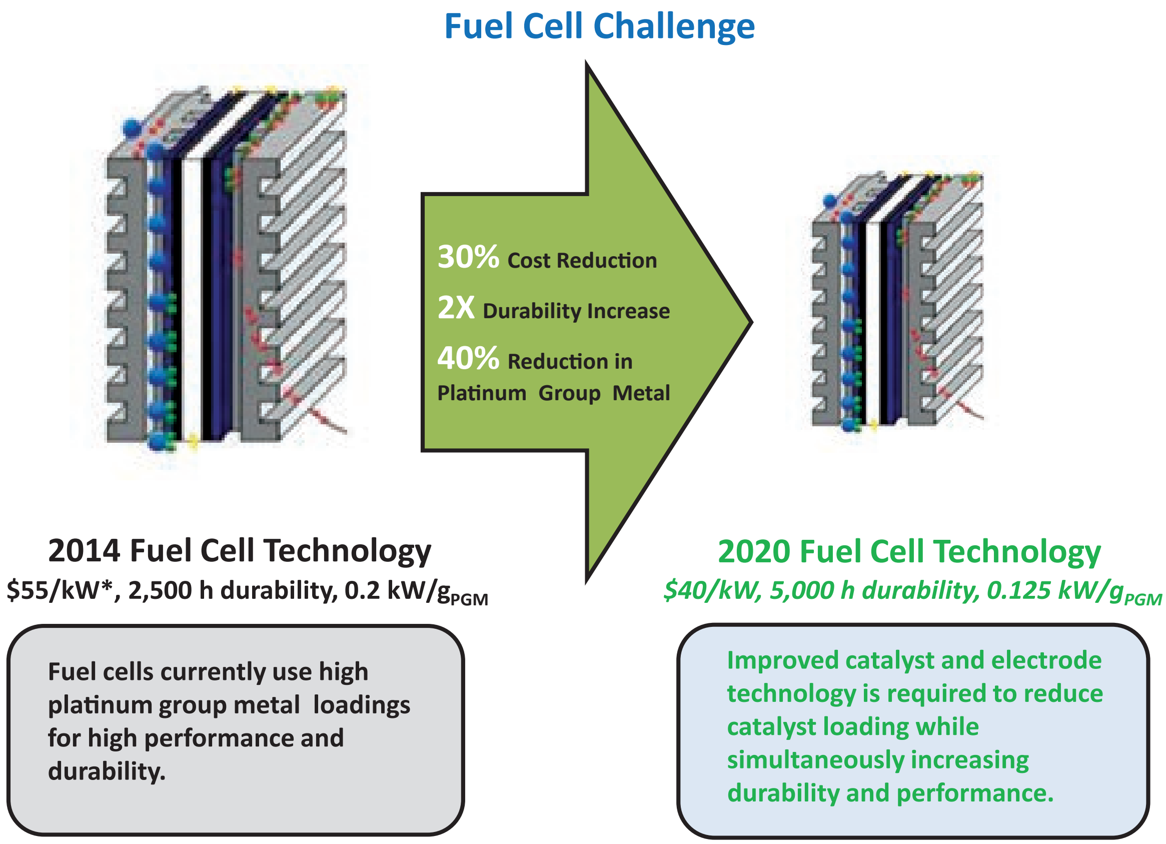
Specific technical targets are shown in Table 8.9 for automotive fuel cells. Some targets have already been met individually, but all targets should be met simultaneously by a single system to enable full market penetration.

While significant progress is being made and the catalyst-specific power of fuel cells was improved to 6.0 kW per gram of PGM[53] in 2013 (more than double the 2008 baseline of 2.8 kW/g_{PGM}), continued R&D is needed to achieve the 2020 target of 8.0 kW/g_{PGM}. Reductions in catalyst loading typically cause a loss of durability, increasing the challenge of reaching the 8.0 kW/g_{PGM} target while simultaneously increasing durability to 5,000 hours. While near-term R&D focuses on PGM-based catalysts as the only viable catalysts for initial commercialization, R&D is also needed for the development of next-generation non-PGM catalysts and membrane electrode assemblies through the application of high-performance computing, high-throughput combinatorial approaches and advanced modeling. Furthermore, longer-term technologies (e.g., anion-exchange [alkaline] membrane fuel cells) could be explored to enable transformative changes in fuel cell technology, such as commercialization of fuel cells that are completely PGM-free.

8.5.2 Hydrogen Storage

The current near-term technology for onboard automotive hydrogen storage is focused on 350 bar (for fuel cell buses) and 700 bar (for fuel cell cars) nominal working-pressure compressed vessels (tanks). Compressed gas storage systems have been demonstrated in hundreds of prototype fuel cell vehicles and are commercially available at low production volumes. The tanks within these systems have been certified worldwide. The high-

Figure 8.15 Fuel Cell Performance Advancements Needed to Enable a Large Market Penetration of FCEVs[51]



*$55/kW at 500,000/yr, $280/kW at low volumes

Table 8.9 Status and Targets for Automotive Fuel Cell System[52]

Characteristic	2014 status	2020 target	Ultimate target
Peak energy efficiency	60%	65%	70%
System power density	640 W/L	650 W/L	850 W/L
System specific power	659 W/kg	650 W/kg	650 W/kg
Catalyst specific power	6.0 kW/g$_{PGM}$	8.0 kW/g$_{PGM}$	(a)
Cost	$55/kW	$40/kW	$30/kW
Durability with cycling	2,500 hours	5,000 hours	5,000 hours

