Review of the U.S. Department of Energy's Heavy Vehicle Technologies Program

Committee on Review of DOE's Office of Heavy Vehicle Technologies
Board on Energy and Environmental Systems
Commission on Engineering and Technical Systems
National Research Council

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This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report: Gary Borman, University of Wisconsin (retired); Norman A. Gjostein, University of Michigan, Dearborn; Jason Mark, Union of Concerned Scientists; John P. McTague, Ford Motor Company (retired); Vernon Roan, University of Florida; Dean P. Stanley, Navistar International (retired); C. Michael Walton, University of Texas.

While the individuals listed above have provided constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

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The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy oversees the Office of Transportation Technologies, which includes the Office of Heavy Vehicle Technologies (OHVT), the Office of Advanced Automotive Technologies (OAAT), the Office of Fuels Development, and the Office of Technology Utilization. OHVT was created in March 1996 when the Office of Transportation Technologies was reorganized. Its sister organization, OAAT, focuses on the development of advanced automotive technologies, while OHVT focuses, for the most part, on technologies for trucks. The mission of OHVT is "to conduct in collaboration with our heavy vehicle industry partners and their suppliers, a customer-focused national program to research and develop technologies that will enable trucks and other heavy vehicles to be more energy efficient and capable of using alternative fuels while simultaneously reducing emissions."

Fuel use for all classes of trucks is increasing faster than for automobiles. If current trends persist, fuel consumption in 2020 will be approximately 4 million barrels (bbl)/day (oil equivalent) for automobiles, 4.5 million bbl/day for Class 1 and 2 trucks (pickup trucks, vans, sport utility vehicles [SUVs]), and about 3 million bbl/day for Class 3 through 8 trucks.[1] By 2020, therefore, trucks will dominate on-highway fuel consumption, consuming about twice as much fuel as automobiles in the United States.

As national priorities have been focused both on reducing fuel consumption and improving air quality, attention has increased on reducing emissions from many types of vehicles, including light-duty, medium-duty, and heavy-duty diesel-powered vehicles. Meeting the recently promulgated (and proposed) emission standards and simultaneously increasing fuel economy will pose especially difficult challenges for diesel-powered vehicles and will require the development of new emission-reduction technologies.

In response to a request from the director of OHVT, the National Research Council formed the Committee on Review of DOE's Office of Heavy Vehicle Technologies to conduct a broad, independent review of its research and development (R&D) activities. This Executive Summary includes the committee's major findings and recommendations. Findings and recommendations for specific technical programs can be found in the body of the report.

MAJOR FINDINGS AND RECOMMENDATIONS

The committee recognizes that the managers of the OHVT program have many constraints on how they can distribute resources for research. Laws passed by Congress related to the program must be implemented; fuel prices or emission or safety standards may change; and policies can be changed, which might require that programs be reoriented. In light of these constraints, the committee focused on recommendations for improving the chances that the technologies under development will meet the goals of the program and, in the long term, will be commercially successful.

To date, OHVT has responded responsibly to congressionally mandated legislation. In addition, OHVT follows the legislative process closely and has provided Congress with the technical information it needs to make reasonable decisions. The committee applauds cooperative activities with other DOE programs and the Environmental Protection Agency (EPA) to address the issue of sulfur levels in diesel fuel. OHVT has also successfully reached out to its stakeholders and industry to identify needs and develop a technology road map to meet the challenges facing heavy-duty diesel-engine technologies and leverage its budget. In the past year, OHVT has also made a significant effort to reach out to other stakeholders and industries that are important to

[1]The gross vehicle weight of Class 1 trucks is 6,000 lbs or less; Class 2 trucks range from 6,001 to 10,000 lbs; Class 3 through Class 8 trucks weigh more than 10,001 lbs.

the trucking industry. The committee commends OHVT on its systematic approach to its R&D program.

As a result of outside constraints, such as stakeholder interests and the congressional budget process, OHVT has changed the focus of its research in several areas toward shorter term development. Funding for R&D in fiscal year 1999 reflects this change: 72 percent for projects by industry; 18 percent for projects at the national laboratories; 4 percent for projects at universities; and 6 percent for projects by others (e.g., small businesses, states, etc.). Nevertheless, OHVT has documented, and the industrial experience of committee members suggests, that because it takes approximately eight years from the start of a research program to the appearance of its results in commercial production, long-term interests of the United States would be best served if OHVT directs most of its R&D toward long-term goals. A Go/No Go decision-making framework for planned R&D would make it easier for OHVT to set priorities and reorient programs in response to changing circumstances to keep them focused on longer term program goals.

As multinational corporations expand, international trade increases, and global transportation knits the global economy together, industry will increasingly operate in a global marketplace. At the same time, the cost of petroleum is expected to increase, although it is difficult to predict how much or how quickly, and transportation costs will remain a significant factor in production costs in modern economies. Transportation emission standards in the industrialized world are becoming more stringent in general, although there are no uniform global emission standards or test procedures for vehicles. Therefore, the trade-off of reducing fuel economy to meet new emission standards will become increasingly important. Thus, emission standards and global competitiveness are related both to the cost of moving goods and the cost of importing and exporting vehicles. To maintain the competitiveness of U.S. industry, and because emission standards are government mandated, government and industry must work together to achieve optimum levels of fuel consumption and environmental standards.

Finding 1. Energy and environmental policies, as well as emission standards, are continually changing in response to factors beyond the control of the Office of Heavy Vehicle Technologies (OHVT). Consequently, goals, objectives, and timetables for research and development (R&D) can become outdated. For example, an R&D program designed to achieve lower emission levels will be of little practical use for initial production vehicles unless the R&D is completed significantly in advance of new standards (i.e., in time for the results to be used in production vehicles). (However, new technologies could be brought on line for later vehicle models.)

Recommendation 1. The Office of Heavy Vehicle Technologies (OHVT) should modify its program goals to reflect a time horizon of eight years or more. The longer time frame would allow industry time to incorporate research results into products, universities to contribute more significantly to solving problems, and OHVT to adjust the balance of its resources to support research by industry, the national laboratories, and universities.

OHVT should revise its existing programs to ensure that the basic technical information produced by individual programs will be available at least three years before the technology is scheduled for commercial production. The revised mix of programs, which should be implemented by fiscal year 2003, will shift the emphasis to new advanced technologies and away from near-term development.

Finding 2. Both light-duty and heavy-duty vehicles will require improved energy efficiency with minimum adverse environmental effects and competitiveness in a global economy. Meeting these often-conflicting goals will require that government and industry work together. The Office of Heavy Vehicle Technologies (OHVT) is successfully working with industry and other stakeholders to meet these challenges. However, the committee did not see much evidence that OHVT has established a Go/No Go decision-making process for evaluating and dealing with technical show-stoppers at critical milestones.

Recommendation 2. Office of Heavy Vehicle Technologies (OHVT) programs should be updated annually, and program strategies and priorities should be reassessed. New programs should have a long-term focus. In addition, OHVT should implement a Go/No Go decision-making framework to keep OHVT programs focused on program goals, to establish or modify priorities and to change directions, as necessary.

The diesel engine is the most efficient, economical power plant available today for trucks. As integrated emissions-control technology advances, the diesel engine can be increasingly optimized to its duty cycle. From the perspective of efficiency, and therefore fuel savings, the diesel engine could play a key role in reducing the rate of increase of petroleum use in the United States. However, the fuel economy benefit of the diesel engine will not be realized unless emission standards can be met. With present technologies, both the gasoline engine and the diesel engine will require exhaust-gas after-treatment to meet the projected emission standards for 2007–2010. Therefore, OHVT programs must be sharply focused on meeting future emission standards.

Finding 3. The most critical barrier to improving fuel economy is the emission of oxides of nitrogen and particulate matter. Current activities are spread across too many areas and not focused on overcoming this critical barrier. Given the available resources, a smaller number of carefully chosen projects would be more productive.

Recommendation 3. The Office of Heavy Vehicle Technologies (OHVT) should reevaluate its priorities and increase its support for projects focused on overcoming the most critical barriers to success. For example, meeting emissions standards will be critical to OHVT's program on advanced combustion engines. Therefore, emissions should be a major focus of this program. In addition, OHVT must be more proactive and forward thinking in anticipating future emission standards and should focus on improving the understanding of physical and chemical characteristics of emissions. In anticipation of more stringent emissions standards than are currently planned by the Environmental Protection Agency, OHVT should undertake technology-forcing research.

To meet future emission standards, particularly for oxides of nitrogen (NO_x) and particulate matter (PM), some proposed exhaust-gas after-treatment technologies will require a low sulfur fuel to improve NO_x conversion efficiency. Sulfur compounds in the exhaust gas may also contribute to the formation of ultrafine exhaust particles. Automotive manufacturers prefer very low levels of sulfur (5 parts per million [ppm]) to benefit automotive emissions-control systems; the petroleum industry has suggested a standard of 30 ppm (average) and a 50 ppm (maximum) limit to control increases in fuel costs and avoid supply problems. EPA has a proposed regulation for sulfur concentration in diesel fuel of 15 ppm.

Finding 4. Regulations are being considered to reduce the levels of sulfur in fuel used for on-highway diesel vehicles. The sulfur levels for some current after-treatment technologies, such as NO_x traps, will have to be very low and could require sulfur traps that would have to be changed periodically. Some technologies, such as selective catalytic reduction, are less sulfur sensitive but require the addition of a reductant (e.g., urea). Consequently, the economic trade-offs between sulfur levels in fuel and after-treatment technologies will be an important consideration in the development of cost-effective emission-control systems.

Recommendation 4. The Office of Heavy Vehicle Technologies should place a high priority on integrated emissions-control technology (engine combustion and after-treatment technologies) to meet future emission requirements. Research and development (R&D) should be focused on sulfur-tolerant catalysts, sulfur traps, and selective catalytic reduction, for diesel fuel with sulfur levels of 5 to 50 parts per million. R&D should be focused on both experimental work and modeling related to basic in-cylinder combustion and after-treatment technologies.

Because fuel consumption by light trucks and SUVs is increasing, "dieselization" for light trucks and SUV markets makes sense. Indeed, dieselization is a significant part of OHVT's program. However, if the diesel engine cannot meet emission standards, it will not be a viable alternative for this market segment. Although OHVT's program is focused on addressing the technical barriers to meeting emission standards with diesel engines, OHVT should also keep abreast of progress on other engine types that could meet emission standards more easily, although with poorer fuel economy (e.g., the gasoline engine).

Finding 5. The Office of Heavy Vehicle Technologies (OHVT) is actively involved in 50/50 cost-share projects with Cummins-DaimlerChrysler, Detroit Diesel-DaimlerChrysler, and Caterpillar-Ford to develop a competitive Class 2 diesel truck engine for use in sport utility vehicles (SUVs) and light trucks. OHVT's funding is being used to facilitate interactions between the heavy-duty engine industry and automotive manufacturers, and research on these projects is being done solely by the partnering companies. The proprietary results will be protected from public disclosure for five years. Therefore, the committee found it difficult to assess the scope and focus of OHVT's light-duty engine program. There was some indication, however, that one of the companies in the program is working on technologies that could be incorporated into hardware components for a Class 1 or Class 2 light-duty truck engine. The committee supports OHVT's promotion of industry research on promising, high-risk approaches to configuring engine emission-control systems that could facilitate the introduction of more fuel-efficient engines into the light-truck and SUV market. However, the committee does not endorse the use of OHVT funds to support specific engine or component development programs by industry.

Recommendation 5. The committee believes it appropriate for the Office of Heavy Vehicle Technologies (OHVT) programs to provide basic technical information (e.g., improved understanding of physical processes, new and/or improved system optimization and control techniques, etc.) that will promote more fuel-efficient engine-emission systems by the private sector for the light-truck and sport utility vehicle market. OHVT should evaluate the effectiveness of its 50/50 cost-share programs with industry to determine if they are creating needed basic information. OHVT should not support the development of a specific engine or component.

Some of the biggest improvements in the overall fuel efficiency of heavy-duty trucks can be achieved by improving aerodynamics, using lightweight materials, and decreasing rolling resistance. Aerodynamic losses for all trucks can be large (e.g., at 70 mph on a level road, roughly 65 percent of the power requirements are attributable to aerodynamic drag). For trucks limited by weight requirements (e.g., flatbed trucks), a decrease in vehicle weight would allow for an increase in payload weight. Therefore, large increases in material transport efficiencies, perhaps larger than can be made through improvements in engine performance, may be possible through decreases in aerodynamic drag, reductions in weight, and decreases in rolling resistance. However, new truck designs must also take into account the interaction of heavy trucks with roadways (e.g., the rate of damage from a fully loaded Class 8 truck is equivalent to that of 5,000 cars), as well as congestion and disruption to the transportation system from road repair.

Several factors should be taken into account in a systems view of fuel economy. First, double trailers (sometimes even triple trailers, although not allowed in all states) have different aerodynamics than single-tractor trailers and also different cargo-carrying capacities. Because they are heavier than single trailers, they consume more gallons of fuel per mile; however, because they can carry more cargo weight, the appropriate measure for the fuel economy of trucks carrying cargo should be ton-miles/gallon (ton refers to the weight of the cargo being transported).

Second, the driving duty cycle should be specified for all vehicles targeted for improvements in fuel economy. Without specified driving cycles, fuel economy goals are not very meaningful. OHVT has done this for Class 7 and 8 vehicles by specifying constant-speed driving at 65 mph, a very simple driving cycle. Third, the performance level of the vehicle must be indicated because fuel economy improvements can be made by sacrificing vehicle performance, and this trade-off should be included in an evaluation of the improvement.

Finding 6. Engine efficiency is a significant, but not the only, factor in increasing the fuel economy of heavy vehicles. The overall Office of Heavy Vehicle Technologies (OHVT) program is focused too heavily on improving engine efficiency and not enough on other factors that affect fuel economy. The committee recognizes that some of these factors may be outside OHVT's mission and that addressing them will require interagency cooperation.

Recommendation 6. The Office of Heavy Vehicle Technologies (OHVT) should focus more on factors other than engine efficiency that affect on-road fuel economy, especially improving aerodynamics, reducing the use of accessory power, decreasing rolling resistance, and decreasing unloaded vehicle weight by innovative design incorporating high-strength, weight-reduction materials (in keeping with safety considerations, as well as highway wear and tear). OHVT, in cooperation with other government agencies, should conduct an analysis to clarify the trade-offs and opportunities among engine efficiency and other factors affecting vehicle fuel economy and reorient its programs accordingly.

To achieve a 10-mpg fuel economy in Class 7 and 8 trucks, OHVT should monitor trends in installed engine power and steps the commercial market is taking to achieve this. Trip time may be a more economically important parameter than fuel economy. OHVT's analysis should include vehicle systems models to identify opportunities for improving the vehicle system that could lead to improvements in fuel economy. For each truck classification, the driving duty cycle associated with each fuel economy goal should be specified. In addition, OHVT should evaluate which measure of fuel economy, miles/gallon or ton-miles/gallon, is most appropriate for each class of vehicle. The expansion of OHVT's programs in this recommendation will require an increase in funding.

The most promising alternative to diesel fuel is natural gas. OHVT's program is now focused on urban trucks and buses with hybrid electric power trains, especially configurations that use natural gas. OHVT plans to work with competitively selected industry teams of hybrid-vehicle system developers and vehicle manufacturers. Because of the lack of an extensive infrastructure for natural-gas fueling stations, the focus will be on urban trucks and buses, which can more easily be fueled at central stations than privately owned vehicles. When comparing compressed and liquefied natural gas, vehicle energy consumption should be measured on a "well-to-wheels" basis.

Finding 7. The goals of the Natural Gas Vehicle Program include demonstrations of two natural-gas vehicles by 2004 that are competitive in cost and performance with their diesel-fueled counterparts. One will be a Class 3 to 6 vehicle that operates on compressed natural gas (CNG); the other will be a Class 7 or 8 vehicle that operates on liquefied natural gas (LNG). Three types of natural-gas engines have been proposed: the SING (spark-ignited natural gas), the PING (pilot-injection natural gas), and the DING (direct-injection natural gas). The size, weight, and cost of onboard fuel storage systems, as well as the limited availability and high cost of natural-gas fueling stations, are also being addressed. Completion of the demonstration program will help to clarify the position of heavy-duty, natural-gas engines relative to diesel engines in terms of compliance with future emission standards and fuel economy.

Recommendation 7. The Office of Heavy Vehicle Technologies should refocus its natural-gas research on meeting emission standards for 2007. Support for the PING (pilot-injection, natural gas) engine, DING (direct-injection, natural gas) engine, and the SING (spark-ignition, natural gas) engine should be continued until their performance and emissions characteristics are well understood. At that point, support for the SING engine should be discontinued unless it proves to have a substantial emissions advantage over the PING and DING engines. Research on onboard storage of natural gas should be focused on novel methods rather than on conventional compressed natural gas and liquefied natural gas storage technologies. A "well-to-wheels" analysis should be used to compare options for onboard storage. Research on refueling should be limited to the central refueling option.

The R&D programs in materials appear to be well managed. However, projects are not prioritized based on their importance to the success of the OHVT program as a whole and their likelihood of success.

Considering the myriad of problems and opportunities in materials R&D, OHVT must develop a process for identifying the most significant materials-related barriers to improved performance and prioritize them according to need. Then, relevant technologies should be evaluated in terms of their probability of success, and the most promising technologies should be selected. Finally, OHVT should establish long-range research programs to address needs that cannot be addressed by current technologies. Unless a disciplined, systematic approach is adopted, almost any materials-related R&D can be justified as being relevant to the OHVT program. OHVT must ensure that the projects it supports are not just relevant but also (1) address a priority need, (2) have a reasonable chance of success, or (3) are long-term research projects that may have high risks but also have potentially large payoffs.

Finding 8. The Office of Heavy Vehicle Technologies has no systematic process for prioritizing high-strength, weight-reduction, materials-related research or for monitoring other relevant, federally funded materials R&D.

Recommendation 8. A systematic process should be developed and put in place to monitor relevant, federally funded, materials research and development (R&D), to prioritize materials needs, and to identify high-priority opportunities for R&D. This process should use vehicle-systems modeling analyses to set specific goals for vehicle, power train, and chassis weight to meet overall fuel economy goals.

1

Introduction

Trucks range in size and use, although many associate "trucks" with large vehicles, such as delivery vans and tractor trailers. Trucks are categorized by gross vehicle weight (GVW). Heavy-duty trucks weigh more than 26,000 pounds (lbs). (For current emissions regulations, heavy-duty trucks are defined as vehicles with a GVW of more than 8,500 lbs). Medium trucks weigh between 10,001 and 26,000 lbs, and light trucks weigh less than 10,000 lbs. In addition, finer distinctions are made by size. Figure 1-1 shows the truck classes used by the U.S. Department of Energy (DOE) Office of Heavy Vehicle Technologies (OHVT). The definition of light-duty trucks varies in the transportation literature: some data sources use 8,500 lbs as a maximum; others use 10,000 lbs as a maximum.

Sales of light-duty trucks have increased very rapidly in the past decade as consumers have opted to buy pickup trucks, vans, and sport utility vehicles (SUVs) instead of automobiles for personal transportation. Light-duty trucks of 8,500 lbs or less now represent about 50 percent of annual automotive sales. In addition, the number of medium and heavy-duty trucks has increased substantially as the economy has grown (see Figure 1-2).

In 1973, the transportation sector accounted for about 51.2 percent of total U.S. petroleum consumption. By 1998, it had increased to 66.3 percent (Davis, 1999). At the same time, domestic petroleum production has declined steadily since 1985. In 1998, petroleum consumed in the transportation sector as a whole was close to 12 million barrels (bbl)/day (crude oil equivalent), the highest level since 1973. In 1997, all on-highway vehicles used about 76 percent of the petroleum consumed in the transportation sector; trucks (including light trucks) used about 41 percent of transportation consumption.

The growth rate in fuel use for trucks in general is higher than for automobiles. If current trends persist, automobiles in 2020 will consume about 4 million bbl/day; Class 1 and 2 trucks (pickup trucks, vans, and SUVs) about 4.5 million bbl/day; and Class 3 to 8 trucks about 3 million bbl/day (see Figures 1-2 and 1-3). Hence, by 2020, trucks will dominate on-highway fuel consumption (DOE, 1996, 1997, 2000; EIA, 1999).

