MESSAGE FROM THE SECRETARY OF ENERGY

Today, our nation is at a cross road. While we have the world's greatest innovation machine, countries around the world are moving aggressively to lead in the clean energy economy. We can either lead in the development of the clean energy economy or we can stand back and wait for others to move first toward a sustainable energy future. For the sake of our economic prosperity and our national security, we must lead. The Department of Energy (DOE) plays a central role in that effort by unleashing technological innovation, which can create new jobs and industries while building a cleaner, more efficient, and more competitive economy.

During this time of hard budget choices and fiscal challenge, we must ensure that our work is impactful and efficient. The question we face is: “How should the Department choose among the many technically viable activities it could pursue?” This first Quadrennial Technology Review (QTR), launched at the recommendation of the President's Council of Advisors on Science and Technology, lays out the principles I believe must guide these difficult choices.

Traditionally, the Department's energy strategy has been organized along individual program lines and based on annual budgets. With this QTR, we bind together multiple energy technologies, as well as multiple DOE energy technology programs, in the common purpose of solving our energy challenges. In addition, the QTR provides a multi-year framework for our planning. Energy investments are multi-year, multi-decade investments. Given this time horizon, we need to take a longer view.

We also recognize that the Department is not the sole agent of energy transformation. Our efforts must be well coordinated with other federal agencies, state and local governments, and with the private sector, who are the major owners, operators, and investors of the energy system.

This Report specifically places our efforts in a multi-agency policy framework. While the Department’s QTR is not by itself an integrated federal energy policy, I believe it is the necessary first step of a multi-agency Quadrennial Energy Review that could dramatically improve the integration and effectiveness of the government's energy policy.

Finally, I would like to commend and thank Under Secretary for Science Steven Koonin for leading this inaugural review. He and his dedicated team sought advice from hundreds of energy stakeholders; engaged experts from academia, industry, and national laboratories; and consulted with our agency counterparts from across the government. As part of the Obama Administration's commitment to open government, the Review was conducted transparently and inclusively. It establishes a firm foundation upon which we can make significant progress in addressing our Nation's energy challenges.

The stakes are high for our country, and I am optimistic that we can still lead the world in technological innovation. The QTR will help ensure that we make thoughtful, wise investments to achieve our national energy goals and to strengthen our economic competitiveness in the 21st century.

Steven Chu
Secretary of Energy
Different Fuels for Different Uses

Fossil fuels currently provide 83% of U.S. primary energy, with almost all coal (93%) used for power and most oil (72%) used for transport. Natural gas (methane) is a flexible fossil fuel that is used for power and heat across multiple sectors of the economy (industrial, commercial, and residential), as well as for chemicals production. Petroleum-derived liquids (gasoline and diesel) are the near-exclusive fuel of transport, while many sources beyond fossil fuels are used to generate electricity, most significantly nuclear fission (20% of electricity) and hydropower (6% of electricity). Today, other renewable sources supply less than 4% of U.S. electricity, mainly wind (2%) and biomass (1%); however, wind generation in 2012 will be about 150% larger than it was in 2008.

Electricity and heat (produced on-site from natural gas) are the principal forms of energy used by the residential and commercial sectors, about 40% of U.S. primary energy consumption. The industrial sector, supplied by diverse feedstocks, consumes another 30% of the Nation’s energy. New energy technologies to supply those stationary energy consumers must compete against an existing infrastructure that delivers energy reliably and at a low cost.

Figure 1. U.S. Energy Flows in 2009

Values are in quadrillion British thermal units. Total energy input is approximately 95 Quads. EIA data as portrayed by Lawrence Livermore National Laboratory.
Improve vehicle efficiency is the most effective short-term route to reduce liquid fuel consumption. Today's technologies allow new vehicles to be twice as efficient as those they replace, while retaining the same consumer characteristics. Fully compatible with current fuels and infrastructures, efficiency improvements could save some 2 million barrels a day within a decade. For comparison, multi-decadal efforts have built Gulf of Mexico offshore oil production to 1.6 million barrels per day and U.S. corn ethanol production to 0.8 million barrels per day gasoline equivalent.
The performance of new vehicles has improved steadily over the last decades, even as fuel economy remained largely unchanged.\textsuperscript{103}

Light-duty vehicle fuel economy remained largely unchanged between 1980 and 2005 (Figure 8). Improvements in engine efficiency during this time were dedicated to increasing vehicle size, features, and performance, as opposed to improving overall vehicle fuel economy.