(a) Current assessment is that greater than 8.0 kW/g$_{PGM}$ may be needed to meet the ultimate cost target pressure hydrogen storage tanks for LDVs consist of either a metallic (Type III) or non-metallic liner (Type IV) overwrapped with a carbon fiber reinforced composite. To provide a 300-mile driving range for LDVs, current cost projections for a 700-bar Type IV system are approximately $2,800 ($17/kWh) if manufactured at 500,000 systems per year, but approximately $5,500 ($33/kWh) if manufactured at only 10,000 systems per year.[54] Additionally the system would require a volume roughly three to four times that of typical gasoline tanks. While automakers have demonstrated these systems can offer a driving range close to 300 miles, this cannot be accomplished across the full range of vehicle platforms at acceptable costs.

In order to provide at least a 300-mile driving range across all vehicle platforms—while not reducing passenger and cargo space—R&D is needed to enable cost reductions and advanced technologies with higher energy density. Table 8.10 lists cost, specific energy (kWh/kg) and energy density (kWh/L) targets for onboard hydrogen storage systems. These targets were developed in conjunction with vehicle manufacturers to be able to meet vehicle performance across the range of LDV platforms. Additionally, the current projected status of several hydrogen storage technologies is provided in Table 8.9. For near-term compressed hydrogen storage tanks, the key technological challenge is to reduce the cost while meeting safety and performance requirements. Additional R&D could focus on conformable tank designs that can be more efficiently packaged onboard LDVs. For the long-term, R&D efforts are required for successful development of advanced technologies that have potential to increase the energy density, and therefore reduce the required system volume, so that sufficient hydrogen can be stored onboard all vehicle platforms to provide at least a 300-mile driving range.

Advanced hydrogen storage technologies include sub-ambient temperature compressed storage and materials-based storage. The density of hydrogen increases at reduced temperature so the use of cold (150 K to near-ambient) or cryogenic (<150 K) temperatures offers the potential to reduce overall system volume. These storage tanks require insulation to minimize heat leakage into the stored hydrogen.

Materials-based storage technologies takes advantage of the fact that significantly higher hydrogen densities at lower pressure (typically 100 bar or less) can be obtained when adsorbed on the surface of porous solids or bonded to other elements within compounds. The three primary classes of materials are hydrogen adsorbents, reversible metal hydrides, and chemical hydrogen storage materials, which are described below:

- For adsorbents, high-surface area, micro-porous materials, such as activated carbons and metal organic frameworks (MOFs), are being developed for hydrogen and natural gas storage. While many of the preferred material characteristics are similar for hydrogen and natural gas adsorption, a key difference is that the van der Waals binding strength for hydrogen is much lower, resulting in the need for cryogenic temperatures for significant adsorption. Therefore, development of materials with high micro-pore density as well as having higher hydrogen binding strengths is required.[56]
- Reversible metal hydride hydrogen storage is fairly mature and well-proven, as it is the basis of nickel-metal hydride (NiMH) battery technology, but the conventional intermetallic alloys used are considered too expensive and too heavy for LDV hydrogen storage applications. Therefore, development of hydrides composed primarily of lighter elements is required.[57]
- Chemical hydrogen storage materials are compounds with strongly bound hydrogen where the hydrogen is released through non-equilibrium processes, and thus cannot be recharged simply through application of pressurized hydrogen. While materials in this class have been developed for several niche applications, materials need to be easily filled onboard for automotive use and the spent product easily removable from the vehicle. In addition, the spent materials will need to be regenerated efficiently at low cost.[58]

While some promising storage materials have been identified, no single material meets all storage targets simultaneously; to address this will require R&D on advanced storage materials. To support and accelerate the advancement of hydrogen storage materials, a database to provide the research community with easy access to searchable, comprehensive, and up-to-date materials data on adsorbents, chemicals, and metal hydrides, in one central location has been developed.[59] The database includes information from research pulled from a number of sources, including the historical Hydride Information Center database.[60]

The system engineering of all the materials-based technologies is at an early stage of development, but validated models are emerging and were used to predict the performance for the materials-based systems in Table 8.10.[61] These complete system models have been developed and are available as a tool online so that materials developers can project how their developed materials would perform when incorporated into a complete system for automotive application.[62]

Table 8.10 Hydrogen Storage Targets for FCEVS and Projected Hydrogen Storage System Performance for Type IV Tanks and Materials-Based Systems (current technology at high volumes)[55]

	Gravimetric kWh/kg ($kg\ H_2/kg$ system)	Volumetric kWh/L ($kg\ H_2/L$ system)	Costs $/kWh @500k/yr ($\$/kg\ H_2$)
Storage targets			
2017	1.8 (0.055)	1.3 (0.040)	$12 ($400)
Ultimate	2.5 (0.075)	2.3 (0.070)	$8 ($266)
Projected hydrogen storage system performance			
700 bar compressed (Type IV)	1.5	0.8	17
350 bar compressed (Type IV)	1.8	0.6	13
Metal hydride ($NaAlH_4$)	0.4	0.4	TBD
Sorbent (MOF-5, 100 bar) MATI, LN2 cooling [HexCell, flow-through cooling]	1.1 [1.2]	0.7 [0.6]	16 [13]
Chemical hydrogen storage (AB-50 wt.%)	1.7	1.3	16

