REVIEW OF THE 21ST CENTURY TRUCK PARTNERSHIP

Committee to Review the 21st Century Truck Partnership

Board on Energy and Environmental Systems
Division on Engineering and Physical Sciences

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The Committee to Review the 21st Century Truck Partnership extends its thanks to the representatives of the 21st Century Truck Partnership and to all of the company and national laboratory representatives who contributed significantly of their time and effort to this National Research Council (NRC) study, either by giving presentations at meetings or by responding to committee requests for information.

The committee also acknowledges the valuable contributions of other individuals who provided information and presentations at the committee's open meetings. (Appendix B lists all of those presentations.) The committee particularly expresses its appreciation to Ken Howden, U.S. Department of Energy, Office of FreedomCAR and Vehicle Technologies, for his extensive effort in coordinating responses to our questions and in making presentations to the committee. Finally, the committee chair wishes to recognize the committee members and the staff of the NRC Board on Energy and Environmental Systems for organizing and planning the committee meetings and gathering information and drafting sections of the report. Duncan Brown in particular has done an outstanding job of facilitating the work of the committee, which required reviewing a significant amount of background material and helping the committee to focus on writing a concise and timely report. Jim Zucchetto was also always available to help guide the committee and to use his vast experience to help the committee in its deliberations. Lastly, the committee chair expresses his appreciation to Dale Stein, who chaired the first meeting, and Pat Flynn, who helped Duncan Brown set up the second meeting.

This report has been reviewed in draft form 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 institution in making its 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 review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

- Betsy Ancker-Johnson (NAE), General Motors Corporation (retired)
- Rodica A. Baranescu (NAE), University of Illinois at Chicago
- David E. Foster, University of Wisconsin
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- Jason Mark, The Energy Foundation
- Joe Mauderly, Lovelace Respiratory Research Institute
- Anne T. McCartt, Insurance Institute for Highway Safety
- James F. Tipka, American Trucking Association
- John J. Wise (NAE), Mobil Research and Development Corporation (retired)

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by William Agnew (NAE), General Motors Research Laboratory (retired). Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

The amount of fuel consumed annually by heavy-duty trucks and buses has more than doubled over the past 35 years and now accounts for 21 percent of the total surface-transportation fuel used in the United States (DOE, EERE, 2005). Improving the fuel economy of trucks and reducing emissions to help meet environmental goals have become significant issues in the United States as well as in Europe and Asia.

Worldwide oil consumption has risen rapidly in the past few years, mainly owing to rapid economic growth. This increased demand has resulted in a rapid rise in oil prices even though production capacity has kept pace with demand and is expected to exceed demand in 2009. With the United States being very dependent on imported oil, this increase in price has put a strain on the U.S. economy. As a consequence, the nation is pursuing alternative sources for fuel and attempting to increase efficiency in oil usage.

The 21st Century Truck Partnership (21CTP), a cooperative research and development (R&D) partnership formed by four federal agencies with 15 industrial partners, was launched in the year 2000 with high hopes that it would dramatically advance the technologies used in trucks and buses, yielding a cleaner, safer, more efficient generation of vehicles. The Partnership was at first under the leadership of the U.S. Department of Defense (DOD; specifically, the U.S. Army Tank-Automotive Research and Development Command). In November 2002, leadership of the Partnership passed from the Department of Defense to the U.S. Department of Energy (DOE). Within DOE, the operational responsibility for the Partnership is assigned to the Office of FreedomCAR and Vehicle Technologies, which organizes meetings and conference calls, maintains the information-flow infrastructure (such as Web sites and e-mail lists), and has led the discussions for and preparation of the updated version of the 2006 21CTP roadmap and technical white papers (DOE, 2006), which together lay out Partnership goals.

The management of specific projects under the 21CTP umbrella rests with the individual federal agencies that have funded the work. These agencies use the 21CTP information-sharing infrastructure to coordinate efforts and ensure that valuable research results are communicated and that any overlap of activities is reduced.