In 1975, Congress enacted the Energy Policy and Conservation Act, requiring that automotive manufacturers selling cars in the United States increase the corporate average fuel economy (CAFÉ) of their new car fleet to 27.5 miles per gallon (mpg) in model year (MY) 1985 and thereafter (unless the requirement was relaxed by the Secretary of Transportation). Because the CAFÉ standard for light trucks is 20.7 mpg for MY00, and because light trucks now constitute a larger fraction of vehicle sales for personal use, the fuel efficiency of the vehicle fleet as a whole has declined. Overall fleet fuel economy for passenger cars dropped by 0.4 mpg from MY98 to MY99. The light truck fleet CAFÉ has been almost constant for the last five MYs (DOT, 2000). If the decline in domestic oil production continues, the nation's dependence on imported petroleum will increase. Therefore, improving fuel economy or using fuels that are not derived from petroleum and are available domestically would help to reduce reliance on petroleum imports.[1]

Improved fuel economy would also reduce the amount of carbon dioxide emitted per mile driven. The transportation sector accounted for about 31 percent of U.S. carbon dioxide emissions from fossil fuel consumption in 1997 and, in particular, highway vehicles accounted for almost a quarter of U.S. carbon dioxide emissions (Davis, 1999). Although carbon dioxide is not a regulated pollutant, it is a greenhouse

[1]Light trucks of less than 10,000 lbs GVW consumed about 226 trillion British Thermal Units (Btus) of diesel fuel and 5,950 trillion Btus of gasoline in 1997. Thus, eliminating diesel engines would not have an enormous impact on gasoline consumption for light trucks, but the inability to use higher efficiency diesel engines to replace gasoline engines would be a lost opportunity for improving fuel efficiency for light trucks.

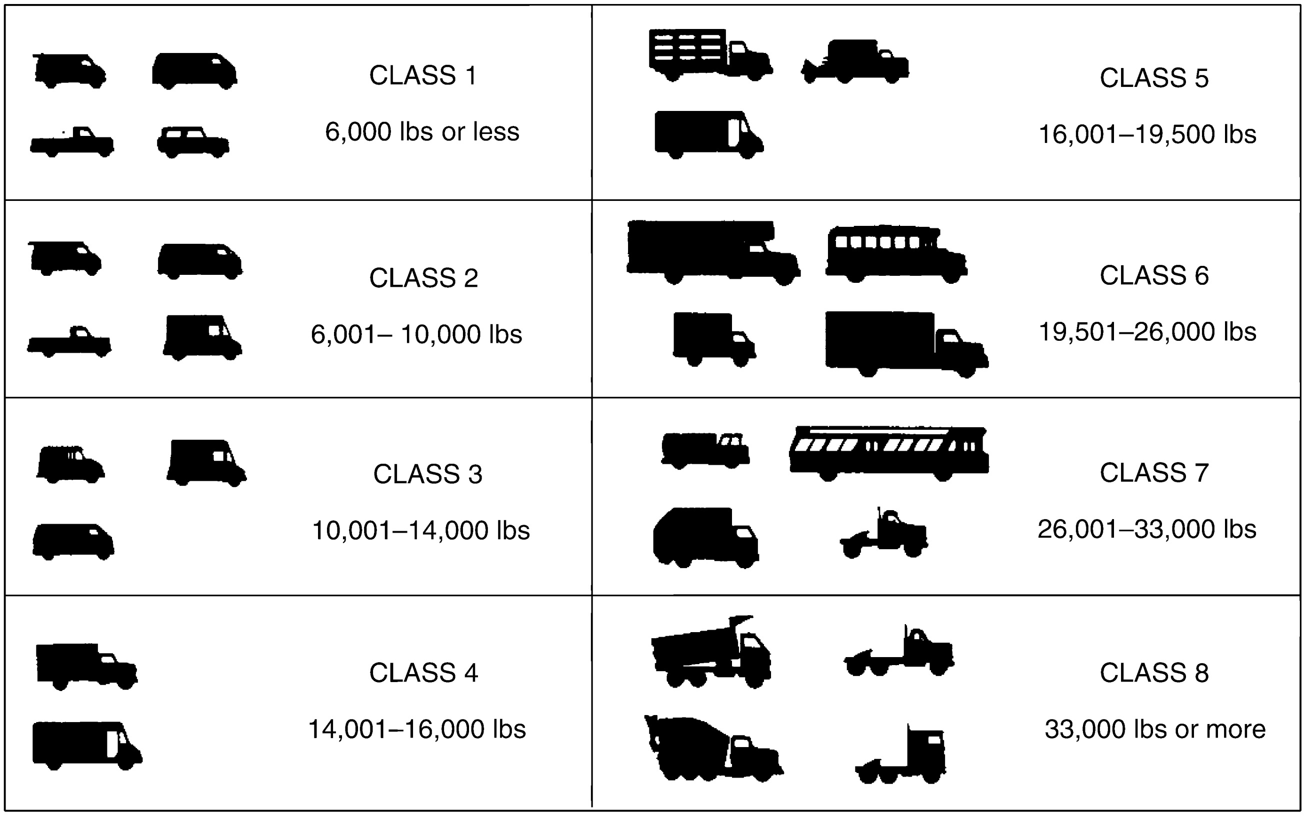

FIGURE 1-1 Truck classification by gross vehicle weight (GVW). Note that Class 2 is composed of Class 2a (6,001–8,500 lbs), and Class 2b (8,501–10,000 lbs). Tractor trailers in Class 7 or Class 8 can be single trailers, double trailers, and, in some cases, triple trailers. Source: DOC, 1995; Davis, 1999; Eberhardt, 2000a.

gas. If regulations are imposed in the future to reduce greenhouse gases because of concerns about climate change, improved vehicle fuel economy would help reduce greenhouse gas emissions.

Improved fuel economy would help heavy-duty trucks to compete in the very price-sensitive freight hauling market, in which the cost of fuel affects truck operating expenses significantly. The recent rise in fuel prices has focused attention on how actions by the Organization of Petroleum Exporting Countries (OPEC), disruptions in supply (e.g., pipeline disruptions), low stocks, increased driver demand, as well as requirements for cleaner fuels, such as reformulated gasoline, can lead to increased fuel prices. The level at which sulfur is regulated in future diesel fuels may also have a significant impact on fuel prices.

Another important public policy issue is the impact of the transportation sector on air quality. The primary concern about emissions from combustion engines is the effects of pollutants on health and the environment (HEI, 2000). Although the contribution of the transportation sector varies by region and metropolitan area, it is significant. In 1997 (for emissions from economic activity), highway vehicles accounted for about 57.5 percent of carbon monoxide (CO), 29.8 percent of oxides of nitrogen (NO_x), 27.2 percent of volatile organic compounds (VOCs), 0.8 percent of fine particulates (less than 10 micrometers aerodynamic diameter or less, PM_{10}), 2.5 percent of $PM_{2.5}$ (less than 2.5 micrometers aerodynamic diameter), 1.6 percent of sulfur dioxide, and 7.6 percent of ammonia emissions (Davis, 1999). Table 1-1 summarizes the contributions of light trucks and heavy vehicles compared to on-highway vehicles as a whole (Davis, 1999).

In response to growing concerns about current and projected levels of air quality, more stringent emission standards have been instituted both in California and at the national level. These complex emission regulations vary depending on vehicle type, and all standards have phase-in schedules and durability requirements. The following discussion focuses on the technical challenges facing diesel-powered vehicles for meeting these standards.

In December 1999, the Environmental Protection Agency (EPA) issued the Tier 2 standards, which will eventually

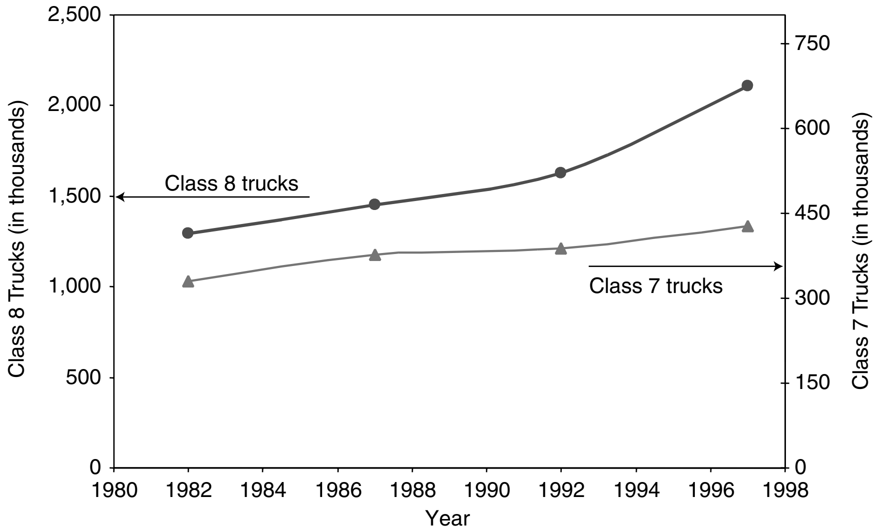

FIGURE 1-2 Number of Class 7 and 8 trucks in use, 1982–1997. Source: Eberhardt, 2000a.

supplant the current Tier 1 emission standards. Tier 1 and Tier 2 standards differ for light-duty trucks (Classes 1 and 2), depending on the class and weight of the truck; the phase-in period for Tier 2 is 2004–2009. Figures 1-4 and 1-5 illustrate the dramatic changes that will be realized with Tier 2 NO_x and PM standards once they are finally phased in (France, 2000). Current emission standards differ for different vehicle weights, but Tier 2 standards will eliminate these differences and reduce vehicle emissions by as much as 95 percent.

The Tier 2 standards treat vehicles and fuels as a system and apply the same emissions standards to all light-duty vehicles and light-duty trucks. In addition, large passenger vans and SUVs are included in the Tier 2 program under a new category of vehicles called medium-duty passenger vehicles (MDPVs), which includes SUVs and passenger vans weighing between 8,500 and 10,000 lbs GVW but excludes pickup trucks in this weight range.

EPA has also created a "bin" system that allows manufacturers to average emissions across the fleet of vehicles they sell each year. Table 1-2 shows the "Full-Life Exhaust Emission Bins." EPA believes that the combination of bins, averaging, and a phase-in period will promote the orderly development of clean diesel technology and that the interim standards are feasible based on the current 500 ppm level for sulfur in fuel. The final standards will require after-treatment technology and low-sulfur fuel (proposed to be no greater than 15 ppm by June 1, 2006 [EPA, 2000]). The highest bin

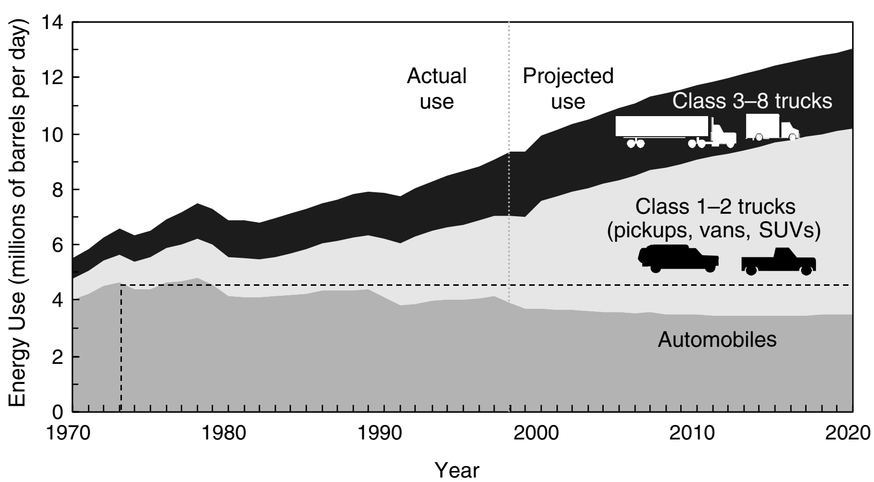

FIGURE 1-3 Energy use by trucks, 1970–2020. Source: DOE, 2000; Eberhardt, 2000a; EIA, 1999.

TABLE 1-1 Emissions from Light Trucks and Heavy Vehicles in 1997 (as a percentage of emissions from all highway vehicles)

Vehicles	CO	NO_x	VOCs	PM_{10}	$PM_{2.5}$
Gasoline Powered Vehicles					
Light trucks[a]	36.5	27.0	37.6	15.0	12.1
Heavy vehicles	6.7	4.6	5.1	3.4	2.9
Diesel-Powered Vehicles					
Light trucks	0.0	0.2	0.1	0.7	1.0
Heavy vehicles	2.9	26.8	4.2	57.7	65.7
Other Vehicles[b]	53.9	41.4	53.0	23.2	18.3
TOTAL	100.0	100.0	100.0	100.0	100.0

Note: Estimates of total emissions from economic sectors are approximate. Estimates from the transportation sector are based on computer models, which were critiqued in a recent report (NRC, 2000).

[a] Less than 8,500 lbs.
[b] Includes automobiles, other light vehicles of less than 8,500 lbs GVW, and motorcycles.

Source: EPA, 1998; Davis, 1999.

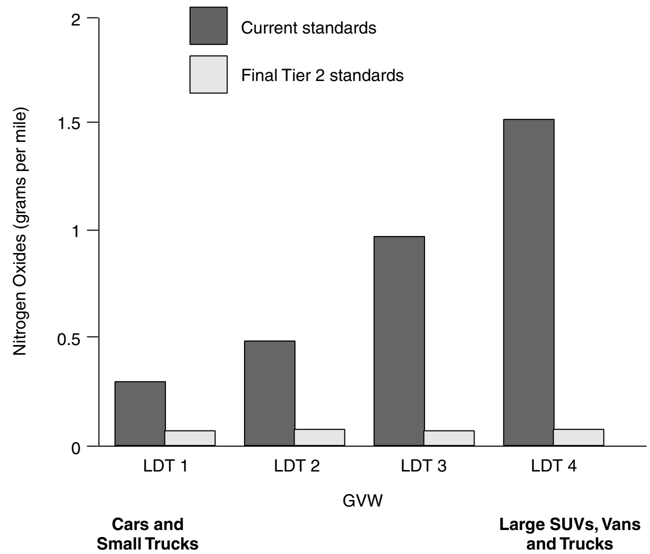

FIGURE 1-4 Comparison of current vehicle emission standards for oxides of nitrogen (NO_x) and final Tier 2 standards. (Reductions range from 77 to 95 percent.) Source: France, 2000.

Note: LDT1 (light-duty truck 1) has a GVW of up to 6,000 lbs and a loaded vehicle weight (LVW) of up to 3,750 lbs; LDT2 has a GVW of up to 6,000 lbs and between 3,751 and 5,750 lbs LVW; LDT3 has a GVW between 6,001 and 8,500 lbs and a test weight (TW) of up to 5,750 lbs; LDT4 has a GVW between 6,001 and 8,500 lbs and a TW of more than 5,750 lbs. LVW= curb weight + 300 lbs; TW= average of curb weight and GVW.

in the interim program is a maximum at 0.6 g/mile for NO_x and 0.08 g/mile for PM (Bin 10). Hence, diesel, heavy light-duty trucks can be certified in this bin during early product introduction (2004–2006) and then certified with low-sulfur fuel and an integrated emissions-control system that includes after-treatment for NO_x and PM emissions in 2007–2009. Bin 11, which is for MDPVs, is phased out in 2008. Diesel-powered MDPVs can meet the heavy-duty standards until 2007. The highest bin of the eight bins that are phased in by 2009 is 0.2 g/mile NO_x and 0.02 g/mile PM. The final standards are not fully phased in for heavy light-duty trucks (HLDTs; 6,001 to 8,500 lbs) and MDPVs until 2009.

Certification bins 1–8 will remain in effect in 2009 when the Tier 2 emission standards are fully phased in. The vehicles certified in a particular bin must meet all of the individual emission standards (NO_x, nonmethane organic gases, CO, formaldehyde, PM) for that bin. In addition, the average NO_x emissions level of the entire fleet sold by a manufacturer will have to meet the average NO_x standard of 0.07 g/mile.

Emissions from diesel engines used in heavy-duty trucks (more than 8,500 lbs GVW) must also be reduced. In the early 1980s, some heavy-duty truck engines had emissions of 10 to 15 g/brake horsepower-hour (bhp-h) of NO_x and 1 g/bhp-h of PM.[2] The standards have been significantly reduced in the past two decades (see Table 1-3). In 1996, the EPA, the state of California, and major engine manufacturers prepared a Statement of Principles (SOP) that required emissions reductions to 2.4 g/bhp-h of NO_x plus nonmethane hydrocarbons (NMHC) or 2.5 g/bhp-h of NO_x plus NMHC, with a maximum of 0.5 g/bhp-h of NMHC by 2004. A recent action by the EPA and the U.S. Department of Justice resulted in a Consent Decree with seven major diesel-engine manufacturers that moves the SOP requirements up to October 2002 and places caps on emissions at all operating conditions. Meeting tighter emissions standards without new technology usually requires a trade-off with reductions in engine efficiency.

In May 2000, the EPA proposed new standards for heavy-duty engines and vehicles and highway diesel-fuel sulfur-control (EPA, 2000). EPA's proposed PM emissions standard for new heavy-duty engines (see Table 1-3) would take full effect in MY07. The NO_x and NMHC standards would be phased in together from 2007–2010. The phase-in would be on a percent-of-sales basis: 25 percent in 2007, 50 percent in 2008, 75 percent in 2009, and 100 percent in 2010.

[2]Heavy-duty truck emission standards (mass per horsepower-hour) are based on engine dynamometer tests, whereas emission standards (mass per mile) for automobiles and light trucks are based on vehicle dynamometer tests.

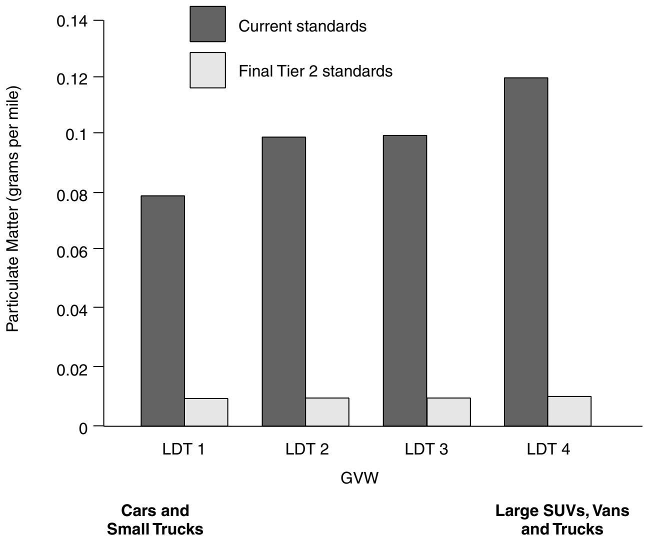

FIGURE 1-5 Comparison of current vehicle emission standards for particulate matter (PM) and final Tier 2 standards. (Reductions range from 88 to 92 percent.) Source: France, 2000.

Proposed standards for certifying heavy-duty vehicles would be implemented on the same schedule as engine standards. EPA notes that these standards would not apply to vehicles of more than 8,500 lbs that are classified as MDPVs under Tier 2 because of their primary use as passenger vehicles. The certification of complete vehicles by a chassis test for vehicles of more than 8,500 lbs GVW is new in these proposed regulations. In the past, heavy-duty engine standards have been based on an engine dynamometer test.