For near-term compressed hydrogen storage systems, reducing system costs and packaging them for vehicles requires R&D to address the following:

- **Composites:** Low-cost, high-performance composites to lower costs while maintaining performance
- **Materials:** Alternative high-strength materials that can be used for balance-of-plant components in high-pressure hydrogen service applications
- **Conformability:** Systems capable of having non-cylindrical shapes to be packaged onboard vehicles more efficiently

For the long-term, advanced storage technologies with significantly improved energy density are important for system performance. Successful development of cold/cryogenic compressed hydrogen storage requires research, including in the following areas:

- **Composite performance:** Improved understanding of the performance of composite materials in cryogenic, high-pressure gas storage applications
- **Dormancy**: Low-cost, high-performance insulation and system designs that will minimize thermal leakage into the system, allowing for longer-term storage without venting of the stored hydrogen

Successful development of materials-based hydrogen storage technologies requires research, including in the following areas:

- **System engineering**: Improved understanding of system-level performance and modeling the translation from materials' performance to system performance
- **Hydrogen adsorbents**: High surface area materials with improved pore density to increase energy density and with higher van der Waals bonding so that significant hydrogen adsorption occurs near ambient temperatures
- **Reversible metal hydrides**: Materials with greater durability and that have higher storage capacity by mass and with fast kinetics within the operating temperature range of the fuel cell
- **Chemical hydrogen storage materials:** Materials that are liquid throughout the states of hydrogen charge/discharge and operating temperature range that can be regenerated efficiently and at low cost

8.5.3 Fuel Cell Vehicle Systems

A safe, cost-effective, and convenient vehicle-infrastructure interface is a key issue for the widespread deployment and consumer acceptance of FCEVs. While the hydrogen production component of infrastructure is covered in Chapter 7, the dispenser-vehicle interface—including refueling protocols to ensure a typical three to five minute fueling time—needs to be addressed. Pre-cooling is the strategy currently planned to avoid overheating of storage tanks during fast-fueling of FCEVs at high pressures, but in the long-term novel refueling strategies or lower-pressure operation would reduce cost and complexity. Additional areas requiring further work for successful development include: communication between the vehicle and the dispenser, metering to ensure accurate amounts of hydrogen dispensed, sensor technology both for hydrogen and contaminants, and the impact of fuel quality.

R&D can provide critical data required for the development of technically sound codes and standards, a prerequisite for safe deployment and large-scale commercialization. For example, an update to the hydrogen bulk storage separation distances used in key codes (e.g., National Fire Protection Association [NFPA] 52 and NFPA 2) reduced required separation distances by as much as 50%.[63]

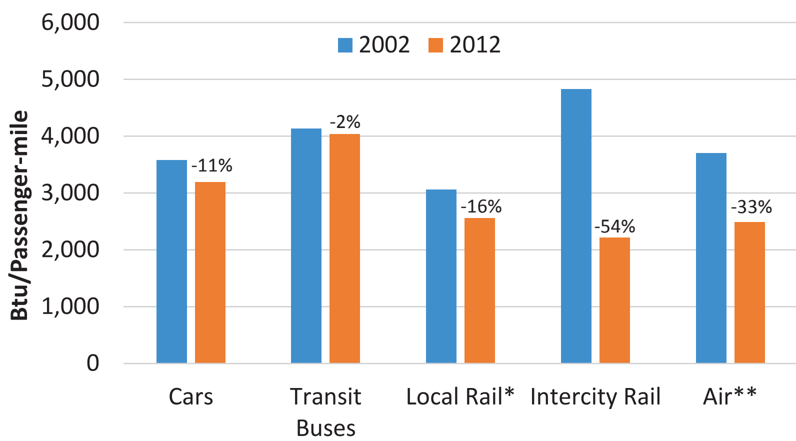
Finally, from a systems perspective, the opportunity for vehicle-to-grid (V2G) or vehicle-to-building (V2B) in the case of hydrogen FCEVs has largely been unexplored. As with PEVs, V2G and V2B systems would enable FCEVs to provide power to the electricity grid or building, respectively, when needed, such as during peak electricity load times or when backup power is needed.[64] The concept of a power offtake unit that allows the nominally 100 kW fuel cell in a FCEV to power a home for several days needs to be investigated to assess viability, economic value, and impact on component durability. Such approaches may improve the cost-benefit proposition for the consumer and provide options for backup or emergency power operation for a number of applications.

Ultimately, the market success of a new hydrogen or fuel cell technology may be driven by its ability to reach self-sustaining commercialization. Therefore, an important research activity is identifying niche markets for the technologies to exploit economies of scale. Research into overcoming logistical and infrastructure barriers is an important task because it resides outside the purview of most private industries, but is critical to building a large-scale hydrogen economy.