As described in the 21CTP roadmap and technical white papers, the general goal of the 21st Century Truck Partnership is to "reduce fuel usage and emissions while increasing heavy vehicle safety. The purpose of the Partnership is to support research, development, and demonstration that enable achieving these goals with commercially viable products and systems." The vision of the Partnership is "that our nation's trucks and buses will safely and cost-effectively move larger volumes of freight and greater numbers of passengers while emitting little or no pollution and dramatically reducing the dependency on foreign oil" (DOE, 2006, p. 1).

In support of its general goal and vision, the Partnership carries out research in these areas of technology:

- Integrated vehicle systems for commercial and military trucks and buses;
- Engine-combustion, exhaust aftertreatment, fuels, and advanced materials to achieve higher efficiency and lower emissions;
- Heavy-duty hybrid propulsion systems;
- Reduction of parasitic losses to achieve significantly reduced energy consumption;
- Technologies to improve truck safety, resulting in the reduction of fatalities and injuries in truck-involved crashes; and
- Technologies that reduce energy consumption and exhaust emissions during idling.

STATEMENT OF TASK

In response to a request from the director of the DOE's Office of FreedomCAR and Vehicle Technologies, the National Research Council formed the Committee to Review the 21st Century Truck Partnership (see Appendix A for biographical information on committee members). The committee was asked to fulfill the following statement of task:

> The committee will conduct an independent review of the 21st Century Truck Partnership. In its review, the committee will critically examine and comment on the overall adequacy and balance of the 21st Century Truck Partnership to accomplish its goals, on progress in the program, and make recommendations, as appropriate, that the committee believes can improve the likelihood of the Partnership meeting its goals. In particular, the committee will:
>
> 1. Review the high-level technical goals, targets, and timetables for R&D efforts, which address such areas as heavy vehicle systems; hybrid electric propulsion; advanced internal combustion engines (ICEs); and materials technologies.
> 2. Review and evaluate progress and program directions since the inception of the Partnership toward meeting the Partnership's technical goals, and examine ongoing research activities and their relevance to meeting the goals of the Partnership.
> 3. Examine and comment on the overall balance and adequacy of the 21st Century Truck Partnership's research effort, and the rate of progress, in light of the technical objectives and schedules for each of the major technology areas.
> 4. Examine and comment, as necessary, on the appropriate role for federal involvement in the various technical areas under development.
> 5. Examine and comment on the Partnership's strategy for accomplishing its goals, which might include such issues as (a) program management and organization; (b) the process for setting milestones, research directions, and making Go/No Go decisions; (c) collaborative activities within DOE, other government agencies, the private sector, universities, and others; and (d) other topics that the committee finds important to comment on related to the success of the program to meet its technical goals.
>
> After examining the 21st Century Truck Partnership activities and receiving presentations from federal government representatives and industry representatives, and outside experts, as appropriate, the committee will write a report documenting its review of the Partnership with recommendations for improvement, as necessary.

MAJOR FINDINGS AND RECOMMENDATIONS

The 21CTP has had a number of successful programs since its beginnings in 2000. These efforts are discussed in this report. The major findings relate to the most important aspects of the program and the recommendations to the highest-priority requirements for change. The committee's findings and recommendations include 2 pairs of "overall," or general, findings and recommendations and 13 pairs that are selected from individual Chapters 2 through 7, as the highest priority in those particular areas. The latter retain their original numbering to help the reader gain context by going to the original discussions.

Overall Report Finding 1-1. The key benefit of the 21CTP is the coordination of research programs directed toward the goal of reducing fuel usage and emissions while increasing heavy vehicle safety. Federal involvement is bringing stakeholders to the table and accelerating the pace of development. Very few U.S. manufacturers of trucks and buses or heavy-duty vehicle components have the R&D resources to develop new technologies individually. Thus, the 21CTP is giving some of those companies access to extraordinary expertise and equipment in federal laboratories, in addition to seed funding that draws financial commitment from the companies to push forward in new technology areas. The Partnership provides the United States with a forum in which the various agencies, in combination with industry and academia, can better coordinate their programs. Research funding of the 21CTP has been declining steadily in recent years, and this decline is threatening the attainment of program goals. The current level is not in proportion to the importance of the goal of reducing fuel consumption of heavy-duty vehicles.