TABLE 1-2 Full-Life Exhaust Emission "Bins" (g/mile)

Bin Number	NO_x	NMOG	CO	HCHO	PM
11	0.9	0.280	7.3	0.032	0.12
10	0.6	0.156/0.230	4.2/6.4	0.018/0.027	0.08
9	0.3	0.090/0.180	4.2	0.018	0.06
[The bins above expire in 2006 (for LDV and LLDTs) and 2008 (for HLDTs and MDPVs)]					
8	0.20	0.125/0.156	4.2	0.018	0.02
7	0.15	0.090	4.2	0.018	0.02
6	0.10	0.090	4.2	0.018	0.01
5	0.07	0.090	4.2	0.018	0.01
4	0.04	0.070	2.1	0.011	0.01
3	0.03	0.055	2.1	0.011	0.01
2	0.02	0.010	2.1	0.004	0.01
1	0.00	0.000	0.0	0.000	0.00

Note: NMOG = nonmethane organic gases; CO = carbon monoxide; HCHO = formaldehyde; LDV= light-duty vehicle; LLDT= light LDT (up to 6,000 lbs GVW); HLDT= heavy LDT (6,001 to 8,500 lbs). For LDVs and LLDTs, full useful life is a period of use of 10 years or 100,000 miles, whichever occurs first. For HLDTs, full useful life is a period of use of 11 years or 120,000 miles, whichever occurs first. Bin 11 is for MDPVs and expires after MY08. Source: France, 2000.

TABLE 1-3 Heavy-Duty Truck Engine Emission Standards (g/bhp-h) and Complete Vehicle Standards (g/mile)

	PM	NO_x	NMHC
1998	0.10[a]	4.0	
2002	0.10[a]	2.4[b]	
Proposed Standards			
2007	0.01	0.2[d]	0.14[d]
2010	0.01	0.2	0.14
Complete Vehicle Standards[c]			
8,500–10,000 lbs	0.02	0.2	0.195
10,000–14,000 lbs	0.02	0.4	0.230

[a] PM emissions are less than 0.05 g/bhp-h for transit buses.
[b] Standard for NO_x + NMHC.
[c] Proposed standards for heavy-duty vehicles would be implemented on the same schedule as engine standards. The new standards would not apply to vehicles of more than 8,500 lbs, which EPA classifies as medium-duty passenger vehicles (MDPVs) as part of the Tier 2 program because of their primary use as passenger vehicles.
[d] Twenty-five percent of sales in 2007; 50 percent of sales in 2008; 75 percent of sales in 2009; and 100 percent of sales in 2010.

Source: DOE, 2000; EPA, 2000.

EPA is proposing that diesel fuel sold to customers for use in highway vehicles have a sulfur content of no more than 15 ppm beginning June 1, 2006. This proposed sulfur cap (maximum value) is based on EPA's assessment of how advanced sulfur-intolerant after-treatment technologies will be and a corresponding assessment of the feasibility of low-sulfur fuel production and distribution (EPA, 2000).

California has different vehicle emission standards, with different categories of vehicles, as well as durability categories. For example, low-emission vehicle II (LEV II) standards for new 2004 and subsequent MYs for light-duty trucks (8,500 lbs GVW or less), medium-duty vehicles of 8,501 to 10,000 lbs GVW, and medium-duty vehicles of 10,001 to 14,000 lbs GVW are divided into LEVs, ultra low-emission vehicles (ULEVs), and super low-emission vehicles (SULEVs). Table 1-4 summarizes emission levels for three LEVs and three pollutants (CARB, 1999). The California Air Resources Board (CARB) has labeled PM emissions from diesel-fueled engines as a toxic air contaminant (TAC) (CARB, 1998). California has also instituted a process to reduce the adverse health effects of TAC emissions from diesel-fueled engines.

Up to now, the California standards have typically been more stringent than the federal standards and have addressed

TABLE 1-4 California LEV II Exhaust Emission Standards (g/mile)

Type of LEV	NMOG at 50,000 miles	NO_x at 50,000 miles	PM at 120,000 miles
LEV	0.075	0.05	0.01
ULEV[a]	0.040	0.05	0.01
SULEV	0.010	0.02	0.01
All at 120,000 miles			

[a] Fleet average nonmethane organic gases (NMOG) standard of 0.035 g/mile means most vehicles will have to meet ULEV standards.

diesel emissions sooner. As federal Tier 2 emissions standards are phased in, federal and California standards are expected to be in closer alignment. However, the LEV II program includes a requirement for a zero-emission vehicle that will force advanced technology development. The more stringent federal and California emission standards represent a major technical challenge for diesel-fueled vehicles, which will probably require new fuel formulations, catalyst systems, and emission-control systems.

SUMMARY OF OHVT'S ACTIVITIES AND BUDGET

The DOE Office of Energy Efficiency and Renewable Energy oversees the Office of Transportation Technologies, which includes OHVT, the Office of Advanced Automotive Technologies (OAAT), the Office of Fuels Development, and the Office of Technology Utilization. OHVT was created in March 1996 when the Office of Transportation Technologies was reorganized. The OAAT focuses on the development of advanced automotive technologies, while OHVT focuses mostly on technologies for trucks. OHVT's mission is "to conduct in collaboration with our heavy vehicle industry partners and their suppliers, a customer-focused national program to research and develop technologies that will enable trucks and other heavy vehicles to be more energy efficient and capable of using alternative fuels while simultaneously reducing emissions" (Eberhardt, 2000a).

Table 1-5 summarizes OHVT's budget from fiscal year 1996 (FY96) to FY00, as well as the budget request for FY01 (see Chapter 2 and the *OHVT Roadmap* [DOE, 2000] for more detail). The program started off at a relatively modest funding level of about $30 million/year. Funding was increased about 50 percent from FY99 to FY00 and increased again in the administration's request to Congress for FY01. In FY99, the balance of funding for research and development was distributed as follows: 72 percent by industry; 18 percent by the national laboratories; 4 percent by universities; and 6 percent by others (e.g., small businesses, states, etc.) (Eberhardt, 2000a).

21ST CENTURY TRUCK INITIATIVE

During this study, the committee was given a presentation on the 21st Century Truck Initiative, which was announced by Vice President Gore on April 21, 2000 (Eberhardt, 2000b; Skalny, 2000). If this new initiative moves forward as planned, it will have a major impact on OHVT. The program's target year is 2010. The government agencies that will be involved include DOE, the U.S. Department of Transportation, the U.S. Department of Defense, and EPA; a number of private companies are also expected to join the partnership. The goal of this government-industry research program will be to develop production prototype vehicles with the following characteristics:

- improved fuel efficiency by (1) doubling the Class 8 long-haul truck fuel efficiency;[3] (2) tripling the Class 2b and Class 6 truck (delivery van) fuel efficiency; and (3) tripling the Class 8 transit bus fuel efficiency
- lower emissions than expected standards for 2010
- meeting or exceeding the motor carrier safety goal of reducing truck fatalities by half
- affordability and equal or better performance than today's vehicles

The committee was not charged with reviewing the 21st Century Truck Initiative, and the technical details of the proposed program were not included in the presentation. However, the committee wishes to highlight the ways in which the initiative is relevant to OHVT. First, the technical goals of the 21st Century Truck Initiative parallel those of the OHVT program (i.e., the intent of the new initiative is to produce knowledge and technical developments to improve future fuel economy and meet low emission standards). Second, the fuel economy goals of both programs are very challenging. Third, the R&D areas proposed by both programs are generally parallel. And finally, the 21st Century Truck Initiative faces many of the same constraints as OHVT, such as changing regulatory requirements, uncertain funding, and globalization of the marketplace.

Regardless of the direction of these programs, interaction between OHVT and the 21st Century Truck program will be beneficial, and OHVT should be a major participant in the program if it moves forward. As discussed in Chapters 2 and 3, the time horizon of the new initiative is consistent with the committee's recommendations that the OHVT program establish longer term objectives for its R&D.

SCOPE AND ORIGIN OF THIS STUDY

In response to a request from the director of OHVT, the National Research Council established the Committee on

[3] Fuel efficiency in the 21st Century Truck Initiative is measured on a ton-mile per gallon basis.

TABLE 1-5 OHVT Budget by Activity (millions of dollars)[a]

Program Activity	FY96	FY97	FY98	FY99	FY00	Total for FY96–FY00	FY01
Vehicle Technologies							
Advanced combustion engine							
Combustion and after-treatment	1.95	1.5	1.8	3.4	3.15	11.8	4.0
Light-truck engines	—	5.6	9.4	14.8	18.0	47.8	18.0
Heavy-truck engines[b]	3.45	—	—	—	5.0	8.45	7.0
Health impacts	—	—	—	—	—		1.0
Heavy-vehicle systems							
Vehicle-system optimization	—	—	1.7	1.5	3.0	6.2	4.5
Truck safety systems	—	—	—	—	—		0.5
Stimulation of truck innovative concepts and knowledge	—	—	—	—	—		0.65
Hybrid systems							
Heavy-vehicle propulsion systems	—	—	—	—	4.0	4.0	3.5
Subtotals	5.4	7.1	12.9	19.7	33.15	78.25	39.15
Fuels Utilization							
Advanced petroleum-based fuels							
Heavy trucks	0.0	0.0	2.4	2.7	4.0	9.1	5.0
Alternative fuels							
Heavy trucks	9.3	12.4	3.765	3.27	4.3	33.035	3.5
Medium trucks	0.0	0.0	6.31	4.7	4.3	15.31	3.5
Fueling infrastructure	0.0	0.0	0.0	0.2	2.0	2.2	2.5
Environmental impacts	—	—	—	—	—		2.0
Subtotals	9.3	12.4	12.475	10.87	14.6	59.645	16.5
Transportation Materials Technology							
Propulsion materials technology							
Heavy-vehicle propulsion system materials	8.0	5.0	4.95	5.3	6.05	29.3	7.0
Lightweight-materials technology							
High-strength, weight-reduction materials	2.5	2.8	3.1	4.2	5.95	18.55	4.9
High-Temperature Materials Laboratory							
Heavy-propulsion systems	5.2	4.7	5.2	5.5	8.5	29.1	5.6
Subtotals	15.7	12.5	13.25	15.0	20.5	76.95	17.5
TOTALS	30.4	32.00	38.625	45.57	68.25	218.845	73.15

[a] FY96 to FY00 represent congressional appropriations. FY01 represents the administration's budget request.
[b] Note that in FY97 R&D focused on light-truck engines.

Source: Eberhardt, 2000a.

Review of DOE's Office of Heavy Vehicle Technologies (see Appendix A for biographical information on committee members). The committee was asked to fulfill the following Statement of Task:

> A National Research Council committee will be established to conduct an independent review of the DOE's Office of Heavy Duty Technologies. It will examine goals, objectives, strategy for program implementation, program activities which duplicate or overlap activities conducted by other organizations, and whether there are activities which, based on the program goals, should be included in the program but have been omitted. The committee will also consider and comment on: the program's balance among the three program elements (Vehicle Technologies, Fuels Utilization, Material Technologies); program's balance between industry, national laboratories and universities; adequacy of program funding; reasonableness of program milestones. After examining the OHVT program and receiving presentations from DOE representatives, the committee will write a report documenting its review of the OHVT program with recommendations for improvement, as necessary.

STUDY PROCESS AND ORGANIZATION OF REPORT

The committee held three meetings. Information-gathering sessions included presentations on OHVT program activities by representatives of the OHVT program, as well as individuals outside the program with expertise in the measurement and control of engine emissions, issues related to light-duty and heavy-duty trucks, and development needs relevant to the OHVT program (see Appendix B). To clarify some aspects of the OHVT program, the committee also sent written questions to OHVT representatives. The committee's conclusions and recommendations are based on the information gathered during the study and the expertise and knowledge of committee members.

Chapter 1 presents some brief background material related to light-truck and heavy-truck issues and the rationale for the OHVT program. Chapter 2 reviews the components of the OHVT program and makes recommendations, as appropriate, for these component activities. Chapter 3 focuses on the findings and recommendations for the OHVT program as a whole.

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2

Program Assessments

This chapter contains a summary of OHVT's strategy and goals, followed by assessments of individual OHVT R&D programs: on vehicle technologies, on fuels utilization, and on materials technologies. Activities related to environmental and health issues, which are a minor part of the OHVT program, are also addressed. The committee makes recommendations for components of the OHVT R&D program, as appropriate.

OVERALL STRATEGY AND GOALS

The committee commends OHVT on its systematic approach to R&D. Since OHVT's creation in 1996, the program has developed a technology road map and identified the barriers to achieving the goals of the program. The first road map, which was issued in October 1997, was recently revised, updated, and republished (DOE, 1997, 2000a). OHVT sponsored many workshops in developing its multiyear plans for the road map, eliciting input from the broader technical community and developing relationships with its "customers." The recommendation for a road map resulted from an OHVT workshop in April 1996 to elicit input from DOE's customers in the heavy-vehicle industry, including truck and bus manufacturers, diesel-engine manufacturers, fuel producers, suppliers to these industries, and the trucking industry.

The development of the road map entailed formulating goals consistent with DOE's strategic plan, assessing the status of technologies, identifying technical targets, identifying barriers to achieving the targets, developing a strategy for overcoming the barriers, and determining schedules and milestones (DOE, 2000a). This structure was followed for the three groups of truck classifications: Classes 1 and 2 trucks (pickups, vans, SUVs), Classes 3 to 6 trucks (medium-duty trucks, such as delivery vans), and Classes 7 and 8 trucks (large, heavy-duty, on-highway trucks).

OHVT envisions the development of energy-efficient diesel engine technologies for all three classes with near-zero emissions. The following goals are stated in the road map (DOE, 2000a):

- Develop by 2004 the enabling technologies for a Class 7 and 8 truck with a fuel efficiency of 10 mpg (at 65 mph) that will meet prevailing emission standards.
- For Class 3–6 trucks operating on an urban driving cycle, develop by 2004 commercially viable vehicles that achieve at least double the fuel economy of comparable current vehicles (1999), and, as a research goal, reduce criteria pollutants to 30 percent below EPA standards.
- Develop by 2004 the diesel engine enabling technologies to support large-scale industry dieselization of Class 1 and 2 trucks, achieving a 35 percent fuel efficiency improvement over comparable gasoline-fueled trucks, while meeting applicable emissions standards.

The road map identifies the following key enabling technologies and areas for study:

- emission controls (including exhaust-gas after-treatment technologies)
- combustion technology
- materials, environmental science, and health effects
- truck safety
- engineering simulation and modeling

OHVT's strategy includes the active involvement of customers/stakeholders in developing government/industry partnerships. First, DOE and OHVT's missions, as well as governing statutes, laws, and directives from Congress, must be satisfied. Second, the intersection of the federal mission and the customer's interests must be determined. To help with this step, OHVT conducted a customer focus workshop(s). Third, OHVT has sponsored workshops to identify customers' needs, from which road maps were developed with goals, barriers to development, and multiyear program plans to overcome the barriers. OHVT plans to modify these road maps as new information is collected and use them to determine resource requirements and prepare budgets. Finally, mechanisms have been developed for partnering with organizations outside the federal government. The lessons learned are then used to change the development process and modify the road maps.

The committee believes that OHVT has identified its mission well and articulated its vision clearly. The programs seem to be well managed, and OHVT seems receptive to input from its stakeholders, as evidenced by the recognition of the fuel economy implications of the 1998 Consent Decree and the adaptation of program goals to address these new challenges. In addition, program managers have been very effective in identifying competent research teams to conduct projects.

The focus of OHVT's initial planning with customers/stakeholders was a workshop in April 1996 attended by representatives of the heavy-vehicle industry including diesel-engine manufacturers, truck manufacturers, truck owners and operators, and trade organizations, as well as representatives of DOE. Workshop participants developed a common vision for the heavy-vehicle industry of the future and recommended that a technology road map addressing common R&D needs and interests be developed.

Customers/stakeholders included U.S. diesel-engine manufacturers and heavy-vehicle manufacturers, U.S. automakers (truck divisions), component manufacturers, fleet operators and owners, industry trade organizations, fuel suppliers, materials suppliers, universities, and research organizations (Eberhardt, 2000). Private sector participants included Caterpillar, Inc., Cummins Engine Company, Detroit Diesel Corporation (DDC), International Truck and Engine Corporation (Navistar International Corporation is the parent company), Deere and Company, Johnson Matthey, Englehard, Freightliner, Kenworth, Mack, ARCO, BPAmoco, ExxonMobil, Shell, representatives of the natural gas industry, and others. Since 1996, as part of its R&D strategy to solicit customer input, OHVT has sponsored about 34 workshops, meetings, and symposia focused on a broad spectrum of technologies and needs for the OHVT R&D program. OHVT continues to solicit input from its stakeholder and customer base.

OHVT's R&D strategy is to "focus on the Diesel-cycle engine and its fuel requirements as the confluence of energy efficiency, fuels flexibility, and very low emissions for trucks of all classes" (Eberhardt, 2000). The R&D strategy involves the development of clean diesel fuels and blends that can be derived from a variety of feedstocks (e.g., petroleum, natural gas, coal, and biomass) and can be used in advanced, high-efficiency, clean diesel engine technologies. The goal is to produce more efficient light-duty, medium-duty, and heavy-duty trucks.

When reviewing federal R&D programs, the role of federally funded R&D vis-à-vis the private sector must always be considered. The *National Transportation and Technology Strategy* defines research and technology programs that should be supported by the federal government as research that supports long-term national transportation goals. Federal research and technology investments often promote the development of benefits with broad applications to the public that would be difficult for individual companies to fund because they might not recoup their investment or realize a profit. A government role is generally associated with high-risk research beyond the capacity of individual companies. Finally, federal research and technology development generates benefits that will be realized in the long term and, therefore, do not meet the criteria for private sector investment (NSTC, 1994).

IMPROVING ENERGY EFFICIENCY

A basic understanding of how fuel energy is used in a typical vehicle is essential for determining how investments in R&D could lead to improved energy efficiency. The distribution of fuel energy is difficult to determine in detail because it varies with the type of engine and, for a given engine, varies with the operating conditions.

Figure 2-1 illustrates an average fuel-energy distribution for an automobile (NRC, 1992), which includes three energy-distribution categories: exhaust heat, cooling system, and brake work (i.e., the net work delivered to the flywheel). Analyzing the energy distribution in a vehicle is difficult. For example, the transmission has an oil cooler to dissipate losses. One must then determine if these losses should be reflected in the transmission or the cooling system. Designs for improved energy efficiency would minimize the amount of fuel energy going to exhaust heat and the cooling system and increase the fraction of fuel energy going to brake work. In fact, modern diesel truck engines already have a turbocharger to use exhaust energy to supercharge the engine to increase power.

For diesels, exhaust flow rate and energy content decrease with load. Many proposed systems would use more of the exhaust energy and add weight and volume to the engine system; to date, none has proven to be cost effective. Another option, an "adiabatic" engine, has the potential to reduce the energy flow to the cooling system but has other significant drawbacks and is not being pursued (NRC, 1987). A more efficient cooling system could reduce power usage a little (Lehner, 1999). So at this point, only small reductions in exhaust heat and the cooling system seem feasible.

For a given indicated horsepower, decreases in engine friction, pumping losses, use of accessory systems, and transmission losses will increase brake horsepower. If these four losses remain constant, an increase in indicated horsepower will increase brake horsepower. Tables 2-1 and 2-2 show the results of computer simulations of a Class 8

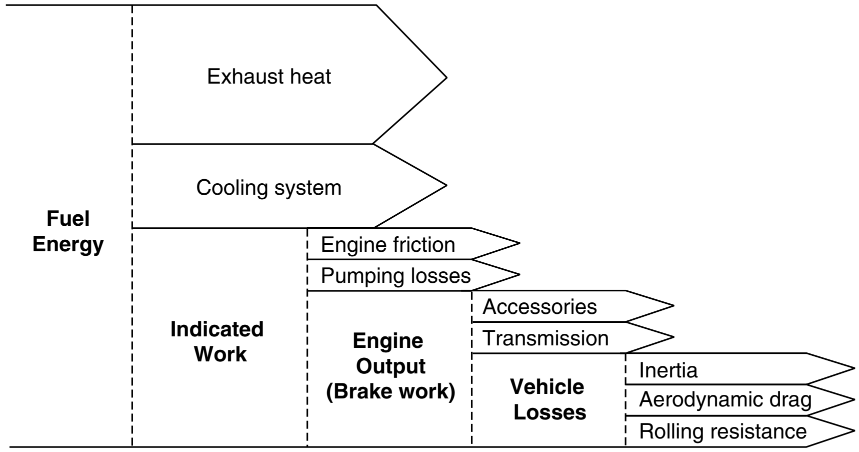

FIGURE 2-1 Average fuel-energy distribution for an automobile. Note: proportions vary with vehicle design and operating conditions. Source: NRC, 1992.

heavy-duty truck using a commercial diesel engine operating at its rated speed and power while pulling an 80,000-lb GVW vehicle up a 1 percent grade.