8.6 Other Modes

This assessment focuses on the highest energy-consuming sectors, light-duty vehicles and heavy trucks, as described in Section 8.1. However, energy consumption by other modes is increasing, and the U.S. Energy Information Administration projects that while energy consumed by all U.S. transportation will remain nearly flat from 2015 to 2040, the demand from trucks (medium and heavy duty), air, and off-highway modes will increase by 27%, 13%, and 15%, respectively.[65] By 2040, air, water, off-highway, and rail are projected to

Figure 8.16 Energy per Passenger-mile by Mode in 2002 and 2012 with Percent Change from 2002 to 2012 Shown Above the 2012 Bars[66]



* Passenger mile-weighted average of transit and commuter rail

** Commercial (certificated route) aviation, including domestic scheduled service and one-half of international scheduled service

consume the equivalent of 1.4, 0.4, 0.5, and 0.3 million barrels of oil per day, respectively. Therefore the technical potential for increasing the energy efficiency of these modes and for the use of alternative fuel in these modes is worth consideration.

The energy efficiency of passenger travel—as measured by energy per passenger-mile—by non-highway modes has increased in recent years, particularly for air and rail, as shown in Figure 8.16. Potential future improvements in energy efficiency of non-highway modes for both passenger travel and freight movement are discussed below in terms of energy intensity (EI) improvement, which comprises technology and operational efficiency improvements in aviation, marine, pipeline, rail, and off-road transportation modes. EI is the energy per unit activity, where activity metrics are defined for each mode as described in the following sections. Though these modes are relatively understudied, especially in comparison to the highway modes discussed previously in this chapter, analysis has indicated that energy intensity improvements are possible, both through direct technology improvements (either by mode-specific R&D, or by spillover benefits from R&D in light- medium-, or heavy-duty vehicle research with analogous applications in these modes) or operational optimizations. The collected estimated possible improvements are summarized in Table 8.11.

8.6.1 Aviation

Aviation comprises 71% domestic, 19% international, and 10% general aviation. Aviation EI is computed as energy per revenue passenger-mile. Technologies that enhance aviation EI include improved compressor operation, geared turbofan engines, open rotor and/or high bypass ratio engines, reduced weight through increased use of composite materials, longer and thinner wings with truss-braced design, blended winglets to improve lift, and riblets to reduce turbulence and drag. By 2050, these technologies are projected to reduce EI by 40%–50%. Operational improvements that reduce EI include increased load factor and controlled airport approach, takeoff, and landing procedures (better air traffic management). Other long-term improvements—not likely to be introduced before 2030—are blended wing design (moving away from tube-and-wing design), high aspect ratio wings, laminar or hybrid laminar flow wing design, and slower cruise speed at high altitude. The projected EI reduction potential is 40% by 2035 and 65% by 2050 based on review of available literature.[68]

Aircraft engines can use petroleum jet fuel blended with two types of biofuels: hydro processed renewable jet fuel and pyrolysis jet fuel. American Society for Testing and Materials (ASTM) International has approved up to 50% blend of biofuels with petroleum jet fuel, which would complement efficiency benefits.[69]

8.6.2 Marine

Marine energy use in the United States is 82% for freight movement and 18% for recreation. The recreation energy consumption has varied little historically, and is not expected to change dramatically. Marine EI is computed as energy per ton-mile for domestic marine and energy per billion dollars of trade for international marine.

Table 8.11 Estimated Possible Energy Intensity Gains Through 2050 in Other Modes

	Aviation	Domestic marine	International marine	Pipeline	Rail	Off-road
Projected activity growth	156%§	-24%‡	484%Δ‡	40%‡	5%‡	15%¶
Business as usual energy intensity reduction	29%§	13%‡	87%‡	13%‡	22%‡	5%
Achievable energy intensity reduction	65%	20%	90%	25%	35%	15%
Net change	-10%	-39%	-42%	5%	-32%	-2%

§ FAA[67] projections extrapolated
‡ U.S. Energy Information Administration AEO 2014 projections extrapolated
Δ Growth in dollar value of trade (EIA)
¶ Projected at half the population growth
Note: Net Change = (1+Activity Growth) * (1-EI Reduction) - 1

Technologies that improve existing domestic marine vessel EI include improved hull retrofit, scalloped aft ends, and streamlined support brackets for propellers. Additional improvement can be achieved through replacing old propellers with flattened ducted propellers and replacing old engines with newer, more energy efficient engines. New vessel EI can be improved with more efficient engines, optimized hull design, air lubrication, and diesel electric propulsion. Such technologies as whale-tail propulsion (a cylindrical wheel with blades that simulate whale-tail action to propel ships) and increased use of lightweight materials may have longer payback periods. Larger capacity barges would improve EI, but may not achieve widespread acceptance due to waterway limitations. A 20% improvement in domestic marine EI is possible by 2050.[70] Combined, these technologies have higher EI improvement potential, but because marine vessels have forty- to fifty-year service lives, the improvement potential is lowered.

Technological and operational changes would improve international marine EI. Operational changes include reduced speed (slow steaming), route planning, use of on-shore energy sources for hotel power while at ports (cold ironing), vessel load management, traveling at steady power, optimizing propeller pitch and rudder management, and ballast management. Technological changes include optimized vessel design, use of lightweight materials, transverse thruster openings, coatings that reduce friction, bulbous bows, optimized propeller designs, efficient engines, engine waste heat recovery, and use of sails and Flettner rotors. These measures are estimated to improve international marine energy intensity by 90%.[71]

Marine engines can use petroleum fuels blended with such biofuels as pyrolysis and Fischer-Tropsch diesels. Marine engines can also operate on liquefied natural gas (LNG). However, the existing engines would require retrofitting to operate on LNG.