Overall Report Recommendation 1-1. The 21st Century Truck Partnership should be continued, but the future program should be revised and better balanced based on the recommendations of this report. In addition, more manufacturers should be recruited as participants, such as the major truck manufacturers and suppliers that are not in the Partnership. Research funding should be commensurate with well-formulated goals that are strategic to reducing fuel consumption of heavy-duty vehicles while improving safety. The 21CTP should also conduct an assessment of heavy-truck research activities overseas and determine if any changes in the future program would be appropriate based on foreign programs.

Overall Report Finding 1-2. Many of the program goals were not met, because some of the goals were not plausible, from either an engineering or a funding perspective. Other goals were not met because some of the technologies proposed for meeting the goals were not applied. Notable failures of that kind are discussed in Chapter 3, under the headings "Goal of Thermal Efficiency of 55 Percent" and "Goals Involving Fuels."

Overall Report Recommendation 1-2. A clearer goal-setting strategy should be developed, and the goals should be clearly stated in measurable engineering terms and reviewed periodically so as to be based on the available funds.

Management Strategy and Priority Setting

Finding 2-1. The 21CTP is operated as a virtual network of agencies and government laboratories, with an unwieldy structure and budgetary process. Agency personnel meet frequently and industry partners meet periodically for limited sharing and communication. This has been the extent of the coordination. Both government agencies and industry partners, per their remarks to the committee, have found the arrangement less than effective. The program was most productive when a full-time person from industry was assigned to coordinate the cross-agency efforts.

Oversight of the 21CTP is provided through an Executive Committee with representation from DOE, DOT (the U.S. Department of Transportation), EPA (the U.S. Environmental Protection Agency), DOD, and the industry partners. Although that committee lacks authority to make cross-agency decisions and implement firm actions, it has been most effective when chaired by a full-time executive. This seemed to be an effective measure to ensure cooperation among agencies and address program challenges.

Recommendation 2-1. A full-time, technically capable leader with consensus-building skills should be appointed to coordinate the 21CTP program among industry partners and government agencies. This person could chair the Executive Committee and would be authorized to make recommendations to the committee on behalf of the entire program on stopping or redirecting existing research, on setting research priorities, and on future funding levels.

Finding 2-2. As confirmed in meetings with the DOE and other agencies, there is no single source of funds for the 21CTP, as perhaps intended by its creators. Instead, each of the four agencies has its own stream of funds. DOE, DOT, DOD, and EPA budget and optimize funding based on their own priorities. In addition, they maintain funding to companies with multiyear cooperative agreements. Thus, managing the 21CTP program and projects across multiple agencies has been challenging, and there have been difficulties in setting program priorities, especially in aligning budgets to programmatic requirements. A result has been difficulty in balancing between near- and long-term projects and setting appropriate metrics and measures. In addition, variation in funding levels from year to year has diminished the impact of project achievements and results and reduced the probability of success and commercialization. The result of this complexity and lack of transparency is that some federal funds were spent by industry partners and by other federal agencies in ways that cannot be accounted for in the funding structure by fiscal year.

Recommendation 2-2. A portfolio management process that sets priorities and aligns budgets among the agencies and industrial partners is recommended. A proposed table of project priorities (Figure 2-5) would provide an objective way of ranking research and development projects according to their expected outcomes. This could evolve into a budgeting process that ensures support for programs of merit beyond a single year. Precompetitive, collaborative technology and concept development could receive proper focus for successful programs.