As Figure 2-2 shows, fuel-energy distribution varies widely for a tractor-trailer combination depending on operating conditions. Reducing vehicle speed or drag is an obvious way to reduce fuel consumption significantly. (OHVT's goal of 10 mpg was for 65-mph vehicle speed.) However, reducing vehicle speed entails trade-offs, such as increased trip transit time and, therefore, increased indirect costs to the trucker, impedance of traffic flow by slow vehicles, possible safety problems, and so on. Reducing the drag coefficient also requires trade-offs. Changes in the shape and contour of the vehicle may reduce load-carrying capability in vehicles with regulatory-restricted sizes and volumes.

Return on investment and labor costs tend to push the trucking industry towards higher speeds for greater productivity. Technologies that reduce aerodynamic drag are, therefore, very important. Aerodynamic drag has a nonlinear relation to vehicle speed while the sum of rolling friction and accessory power is estimated to be linearly related to vehicle speed (see Figure 2-2). Therefore, a reduction in drag can have very large payoffs in terms of reduced energy consumption. For example, a reduction in vehicle speed from 70 mph to 64 mph could yield about a 25 percent reduction in power consumed by drag. One of the drag reduction projects discussed later in this report anticipates this kind of drag reduction (Diamond, 2000).

Significant reductions in vehicle drag or reduced speeds are the only obvious ways to reduce fuel consumption substantially. Given the practical barriers, however, reductions will probably have to be achieved by small improvements in other areas, such as reducing rolling resistance or accessory power. The remainder of this chapter addresses the primary areas of activity indicated in OHVT's R&D budget breakdown (see Table 1-4): on vehicle technologies, on fuels utilization, and on transportation materials. The committee's review is focused primarily on FY00 but also includes some activities related to environmental and health issues.

TABLE 2-1 Distribution of Fuel Energy for a Truck Engine

Category	Percentage of Fuel Energy
Exhaust heat	33.5
Cooling system	24.5
Brake work	42.0
TOTAL	100.0

VEHICLE TECHNOLOGIES

Advanced Combustion Engines

Introduction

OHVT has identified six key enabling technologies for meeting its goals: emission controls (including exhaust-gas after-treatment technology); combustion technology; materials; environmental science and health effects; truck safety; and engineering simulation and modeling. The OHVT road map also notes that R&D on fuels and lubricants is conducted

TABLE 2-2 Indicated Work Distribution for a Truck Engine

Category	Percentage of Fuel Energy	Comments
Indicated Work	47.0	This energy only includes work at the top of the piston on the compression and expansion strokes.
Engine friction (including oil and water pumps)	2.5	Most of this energy goes to the cooling system.
Pumping losses	2.5	Most of this energy goes to the exhaust heat.
Brake work	42.0	This number, which was used in the Consent Decree and is changing with time, represents an efficient modern engine.

jointly by OAAT and OHVT. The committee has determined that two of these, emission controls and combustion technologies, fall into the general category of advanced combustion-engine technologies.

Overview of Programs in Combustion and Emissions

OHVT's program goals are grouped according to the class range of trucks to which they apply (Classes 1 and 2, Classes 3 to 6, Classes 7 and 8). Using its three main goals as guidelines, OHVT then identified objectives for each class range of trucks and selected projects to address these specific objectives.

The programs related to light trucks (Classes 1 and 2) are focused on the development of technologies for clean diesel engines that could replace current gasoline engines. The goal is to improve the fuel economy of light trucks by at least 50 percent (on a gasoline fuel economy equivalent basis), while meeting EPA Tier 2 emissions standards. The OAAT also has a program for light trucks, which is addressing the entire vehicle power train system, rather than focusing on engine development. Thus, OAAT's projects are based on different philosophies of power transmission, such as hybrid-electrical vehicle (HEV) propulsion. Thus, the approaches of OAAT and OHVT are complementary, not duplicative.

OHVT's combustion and emission projects are being coordinated through the Diesel Cross-cut Team, which is linked to R&D on diesel engines being conducted under the Partnership for a New Generation of Vehicles (PNGV, which includes most of OAAT's programs). The advantage of

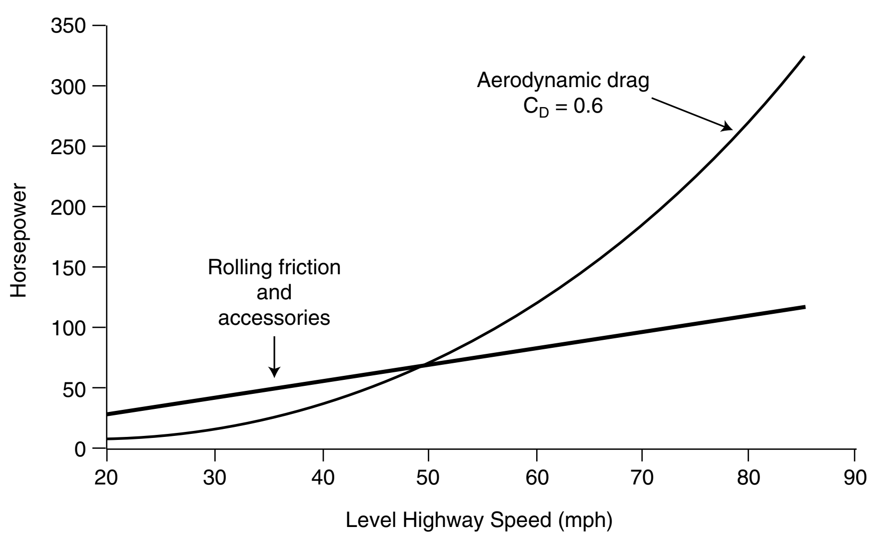

FIGURE 2-2 Accessories, aerodynamic drag, and rolling friction as a function of highway speed for a typical Class 8 tractor trailer. (C_D= coefficient of drag) Source: McCallen et al., 1998.

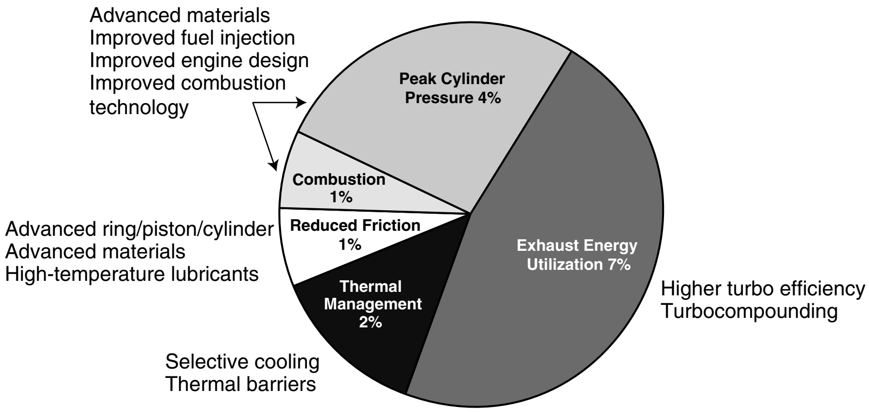

FIGURE 2-3 Projected contributions of advanced technologies to diesel engine efficiency. Source: DOE, 1997.

coordinating R&D by OHVT and PNGV through the Diesel Cross-cut Team is significant leveraging of OHVT funds. However, it also limits OHVT to the time frame and engine-power levels being pursued by PNGV, which has a goal of developing a production prototype of a midsized family sedan with up to three times the gasoline fuel economy equivalent of 1994 cars by 2004 (NRC, 2000).

The objective of OHVT's program for heavy-duty trucks (Classes 7 and 8) is to provide basic technical information (e.g., improved understanding of physical processes, new and/or improved system optimization and control techniques) that will lead to the development by 2004 of the enabling technologies for a 10-mpg truck (at 65 mph) while meeting the emission requirements set forth in the Consent Decree. The technical target for the heavy-vehicle engine is a brake thermal efficiency of 50 percent. In anticipation of more stringent emission standards, longer range (by 2006) emission targets of 1.0 g/bhp-hr for NO_x and 0.05 g/bhp-hr for PM, or the EPA 2008 standards,[1] (whichever is lower), have also been set as research goals. The funding level for OHVT's heavy-duty truck engine program for FY00 is $5.0 million. The program was not funded at all in the previous two years.

The goal for medium-duty trucks (Classes 3 to 6) is to develop and demonstrate, by 2004, commercially viable vehicles that achieve, in use, at least double the fuel economy of comparable 1999 vehicles. Another goal is to reduce criteria pollutant emissions to at least 30 percent below the EPA standards prevailing in 2004. Under the newly proposed EPA standards, technologies that produce emission levels 30 percent below the 2004 standards would only have a three-year life because 2007 standards will be much stricter.

Because the typical driving cycle of a medium-duty truck is primarily urban delivery, which requires many stops and starts, OHVT believes these vehicles are prime candidates for HEV technology. Consequently, OHVT's research is focused on HEV concepts, and OHVT-supported research on combustion and emission is not directly intended for medium-duty vehicles. However, OHVT program managers expect emission improvements obtained in its programs on light-duty and heavy-duty trucks to be applicable to medium-duty truck engines.

Technical Challenges

A very aggressive target of 50 percent for the brake thermal efficiency has been set for Classes 7 and 8 trucks. The goal in OHVT's initial road map was 55 percent (DOE, 1997), but this has been lowered to account for the fuel economy penalty likely to be incurred by exhaust-gas after-treatment systems for emissions control. Nevertheless, 50 percent brake thermal efficiency would represent an improvement of about 15 percent in engine efficiency over state-of-the-art engines and would also meet the more stringent emission regulations. Research is being focused on advanced combustion-chamber components for high peak pressure, advanced fuel-injection systems, better air-handling systems, and improved piston/cylinder liner designs to reduce friction. Figure 2-3 shows OHVT's projections for a 15-percent overall improvement in the engine system. OHVT estimates that improved combustion would represent a 1 percent potential improvement in fuel economy, but optimizing the integrated system performance of the power train, including the fuel, engine, and exhaust-gas after-treatment system, will most likely be essential.

The distinction between combustion and peak cylinder pressure are hazy at best because the same technologies are being used for both. Therefore, in the committee's opinion, Figure 2-3 represents the results expected for a given project rather than potential improvement.

[1]2008 was stipulated in the OHVT road map before EPA issued its proposed heavy-duty emissions standards.

In addition, the potential gain distribution shown in Figure 2-3 should be updated. New computations optimizing reductions in emissions and fuel consumption in given operating conditions have shown that dramatic reductions in emissions and fuel consumption may be possible, indicating that an optimized combustion process could be important for lowering both emissions (optimization studies have predicted a factor of 300 reduction in particulate matter and a 30-percent reduction in NO_x) and fuel consumption (by 10 to 15 percent) (Senecal and Reitz, 2000; Senecal et al., 2000). Of course, real-life reductions must reflect the entire vehicle operating regime. However, an optimized combustion process, combined with a camless engine that would optimize the engine configuration at a given operating point, might provide major reductions in emissions and, therefore, lessen the need for a complex after-treatment system.

Considering the potential significance of these new computations, OHVT should continue to support work on in-cylinder modeling and simulation. In addition, OHVT should review and update the potential gain distribution shown in Figure 2-3, and the new estimates should be reflected in future budget allocations.

Improved fuel economy must be accomplished under the constraint of meeting future EPA and CARB emission standards for all classes of trucks, and these standards are currently driving the choices of technology being investigated and/or developed by the engine industry. The gain in fuel economy that could be attained by "dieselization" of light-duty trucks is well known (fuel economy is the primary reason diesel engines are the power plants of choice for medium-duty and heavy-duty trucks). However, unless the emission standards can be met, diesels cannot be used. Exhaust-gas after-treatment systems and changes in fuel composition, combined with continued improvements in combustion, appear to be the best hope for meeting the emission standards and for meeting OHVT's program goals.

Specific Projects, Objectives, and Goals

The list of projects and participants in OHVT's combustion and emission programs is impressive (see Appendix C). Studies on fundamental combustion and spray processes are being performed at the Combustion Research Facility at Sandia National Laboratories (SNL), Livermore, California. Research includes a study of in-cylinder diagnostics to improve the understanding of combustion and emission formation processes, an investigation of homogeneous-charge compression-ignition (HCCI) combustion, a study of injection spray behavior in a constant volume vessel, and the establishment of a special laboratory for investigating alternative fuels.

The work at Sandia has the potential of providing knowledge and tools that will help solve critical problems in a longer time frame (2007–2010). However, the committee is not convinced that these programs fit into OHVT's strategic plan, which has a 2004 time frame. Research on HCCI is a longer term, high-risk, high-payoff project. In HCCI combustion (sometimes referred to as "flameless" combustion), the release of chemical energy is brought about in an essentially homogeneous mixture. Although HCCI combustion is limited to light-load operation, it could be very useful if it could be integrated into the combustion strategy as a portion of the engine-operating regime. A completely developed and implemented HCCI system would represent a "new" mode of combustion, with the potential of reducing in-cylinder emissions more than the target levels for conventional diesel combustion. Although the committee believes R&D on HCCI is important and should be continued, HCCI will almost certainly not be an "enabling" technology by 2004.

The fundamental investigation of spray processes in a constant-volume vessel is also valuable fundamental research. However, a constant-volume vessel and an engine differ significantly. For example, the interaction between the fuel injection and the in-cylinder fluid motion, which is not duplicated in a constant-volume vessel, is a critical aspect of achieving maximum performance in an engine. Therefore, at this time, the results of an injection system with a constant-volume vessel cannot be transferred directly to an engine. The results of OHVT's basic research will provide a basis for testing the validity of advanced computational models and will be helpful in determining directions for further improvements in injection-combustion systems. New insights into air-fuel mixing processes and the preparation of combustible mixtures via fuel injection might also be provided. Like R&D on HCCI, this work has a potentially high payoff and should continue to be part of the OHVT program. Also like HCCI, however, it is not likely to help OHVT meet its near-term goals.

Lawrence Livermore National Laboratory (LLNL) has expertise in comprehensive kinetic modeling. For OHVT's projects, modeling efforts are directed towards diesel engine combustion, HCCI combustion, and multicylinder HCCI analysis. At the Los Alamos National Laboratory (LANL), work is proceeding on the development of a next-generation computational tool called CHAD (computational hydrodynamics for advanced designs). Like the projects at Oak Ridge National Laboratory (ORNL) and LLNL, this work is expected to yield valuable tools and knowledge for longer term development (2007–2010).

Other national laboratories are also actively involved in the OHVT program, primarily through cooperative research and development agreements (CRADAs). Argonne National Laboratory (ANL) is involved in a CRADA with Caterpillar and the University of Wisconsin to study reducing in-cylinder emissions via injection of air late in the combustion cycle. ORNL is involved in a CRADA with DDC on diesel exhaust speciation and analysis of lean-NO_x catalysts. Additional CRADAs at ORNL include one with Cummins Engine Company to study NO_x control in after-treatment systems and catalyzed soot filters and one with Ford-Visteon to study NO sensors.

Pacific Northwest National Laboratory, which has expertise in plasma-assisted catalysis and nonthermal plasmas, is involved in two CRADAs, one with Caterpillar and the other with Delphi-DDC. Initial tests on nonthermal plasmas and the plasma-assisted catalysis systems indicate that these approaches to emission reduction may be tolerant to sulfur in fuel (see a later section in this chapter on Fuels Utilization). The R&D at Pacific Northwest is high risk but could have a very high payoff, and OHVT should continue to pursue it. Some carefully controlled engine testing is scheduled to begin soon, but neither of the technologies being investigated at Pacific Northwest will provide a near-term solution to meeting the 2004 emission standards.

Finally, OHVT is actively involved in 50/50 cost-share projects with Cummins-DaimlerChrysler, DDC-DaimlerChrysler, and Caterpillar-Ford to develop a competitive Class 2 truck diesel engine for introduction into the SUV and light-truck market. OHVT's funding is being used to facilitate interactions between the heavy-duty engine industry and automotive manufacturers. The work is being performed solely by the partnering companies and is proprietary; results are protected from public disclosure for five years. Therefore, the committee found it difficult to assess the scope and focus of the light-duty engine program, and conclusions about these projects are based on a variety of other sources and the committee members' expertise and experience. One of the companies in the program is probably working on developing technologies that could eventually be incorporated into hardware components for a Class 1 or Class 2 light-duty truck engine. The committee supports OHVT's promotion of industry research on promising, yet high risk, approaches to configuring engine-emission control systems that might facilitate the introduction of more fuel-efficient engines into the light-truck and SUV market. Because the committee did not have access to the 50/50 cost-share programs in their entirety, the focus of the program could not be determined. However, the committee does not endorse using OHVT funds to support specific engine or component development programs by industry.

The committee also noted that none of these programs includes other engine configurations, such as gasoline-engine HEVs, which might be able to meet the emission standards more easily and at lower cost than a diesel engine and still have better fuel economy than the gasoline engine currently used in SUVs and light trucks.

The committee approves of the longer time frame of many of the projects listed above and encourages OHVT to continue to support them. However, the committee was not convinced that these programs together provide a strategy for meeting OHVT's stated goals in the 2004 time frame. These programs can all stand on their own merit and can be justified as "enablers" for meeting OHVT's long-term research targets, but they should not be included in the strategy for meeting OHVT's near-term goals.

Budgets

The funding level for all R&D in combustion and emission control at the national laboratories for FY00 is $4.215 million (see Appendix C): $1.35 million is being spent on after-treatment research systems; $1.94 million on combustion research; and $925,000 on control technology, technology evaluation, and support for the Diesel Cross-cut Team. OHVT's budget for the 50/50 cost-share program for the Class 2 diesel engine development is $18.0 million.

Program Balance

Funding for the OHVT program as a whole is weighted very heavily towards industry and the national laboratories: industry, 72 percent; national laboratories, 18 percent; other (e.g., small businesses), 6 percent; and universities, 4 percent. The advantage is that OHVT has tremendous leverage of its financial resources. The disadvantage is that the emphasis and the bulk of the funding may be inconsistent with a long-term research time horizon. The committee is also concerned that the portfolio of projects covers too broad a range of activities rather than focusing on critical technologies. OHVT appears to have established good communications with OAAT programs in the PNGV program. OHVT should continue to participate in this dialogue to ensure that OHVT programs and OAAT/PNGV programs are as well coordinated as possible.

The delay between the initiation of a research program for engines and the introduction of a product is approximately eight years (see Figure 2-4). The delay between the decision to produce a product and production is approximately three years. This leaves only five years between the initiation of a research program and the use of the results to produce or improve a product. Therefore, for OHVT to meet its 2004 production target, programs initiated in 1997 should be nearing completion, and newer programs with a longer time horizon should be under way. The initial program was organized to be consistent with the eight-year delay. However, OHVT has not periodically reevaluated its research portfolio in terms of the eight-year horizon.