8.6.3 Pipeline

Natural gas pipelines use natural gas and electricity to transport natural gas, while other pipelines use electricity. Natural gas pipelines used 0.69 quads of natural gas and 0.01 quads of electricity in 2010, while other pipelines used 0.07 quads of electric energy.[72] Natural gas pipeline EI is computed as energy per thousand cubic feet.

Pipeline EI can be improved by replacing older less efficient natural gas internal combustion engines and compressors with new and more efficient units. Also, new pipelines would use more energy efficient engines and compressors. The estimated EI improvement potential for pipelines is 15% by 2030 and 25% by 2050, both over the 2010 value.[73]

8.6.4 Rail

Rail energy is used 16% by passenger and 84% by freight rail. The freight rail energy intensity is measured as energy per ton-mile. Freight rail energy intensity has been halved since 1980[74] through more efficient locomotives, changes in commodity mix, longer trains (more cars per train with better use of motive power), increased use of longer unit trains with higher-capacity rail cars, and improved operation. The mode is continuously improving with more locomotives equipped with alternating current (AC) motors. AC motors provide more adhesion and tractive power at low speeds, making it possible to use fewer locomotives. New locomotives also use the latest diesel engine technology, which has higher thermal efficiency. Rail lubrication and steerable (or radial) trucks (in rail, trucks are the frame that holds the wheelsets) can also reduce friction and improve energy intensity. Operation-related improvements include system wide acceptance of electronically controlled pneumatic brakes and positive train control. The rail mode has potential to achieve a 17% improvement in energy intensity by 2030 and a 35% reduction by 2050, both relative to 2010.[75]

At present, a majority of passenger rail energy consumption is for local travel by transit rail (51%) and commuter rail (34%). However, intercity high-speed rail has potential to divert passengers from light-duty vehicles and aviation in congested corridors. The energy intensity of high speed rail, measured as energy per passenger-mile, would depend on its load factor, so it is difficult to project high speed rail's EI advantage. However, it could be 25%–50% lower than low-occupancy light-duty vehicles and short-range air travel.[76]

Rail locomotives can use petroleum diesel blended with pyrolysis diesel and Fischer-Tropsch diesel. Locomotives can also operate on LNG. However, existing locomotives will require retrofitting to operate on LNG. Hybrid locomotives that store energy from braking or downhill travel for onboard use have been demonstrated but are not yet widespread.

8.6.5 Off-Road

Off-road equipment comprises primarily construction and mining (37.5%), agricultural (23.4%), lawn and garden (15.3%), and industrial (14.8%) equipment, with an additional 9% accounted for by other categories. Fuel consumed is typically diesel (69%), gasoline (22%), LPG (8%), or CNG (<1%). The total energy use by off-road equipment is approximately 2.4 quads. Off-road equipment EI is computed as energy per hour of operation. Off-road petroleum is often not counted in transportation because fuel used is not subject to motor vehicle taxes, but technologically, the equipment is somewhat similar to on-road, heavy-duty transportation.

Major off-road equipment manufacturers are researching technologies that would improve energy intensity of off-road equipment. John Deere has introduced hybrid electric lawn equipment[77] and a front-end loader for commercial use,[78] while Caterpillar has introduced a hybrid electric excavator.[79] Vyas and colleagues[80] estimated that a 15% improvement in off-road energy intensity was possible by 2050, decreasing petroleum use and GHG emissions per hour of service.

As with highway vehicles, off-road equipment can use bio-based or alternative fuel diesel substitutes to complement efficiency.

8.7 Vehicle Automation

Vehicle automation refers to the ability of a vehicle to operate with reduced or without direct human operation. Using a combination of advanced sensors and controls, sophisticated learning algorithms, and global positioning system and mapping technologies, demonstration vehicles have been able to operate in varied environments and over long distances with a human driver present but not operating the vehicle. This new technology has led to speculation that automation could enable dramatic changes to the transportation system, with a focus on improved safety, reduced congestion, and novel services and business models. However, automation of the transportation system may also have dramatic effects on transportation energy use. While the final effects will depend on an enormous variety of behavioral factors, system effects, and policies, early estimates point to a wide range of possible outcomes. If only the energy benefits of automation manifest, there is the potential for a dramatic improvement in vehicle petroleum use and greenhouse gas emissions, but unintended consequences could reduce or even reverse those benefits.

The U.S. Department of Transportation defines automated vehicles[81] as "those in which at least some aspects of a safety-critical control function (e.g., steering, throttle, or braking) occur without direct driver input." Autonomous vehicles are the subset of automated vehicles where self-driving operation is possible. The term "Connected and Automated Vehicles" (CAV) represents a broader category of vehicles with advanced information technology functionality. Connected refers to the ability of vehicles to communicate with each other ("vehicle-to-vehicle," or V2V), or with the physical infrastructure, ("vehicle-to-infrastructure," or V2I).

The National Highway Traffic Safety Administration (NHTSA) has defined five levels of automated vehicles (AV) functionality, ranging from no AV features (Level 0) to full automation without the need for a human driver (Level 4). Levels 1 and 2 are defined as more limited AV capability, including lane assist, adaptive cruise control, and collision avoidance technology, either operating independently (Level 1) or in unison (Level 2). Level 3 refers to limited automation, enabling "the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions," but expecting the driver "to be available for occasional control" with adequate warning. The Society of Automotive Engineers[82] has expanded these definitions to include Level 5 (full automation without driver controls).