Engine Systems and Fuels

Finding 3-1. Although DOE has concluded that the 50 percent thermal efficiency goal has been achieved, the experimental test results show that none of the industry partners achieved the goal of 50 percent thermal efficiency at 2010 emissions standards with a complete engine system. Each partner either failed to test a complete engine system on an engine dynamometer and used analysis to project results or failed to achieve 50 percent thermal efficiency at 2010 emissions standards with a complete system. Details of the analytical projections were proprietary and were not provided to the committee. Moreover, the work that was accomplished was at the intrinsically more efficient peak torque condition rather than at an engine speed and load representative of 65 mile per hour (mph) road load.

Recommendation 3-1. Objective and consistent criteria should be used to assess the success or failure of achieving a key goal of the 21CTP such as the attainment of 50 percent thermal efficiency. Detailed periodic technical reviews of progress against the program plan should be conducted so that deficiencies can be identified early and corrective actions implemented to ensure success in accomplishing program goals. DOE should continue to work toward demonstrating 50 percent thermal efficiency at the peak efficiency condition as well as at a representative 65-mph road load engine speed and torque condition. DOE should also consider reducing the number of industry contracts on specific engine projects that are funded so that only the engine systems most likely to meet the goal, based on system modeling and analytical projections, will be developed and tested experimentally.

Finding 3-8. DOE is shifting prematurely to component research to support the 2013 stretch goal of 55 percent thermal efficiency before completely demonstrating the earlier 2010 goal of 50 percent. Importantly, after analyzing the results of the lengthy and extensive efforts carried out in the area of low-temperature combustion (LTC), it is considered unlikely that this technology will be a successful enabler of the 55 percent stretch goal at any time in the near term because it cannot be adequately controlled over the full range of operating conditions of heavy-duty engines and has not demonstrated inherent fuel-consumption advantages. Based on the open literature, the chances for success of LTC as a practical technology appear limited.

Recommendation 3-8. DOE should complete the demonstration of the 50 percent thermal efficiency goal before embarking on the 55 percent goal. With respect to ongoing work on low-temperature combustion, DOE should objectively analyze the potential viability of this combustion concept for heavy-duty engine applications, recognizing the many issues that would need to be resolved to achieve commercial viability.

Finding 3-13. It is unlikely that the goal of identifying and validating nonpetroleum fuel formulations, optimized for use in advanced combustion engines, will be achieved by 2010. DOE's nonpetroleum fuels effort is focused on resolving biodiesel operational issues and commercialization barriers, but DOE did not provide a timetable for successful resolution of these efforts. DOE is also investigating oil sands and shale oil as other sources of petroleum fuel replacement. DOE did not present a plan for 5 percent replacement of petroleum fuels. The Renewable Fuels Standard of the Energy Policy Act of 2005 is likely to have a role in accelerating the availability of nonpetroleum fuels.

Recommendation 3-13. DOE should continue to work with biodiesel developers and users to ensure compatibility when biodiesel is blended with conventional diesel fuel and problem-free use of biodiesel fuels in diesel engines. Successful deployment will require resolving operational issues and updating the biofuel specifications. Development of refining technology to make acceptable diesel from shale oil or tar sands is not high-risk research suitable for federal funding and should be left to the private sector. DOE should develop specific plans, including key actions and timetables, for 5 percent replacement of petroleum fuels.

Heavy-Duty Hybrid Vehicles

Finding 4-1. Challenges with lithium-ion anode/cathode materials and chemical stability under high power conditions will likely preclude achieving the 15-year durability targets by 2012.

Recommendation 4-1. Much closer interaction between military and commercial suppliers is recommended to identify the highest-priority areas for further research in an attempt to expedite the development of commercially viable battery or battery/ultracapacitor systems that can accomplish the unique high-power needs of heavy-duty vehicles.