OHVT's R&D on advanced combustion engines has potential short-term, midterm, and long-term payoffs. However, OHVT did not demonstrate to the committee an updated logical structure or global vision for future programs. The committee believes it essential that OHVT put in place a process for periodically (at least annually) reviewing and updating its individual programs and their overall goals and targets to reflect an eight-year or longer time horizon. The initial review should also develop a logical structure and global vision for the program. The rationale of this process should be to identify OHVT technologies that, if successfully developed in the next decade, would be of maximum benefit to the nation. The review process would also enable

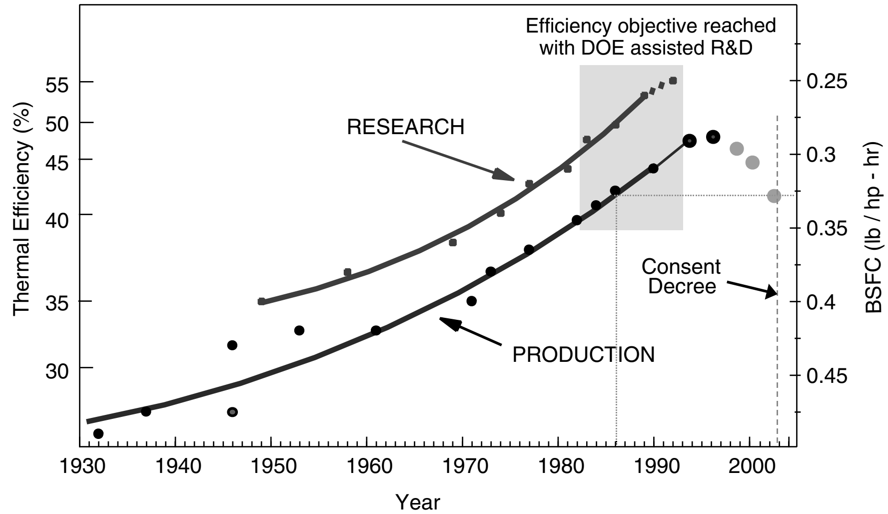

FIGURE 2-4 Increasing the efficiency of diesel engines and brake-specific fuel consumption (BSFC = lbs of fuel per hour per unit of engine power) for research and production engines. Source: Eberhardt (2000), based on information from Caterpillar, Inc.

OHVT to assess the status of current programs and determine if they are yielding benefits.

In the committee's opinion, the most crucial technologies by far are those that will enable diesel engines to meet future emission regulations. If they cannot meet these standards, they cannot be sold, regardless of their potential fuel savings. The committee believes that the development of diesel exhaust-gas after-treatment systems will be one of or the most important enabling technologies in this area and should be made a higher priority. The effect of fuels and lubricants on integrated system performance should also be investigated (Perez, 2000).

The timelines for most of OHVT's research projects are too short and the cost sharing too great for university participation. Most university facilities have advanced instrumentation and computational capabilities but do not have state-of-the-art engine technologies. Also, the process of educating students during a research program usually results in slower progress. Therefore, universities are better suited to conducting long-term, fundamental research. If more of OHVT's program were focused on an eight to ten-year time horizon, universities would have more opportunities to participate.

Advanced Engine Mechanisms

For reciprocating engines, the crank-connecting, rod-piston mechanism has been, and currently is, the mechanism of choice, together with ports and/or cam-operated valves. It is well known from thermodynamic analysis that the compression ratio built into this mechanism can exert a strong influence on engine efficiency. In the diesel engine, the compression ratio is set high enough to promote compression ignition. In the spark-ignition engine, on the other hand, the abnormal combustion phenomenon of autoignition necessitates choosing a lower compression ratio.

Because autoignition occurs primarily at high engine loads, variable-geometry demonstration engines have been built that allow the compression ratio to be increased at part throttle for better efficiency, then decreased at high loads to avoid abnormal combustion. Just such an engine, with an anticipated time frame of 2005, was recently announced by Saab (Crosse, 2000). At light load, the engine runs normally aspirated at high efficiency, with a compression ratio of 14. As the throttle is opened, the compression ratio decreases continuously to a minimum of 8 at full load. At this condition, the engine is highly supercharged by an engine-driven, positive-displacement compressor and intercooled. Primarily because of this supercharging, Saab claims that this 1.6-liter engine has the output of a 3-liter conventional engine.

If this innovative Saab engine proves to be production viable, it should narrow the efficiency gap between the spark-ignition and compression-ignition engines. If the diesel engine cannot meet future emissions standards, a supercharged variable-compression-ratio engine might be an interesting alternative for SUVs or light-duty trucks. The ability to vary the compression ratio might also prove advantageous to the diesel engine for control of emissions or of peak cylinder pressure, or for improved cold starting.

International Truck and Engine Company recently issued a press release announcing a camless-diesel engine technology, in which the valves are hydraulically operated (Brooke, 2000; Navistar, 2000). The combination of electronically actuated and hydraulically controlled cams used in conjunction with computer-controlled, exhaust gas recirculation (EGR) and turbocharging, represents a transition to a "command-controlled" air-induction system. International claims that "NO_x emissions will be reduced by up to 70 percent, with significant gains in fuel economy. Particulate emissions are claimed to be reduced to 90 percent below the EPA's proposed 2010 diesel regulations" (Brooke, 2000).

Command control provides the capability of optimally configuring the engine, for both fuel economy and emissions, for each load and speed condition. This capability is of little value for an engine operating at fixed conditions but could significantly improve both fuel economy and emissions in an engine that operates in a range of conditions. If this technology is perfected, it could minimize engine-out emissions, which in turn would minimize, or possibly eliminate, the reduction requirements of an after-treatment system. Command control would also allow engine operation to be tailored to enhance exhaust-gas after-treatment performance (i.e., promote catalyst light-off or particulate-trap regeneration).

Recently, Flynn et al. (2000) hypothesized that it may not be possible with current diesel engine technology and fuels to meet the 2007 emission standards via in-cylinder emission reduction alone. If this conclusion is correct, exhaust-gas after-treatment systems will be necessary and will become an integral part of the diesel engine power train. OHVT also recognizes this eventuality and has included exhaust-gas after-treatment systems, as well as in-cylinder emission reduction technologies, as a major R&D area.

For contractual reasons, the committee was not informed of all of the details of the engines used in OHVT's programs. Consequently, the committee cannot comment on OHVT's work on advanced engine mechanisms. According to the announcements by Saab and International described above, new technologies have the potential for minimizing or eliminating the need for after-treatment. OHVT should immediately review these advances in advanced engine mechanisms and assess their implications for OHVT's research programs.

Findings and Recommendations

Finding. Engine-related programs cosponsored by the Office of Heavy Vehicle Technologies and industry from 1997 to date have encouraged industry and government together to solve important environmental problems and have produced useful results.

Recommendation. The cooperative government-industry approach being pursued by the Office of Heavy Vehicle Technologies should be continued with the addition of periodic (at least annual) reviews and updates of research on key enabling technologies.

Finding. Continual assessments of past achievements, the appropriateness of stated goals and projects, and the need for new approaches and goals are necessary for coordinating long-term research. It is not clear to the committee that OHVT is following this process. An eight-year time delay from the initiation of research to the introduction of a product has been documented by the Office of Heavy Vehicle Technologies. Three of the eight years have passed since the presentation of the 1997 technology road map. The committee was disappointed that more reassessments and adjustments had not been made since the initiation of the program.

Recommendation. The Office of Heavy Vehicle Technologies should put in place a process by which it can gradually revise its mix of programs and periodically (at least annually) review and update its programs and goals to reflect a time horizon of eight years or more.

Finding. Projects selected encompass a broad range of research areas rather than focusing on critical technologies. Given available resources, a smaller number of carefully chosen projects would be more productive.

Recommendation. The Office of Heavy Vehicle Technologies should carefully identify the most critical problem(s), such as emissions control, and concentrate its resources on research that will provide long-term solutions to these critical problems.

Finding. A significant portion of the program ($18 million in FY00) is focused on Class 1 and Class 2 light-duty vehicle engines through proprietary 50/50 cost-share projects with industry. Although the committee could not determine if funding was being used for that purpose, there was some indication that one of the companies in the program is working on technologies that might be incorporated into hardware components for a Class 1 or Class 2 light-duty engine. The committee supports the promotion of industry research on promising, yet high risk, approaches to configuring engine-emission control systems. The committee does not endorse the use of government funding to support specific engine or component development programs by industry.

Recommendation. The committee believes it appropriate for the Office of Heavy Vehicle Technologies (OHVT) programs to provide basic technical information to promote the development of more fuel-efficient engine-emission systems by the private sector for the light-truck and sport utility vehicle market. OHVT should evaluate the effectiveness of its 50/50 cost-share agreements with industry based on the extent to which each program is creating this basic information. OHVT should not support any cooperative agreement to develop a specific engine or component.

Heavy Vehicle Systems

The objective of the OHVT program is to increase fuel efficiency and reduce emissions, while maintaining and improving operational safety. OHVT's methodology is to analyze and optimize a heavy vehicle as a totally integrated system. The fuel economy goal for Classes 7 and 8 trucks is

10 mpg while meeting prevailing emission standards. A complete systems view of the total vehicle system includes engine systems technology, fuels, and a general category called systems technology, which includes the rest of the vehicle. The components of the heavy vehicle systems technology are: aerodynamic drag, auxiliary systems, rolling resistance, friction and wear, thermal management, high-strength, weight-reduction materials, and a category called others. These programs are addressed in this section.

Overall Systems View

As far as the committee could determine, OHVT has not conducted a total systems analysis except to generate a list of categories. Based on discussions with some investigators in the systems technology program, the committee believes that the lack of a total systems approach will result in the program failing to achieve its goal of a 10-mpg truck (McCallen, 2000; Englar, 2000a). The subareas in the systems technology program are not well coordinated with OHVT's overall goals, which increases the likelihood that the program goals for heavy-duty trucks will not be reached.

Given the significant impact of reduced power requirements, both in terms of economics and fuel consumption, the percentage of the budget devoted to reducing power requirements should be very large and R&D on vehicle systems should be continued past the stated ending date of 2001 (DOE, 2000a). Fortunately, much of the R&D is still in the planning stage and can still be reconsidered. If possible, the changes should be made without seriously disrupting the individual parts of the program. To this end, OHVT might consider giving a private contractor the responsibility of integrating the total systems approach. The integrated programs should meet OHVT's specific requirements for coalition building, and the national laboratories should be an on-call resource.

Finding. Because the heavy vehicle systems R&D element of the OHVT program is not well coordinated, the results will have little chance of contributing to the trucking industry in a timely fashion.

Recommendation. The present program of loosely coordinated projects should be replaced with a focused, results-oriented task structure and clearly stated goals for each project. Funding should then be allocated according to the potential for gains in fuel economy within the constraints of emission standards. In addition, the program should be extended well beyond 2001.

Multiyear Program Plan for the Aerodynamic Drag Program

The current plan for R&D on reducing aerodynamic drag has a three-tier, temporal structure: a plan with long-term benefits, a plan with midterm benefits, and a plan with short-term benefits. All of these are separate projects. The overall goal is to reduce drag by 15 to 25 percent (Diamond, 2000).

The long-term projects are centered at the national laboratories and focused on advancing the technology of computational fluid dynamics (CFD) in the area of drag prediction for Class 8 trucks. The research team includes investigators from LLNL, SNL, National Aeronautics and Space Administration (NASA), the University of Southern California, and the California Institute of Technology. Three different computational methods are being developed and validated experimentally. Although the projects are focused on a fundamental understanding of the flow physics, researchers have also been meeting with industry representatives to solicit their support and determine their expectations.

The midterm program includes one project with Georgia Technical Research Institute (GTRI) on pneumatic aerodynamics (pressurized air blowing) that uses jets of air to control and augment or reduce the aerodynamic forces and moments on the vehicle (Englar, 2000a). This technology, which was developed for short takeoff and landing aircraft, is expected to be efficient and mechanically simple.

The short-term program, which is focused on applying known technology to current production vehicles, consists of one consultant employed at a firm called Dynacs. Some progress has been made. For example, an existing truck with a deflector mounted on the cab was not reducing drag as planned, but was actually increasing drag. The consultant was able to identify the cause as a slight (10 to 11 inch) increase in space between the cab and the following trailer and to expedite the improvement.

OHVT has identified reduction in aerodynamic drag as a key element in reducing overall fuel consumption. In fact, it may be the single most important factor for trucks that spend most of their time on interstate highways (see Figure 2-2). However, OHVT's overall level of effort in aerodynamics does not reflect this importance, and is being done largely without industry involvement. By contrast, work on engine-related activities is being done with direct involvement of the engine manufacturers.

In fact, the program is heavily weighted toward the development of CFD models. The CFD project does include wind-tunnel tests, but they must be refined to represent the full complexity of a truck. Therefore, the value of the wind tunnel models will be to verify the CFD models, which may be computationally challenging but will not provide guidance to real-world truck designers. Improving the technology of CFD for drag predictions is a worthwhile goal and should be continued, but the goal of a 10-mpg truck will not be met unless applications are developed for a tractor-trailer vehicle. OHVT is funding CFD development at seven research locations with a combined FY00 budget of $992,000.

All of the CFD approaches being investigated appear to be completely independent of one another, except for the exchange of information among project participants, and no decision point is planned for choosing among them (e.g., a Go/No Go decision framework); at that point some of them would be discontinued and efforts would be concentrated on the most successful codes to ensure that they would be user friendly and usable to the trucking industry.

A new technology being funded by DOE through OHVT is being investigated at GTRI by staff from the former Lockheed aerodynamic group using a wind tunnel, which was donated to the Georgia Institute of Technology by Lockheed. Aerodynamicists at GTRI have developed and applied surface blowing and suction techniques (called pneumatic technology) to short takeoff and landing aircraft have proposed using this technology to reduce the drag of the nonstreamlined shapes of trucks. They also suggest that they can provide lift to reduce the weight on the wheels. A quick bounding calculation suggests that this effect is likely to be less than 5 percent of vehicle mass. Nevertheless, aerodynamic lift could conceivably reduce drag, rolling resistance, and damage to highways. The highly nonlinear effect of weight on highway damage might provide a significant advantage (AASHTO, 1994). The aerodynamic lift technology can reportedly be controlled very quickly for optimal operation in a dynamic process, such as braking.

A more complete integration of total truck systems would help investigators at GTRI determine better ways of integrating their technology developments into the truck as a whole (i.e., the impact on the engine, exhaust emissions, and the operating modes of an engine in a truck environment) (Englar, 2000b). GTRI is planning a demonstration of this technology on an actual truck, which might further the transfer of this new technology to the heavy truck industry, in which manufacturers are primarily assemblers.

Aerodynamic improvements will require much closer collaboration between vehicle designers, wind tunnel experiments, and computational modelers. The many complexities (e.g., spinning wheels, cooling system airflow, flow into and out of the underhood area, exposed frame rails and cross members) will have to be taken into account by the computational analysts and their importance determined in the aerodynamic drag of a truck. Wind tunnel tests using detailed models can assist in the development of models and in the empirical design of truck shapes.

The high cost of computers able to handle the computational codes will necessitate close cooperation between the trucking industry and the national laboratories. However, the massive parallel computational capabilities available at the national laboratories are being used to develop CFD codes. The committee believes OHVT (and DOE) should develop a plan to make these capabilities, which will not be affordable for many years, available to the truck manufacturing industry.

Finding. The development of different computational fluid dynamics (CFD) codes are proceeding independently of one another. No plan has been developed to coordinate these activities to provide useful results for the trucking industry.

Recommendation. A decision point should be defined at which time the most suitable single methodology of computational fluid dynamics (CFD) technologies should be selected for further support. A significant effort should be made to ensure that the final CFD model is user friendly.

Finding. The program on pneumatic technology in the Office of Vehicle Technologies plan may be useful in the near term for the aerodynamic design of vehicles and may warrant expansion.

Recommendation. The Office of Vehicle Technologies (OHVT) should study the benefits and costs associated with pneumatic technology and, if the results are favorable, should provide enough funding to thoroughly investigate this, including the impact of providing compressor power. Experimentally oriented programs should take an integrated approach to flows outside the truck and under the hood, including the integration of the engine compartment, underbody flows, and flows around the wheels. OHVT should also ensure that pneumatic technology, rotating tires, and underhood flows are included in the capabilities included in the development and benchmarking of the computational fluid dynamics model. Studies should focus on aerodynamic design, as well as the safety of vehicles equipped with pneumatic technology.

Finding. The benefits of computational fluid dynamics design methods will not be immediately useful to the trucking manufacturing industry unless the industry has access to the leading-edge computational power necessary to apply them.

Recommendation. The Office of Heavy Vehicle Technologies should provide industry with some means of access to the high-scale, massively parallel computers at the national laboratories until this level of computational power becomes affordable to industry and the value of the new computational fluid dynamics models have been demonstrated.

Rolling Resistance

The targeted goal of this program is to reduce rolling resistance by 8 to 10 percent through a multiyear plan for energy efficiency in heavy-duty vehicle tires, drive trains, and braking systems (DOE, 2000a; Blau, 2000). The preferred mechanism for reducing rolling resistance is the use of super single tires, which have been commercially available for more than a decade but have not been widely used for commercial trucks. The super single tire is both larger in diameter and wider than the most common tires used on Class 8 trucks. It also operates at higher pressure and requires a wider wheel rim. A super single tire of this configuration would be used in place of a pair of conventional truck tires.

Super single tires have not been widely adopted for many reasons, including concerns about safety, stability, and loss of cargo volume. Another concern is the possible acceleration of road damage. OHVT plans to work with the U.S. Department of Transportation and the American Trucking Association to explore the issues surrounding the use of super single tires. OHVT also plans to conduct tests to compare road damage from dual and single tires. OHVT plans to develop and maintain a tire-material database and to develop software for modeling tire materials and instrumentation systems for sensing real-time tire condition and misalignments. Unfortunately, the national laboratories do not have much expertise in tire technology, which is highly competitive and proprietary.

For most trucks, the larger diameter of the super single tire is a sufficient reason for not using it. The larger diameter can be accommodated only by raising the bed of the truck or trailer. Since the overall height, width, and length of trailers is set by regulation, and since most Class 8 trailers are built to the regulated limits, raising the truck bed would reduce the cargo space. In a van trailer that hauls volume-limited (as opposed to weight-limited) loads, the productivity of the truck is directly proportional to cargo volume. Furthermore, the height of loading docks has been standardized at the height of current truck beds. For these reasons, even if all other problems were solved, low-height trucks, such as tankers, are the only trucks likely to adopt super singles.

OHVT has no plan to encourage tire manufacturers to develop a better alternative. A competition could be held, for example, to develop an acceptable tire with reduced rolling resistance that meets the need for wet and dry road grip, tread wear, ride, noise, aging, cost, robustness against road hazards, and protection of the highways against road damage. The new tire would be much more acceptable and would benefit the nation sooner if it could be retrofitted to today's fleet. The truck operators, who will play a major role in deciding whether to purchase the new technology, should also play a major role in the evaluation of new tires.

Designing heavy-duty trucks for increased fuel efficiency must take into account vehicle interactions with roads and bridges. The weight of trucks is a major factor in the design life of roads. Damage to a road from a single fully loaded Class 8 truck is equivalent to the damage from about 5,000 cars (AASHTO, 1994). A 10-percent increase in truck weight would increase the damage rate by about 50 percent. As one would expect, the damage rate depends on tire configuration. Therefore, changing to high-pressure tires or to any other new tire configuration will have to be thoroughly evaluated to determine the effect on roads. The American Association of State Highway and Transportation Officials (AASHTO), which has existing databases and has developed the current models of road damage, should be included in the team that evaluates road damage.

Finding. Expertise in tire technology is mainly in the private sector.

Recommendation. The Office of Heavy Vehicle Technologies (OHVT) should consider restructuring its research on rolling resistance to encourage the development of superior tires by the tire industry.

Finding. Approaches to decreasing rolling resistance could have significant impacts on highway infrastructure.

Recommendation. The Office of Heavy Vehicle Technologies should devote more resources to evaluating the impacts of new tire designs on highways.

Reducing Friction and Wear in Heavy Vehicles

The plan for reducing friction and wear is almost totally focused on materials-related issues, including: (1) surface-modification technologies; (2) chemistry of lubricants and additives; (3) failure mechanisms; (4) advanced computer codes; (5) predictive bench-top tests; and (6) other issues. The target is a 15-percent reduction in losses caused by friction in the drive train and the engine (Fessler and Fenske, 1999).

Wear is closely related to the breakdown of lubricant film, surface hardness, material compatibility, and oil contamination, rather than engine friction. In modern truck engines, wear is not a problem unless the lubrication system (including the regulation of lubricant temperature) operates improperly or improper lubricants and/or change intervals are used. Therefore, OHVT seems to place too much emphasis on the problem of wear in the engine.