Automation requires a confluence of sensors, automotive technologies (such as drive-by-wire), and information technology such as machine learning and processing of large datasets. Although work on automation has been conducted in academic labs since at least the 1980s, the modern fully-automated vehicle has roots in a series of Defense Advanced Research Projects Agency "grand challenges" from 2004 to 2013 that required teams to build vehicles that could navigate a desert or urban course with no human intervention based on a suite of novel technologies:

- **Cameras,** which are mounted on various locations to identify and monitor terrain, traffic signals, road markings, identify pedestrians, cyclists, other vehicles, and inanimate obstacles.
- **Radar,** which is often mounted on the front and rear bumpers for detection and range finding of faraway objects.
- **LIDAR,** a portmanteau of light and RADAR, which uses spinning lasers in a radar-like application. It is mounted on the roof of the car and scans a wide radius to precisely measure the distance to nearby objects and map physical terrain.
- **GPS units,** which use data from satellites to determine vehicle location that are then compared to detailed maps of physical features, known hazards, and lane and traffic structures.

Most major manufacturers that have announced CAVs have deployed some automation technology for safety, and are adding technologies to more models by 2017. Some Level 3 systems are expected between 2017 and 2020. Google has announced plans to release a NHTSA-Level 4 (full AV) system by 2017,[83] and Tesla has announced its intention to do so by 2020.[84] Even with these announcements, researchers disagree by decades on if and when highly automated CAVs will become generally available, and how widespread they will become.

The most commonly cited potential benefits of CAVs are improved safety, reduced or more manageable traffic congestion, higher service quality, and availability of affordable transportation to those who are currently underserved. But automation is a key factor for the future of transportation energy as well. Researchers[85] have noted that there are a wide variety of possible effects of a highly automated transportation system, some of which are likely to be beneficial for energy, while others could increase energy demand.

Estimates of these effects and their possible interactions vary widely. Use intensity may increase (i.e., more travel, new passengers) or decrease (i.e., high-occupancy vehicles, less hunting for parking); energy intensity may increase (faster travel) or decrease (vehicle redesign, efficient driving and routing, and platooning); and fuel intensity may significantly decrease due to symbiosis with advanced alternative fuel technologies, such as PEVs or FCEVs. Early summary analysis implies that the energy implications of CAVs may be large, with cases ranging from more than a 90% savings in petroleum use and emissions if only benefits occur, to more than a 250% increase if only the fuel-increasing effects are manifested. Improvements to traffic systems and infrastructure management can reduce losses from congestion, but could also induce additional travel.

Freight technology can also benefit from automation. Platooning has been demonstrated to improve fuel economy 5%–10% in test hauls,[86] and routing and logistics can potentially be improved. However, automation by ground-based or air-based drones could enable cheap and rapid at-home delivery twenty-four hours a day, potentially increasing overall goods movement and energy use.

The future policy landscape for CAVs is highly uncertain at the federal and state level. Legal allowance of automated function, licensing for vehicles, and fault and insurance issues will all need to be worked out over time for long-term policy success. Technology will be a key part of these discussions, as the performance of the vehicles and their rate of safe operation is at the heart of each of these policy issues.

The energy implications of CAVs may also be shaped by current and future policies. Current fuel economy standards do not take the operation of the vehicle into account, so the rating of a vehicle would not be affected by either an efficient or inefficient driving algorithm.