Finding 4-6. R&D on heavy-duty hybrid trucks and buses has demonstrated significant progress, achieving 35 to 47 percent fuel economy improvements in hybrid-electric delivery vans and urban buses, with specialized applications and the hydraulic hybrid delivery van in the 50 to 70 percent range (60 percent is the present 21CTP target). Commercial success has already been achieved with hybrid electric urban buses, albeit with major governmental subsidies. Despite the promising progress, significant hurdles still remain to achieving the fuel economy improvement targets for a broader range of heavy-duty hybrid vehicle (HHV) applications, reducing the cost, and improving HHV reliability sufficiently to achieve broader commercial success. In addition, there are opportunities for achieving significant system-level improvements that would make HHVs more attractive to original equipment manufacturers and users, such as the merging of hybrid propulsion and idle reduction features, including start-stop operation and creeping under all-electric power.

Recommendation 4-6. Development and demonstration of heavy-duty hybrid truck technology should be continued as part of the 21CTP program in order to reduce barriers to commercialization. These development projects should include efforts to capitalize on opportunities for system-level improvements made possible by HHV technology in order to extract the maximum possible value from any new hybridized propulsion equipment that is installed in future trucks and buses.

Finding 4-7. Progress in the development of HHV technology under the 21CTP program has been hindered by the decision to focus on component-level technology rather than systems. Successful development and commercialization of HHV technology require coordinated, customized development of the combustion engine, electrical/hydraulic drive equipment, mechanical powertrain, and controls as components of an integrated system, in order to realize its full potential. In addition, the coordination of HHV project activities among the 21CTP's federal partners (DOD, EPA, and DOE) has not matched the level achieved in other 21CTP programs such as nighttime idle reduction, making it more difficult to achieve ambitious HHV technology targets.

Recommendation 4-7. Coordination of all 21CTP heavy-duty hybrid truck development and demonstration activities should be strengthened across components, programs, and agencies to maximize the system benefits of this technology and to accelerate its successful deployment in commercial trucks and buses. In addition to improved cross-agency coordination, HHV stakeholder-based organizations including the Validation Working Group and the Hybrid Truck Users Forum should be engaged more aggressively to assist in identifying and overcoming key hurdles to the successful commercialization of HHV technology.

Finding 4-8. Emissions of heavy-duty trucks are currently measured and certified by EPA for each engine type rather than for any truck as a complete unit. Current procedures do not allow either the fuel economy or emissions of complete hybrid propulsion systems to be certified, and so neither the fuel economy improvements nor emissions reductions of hybrid trucks are appropriately recognized. Prior to mid-

2007, these procedures served as deterrents to commercialization of HHV technology since there was no practical way for truck purchasers to derive any direct tax credits for buying hybrid trucks as called for in the U.S. Energy Policy Act of 2005, which expires in 2009. Developing the necessary test procedures is expected to be a complex and lengthy process, and EPA has not been able to devote sufficient resources to developing such procedures in a timely manner.[1]

Recommendation 4-8. Since tax credits for hybrid trucks established in the Energy Policy Act of 2005 expire at the end of 2009, and there are not established engineering test procedures, DOE should work with EPA and stakeholders to accelerate the development of fuel economy and emissions certification procedures for heavy-duty hybrid vehicles so that the actual benefits of hybridization can be recognized and rewarded to further encourage commercial adoption.

Parasitic Losses of Energy

Finding 5-1. The More Electric Truck program demonstrated an integrated system to reduce idling emissions and fuel consumption. The test program showed significant progress toward achieving the objectives of both Goal 2 in Chapter 5 ("Develop and demonstrate technologies that reduce essential auxiliary loads by 50 percent, from the current 20 hp to 10 hp, for Class 8 tractor-trailers") and Goal 6 in Chapter 6 ("Produce by 2012 a truck with a fully integrated idling-reduction system to reduce component duplication, weight, and cost"). It did so by demonstrating 1 to 2 percent estimated reduction in fuel use including significant truck idling reductions. According to DOE, this translates into an overall annual fuel savings for the U.S. fleet of 710 million to 824 million gallons of diesel fuel (about $2 billion per year at $2.75 per gallon).