Friction reduction is another area in which OHVT's emphasis on materials research is excessive, at least for the engine. In the program plan, power consumption in engines is said to relate to material-based properties, but many sources in the open literature contradict this (Assanis, 1999). In fact, the figure in the plan showing the breakdown of mechanical friction does not represent a typical heavy-duty engine (Fessler and Fenske, 1999, p. 12), and many other questions could be raised about its validity. The data seems to be either from a very atypical engine or simply inaccurate.

Finding. The present friction and wear program is concentrated too heavily on materials research and not enough on practical techniques for reducing friction and constraints on those techniques. For example, a change that lowers friction but sacrifices oil control may have an unacceptable effect on emissions.

Recommendation. Research on reducing friction in the engine should be incorporated into the engine program. Funding for research on wear in the engine should be cut back.

Under-Hood Thermal Management

The OHVT *Technology Roadmap* (DOE, 2000a) specifically states:

> Aerodynamic designs offer new challenges in designing the under-hood systems and components of trucks. Optimal location and shape of components (e.g., engine, fans, radiators, heat exchanges, intake manifolds) have to be determined. Advanced high-efficiency trucks require optimization of the thermal performance of the power system and a well-characterized under-hood thermal environment to ensure that electronic control systems and other temperature-sensitive components operate properly. This complicated systems analysis requires the integration of high-fidelity models of thermal-hydraulic processes that stretch the state-of-the-art in CFD and high-performance computing. The computational model should integrate thermal models for convective, conductive, and radiative heat transport as well as integrate models for critical heat management system components, including cooling fans and radiators.

A workshop report and multiyear program plan were recently developed (DOE, 2000b). In the committee's opinion, the under-hood thermal management program seems to be well structured but, as discussed below, is not integrated with the aerodynamics program. The under-hood program is also underfunded.

The quotation above reflects OHVT's approach to under-hood design. The emphasis is on computation alone, rather than on computation for design. No mention is made of the crucial integration of under-hood thermal management and external aerodynamics. Some of the biggest reductions in drag in piston-engine aircraft and automobiles have resulted from an integrated approach to internal and external aerodynamics. In fact, an integrated approach was recommended in a workshop sponsored by the program, but it was not included in the program plan, and principal investigators told the committee they have no plans for integration (McCallen, 2000; Englar, 2000b).

The simulation of the thermal management system is currently of very great interest in heavy-duty truck design because the size, cost, and power requirements for the cooling system are expected to increase substantially with the new emission control levels. EGR and retarded fuel-injection timing, two of the most common techniques used to reduce emissions of NO_x, are both expected to increase heat rejection. Therefore, an integrated system design will be the most effective and economical approach, and simulations will be the best way to evaluate trade-offs. Eventually, designs will have to be verified in demonstration vehicles to convince the trucking industry of their performance.

Simulations of vehicle design with the CFD code CHAD (computational hydrodynamics for advanced designs) may not be practical because it requires very long run times. This deficiency was revealed during a review of the under-hood thermal-management program at ANL (Domanus and Caufield, 1999). Mathematicians at ANL have identified ways of speeding up the CHAD code by two orders of magnitude. If ANL is allowed to develop these changes, all of the programs that use CHAD would benefit.

R&D on controlling nucleate boiling and R&D on nanofluids are both concentrated on improvements in liquid-side heat transfer, whereas under-hood aerodynamics will affect air-side heat transfer. The committee feels that a clear distinction should be made between these two classes of technologies and that the program's focus should be largely on air-side heat transfer, which is the most common limiting mechanism on liquid-to-air systems and is expected to be the principal contributor to aerodynamic drag in the cooling system and auxiliary power consumption by the cooling system. Nevertheless, corrosion and fouling for liquid-side heat transfer, as well as liquid-side cooling in critical regions, such as between the fuel injector and the exhaust valve, are also important and should still be supported by OHVT.

Finding. Under-hood thermal management and overall vehicle drag are closely related and should be considered together in mathematical models if practical design methods are to be developed.

Recommendation. The under-hood thermal management program should explore integrating the vehicle-drag simulation and the thermal-management simulation so that a total system can be simulated. The program should use newly developed tools to proceed with a sample design that includes drag reduction, adequate cooling, and low power consumption. The design should then be validated in a demonstration vehicle.

Finding. The computation time for real problems using the CHAD (computational hydrodynamics for advanced design) computer code is so long that it all but precludes its use in design practice.

Recommendation. Efforts should be made to reduce the running time for the CHAD (computational hydrodynamics for advanced design) code.

Finding. The program on under-hood thermal management includes a wide range of investigations, from comprehensive under-hood models to techniques for investigating solid-to-liquid and solid-to-air heat transfers. The most significant improvements in thermal systems are expected to be provided by improved solid-to-air heat transfer.

Recommendation. The Office of Heavy Vehicle Technologies (OHVT) should ensure that all activities that would enhance and control air-side heat transfer are adequately funded before considering funding for projects on liquid-side heat transfer (other than corrosion and fouling).

Auxiliaries and Other Energy-Saving Projects

OHVT includes the cab comfort-control system and the regenerative shock absorber in the category of auxiliaries and other energy-saving projects. Only R&D on the regenerative shock absorbers is funded for FY00 (a high-risk project about which the committee was provided very little information). The cab comfort system is addressed by the use of an auxiliary power unit that could reduce the need for idling the engine during long overnight truck stops and a plan to inform truck operators of the potential energy savings of reducing long idle operations. OHVT's goal of a 10-mpg truck postulates very significant reductions in power requirements for auxiliaries.

The rationale for a small auxiliary power unit is that it would use less energy and produce fewer emissions than the complete truck engine operating at idle speed and very low load. Even though an auxiliary power unit can probably be developed to meet this expectation, the improvement might be small because of the adverse effects of scaling internal combustion engines to low power levels. OHVT does not have any funded programs in auxiliary power for FY00.

Other potential energy-saving technologies are not included in the program, although the OHVT *Technology Roadmap* projects a large saving in power consumed by auxiliaries. For example, most engine auxiliaries are designed for a particular worst-case condition. If the engine drives the auxiliary power unit by a constant-ratio mechanical drive, its power consumption can be excessive. Alternative auxiliary drives can save substantial energy by matching the performance to the needs of the engine.

Consider, for example, the lubricating oil pump on a truck engine, which is designed with excess capacity to meet the worst-case condition of engine operation at very high speeds when oil pressure must be high enough to fill all of the oil supply passages at a positive pressure at all times to prevent rapid engine failure. Engine failure is most likely when the vehicle is operating in overspeed conditions, such as descending a grade through one of the lower gears. Therefore, the lubricating pump is designed to provide more oil than necessary, even in this extreme condition. An additional margin is included to meet the increased flow requirements of worn crankshaft bearings and the decreased capacity of aging pumps. For many other operating conditions, however, very little oil flow and pressure are required.

The lubrication supply system consists of an engine-driven gear pump and a pressure-relief bypass valve. Because the pump system is designed with extra capacity, the pressure-relief valve is partially open during most engine operations. The flow of oil across the pressure drop of the relief valve constitutes a direct energy loss that must be compensated for by increased input to the pump shaft. Because the pump is not 100 percent efficient, the input power must be greater than the loss in the relief valve. The net loss can be several kilowatts. If the oil supply pressure could be modulated in response to engine operating condition, a substantial portion of the power used to circulate oil through the engine could be saved.

Several options are currently used to increase the efficiency of engine auxiliaries. The trend in the automobile industry is to use electric drive for engine accessories. Even though the efficiency penalties of converting shaft power to electricity and back again are considerable, the benefits of tailoring the power supply to the requirements of the moment result in a net gain in efficiency. In the future, automobiles will have 42-V electrical systems, which will improve the efficiency of generators and motors; heavy-duty trucks are also expected to benefit from 42-V systems.

Other options for increasing the efficiency of engine auxiliaries include mechanical variable-speed drive and variable-geometry pumps and fans. Water pumps, radiator fans, and power steering pumps could all be made more efficient, either by electric drive or by other means. If electronic controls and sensors are used to optimize power use, these accessories could also contribute to better fuel economy.

Finding. Advances in the efficiency of engine auxiliaries and other onboard systems that require power will be important for the development of a 10-mpg truck. OHVT has no program to quantify and demonstrate the full range of advanced technologies.

Recommendation. The Office of Heavy Vehicle Technologies (OHVT) should consider and evaluate the potential energy savings in engine auxiliaries and other system power loads with technologies not currently in the program. Depending on the results of the analysis, OHVT should then consider expanding its development activities in auxiliaries and accessories with low energy consumption.

Hybrid Systems

The goal of the Heavy Vehicle Propulsion Hybrid R&D Program is to develop and demonstrate, by 2004, commercially viable vehicles that achieve at least double the fuel economy of comparable 1999 vehicles in an urban driving cycle and, as a research goal, to decrease criteria pollutant emissions to at least 30 percent below EPA standards prevailing in 2004. The focus is on urban trucks and buses with hybrid-electric power trains, with special emphasis on configurations with natural-gas engines. OHVT plans to work with competitively selected industry teams that include hybrid system developers and vehicle manufacturers (Wares and O'Kain, 2000).

In response to a solicitation for heavy-vehicle hybrid propulsion systems on September 24, 1999, OHVT received several proposals. The winners were announced on March 3, 2000 (Wares and O'Kain, 2000). OHVT representatives indicated that industry response to the solicitation was excellent and that a variety of vehicle hybrid propulsion system designs and vehicle applications were received. The three teams selected are: NovaBus/Lockheed Martin; Electrocore/GM Allison; and A.D. Little/Freightliner/ISE Research/DDC/University of California, Davis. Unfortunately, details of the proposals were not provided to the committee for review. Consequently, the following comments and recommendations are based on committee members' knowledge of the field.

HEV passenger cars have recently been introduced into the marketplace. An HEV uses a power-augmenting electric motor and associated energy storage device (e.g., a battery) to reduce the rated power requirement of the primary power plant (e.g., a diesel engine). Passenger-car HEVs achieve better urban fuel economy than conventional passenger cars for three reasons: more efficient operation of the engine; engine shutoff; and regenerative braking.

First, conventional passenger cars characteristically have high power-to-weight ratios to provide the acceleration performance and hill-climbing ability demanded by American drivers. The high ratio forces the engine to operate much of the time at light loads, at which friction and throttling losses markedly decrease the efficiency of the traditional spark-ignition engine. Because the smaller HEV engine is forced to operate at higher loads, its efficiency is improved. Second, in most HEVs, fuel flow to the engine can be halted during braking and idling. Third, the electric motor operates as a generator during braking. Therefore, part of the kinetic energy invested in the moving vehicle can be recovered and stored in the battery for reuse on demand. This type of generator is sometimes called a regenerative retarder, and recovery of energy during braking is called regenerative braking.

The additional weight of the HEV electrical system generally exceeds the weight saved by the smaller engine. The resulting increase in net weight offsets some of the fuel savings expected from an HEV. The trade-off is influenced by the driving schedule and must be evaluated analytically prior to hardware commitment.

A driving schedule featuring frequent starts and stops, such as for urban delivery vans or buses, is conducive to fuel-economy gains in an HEV with regenerative braking. However, in fast decelerations from high speeds, as might occur for on-highway trucks, much of the available braking energy may have to be sacrificed because of limitations on the battery charging rate. If the decelerations are consistently from low road speeds, regenerative braking will probably be less effective because of poor generator efficiency at low speeds. More information on regenerative braking may soon be available through a planned DOE program on regenerative retarders (Blau, 2000). Vehicle systems simulations can determine the potential fuel economy and emissions benefits of HEVs.

Power electronics are an essential element of HEVs. Normally, the motor/generator is an alternating-current machine, but the battery storing the electricity is a direct-current device. The power electronics must convert the current between the two devices efficiently and with precision control. The battery storage is a critical component of an HEV drive train. As a battery accumulates service time, its performance deteriorates until eventually it must be replaced. The characteristics of an HEV may, therefore, depend on battery age. Other problems are also related to electrochemical storage batteries. The performance of some batteries is drastically reduced at subfreezing temperatures. Some cannot be fully charged at high ambient temperatures. Some cannot be quickly charged, which may be essential for regenerative braking. Some have unresolved safety concerns.

Meeting emission standards will be critical to the success of improved vehicle technologies, including hybrid vehicles. Even demonstrating an emissions reduction of 30 percent below the 2004 EPA standards in a production prototype by 2004 may be insufficient. Given the lead time required by industry to progress from a prototype to actual production, an appropriate emissions target would be meeting the standards for 2007, which are more than 30 percent below the 2004 standards.

OHVT has been working with its stakeholders and industry to develop road maps and carry out technology development. As noted above, a number of teams have been formed, and vehicle projects have been selected for heavy-vehicle hybrids. None of these teams includes the customer, however, who is the ultimate user of the vehicle. Vehicle manufacturers can offer HEVs in the marketplace, but if they do not have the qualities desired by the owner/operator, they will have no chance of making a significant market penetration.

Natural gas should be compared to diesel fuel in a broad context of the entire fuel cycle (see Fuels Utilization section). In terms of energy conservation and the production of greenhouse gases, as well as cost and domestic availability, processes ranging from fuel recovery to delivery, energy costs of compressing natural gas to make compressed natural gas (CNG) and the liquefication of natural gas to make liquefied natural gas (LNG), as well as onboard storage, will have to be considered.

Finding. Computer simulations of vehicle systems will be necessary to identify the potential fuel economy and emissions of hybrid electric vehicles.

Recommendation. If it has not already done so, the Office of Heavy Vehicle Technologies should evaluate the candidate hybrid electric vehicles by computer simulation. For the simulations to be meaningful, the specific driving schedule on which the gain in fuel economy is assessed must be defined.

Finding. Acceptance by the ultimate end-user or owner of the vehicle will be critical to ensure significant market penetration of heavy-duty hybrid vehicles.

Recommendation. The Office of Heavy Vehicle Technologies should ensure that the customer (i.e., the anticipated user/owner of the vehicle) is consulted as the program progresses. The customer may also have useful insights for planning future programs.

FUELS UTILIZATION

OHVT's fuels program currently focuses on two fuels: low-sulfur diesel and natural gas. The fuels utilization R&D

budget was about $14.6 million in FY00, or about 21 percent of the OHVT budget. Programs on Fischer-Tropsch liquids, oxygenates, and biodiesel have essentially been completed. The committee believes that the current focus is appropriate. Continued monitoring of R&D on oxygenates outside of the program may be useful to determine if new opportunities develop.

OHVT is focusing on the current range of interest for sulfur concentration (5 to 50 ppm). Low-sulfur fuel is necessary to minimize both particulate emissions and minimize the deleterious effects of sulfur oxides produced in the engine that reduce the efficiency of the after-treatment systems. One candidate after-treatment system uses an NO_x trap, which can be poisoned by sulfur oxides. Another, less sulfur-sensitive system, uses an additive (e.g., urea) to reduce NO_x to nitrogen. The engine builders have suggested a sulfur limit of 5 ppm primarily to protect the catalyst in the NO_x trap (Thoss, 2000). The petroleum industry has recommended that sulfur specifications in diesel fuel be lowered to an average of 30 ppm, with a maximum of 50 ppm, arguing that sulfur limits lower than that would be very costly and could cause fuel shortages (Cavaney, 2000). EPA has proposed a standard of 15 ppm. Research on a variety of after-treatment technologies using fuels with a range of sulfur concentrations will be necessary to determine which technology will meet the emission standards at minimal cost to the consumer for the fuel-vehicle system.

Determining the size distribution and chemical character/toxicity of particulates in the exhaust gas from the after-treatment system will also be necessary because of concerns about diesel particulates as TACs.

Natural Gas

The Alternative Fuels Program supports the development of a viable heavy-duty, vehicular, natural-gas engine. Such engines are already being marketed for urban transit vehicles and school buses. Natural gas is the preferred fuel because its engine-out emissions are lower than with diesel fuel. However, to meet the new emission standards, after-treatment will be necessary. Vehicles with heavy-duty, natural-gas engines are frequently purchased through government agencies rather than by private companies, often encouraged through legislation and/or financial incentives such as subsidies and tax relief. In the long term, however, natural-gas vehicles (NGVs) will have to be cost competitive with diesel vehicles, except in special circumstances, such as urban use where low emissions and other environmental benefits may be more important than cost.

Specific goals of the OHVT Natural Gas Vehicle Program include demonstrating two hybrid NGVs by 2004 that are competitive in cost and performance with their diesel-engine counterparts. One will be a Class 3 to 6 vehicle operating on CNG; the other will be a Class 7 to 8 vehicle operating on LNG.

OHVT has identified four technology barriers to broad acceptance of NGVs. The first is inferior engine efficiency. Three types of natural-gas engines have been proposed: the spark-ignited natural gas engine (SING), the pilot-injection natural gas engine (PING), and the direct-injection natural gas engine (DING). The SING, which normally uses an inducted, premixed, near-stoichiometric charge of fuel and air, is limited to a compression ratio lower than that of the diesel engine because of combustion knock, despite the high octane rating of natural gas. Consequently, even though its efficiency will exceed that of a spark-ignited gasoline engine, the SING is not likely to match the efficiency of the diesel engine. The compression ratio of the PING, which employs compression ignition of a pilot injection of diesel fuel to initiate combustion of the natural gas, does not have the same limitation. The DING, which injects natural gas directly into the cylinder and uses glow-plug-assisted ignition, is even less likely to experience combustion knock.

A second technology barrier to natural-gas engines is the size and weight of onboard fuel storage containers. At the commonly used pressure of 250 atm, CNG occupies about four times as much space as diesel fuel. High pressures dictate long, cylindrical, thick-walled storage tanks that are often difficult to package in a vehicle. Moreover, the tanks are heavy and expensive. LNG consumes only about two-thirds more space than diesel fuel with the same energy content. However, LNG is a cryogen, having a temperature of about –150°C. Therefore, LNG must be stored in a bulky vacuum-jacketed tank. As the tank is warmed by the environment, gas must be vented to avoid the buildup of pressure. For safety reasons, this would discourage the use of LNG in vehicles that are either serviced or parked in enclosed buildings.

OHVT is investigating a storage system involving the adsorption of natural gas onto carbon fibers in a tank pressurized to 34 atm. Because heat is generated during fast charging of the tank, it would require cooling. An electric heater would be used to drive gas from the tank. Although adsorption storage of natural gas is not a new technology, the potential of this particular system has not yet been thoroughly defined.

A third technology barrier is the limited availability of fueling stations. In 1998, there were 5,318 CNG fueling sites and 486 LNG fueling sites (70 percent of them in California) in the United States (Davis, 1999). By comparison, there were between 150,000 and 200,000 gasoline stations. Thirty-five states had only one or no LNG sites. In 1999, federal, state, and local governments operated 45 percent of the heavy-duty CNG vehicles and 78 percent of the heavy-duty LNG vehicles (Davis, 1999).

A fourth technology barrier is the high cost of a natural-gas fueling station. To provide for fast filling (as opposed to overnight filling, which might be acceptable for a privately owned passenger car and some short-range urban delivery trucks), a CNG service station normally uses a large compressor that pumps natural gas from a modest supply-line pressure up to a pressure exceeding that of the vehicle storage tank. On demand, the gas flows from the station tank to the vehicle tank via the pressure difference. The total energy expended in compressing the station gas is minimized by pumping only part of the gas to maximum station pressure. The remainder is compressed to a series of lower pressure levels and stored in a cascade of intermediate-pressure tanks. A fast-fill cascade can be designed to refuel an NGV in a reasonable period of time. When refueling a series of NGVs, however, enough time must elapse between vehicles so that the station compressor can refill the cascade.

LNG is transferred to the vehicle tank by a liquid pump. Pumping LNG as a cryogenic liquid consumes less energy than compressing it as a gas to CNG storage pressures. However, liquefying the fuel consumes much more energy than compressing CNG.

Finding. The low-sulfur fuel program is appropriately focused on 5 to 50 ppm, the range of current interest. The program approaches the fuel, engine, and after-treatment as an integrated system. The oil industry, the after-treatment industry, and engine builders are all participants in the program.

Recommendation. The Office of Heavy Vehicle Technologies should place a higher priority on its low-sulfur fuel program.

Finding. It is too late to influence engine designs for 2004.