The primary drivers of fuel economy are the CAFE and GHG tailpipe emissions regulations established by DOT and EPA. In May 2009, the Administration increased passenger car CAFE standards for the first time in 25 years. The standards are currently set through 2016, with further increases through 2025 announced.\textsuperscript{104} For new passenger cars, the standards rise from 27.5 miles per gallon (mpg) in 2010 to 39 mpg in 2016; for light trucks, standards rise from 23.5 mpg in 2010 to 30 mpg in 2016.\textsuperscript{105,106} The first standards of this kind for medium- and heavy-duty vehicles were published in August 2011.\textsuperscript{107} While some portion of the increase in fuel economy will be met through hybrid technologies (primarily in the light-duty vehicle fleet), the increased efficiency of conventional vehicle components can also contribute substantially to improvements in fuel economy.
Figure 9. Projected Reductions in the Fuel Consumption of Large Cars and Small Trucks through Technology

The projected costs and impacts of various technologies are shown. Large cars and small trucks (including sport utility vehicles, pickups, and minivans) comprise nearly 60% of the light-duty fleet. The multicolored lines are National Research Council (NRC) data adapted by a National Petroleum Council study committee, while the triangles are from a joint study by the Environmental Protection Agency (EPA) and National Highway Transportation Safety Administration (NHTSA).108

Figure 9 shows that a variety of technologies can increase vehicle efficiency. These technologies can be combined in various ways to achieve cost-effective fuel efficiency improvements. They provide varying crosscutting benefits for a range of vehicle types, sizes, and fuels (see Figure 10 for opportunities in heavy-duty vehicles). Many technologies are commercially available now, but there are opportunities to further reduce costs through innovation, manufacturing experience, and process improvements—collectively referred to as “learning.” The deployment of particular technologies will be determined by the market, which depends upon cost-efficiency tradeoffs and fuel economy, safety, and emission regulations. DOE can have the greatest impact in three efficiency technologies: greater efficiency of internal combustion engines (ICEs), reductions in vehicle weight (lightweighting), and improved aerodynamics.
Engine improvements and hybridization are the dominant efficiency opportunities for service and urban vehicles. Aerodynamics is important for highway vehicles. Heavy-duty vehicle types: Class 3–6 bucket truck, tractor trailer (TT), transit bus, Class 3–6 box truck, Class 8 refuse truck, Class 2b pickup or van, and motor coach. Potential fuel reductions are not additive.¹⁰⁹

Important differences between heavy-duty and light-duty vehicles shape the potential for deploying efficiency technologies. Heavy-duty and light-duty vehicles are subject to different standards and regulations. Heavy-duty vehicles are owned and operated by public and private organizations that have sensitivity to life-cycle costs and make efficiency an important market driver. In contrast, light-duty vehicles are purchased based on consumer preference, in which efficiency is only one factor, and are operated for personal convenience. Heavy-duty vehicles are more heavily used than light-duty vehicles, making operating expenses a larger fraction of the total cost of ownership. Diesel (primarily heavy-duty vehicles) and gasoline (primarily light-duty vehicles) engines also have different emissions profiles, and vehicle efficiency has been in tension with emissions reduction (particularly in diesels). Light-duty vehicles are generally more aerodynamic than heavy-duty vehicles, while heavy-duty vehicle engines are generally more efficient than light-duty vehicle engines. As a result, there is more headroom
for aerodynamic improvements in the heavy-duty vehicle market and more room for engine improvements in the light-duty vehicle market. The ratio of payload to vehicle weight is dramatically different in heavy-duty and light-duty vehicles, so that lightweighting has greater potential in light-duty vehicles. The limited number of technical options for heavy-duty vehicles motivates an intense focus on conventional efficiency improvements and fuel substitution.

**Internal Combustion Engine Improvements**

The performance, low cost, and fuel flexibility of ICEs makes it likely that they will continue to dominate the vehicle fleet for at least the next several decades. ICE improvements can also be applied to both hybrid electric vehicles (HEVs) and vehicles that use alternative hydrocarbon fuels. Historically, engine technologies have taken more than 20 years after first introduced to diffuse throughout the vehicle marketplace. This rate is faster for heavy-duty vehicles where fuel economy provides a business advantage to the vehicle's owner. New flexible manufacturing techniques will likely accelerate technology diffusion in light-duty vehicles; government regulations can accelerate the rate of technology diffusion for all vehicles.

Increased efficiency and reduced emissions of ICEs can be realized through technologies that improve engine design and better integrate systems, potentially doubling the fuel economy of light-duty vehicles and increasing heavy-duty vehicle fuel economy by 60%. In addition, the application of high-performance computing (HPC) and simulations to engine design can reduce the time and cost of integrating new technologies. As ICE technologies are proven and refined, the primary barriers to their adoption include cost, consumer acceptance, resource constraints, capital requirements, and turnover rates.

**Lightweighting**

The weight of a mid-size passenger car is typically evenly distributed among the powertrain, body, chassis/suspension, and remaining non-structural components. The maximum weight-reduction potential of the mid-size passenger car has been estimated to be 50% by 2050. The choice of materials for specific components is based on their material properties (i.e., strength, stiffness, elasticity, heat tolerance, and corrosion resistance), ease of manufacturing and cost.

For vehicles using conventional ICEs, a 10% reduction in vehicle weight can improve fuel economy by 6%–8%, while the same lightweighting of a battery-electric vehicle increases its range by up to 10%. Weight can be reduced through decreasing vehicle size, innovative chassis design, or by introducing light-weight (but structurally-appropriate) materials; consumer expectations make the latter two approaches more likely in the short term.
Cost is a significant barrier to vehicle weight reduction; there are also safety concerns about some measures. There are also tradeoffs with the embedded energy in advanced materials. The growing number of materials likely to be used in a single vehicle raises issues of advanced joining techniques and complexity in recycling, which adds manufacturing and capital costs.