Recommendation 5-1. Given the potential of this program to save fuel, the committee recommends that the 21CTP continue the R&D of the identified system components that will provide additional improvements in idle reduction and parasitic losses related to engine components that are more efficient and provide better control of energy use. The program should focus also on the cost-effectiveness of the technologies.

Engine Idle Reduction

Finding 6-1. Idle reduction is one of the most effective ways to reduce pollutant emissions (especially locally) and improve fuel economy. As a result of the Energy Policy Act of 2005, the authority for this effort now rests with EPA and DOT. Several important lines of research are carried on in the 21CTP. In addition, the EPA SmartWay Transport Partnership voluntary program is effective at promoting the use of electrified parking spaces. The 21CTP, in cooperation with several major shippers, has demonstrated a number of cost-effective technologies (such as fuel-fired cab heaters and coolers) that are being used by existing fleets. (One fleet is installing more than 6,000 heaters, and another is installing more than 7,000.) One trucking company reported that diesel-fired heaters provided 2.4 percent fuel savings and a payback in less than 2 years at $2.40 per gallon.

Recommendation 6-1. The 21CTP should continue to support R&D for the technologies that reduce idle time and address the remaining technical challenges (including California emission requirements, completely integrated APU/HVAC [auxiliary power unit/heating, ventilation, and air-conditioning] systems, and creep devices).

Safety of Heavy Vehicles

Finding 7-1. The DOE program director of the 21st Century Truck Partnership has no direct authority for heavy-duty truck safety projects because there is no budget in the program itself to support safety projects. The program manager will need to continue to work with DOT, because DOT has several initiatives with the goal of making improvements in heavy-duty truck safety. They range from driver education to accident avoidance technology. However, the committee was unable to determine whether the goals would be met as a result of these initiatives.

Recommendation 7-1. DOT should develop a complete and comprehensive list of current and planned heavy-duty truck safety projects and initiatives, and prioritize them in order of potential benefit in reducing heavy-duty truck-related fatalities. The list should provide quantitative projections of fatality reduction potential attributable to each project. The list should also be used to prioritize budget and resource allocations, in order to expedite heavy-duty truck safety progress.

Finding 7-2. Programs are underway to develop and implement technologies and vehicle systems to support safety goals. Indeed, private industry, through internal research and commercial product development, has produced commercially available systems for enhanced braking, roll stability, and lane departure warning. They are beginning to be used in the field. It is now important to determine to what extent these accident avoidance technologies will reduce the number of accidents and therefore fatalities and injuries.

Recommendation 7-2. DOT should continue programs in support of heavy-duty truck onboard safety systems, with an emphasis on accident avoidance and with priorities set

[1]Note added in proof—Currently, EPA is developing a procedure to directly measure fuel economy and emissions of complete heavy-duty vehicles, including hybrids.

by a comprehensive potential cost/benefit analysis (Recommendation 7-1). Particular emphasis should be placed on monitoring the accident experience of heavy-duty trucks as these systems begin to be deployed in the field (for example, as electronic stability control systems begin to penetrate the fleet). It is the role of the manufacturers to develop safety systems for commercial application. DOT can play important roles in (1) providing support for field tests (known to DOT as field operational tests), (2) monitoring field data to help substantiate benefit analyses used to prioritize resources, and (3) implementing regulations that would require the adoption of safety systems that were proved to be effective. With adequate field data, DOT should refine and more rigorously specify and prioritize goals for accident avoidance technologies.

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1

Organization and Background

INTRODUCTION

This report reviews the 21st Century Truck Partnership (21CTP)—a cooperative research and development partnership formed in the year 2000 by four federal agencies (the U.S. Department of Energy [DOE], U.S. Department of Transportation [DOT], U.S. Department of Defense [DOD], and U.S. Environmental Protection Agency [EPA]) with 15 industrial partners (Allison Transmission, BAE Systems, Caterpillar, Cummins, Detroit Diesel, Eaton Corporation, Freightliner, Honeywell, Navistar, Mack Trucks, NovaBUS, Oshkosh Truck, PACCAR, and Volvo Trucks North America).