Recommendations. For demonstrations of a Class 3 to 6 vehicle operating on compressed natural gas and a Class 7 to 8 vehicle operating on liquefied natural gas to be meaningful, the vehicles should meet the proposed emissions standards for 2007.

Finding. The spark-ignited natural gas (SING) engine is not likely to equal the efficiency of the diesel engine, although it may surpass the efficiency of a spark-ignited gasoline engine.

Recommendation. The Office of Heavy Vehicle Technologies should limit its support to the pilot-injection natural-gas engine (PING) and the direct-injection natural gas engine (DING) unless it determines that the spark-ignited natural gas engine (SING) can provide solutions to emissions problems that the other two engines cannot. Support for all three engines is warranted until their performance and emissions characteristics are well understood.

Finding. If similar natural-gas vehicles (one using compressed natural gas [CNG] and the other using liquefied natural gas [LNG]) travel the same distance on a kilogram of natural gas, the CNG vehicle will probably be more energy efficient than the LNG vehicle because of the difference in energy requirements for the fuel.

Recommendation. Evaluations of energy consumption of natural-gas vehicles should include the energy required to deliver the fuel to the vehicle engine. A "well-to-wheels" analysis should be used for assessing technology options.

Finding. Industry is already marketing compressed natural gas (CNG) storage tanks, as well as tanks for cryogenic storage. Hence, unless a new technology that provides significant improvements in performance is identified, there is no need for OHVT to support such developments. OHVT currently supports only minimal research on other advanced storage technologies, such as methane storage with novel adsorbents.

Recommendation. The Office of Heavy Vehicle Technologies should conduct more research on novel adsorption storage for the purpose of determining system requirements for charging and discharging the tank, response to engine transients, and the weight, cost, safety, and energy balance of such a system.

Finding. Until a sufficient number of natural-gas vehicles are operating commercially in the United States with a consequent demand for natural-gas fuel, new commercial natural-gas stations are not likely to be built, except for use by centrally fueled fleets.

Recommendation. Building natural-gas refueling stations should not be a priority for the Office of Heavy Vehicle Technologies at this time. Instead, research should be focused on centrally fueled fleets until natural-gas vehicles have better engine efficiency and marketable onboard energy storage.

Finding. The emissions of particulate matter from natural-gas engines have not been well characterized. In light of recent trends in emission regulations, these emissions have become more important.

Recommendation. The physical and chemical characteristics of particulate emissions from natural-gas engines should be studied, both with and without after-treatment systems.

TRANSPORTATION MATERIALS TECHNOLOGIES

The OHVT *Technology Roadmap* notes that the enabling technology for a new engine component is often the material from which the part can be made (DOE, 2000a). The engines under development will have to operate under more challenging conditions, such as higher temperatures, more hostile environments, and greater stress, than today's engines.

In addition, the chassis weight of the vehicles will have to be reduced to meet the fuel economy and emissions goals. Meeting these challenges will require new and different materials that will entail design changes.

The importance of materials is reflected in OHVT's budget for R&D in this area: $15.7 million in 1996; $12.5 million in 1997; $13.3 million in 1998; and $15.0 million in 1999. These expenditures represented a substantial portion of the total OHVT budget (from more than 50 percent in 1996 to about 33 percent in 1999). In addition, a significant part of the materials budget ($5.2 million in 1996, $5.5 million in 1999) went to support the High-Temperature Materials Laboratory (HTML) at ORNL. Although OHVT uses this laboratory, HTML is a national facility for materials research with a host of clients, and the portion of its budget directly related to the OHVT program is uncertain.

OHVT's materials program is divided into two areas: high-strength, weight-reduction materials and advanced materials for propulsion systems. The goal of the high-strength, weight-reduction program is to reduce the vehicle weight by 35 to 40 percent for Class 1 and 2 vehicles, 25 percent for Class 3 to 6 vehicles, and by 5,000 lbs for Class 7 and 8 vehicles. The goal of the program for advanced materials for propulsion systems is to develop materials to meet the needs of fuel systems, exhaust-gas after-treatment systems, valve trains, and air-handling systems.

Weight reduction for all truck classes faces similar challenges, which, in fact, are similar to those faced by the PNGV program, which is focused on midsized automobiles. Lighter weight materials and design changes will result in lower vehicle weights, but lighter materials may cost more, can be more difficult to join, and have limited databases. Materials for propulsion systems must satisfy requirements for increased strength, greater dimensional precision in production, new and quite different materials that can withstand hostile high-temperature environments, and the ability to withstand higher stress environments.

The committee was given several presentations and information pieces on R&D programs in materials (see Appendix D). Although the committee was not required to evaluate each program, they appear to be well managed. However, projects are not prioritized based on their importance to the success of the OHVT program as a whole and their likelihood of success.

Considering the myriad of problems and opportunities in materials R&D, OHVT must develop a process for identifying the most significant materials-related barriers to improved performance and prioritize them according to need. Then, relevant technologies should be evaluated in terms of their probability of success, and the most promising technologies should be selected. Finally, OHVT should establish long-range research programs to address needs that cannot be addressed by current technologies. Unless a disciplined, systematic approach is adopted, almost any materials-related R&D can be justified as being relevant to the OHVT program. OHVT must ensure that the projects it supports are not just relevant but also (1) address a priority need, (2) have a reasonable chance of success, or (3) are long-term research projects that may have high risks but also have potentially high payoffs.

Finding. OHVT has no systematic process for prioritizing high-strength, weight-reduction, materials-related research and development (R&D) or for monitoring other relevant, federally funded, materials R&D.

Recommendation. A systematic process should be developed and put in place to monitor relevant, federally funded, materials research and development (R&D), to prioritize materials needs, and to identify high-priority opportunities for R&D. This process should use vehicle-systems modeling analyses to set specific goals for vehicle, power train, and chassis weight to meet the overall fuel economy goals.

ENVIRONMENT AND HEALTH ISSUES

The primary mission of OHVT's research programs is to provide a knowledge base for improved fuel economy and control of engine emissions. Other agencies are focusing on the health and environmental effects of engine emissions. However, researchers studying the production of emissions should also have an appreciation of the health and environmental effects of these emissions. To that end, OHVT has participated in a small way in some health and environmental studies. The committee approves of this participation but only to the extent required to optimize OHVT's research on emission-control techniques.

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3

Overall Findings and Recommendations

This chapter summarizes the committee's findings and recommendations for the overall OHVT R&D program, based on presentations on individual OHVT programs (see Chapter 2), OHVT multiyear plans for each program, OHVT road maps, workshop proceedings, presentations by outside speakers, and committee members' personal knowledge of heavy-duty engine technology and the market. The committee recognizes that the managers of OHVT must operate under many constraints that affect the distribution of available resources. For example, Congress may pass legislation related to the program that must be implemented. Fuel prices or emission or safety standards can be changed. Policies can also be changed, which may require that the program be reoriented. The committee has tried to focus its recommendations on improving the chances for the technologies under development to meet the goals of the program and to be successful commercially over the long term. The OHVT program is responding responsibly to congressional legislation and should continue to do so. In addition, OHVT follows the legislative process and provides Congress with the technical information it needs to make reasonable decisions.

The committee applauds the cooperative activities among OHVT, other DOE programs, and the EPA on the issue of sulfur levels in diesel fuel. Continuing cooperative efforts will be essential for the United States to improve fuel economy while maintaining a clean environment and a competitive advantage in a global economy. For example, the proposed 21st Century Truck Initiative is intended to be a long-range government-industry cooperative effort. In addition, OHVT has successfully involved industry and other stakeholders in identifying needs and developing a technology road map to meet the challenges facing heavy-duty diesel-engine technology. In the past year, OHVT has also made a significant effort to reach out to stakeholders and industries important to the trucking industry and has successfully leveraged its budget through cooperative efforts with other DOE programs and with industry. However, because of outside constraints, stakeholder interests, and political realities, OHVT has changed the focus of its research in several areas toward shorter term development. In the committee's opinion, the long-term interests of the United States would be better served if most of OHVT's R&D has a long-term focus.

As multinational corporations expand, international trade increases, and global transportation knits the global economy together, industry is rapidly becoming global in all aspects. Nevertheless, standards and test procedures for vehicular emissions are not uniform across nations. Transportation emission standards in industrialized countries are becoming more stringent, and trade-offs of reductions in fuel economy to meet emission standards will be necessary. At the same time, the cost of petroleum is likely to rise, although the time frame is difficult to predict. Because transportation costs are a significant fraction of production costs in modern economies, there is an indirect relationship between emission standards and global competitiveness related both to the cost of moving goods and the cost of importing and exporting vehicles. Since emission standards are government mandated, government and industry must work together to address fuel economy and environmental issues.

In the past, OHVT programs have appropriately focused on technologies to meet anticipated stricter emission standards. Changing emission standards and an approximate eight-year delay between the start of a research program and the appearance of its results in commercial production have complicated planning of OHVT's R&D programs. Setting priorities and continually reviewing programs to redirect R&D could be more effective if OHVT had a Go/No Go decision-making process for critical milestones.

Finding 1. Energy and environmental policies, as well as emission standards, are continually changing in response to factors beyond the control of the Office of Heavy Vehicle Technologies (OHVT). Consequently, goals, objectives, and timetables for research and development (R&D) can become outdated. For example, an R&D program designed to achieve lower emission levels will be of little practical use for initial production vehicles unless the R&D is completed significantly in advance of new standards (i.e., in time for the results to be used in production vehicles). (However, new technologies could be brought on line for later vehicle models.)

Recommendation 1. The Office of Heavy Vehicle Technologies (OHVT) should modify its program goals to reflect a time horizon of eight years or more. The longer time frame would allow industry time to incorporate research results into products, universities to contribute more significantly to solving problems, and OHVT to adjust the balance of its resources to support research by industry, the natural laboratories, and universities.

OHVT should revise its existing programs to ensure that the basic technical information produced by each individual program will be available at least three years before the technology is scheduled for commercial production. The revised mix of programs, which should be implemented by fiscal year 2003, will shift the emphasis to new advanced technologies and away from near-term development.

Finding 2. Both light-duty and heavy-duty vehicles will require improved energy efficiency with minimum adverse environmental effects and competitiveness in a global economy. Meeting these often-conflicting goals will require that government and industry work together. The Office of Heavy Vehicle Technologies (OHVT) is successfully working with industry and other stakeholders to meet these challenges. However, the committee did not see much evidence that OHVT has established a Go/No Go decision-making process for evaluating and dealing with technical showstoppers at critical milestones.

Recommendation 2. Office of Heavy Vehicle Technologies (OHVT) programs should be updated annually, and program strategies and priorities should be reassessed. New programs should have a long-term focus. In addition, OHVT should implement a Go/No Go decision-making framework to keep OHVT programs focused on program goals and to establish or modify priorities and to change directions, as necessary.

The diesel engine is the most efficient, economical power plant available today for trucks. As integrated emissions-control technology advances, the diesel engine can be increasingly optimized to its duty cycle. From the perspective of efficiency, and therefore fuel savings, the diesel engine could play a key role in reducing the rate of increase of petroleum use in the United States. However, the fuel economy benefit of the diesel engine will not be realized unless emission standards can be met. With present technologies, both the gasoline engine and the diesel engine will require exhaust-gas after-treatment to meet the projected emission standards for 2007–2010. Therefore, OHVT programs must be sharply focused on meeting future emission standards.

Finding 3. The most critical barrier to improving fuel economy is the emission of oxides of nitrogen and particulate matter. Current activities are spread across too many areas and not focused on overcoming this critical barrier. Given available resources, a smaller number of carefully chosen projects would be more productive.

Recommendation 3. The Office of Heavy Vehicle Technologies (OHVT) should reevaluate its priorities and increase its support for projects focused on overcoming the most critical barriers to success. For example, meeting emissions standards will be critical to OHVT's program on advanced combustion engines. Therefore, emissions should be a major focus of this program. In addition, OHVT must be more proactive and forward thinking in anticipating future emission standards, and should focus on improving the understanding of the physical and chemical character of emissions. In anticipation of more stringent emissions standards than are currently planned by the Environmental Protection Agency, OHVT should undertake technology-forcing research.

To meet future emission standards, particularly for oxides of nitrogen (NO_x) and particulate matter (PM), some proposed exhaust-gas after-treatment technologies will require a low sulfur content in fuel to improve NO_x conversion efficiency. Sulfur compounds in the exhaust gas may also contribute to the formation of ultrafine exhaust particles. Automotive manufacturers prefer very low levels of sulfur (5 parts per million [ppm]) to benefit automotive emissions-control systems; the petroleum industry has suggested a standard of 30 ppm (average) and a 50 ppm (maximum) limit to control increases in fuel costs and avoid supply problems. EPA has a proposed regulation for sulfur concentration in diesel fuel of 15 ppm.

Finding 4. Regulations are being considered to reduce the levels of sulfur in fuel used for on-highway diesel vehicles. The sulfur levels for some current after-treatment technologies, such as NO_x traps, will have to be very low and could require sulfur traps that would have to be changed periodically. Some technologies, such as selective catalytic reduction, are less sulfur sensitive but require the addition of a reductant (e.g., urea). Consequently, the economic trade-offs between sulfur levels in fuel and after-treatment technologies will be an important consideration in the development of cost-effective emission-control systems.

Recommendation 4. The Office of Heavy Vehicle Technologies should place a high priority on integrated emissions-control technology (engine combustion and after-treatment technology) to meet future emission requirements. Research and development (R&D) should be focused on sulfur-tolerant catalysts, sulfur traps, and selective catalytic reduction, for diesel fuel with sulfur levels of 5 to 50 parts per million. R&D should be focused on both experimental work and modeling related to basic in-cylinder combustion and after-treatment technologies.

Because fuel consumption by light trucks and SUVs is increasing, "dieselization" for light trucks and SUV markets makes sense. Indeed, dieselization is a significant part of OHVT's program. However, if the diesel engine cannot meet emission standards, it will not be a viable alternative for this market segment. Although OHVT's program is focused on addressing the technical barriers to meeting emission standards with diesel engines, it should also keep abreast of progress on other engine types that could meet emission standards more easily, although with poorer fuel economy (e.g., the gasoline engine).

Finding 5. The Office of Heavy Vehicle Technologies (OHVT) is actively involved in 50/50 cost-share projects with Cummins-DaimlerChrysler, Detroit Diesel-DaimlerChrysler, and Caterpillar-Ford to develop a competitive Class 2 diesel truck engine for use in sport utility vehicles (SUVs) and light trucks. OHVT's funding is being used to facilitate interactions between the heavy-duty engine industry and automotive manufacturers, and research on these projects is being done by the partnering companies. The proprietary results will be protected from public disclosure for five years. Therefore, the committee found it difficult to assess the scope and focus of OHVT's light-duty engine program. There was some indication, however, that one of the companies in the program is working on technologies that could be incorporated into hardware components for a Class 1 or Class 2 light-duty truck engine. The committee supports OHVT's promotion of industry research on promising, high-risk approaches to configuring engine emission-control systems that could facilitate the introduction of more fuel-efficient engines into the light-truck and SUV market. However, the committee does not endorse the use of OHVT funds to support specific engine or component development by industry.

Recommendation 5. The committee believes it appropriate for the Office of Heavy Vehicle Technologies (OHVT) programs to provide basic technical information (e.g., improved understanding of physical processes, new and/or improved system optimization and control techniques, etc.) that will promote more fuel-efficient engine-emission systems by the private sector for the light-truck and sport utility vehicle market. OHVT should evaluate the effectiveness of its 50/50 cost-share programs with industry to determine if they are creating needed basic information. OHVT should not support the development of a specific engine or component.

Some of the biggest improvement in the overall fuel efficiency of heavy-duty trucks can be achieved by improving aerodynamics, using lightweight materials, and decreasing rolling resistance. Aerodynamic losses for all trucks can be large (e.g., at 70 mph on a level road, roughly 65 percent of the power requirements are attributable to aerodynamic drag). For trucks limited by weight requirements (e.g., flatbed trucks), a decrease in vehicle weight would allow for an increase in payload weight. Therefore, large increases in material transport efficiencies, perhaps larger than can be made through improvements in engine performance, may be possible through decreases in aerodynamic drag, reductions in weight, and decreases in rolling resistance. However, new truck designs must also take into account the interaction of heavy trucks with the roadways (e.g., the rate of damage from a fully loaded Class 8 truck is equivalent to that of 5,000 cars), as well as congestion and disruption to the transportation system from road repair.

Several factors should be taken into account in a systems view of fuel economy. First, double trailers (sometimes even triple trailers, although not allowed in all states) have different aerodynamics than single-tractor trailers and also different cargo-carrying capacities. Because they are heavier than single trailers, they consume more gallons of fuel per mile; however, because they can carry more cargo weight, the appropriate measure for the fuel economy of trucks carrying cargo should be ton-miles/gallon (ton refers to the weight of the cargo being transported).

Second, the driving duty cycle should be specified for all vehicles targeted for improvements in fuel economy. Without specified driving cycles, fuel economy goals are not very meaningful. OHVT has done this for Class 7 and 8 vehicles by specifying constant-speed driving at 65 mph, a very simple driving cycle. Third, the performance level of the vehicle must be indicated because fuel economy improvements can be made by sacrificing vehicle performance, and this trade-off should be included in an evaluation of the improvement.

Finding 6. Engine efficiency is a significant, but not the only, factor in increasing the fuel economy of heavy vehicles. The overall Office of Heavy Vehicle Technologies (OHVT) program is focused too heavily on improving engine efficiency and not enough on other factors that affect fuel economy. The committee recognizes that some of these factors may be outside OHVT's mission and that addressing them will require interagency cooperation.

Recommendation 6. The Office of Heavy Vehicle Technologies (OHVT) should focus more on factors other than engine efficiency that affect on-road fuel economy, especially improving aerodynamics, reducing the use of accessory power, decreasing rolling resistance, and decreasing unloaded vehicle weight by innovative design incorporating high-strength, weight reduction materials (in keeping with safety considerations, as well as highway wear and tear). OHVT, in cooperation with other government agencies, should conduct an analysis to clarify the trade-offs and opportunities among engine efficiency and other factors affecting vehicle fuel economy and reorient its programs accordingly.

To achieve a 10-mpg fuel economy in Class 7 and 8 trucks, OHVT should monitor trends in installed engine power and steps the commercial market is taking to achieve this. Trip time may be a more economically important parameter than fuel economy. OHVT's analysis should include vehicle systems models to identify opportunities for improving the vehicle system that could lead to improvements in fuel economy. For each truck classification, the driving duty cycle associated with each fuel economy goal should be specified. In addition, OHVT should evaluate which measure of fuel economy, miles/gallon or ton-miles/gallon, is most appropriate for each class of vehicle. The expansion of OHVT's programs in this recommendation will require an increase in funding.

The most promising alternative to diesel fuel is natural gas. OHVT's program is now focused on urban trucks and buses with hybrid electric power trains, especially configurations that use natural gas. OHVT plans to work with competitively selected industry teams of hybrid-vehicle system developers and vehicle manufacturers. Because of the lack of an extensive infrastructure for natural-gas fueling stations, the focus will be on urban trucks and buses, which can more easily be fueled at central stations than privately owned vehicles. When comparing compressed and liquefied natural gas, vehicle energy consumption should be measured on a "well-to-wheels" basis.

Finding 7. The goals of the Natural Gas Vehicle Program include demonstrations of two natural-gas vehicles by 2004 that are competitive in cost and performance with their diesel-fueled counterparts. One will be a Class 3 to 6 vehicle that operates on compressed natural gas (CNG); the other will be a Class 7 or 8 vehicle that operates on liquefied natural gas (LNG). Three types of natural-gas engines have been proposed: the SING (spark-ignition natural gas), the PING (pilot-injection natural gas), and the DING (direct-ignition natural gas). The size, weight, and cost of onboard fuel storage systems, as well as the limited availability and high cost of natural-gas fueling stations, are also being addressed. Completion of the demonstration program will help to clarify the position of heavy-duty, natural-gas engines relative to diesel engines in terms of compliance with future emission standards and fuel economy.