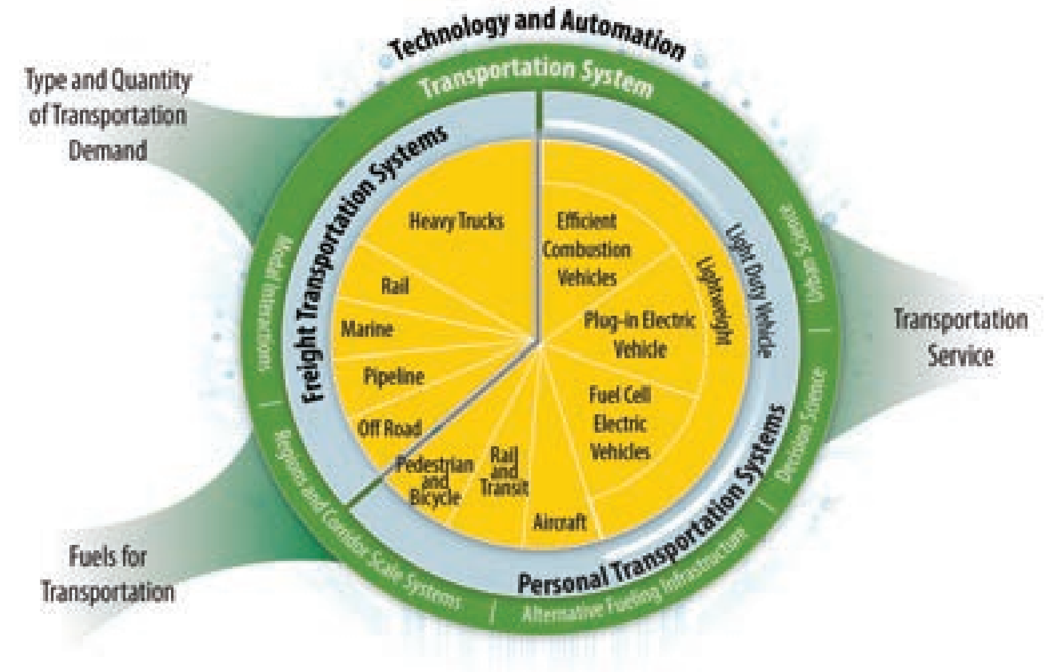
8.8 Transportation as a System

Transportation technology priorities should be considered in the context of the entire transportation system of the United States and with links to other energy systems. Effects of improvements to one technology or mode depend upon a complex web of interactions and interdependencies that can moderate or magnify effects estimated in isolation. Particularly when significant changes are targeted, such as deep reductions in greenhouse gas emissions and petroleum use, effects of technological change must be measured across the whole system. This systems approach considers the interactions and interdependencies, describing the boundaries, external influences, and internal characteristics. With an evolving social and urban landscape and dramatic new technology changes, the transportation system of the future may be significantly improved from today in ways that are challenging to forecast and will affect R&D priorities. Research in multi-scale modeling can allow linking of insights at the technology subsystem level, through technology systems, and all the way up to macro-scale issues and interactions. Additionally, the transportation system is within the mission space of a variety of federal, state, and local organizations, so strong collaboration around R&D topics can improve future outcomes.

Technological change can also provide new alternatives to meet service needs, for example, through information technology that substitutes for physical movement. Similarly, while current business models and technologies have developed together, technological changes could give rise to new opportunities, such as greater sharing of personal vehicles or increased flexibility in freight logistics. Historically, most transportation involved people or goods traveling from point A to point B in a single vehicle acting independently. Soon, nearly all vehicles, both personal and freight, will be able to receive and transmit massive amounts of data.

Because of the system's complexity, there are many ways to categorize and describe systems opportunities. This chapter addresses six system-related opportunities in detail which interact with progress in individual vehicle technologies (Figure 8.17): decision science, urban sciences, alternative fuels infrastructure, corridor or regional scale systems, and modal interactions, in addition to connected and automated vehicles (discussed in Section 8.7).

Figure 8.17 Transportation as a System of Systems. This schematic shows that the transportation system is a complex, nested system of systems that interacts with many other aspects of the economy. Its needs are defined by demand for services. Its inputs are fuels of various characteristics (discussed in detail in Chapter 7). And its output is the transportation service that moves the rest of the economy. The transportation system itself includes many modes and technologies with diverse characteristics for personal and freight movement, and is influenced by information technology and other overarching trends and factors.



Each of these areas can be addressed through tool development, visualization, analysis, system integration, and potentially technology R&D and enabling policies. They will also be enabled by investment in basic science and advanced modeling capabilities, which can support research across the transportation portfolio. The specific areas addressed here are given as key examples and a strong ongoing systems analysis will allow better identification of future needs to capture energy system improvements.

Decision Science

On the demand side, non-technology human factors, including consumer (vehicle purchase) and driver (vehicle use) behavioral considerations play important roles in determining real-world effectiveness of vehicle technologies. One of the biggest uncertainties in the development of a future transportation system is how behavior will change in reaction to the new technologies and new system paradigms. For example, to what extent will reduced marginal costs of travel result in increased travel (the rebound effect)? It will be critical to understand how to make transportation systems effective, especially since cost competitiveness of clean transportation technologies alone is insufficient for widespread adoption; consumer behavior is a key barrier.[87]

Specific considerations about consumer and driver preferences and behavior could benefit significantly from recent and near-term advances in information technology and resulting data from vehicles. As transportation systems are increasingly connected, they can generate vast amount of data in real time. When combined with other equally vast data sets from other sources, such as intelligent infrastructure, and processed quickly enough to provide information back to vehicles and travelers this enables real-time decision making to maximize vehicle and route efficiency.

Additionally, information technology may have a significant role to play in facilitating travel behavior and demand reduction, enabling a variety of substitutes for transportation, creating feasible mechanisms to address certain transportation market failures, and increasing time and energy efficiency. A wide range of activities previously requiring travel can now be accomplished via the Internet, ranging from telecommuting/teleworking to Internet-based public services and Internet commerce, though these may induce other travel, such as commercial delivery, or other energy use. Information technology could serve a role in allowing better management of externalities, such as the opportunity for improved pricing of transportation resources, especially the roadway network. Significant changes in per-capita personal vehicle travel could occur, either the logical result of an improved set of alternatives based on information technology, decision tools, alternative modes, and changes in urban form, or the unexpected result of changing demographics. Scenarios for a 25% reduction in per-capita vehicle miles of travel by 2050 have been explored in the context of deep GHG emissions reductions.[88]

Urban Sciences

The world, including the United States, is becoming more urban as part of a long trend toward city living. This may influence areas of focus within the R&D portfolio and is in itself a topic for research as it has significant energy implications. Cities with smart infrastructure and thoughtful design appear to require less energy use for transportation. On longer time scales, new transportation systems will also affect the choices of where to live and work, which, in turn, will drive the evolution of future cities.