Aerodynamics
As a vehicle’s frontal area increases and average speeds exceed 45 miles per hour, aerodynamic drag tends to dominate vehicle efficiency. Aerodynamics therefore has a large impact on vehicles with a large frontal area and highway-dominated driving patterns in large-vehicle classes, such as tractor trailers, pickups, sport utility vehicles, and passenger vans.

Better aerodynamics could improve on-road truck fuel economy by more than 10%; they require a combination of modeling and real-world validation. The headroom for passenger cars is much smaller due to the smaller frontal area, a drive cycle not dominated by highway driving, and current light-duty vehicle designs that are already quite aerodynamic.

DOE Activities
Increases in fuel economy, and therefore vehicle efficiency, are primarily driven by regulations established by agencies other than DOE. DOE provides technical support to EPA and DOT in setting CAFE and GHG standards, as well as providing information to consumers and the vehicle industry.

DOE works closely with industry to help develop next-generation technologies to further improve vehicle efficiency. DOE’s laboratories are home to unique capabilities for engine R&D. For example, DOE provides facilities for combustion science and technology, and DOE’s HPC facilities are used for ICE and aerodynamics research.

DOE supports pre-competitive vehicle efficiency R&D at its laboratories, universities, and through public-private partnerships. The structure of the vehicle industry, with a few large original equipment manufacturers and a large number of competing and specialized suppliers, is conducive to working with consortia.

DOE will strive to balance its vehicle efficiency R&D efforts between technical issues faced by light-duty and heavy-duty vehicles. While light-duty vehicles are responsible for a larger fraction of national fuel consumption, they are more easily electrified than heavy-duty vehicles. The more limited technical options for heavy-duty vehicles motivates an intense focus on conventional efficiency. Within the vehicle efficiency portfolio, ICE improvements will receive the greatest emphasis. This is both because it contributes to light-duty and heavy-duty vehicle sectors and because DOE’s capabilities are well-aligned with the field’s technical needs.
Smart Truck

Long-haul trucks play a major role in keeping the Nation’s economy moving, carrying 75% of all U.S. freight and supplying 80% of all U.S. communities with all of their consumables. However, these trucks average 6 miles per gallon and emit some 423 million tonnes of carbon dioxide per year. BMI Corporation, an engineering firm in Greenville, South Carolina, teamed up with the Department of Energy’s Oak Ridge National Laboratory to tackle long-haul truck’s efficiency and environmental challenges. Utilizing Oak Ridge’s Jaguar supercomputer, they developed a new “SmartTruck” that has higher fuel efficiency.

Among the technologies simulated on Jaguar is BMI’s Trailer UnderTray System. The system included a variety of fuel-saving components, such as aerodynamic wheel fairings, a special sled that attaches to the axels to direct airflow under the suspension, and a rear diffuser to optimize air flow and boost fuel efficiency. Through simulation, BMI showed that retrofitting existing trucks with advanced components like the Trailer UnderTray will improve current fuel efficiencies by nearly 12%, with the potential of making future advanced trucks up to 50% more efficient.

Courtesy: Oak Ridge National Laboratory

Simulated air flow around a heavy-duty vehicle. The turbulent flow between the tractor and the trailer and the vortex underneath the tractor increase drag and therefore fuel consumption.
Interagency Coordination

To accelerate the adoption and diffusion of innovative vehicle technologies, DOE works closely with DOT and EPA, agencies responsible for setting federal fuel economy standards. As a complement to making vehicles more efficient, both agencies also encourage improvements to urban planning and traffic management that can increase the efficiency of vehicle operations. The National Institute of Standards and Technology (NIST), as part of DOC, encourages interoperability among innovations in the automotive sector through work on standards. Multiple federal agencies also share responsibility for a variety of safety and environmental issues unique to the transportation sector, and intergovernmental engagement with state and local governments is vital to implementation. Table 1 illustrates the diversity of federal agency engagements to support innovation in vehicle technology, ranging from crash-testing ratings to vehicle procurement.

Table 1. Summary of Non-DOE Federal Agency Activities in Vehicle Efficiency with Examples

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<th>Department/Agency</th>
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<th>Regulation</th>
<th>Finance</th>
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<td>Defense</td>
<td>Tank Automotive Research, Development, &amp; Engineering Center (TARDEC)</td>
<td>Procurement</td>
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<td>Clean Automotive Technology Program</td>
<td>Corporate Average Fuel Economy (CAFE) Standards</td>
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<td>Fuel Economy Labeling</td>
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<td>Transportation</td>
<td>Federal Highway Administration (FHWA) Exploratory Advanced Research Program</td>
<td>National Highway Transportation Safety Administration (NHTSA)</td>
<td>Transportation &amp; Climate Change Clearinghouse</td>
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