Recommendation 7. The Office of Heavy Vehicle Technologies should refocus its natural-gas research on meeting emission standards for 2007. Support for the PING (pilot-injection, natural gas) engine, DING (direct-injection, natural gas) engine and SING (spark-ignition, natural gas) should be continued until their performance and emissions characteristics are well understood. At that point, support for the SING engine should be discontinued unless it proves to have a substantial emissions advantage over the PING and DING engines. Research on onboard storage of natural gas should be focused on novel methods rather than on conventional compressed natural gas and liquefied natural gas storage technologies. A "well-to-wheels" analysis should be used to compare options for onboard storage. Research on refueling should be limited to the central refueling option.

The R&D programs in materials appear to be well managed. However, projects are not prioritized based on their importance to the success of the OHVT program as a whole and their likelihood of success.

Considering the myriad problems and opportunities in materials R&D, OHVT must develop a process for identifying the most significant materials-related barriers to improved performance and prioritize them according to need. Then, relevant technologies should be evaluated in terms of their probability of success, and the most promising technologies should be selected. Finally, OHVT should establish long-range research programs to address needs that cannot be addressed by current technologies. Unless a disciplined, systematic approach is adopted, almost any materials-related R&D can be justified as being relevant to the OHVT program. OHVT must ensure that the projects it supports are not just relevant but also (1) address a priority need, (2) have a reasonable chance of success, or (3) are long-term research projects that may have high risks but also have potentially large payoffs.

Finding 8. The Office of Heavy Vehicle Technologies has no systematic process for prioritizing high-strength, weight-reduction, materials-related research or for monitoring other relevant, federally funded materials R&D.

Recommendation 8. A systematic process should be developed and put in place to monitor relevant, federally funded, materials research and development (R&D), to prioritize materials needs, and to identify high-priority opportunities for R&D. This process should use vehicle-systems modeling analyses to set specific goals for vehicle, power train, and chassis weight to meet overall fuel economy goals.

Appendixes

Appendix A

Biographical Sketches of Committee Members

John H. Johnson, chair, is a Presidential Professor, Department of Mechanical Engineering-Engineering Mechanics, Michigan Technological University (MTU), and a fellow of the Society of Automotive Engineers (SAE). His experience spans a wide range of analysis and experiments related to advanced engine concepts, emissions studies, fuel systems, and engine simulation. He has published more than 160 papers and reports on the measurement and control of diesel emissions including modeling of particulate traps and vehicle engine cooling systems. Before joining the faculty of MTU, he was project engineer, U.S. Army Tank Automotive Center, and chief engineer, Applied Engine Research, International Harvester Company. Dr. Johnson has served on many committees related to engine technology, engine emissions, and health effects for the SAE, the National Research Council (NRC), the Combustion Institute, the Health Effects Institute, and the Environmental Protection Agency. He has also been a consultant to a number of government and private-sector institutions. He received his Ph.D. in mechanical engineering from the University of Wisconsin.

Charles Amann is a retired fellow, General Motors Research Laboratories, where he held the positions of research engineer; assistant head, Gas Turbine Research Department; head, Engine Research Department; and director, Engineering Research Council. He has extensive experience in all types of engines. His research interests include fuels and combustion, internal combustion engines, and energy technologies. He received the Colwell Merit Award, SAE, in 1972 and 1984; the James Clayton Fund Prize, British Institute of Mechanical Engineers, in 1975; the Richard T. Woodbury Award, American Society of Mechanical Engineers, in 1989; and an Outstanding Achievement Award from the University of Minnesota in 1991. He is a member of the National Academy of Engineering and recently served on the NRC Committee on the Ozone-Forming Potential of Reformulated Gasoline. He has a B.S. and an M.S.M.E. from the University of Minnesota.

William L. Brown, Jr., is retired from Caterpillar Inc., where his last position was team leader in simulation and combustion, Engine Research. He is currently a part-time consultant for Caterpillar. He has an extensive background in diesel engine development, including laboratory testing and analysis of engine performance and losses, engine simulation, measurement of cylinder pressures, heat transfer, diesel engine combustion chemistry, emissions, and design of production engines. He was senior visiting scientist and has held other visiting appointments at the Engine Research Center, University of Wisconsin; Bradley University; and Los Alamos National Laboratory. He is a member of SAE and the Combustion Institute. Dr. Brown was awarded the Ole Evinrude Fellowship at Purdue University, 1958–1959, and the Arch T. Colwell Award by SAE in 1968 and 1974. He has a B.S.M.E. and M.S.M.E. from Purdue University.

David E. Foster is professor of mechanical engineering, University of Wisconsin, Madison, and former director, Engine Research Center, which has won two center of excellence competitions for engine research and has extensive facilities for research on internal combustion engines. A faculty member at the University of Wisconsin since completion of his Ph.D., Dr. Foster teaches and conducts research in thermodynamics, fluid mechanics, internal combustion engines, and emission formation processes. His specific focus is on perfecting the application of optical diagnostics in engine systems and incorporating simplified or phenomenological models of emission formation processes into engineering simulations. He has published more than 60 technical articles in this field throughout the world and for the leading societies in this country. He is a recipient of the Ralph R. Teetor Award, the Forest R. McFarland Award, and the Lloyd L. Withrow Distinguished Speaker Award of the SAE. He is a registered professional engineer in the state of Wisconsin and has won departmental, engineering society, and university awards for his classroom teaching.

He received a B.S. and M.S. in mechanical engineering from the University of Wisconsin and a Ph.D. in mechanical engineering from the Massachusetts Institute of Technology (MIT).

Thomas A. Keim is director, MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems. He has been vice president and chief engineer, Kaman Electromagnetics Corporation; mechanical engineer, General Electric Corporate R&D Center; research engineer, MIT; and engineer, American Electric Power Corporation. Mr. Keim has broad technical expertise in practical electromechanics, power electronics, and system dynamics and control. The consortium of which he is director has 44 member companies, including major automobile companies and their suppliers, so that he is well acquainted with electronic applications in vehicles. He has an Sc.D. and S.M.M.E. from MIT and a B.S.M.E. from Carnegie Mellon University.

Phillip Myers is Emeritus Distinguished Research Professor and former chairman, Department of Mechanical Engineering, University of Wisconsin, Madison, and a fellow of the American Society of Mechanical Engineers, SAE, and the American Association for the Advancement of Science (AAAS). He was the 1969 president of SAE and has served on numerous NRC committees, including the Committee on Fuel Economy of Automobiles and Light Trucks, the Committee on Toxicological and Performance Aspects of Oxygenated Motor Vehicle Fuels, and the Committee on Advanced Automotive Technologies Plan. He is a fellow of SAE and AAAS and a member of the National Academy of Engineering. His research interests include internal combustion engines, combustion processes, engine emissions, and fuels. He has a Ph.D. in mechanical engineering from University of Wisconsin, Madison.

Gary W. Rogers is president, chief executive officer, and sole director, of FEV Engine Technology, Inc. He is also vice president, North American Operations, FEV Motorentechnik GmbH & Co. KG. His previous positions have included director, Power Plant Engineering Services Division, and senior analytical engineer, Failure Analysis Associates, Inc.; design development engineer, Garrett Turbine Engine Company; and exploration geophysicist, Shell Oil Company. He has extensive experience in research, design, and development of advanced engine and power train systems, including high-speed direction-injection (HSDI) passenger car engines, heavy-duty diesel engines, hybrid vehicle systems, gas turbines, pumps, and compressors. He provides corporate leadership for a multinational research, design, and development organization and is a member of the Advanced Powerplant Committee, SAE, an advisor to the Defense Advanced Research Projects Agency on Heavy-Fuel Engines, and an advisor to Oakland University's Department of Mechanical Engineering. He has a B.S.M.E. from Northern Arizona University.

Dale Stein is President Emeritus of Michigan Technological University and retired professor of materials science. He has held positions at Michigan Technological University, the University of Minnesota, and the General Electric Research Laboratory. He is a recipient of the Hardy Gold Medal of the American Institute of Mining, Metallurgical and Petroleum Engineers and the Geisler Award of the American Society of Metals (Eastern New York Chapter) and has been an elected fellow of the American Society of Metals and AAAS. He has served on numerous NRC committees and has been a member of the U.S. Department of Energy's Energy Research Advisory Board. He is also a member of the National Academy of Engineering and an internationally known authority on the mechanical properties of engineering materials. He received his Ph.D. in metallurgy from Rensselaer Polytechnic Institute.

John Wise is retired vice president of research, Mobil Research and Development Corporation. He has also been vice president, R&E Planning; manager, Process Products R&D; manager, Exploration and Production R&D; director, Mobil Solar Energy Corporation; and director, Mobil Foundation. He served on the Board of Directors of the Industrial Research Institute, was active in the World Petroleum Congress, and was cochair of the Auto/Oil Air Quality Improvement Research Program. He has served as a member and chairman of numerous NRC committees and is a member of the Board on Energy and Environmental Systems, as well as the National Academy of Engineering. He has expertise on fuels, catalysis, R&D management, and the effects of fuels and engines on emissions. He received a Ph.D. in chemistry from MIT.

Gordon Wright is retired manager, Advanced Powertrain Systems and Diesel Engineering, Ford Motor Company, where he was responsible for all advanced, in-line gasoline and diesel engine projects worldwide and engineering teams in the United Kingdom, Germany, and the United States. At Ford, he also held the position of director, Powertrain Research Laboratory. For Ford New Holland, he served as director, Engine Product Development, and at FIAT as director, Engine Product Development for IVECO. He was director of technology and planning, DEDEC, a planned joint venture between Deere & Company and General Motors. He has also held several positions at Deere & Company, including manager, Advanced Engines, and manager, Engine Technology Group. He has extensive industry experience in the development of diesel engines worldwide, including product planning, manufacturing process planning, design, development, testing, and release of engines for vehicle applications. He has a B.S., M.S., and Ph.D. in mechanical engineering from the University of Missouri-Rolla.

Appendix B

Presentations and Committee Activities

1. Committee meeting, February 16–18, 2000, Washington, D.C.

Overview of the Office of Transportation Technologies (OTT)
Tom Gross, Deputy Assistant Secretary, OTT

Mission, History, and Organization of Office of Heavy Vehicle Technologies (OHVT)
Discussion of Committee's Statement of Task
Jim Eberhardt, Director, OHVT

OHVT Program Development and Program Planning Methodology
Jim Eberhardt, Director, OHVT

Overview of OHVT Budgets, Plans, Priorities, and Balance of Activities
Jim Eberhardt, Director, OHVT

OHVT R&D on Advanced Combustion Engine
Gurpreet Singh, Team Leader, Advanced Combustion Engine R&D, OHVT

R&D on Heavy Vehicle Systems and Materials
Sidney Diamond, Team Leader, Heavy Vehicle Systems and Materials R&D, OHVT

Heavy Vehicle Hybrid
Richard Wares, Team Leader, Heavy Vehicle Hybrid, OHVT

Fuels Utilization
Stephen Goguen, Team Leader, Fuels Utilization, OHVT

Environmental Science and Health
Michael Gurivich, Team Leader, Environmental Science and Health Activities, OHVT

Union of Concerned Scientist's (UCS's) Perspective on the OHVT Program
Jason Mark, Senior Transportation Analyst, UCS

Program/Industry Activities in the OHVT Program
Jim Patton, Cummins Engine Company
Nabil Hakim, Detroit Diesel Corporation

2. Committee meeting, April 26–27, 2000, Washington, D.C.

Diesel Fuel Standards and Tier 2 Standards for Light and Heavy Trucks
Chet France, Director, Assessment and Standards Division, Environmental Protection Agency

Particulate Matter Emissions from Gasoline-Powered and Diesel-Powered Vehicles
M. Matti Maricq, Principal Research Scientist, Ford Scientific Research Laboratory

Health Effects Related to Particulate Matter from Diesel-Powered and Gasoline-Powered Vehicles
Dan Greenbaum, President, Health Effects Institute

Health Effects of Diesel-Powered and Gasoline-Powered Vehicle Emissions
Joe Mauderly, Senior Scientist, Lovelace Respiratory Research Institute

Integrated Emissions Control for Heavy-Duty and Light-Duty Diesel Engines
James Thoss, Chief Engineer, Catalytic Systems Division, Johnson Matthey

The 21st Century Truck Initiative
Paul Skalny, U.S. Army Tank Automotive Command

Light Truck Diesel Engine Developments with DOE
John Stang, Cummins Engine Company

Light Truck Diesel Engine Developments with DOE
Eric Fluga, Caterpillar Engine Research

Light Truck Developments with DOE
Charlie Freese, Vice President, Automotive, Detroit Diesel Corporation

Status of Heavy Vehicle Hybrid Solicitation
Jim Eberhardt, Richard Wares, Team Leaders, Heavy Vehicle Hybrid, OHVT

3. Committee meeting, June 14–16, 2000, Washington, D.C.

Questions and Answers on the OHVT Program and DOE's Perspective on the 21st Century Truck Initiative
Jim Eberhardt, Director, OHVT

Appendix C

Funding for Research and Development on Combustion and After-treatment Technologies

The following list of projects is being funded by OHVT for R&D related to combustion and emissions control (Table C-1).

TABLE C-1 Funding for Projects on Combustion and Emission Control (thousands of dollars)

Project	Performer	FY00 OHVT Funding	FY00 Cost Sharing from OAAT
Diesel combustion CRADA: in-cylinder research on an optically accessible Cummins single-cylinder engine	SNL	500	0
Diesel Combustion CRADA: research utilizing a constant-volume combustion vessel	SNL	250	250
Homogeneous charge compression ignition	SNL	150	350
Combustion research at universities	SNL/U. of Illinois, U. of Wisconsin, and Purdue	140	0
Diesel combustion CRADA	U. of Wisconsin/SNL	100	0
Diesel combustion CRADA/CHAD modeling	LANL	250	0
Diesel combustion CRADA/ chemical kinetics	LLNL	200	250
NO_x after-treatment CRADA	ORNL/DDC	150	0
NO_x after-treatment CRADA	ORNL/Cummins	200	0
Technology evaluation	ORNL	100	0
Zero-emission diesel	ORNL	150	0
Precompetitive catalyst R&D	ORNL/Engelhard	100	0
Real-time control	ORNL/DDC	150	0
Technical and cross-cut team support	ORNL	275	0
Nonthermal plasma CRADA	PNNL/Caterpillar	350	0
Nonthermal plasma CRADA	PNNL/Delphi/ DDC	350	0
Nonthermal plasma	LLNL/Cummins	200	0
Emissions CRADA/late-cycle injection of air or oxygen	ANL/Caterpillar	200	0
Total funding for combustion and emission control research at national laboratories		4,215	

Note: The budget represented in this table constitutes one budget line in the OHVT program budget (see Table 1-5). The distribution of funding does not represent the distribution of funds for the OHVT program as a whole.
Acronyms: ANL = Argonne National Laboratory; CRADA = cooperative research and development agreement; DDC = Detroit Diesel Corporation; LANL = Los Alamos National Laboratory; LLNL = Lawrence Livermore National Laboratory; ORNL = Oak Ridge National Laboratory; PNNL = Pacific Northwest National Laboratory; SNL = Sandia National Laboratories

Source: OHVT.

Appendix D

Funding for Materials Research and Development Projects

Tables D-1 and D-2 show funding for research on propulsion system materials and high-strength, weight-reduction materials.

TABLE D-1 Funding for Projects on Propulsion System Materials (thousands of dollars)

Description	Laboratory/Institution	FY00 Funding
Propulsion system materials		
Program taxes		524
Thick thermal-barrier coatings	Caterpillar	200
Insulated cylinder head	Caterpillar	200
Exhaust after-treatment	Caterpillar	0
Lightweight valve train materials	Caterpillar	0
Materials for low-emissions high-efficiency engine	Cummins	233
Fuel-injector materials	Cummins	400
Smart materials for fuel-injector actuators	Detroit Diesel	300
Management/standards development	ORNL	765
Continuous sintering of diesel engine components	SIUC	150
Mechanical characterization	NC A&T	272
Nondestructive evaluation of diesel components	ANL	210
IEA – standard reference powders	NIST	200
Testing standards	NIST	105
NO_x sensor (CRADA)	Ford/ORNL	100
Smart materials	ORNL	400
Intermetallic cermets	ORNL	100
High-toughness materials	ORNL	350
Particulate traps	ORNL	100
Durable diesel-engine materials	ORNL	200
Diesel exhaust-catalyst characterization	ORNL	200
Life prediction	ORNL	200
IEA annex on international standards	ORNL	200
Machining CRADAs	Cummins/Caterpillar	225
Advanced machining concepts	NC State	75
Development of low-cost cast engine materials	ORNL/Cat	75
TBD		95
Total (propulsion systems materials)		5,879
High-Temperature Materials Laboratory (HTML)	ORNL	8,020
Taxes		240
Total (HTML)		8,260

Note: The budget represented in this table constitutes one of budget line in the OHVT program budget (see Table 1-5). The distribution of funding does not represent the distribution for the OHVT program as a whole.
Acronyms: IEA = International Energy Agency; TBD = to be determined.

Source: OHVT

TABLE D-2 Funding for Projects on High-Strength, Weight-Reduction Materials (thousands of dollars)

Description	Laboratory/Institution	FY00 Funding
Program taxes		415
Technical program management	ORNL	180
Ultralarge caster	Alcoa	1,300
Lightweight diesel	Cummins	100
Laser-hardening of rails	ANL	100
Toxic air contaminants support	Thompson	155
Lightweight materials for gaseous storage	ORNL	200
Bus frame – autokinetics	AutoKin	187
Heater/cooler	ORNL	58
Lightweight frame design	PNNL	800
Freightliner/ megalarge caster	PNNL	350
PACCAR/thin-wall steel castings	PNNL	325
Equal-channel angular extrusion	LANL	125
Equal-channel angular extrusion	INEEL	250
Equal-channel angular extrusion	PNNL	150
Carbon-foam materials	ORNL	75
Brake materials	ORNL	200
Joining	ANL	75
Friction and wear	ORNL	100
Outreach	ANL	100
Equal channel angular extrusion – Mg alloys	ORNL	70
TBD		467
Total		5,782

Note: The budget represented in this table constitutes one budget line in the OHVT program budget (see Table 1-5). The distribution of funding does not represent the distribution for the OHVT program as a whole.

Acronyms: TBD = to be determined.

Source: OHVT.

Acronyms and Abbreviations

ANL	Argonne National Laboratory
bbl	barrel
bhp-h	brake horsepower-hour
CAFÉ	corporate average fuel economy
CARB	California Air Resources Board
CFD	computational fluid dynamics
CHAD	computational hydrodynamics for advanced designs
CNG	compressed natural gas
CO	carbon monoxide
CRADA	cooperative research and development agreement
DDC	Detroit Diesel Corporation
DING	direct-injection natural-gas (engine)
DOE	U.S. Department of Energy
EGR	exhaust gas recirculation
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FY	fiscal year
GTRI	Georgia Tech Research Institute
GVW	gross vehicle weight
HCCI	homogeneous-charge, compression-ignition (engine)
HEV	hybrid electric vehicle
HTML	High Temperature Materials Laboratory
LANL	Los Alamos National Laboratory
LDT	light-duty trucks
LEV	low-emission vehicle
LLNL	Lawrence Livermore National Laboratory
LNG	liquefied natural gas
MDPV	medium-duty passenger vehicle
mpg	miles per gallon
mph	miles per hour
NASA	National Aeronautics and Space Administration
NGV	natural-gas vehicle
NMHC	nonmethane hydrocarbons
NO_x	nitrogen oxides
OAAT	Office of Advanced Automotive Technologies
OHVT	Office of Heavy Vehicle Technologies
OPEC	Organization of Petroleum Exporting Countries
ORNL	Oak Ridge National Laboratory
PING	pilot-injection, natural-gas (engine)
PM	particulate matter
PNGV	Partnership for a New Generation of Vehicles
R&D	research and development
SCR	selective catalytic reduction
SING	spark-ignited, natural-gas (engine)
SNL	Sandia National Laboratories
SOP	statement of principles
SULEV	super low-emission vehicle
SUV	sport utility vehicle
TAC	toxic air contaminant
ULEV	ultra low-emission vehicle
VOC	volatile organic compound