Research could enable advancements in the following areas:

- **Integrated and optimized design, planning, and operation:** Tools to optimize zoning, building design, transportation design, and operation with water and energy delivery and city operations
- **Models and analytics:** New city-scale computational models calibrated and validated by sensor and operational data and frameworks and analytical tools for composite models of urban components
- **Sensors, measurements, real-time data:** To enable real-time optimization of traffic and individual vehicles, building energy use and delivery based on conditions

Alternative Fueling Infrastructure

Many advanced vehicles require different fueling infrastructure than conventional vehicles, such as charging for PEVs and hydrogen supply for FCEVs. A lack of or sub-optimal distribution of that infrastructure is likely to be a barrier to alternative fuel vehicle adoption. A smart fueling infrastructure that can best allow use of low-carbon energy sources when they are available can also decrease the emissions of the transportation fleet. Information technology and a smart infrastructure can also enable users to find and easily interact with fueling systems; for example, by locating and finding the status of stations. Additionally, different vehicles and infrastructures may be best suited for deployment in different geographic regions, so linking to corridor and local planning (see below) can support deployment. More discussion of fuel supply can be found in Chapter 7.

Corridor and Regional Scale Systems

In transportation, most infrastructure is planned, funded, and maintained locally or at the regional level. More municipalities are working together to systematically plan transportation investments using more sophisticated tools. There may be significant opportunity to improve the energy and emissions performance of the transportation system if better tools can be developed and used to include these factors. Because of the geographic, economic, and cultural diversity of the United States, different strategies are likely to be more successful in different regions. R&D can provide tools to improve planning of infrastructure for successful expansions of new technologies, thereby reducing investment risk and increasing energy and environmental benefits.

Modal Interactions

For passenger and freight transportation, different modes have very different energy intensity and service characteristics (see Section 8.6). Choice of mode depends on a wide variety of technological, system, and social factors. Examples of influencing factors for mode choice include legislative and regulatory constraints, policy and incentives, trip time, cost (variable and capital), capacity (occupants and cargo, as well as system), reliability, availability, environmental considerations, convenience, and personal space. With so many interacting factors, to facilitate better understanding of mode choice and the energy implications requires research.

Understanding of the modal interactions can also support R&D portfolio planning. For example, technologies developed for one application (such as advanced diesel engines for heavy trucks) can in many cases also benefit other applications (such as off-road equipment). Information technology presents opportunities for logistical advances that can change time and energy performance through improved integration of personal transportation modes with mass transportation, improved freight logistics, and information technology-enabled vehicle sharing or novel business models for providing transportation services.

Interactions with Other Systems

The transportation system features extensive interdependencies with many other sectors of the economy, including transportation demand-inducing activities of individuals and businesses, economic effects on the type and quantity of transportation supply, and various energy systems. Individuals influence the quantity of personal transportation needed through their decisions about where to live and work, where to pursue educational and leisure activities, and where and how to purchase household goods. Businesses influence commercial transportation demand through their locations, manufacturing supply chains, shipping of finished goods, and delivery of goods and services to customers. Other economic sectors influence the type and quantity of transportation supplied; for example, through the costs of the raw materials used for fuel, vehicles, and infrastructure. Transportation interacts dynamically with energy systems for electricity, energy storage, and heating. Interactions between the transportation system and other systems are discussed in Chapter 2. The fuel system, discussed in detail in Chapter 7, links the transportation system to other economic sectors, and includes extraction, processing, distribution, and use of fuels for transportation. While primarily based on petroleum today, technological changes are improving other options that include biofuels and the energy carriers electricity and hydrogen.

8.9 Conclusion

Transportation provides essential services to individuals and to the economy but is the primary user of petroleum in the United States and a major emitter of air pollution and greenhouse gases. There are numerous technology RDD&D options to address these challenges spanning the transportation system. These include light-duty vehicles, trucks, rail, marine, aircraft, pipelines, and transportation system considerations. This assessment focuses on the light-duty vehicle and heavy-duty truck modes as top priorities as these modes currently account for approximately three quarters of transportation energy use and emissions. However, other modes and crosscutting system effects are also addressed because their importance is likely to grow as progress reduces the impacts of now-dominant modes. Additionally, a systems perspective is increasingly important in research portfolio planning and the Quadrennial Technology Review (QTR) addresses opportunities to leverage greater improvements through systems considerations.

To address energy security and economic challenges, pathways to reduce oil imports and oil use are needed across the transportation sector to increase viable substitutes and expand consumer options, which can provide a hedge against price volatility. To dramatically reduce GHG emissions, a larger share of vehicles must efficiently use fuels or power with no on-board carbon-based fuel (or produced from bioenergy) as it is not possible to capture and store onboard carbon dioxide emissions from small, mobile sources. The QTR presents a set of complementary technology opportunities that together inform a possible integrated R&D strategy for GHG emissions reduction involving efficiency improvement, electric drivetrains, renewable fuels, and transportation system efficiencies. Dramatic improvements throughout the system will be necessary to achieve national goals for petroleum use and greenhouse gas reductions. This urgency implies that a coordinated, sustained, and continually improving transportation R&D portfolio is a vital component of the national energy agenda.

Chapter 8: Advancing Clean Transportation and Vehicle Systems and Technologies

Technology Assessments

[See online version.]

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