The goal of the Partnership is to "reduce fuel usage and emissions while increasing heavy vehicle safety. The aim of the Partnership is to support research, development, and demonstration that enable achieving these goals with commercially viable products and systems" (DOE, 2006a, p. 1).

The 21CTP vision is "that our nation's trucks and buses will safely and cost-effectively move larger volumes of freight and greater numbers of passengers while emitting little or no pollution and dramatically reducing the dependency on foreign oil" (DOE, 2006a, p. 1).

The Partnership addresses the following "national imperatives": "(a) Transportation in America supports the growth of our nation's economy both nationally and globally. (b) Our nation's transportation system supports the country's goal of energy security. (c) Transportation in our country is clean, safe, secure, and sustainable. (d) America's military has an agile, well-equipped, efficient force capable of rapid deployment and sustainment anywhere in the world. (e) Our nation's transportation system is compatible with a dedicated concern for the environment" (DOE, 2006a, p. 1).

The strategic approach of the Partnership includes the following elements (DOE, 2006a, p. 1):

1. Integrated vehicle systems R&D approach that validates and deploys advanced technology as necessary, for commercial and military trucks and buses
2. Research for engines, combustion, exhaust aftertreatment, fuels, and advanced materials to achieve higher efficiency and lower emissions
3. Research focused on heavy-duty hybrid propulsion systems
4. Research to reduce parasitic losses to achieve significantly reduced energy consumption
5. Development of technologies to improve the safety of trucks and buses, resulting in the reduction of fatalities and injuries in truck-involved crashes
6. Development and deployment technologies that reduce energy consumption and exhaust emissions during idling
7. Validation, demonstration, and deployment of advanced truck and bus technologies, and growing their reliability sufficient for adoption in the commercial marketplace

Policy Considerations

Worldwide oil consumption has risen rapidly in the past few years, mainly owing to rapid economic growth. This increased demand has resulted in a rapid rise in oil prices even though production capacity has kept pace with demand and is expected to exceed demand in the coming year (2009). With the nation highly dependent on imported oil, this increase in the price of oil has put a strain on the U.S. economy. As a consequence the United States is pursuing alternative sources of fuel and attempting to increase efficiency in oil usage.

Added to the concern over high-priced oil is the concern regarding global warming. Nations around the world are beginning to place more stringent control over human-made emissions, especially greenhouse gases such as carbon dioxide (CO_2). Thus for the foreseeable future, there will be pressure to control and reduce greenhouse emissions.

Both the limited availability of oil and the additional pressures to reduce CO_2 will have a profound impact on automotive vehicles worldwide. These forces will pressure vehicle manufacturers to make renewed efforts to reduce both fuel consumption and exhaust emissions. Light-duty-vehicle manufacturers have already made significant improvements in reducing fuel consumption and even more progress in reducing vehicle emissions. Emissions of oxides of nitrogen (NO_x) and particulate matter (PM) from heavy-duty vehicles will be significantly reduced by regulations that go into effect between 2007 and 2010. However, reductions in fuel consumption of the large commercial truck fleet have not been as impressive, partly because of the growth in the number of miles driven by large trucks during the past decade. Yet if the United States is to reduce its reliance on foreign sources of oil, it will be necessary to reduce the fuel consumption of commercial vehicles. The 21CTP can play an important role in this regard.

Organizational Background of the 21st Century Truck Partnership

In late 2006, the National Research Council (NRC) formed the Committee to Review the 21st Century Truck Partnership, which conducted an independent review of the 21CTP. This report critically examines and comments on the overall adequacy and balance of the 21st Century Truck Partnership to accomplish its goals and on progress in the program, and it presents recommendations, as appropriate, which the committee believes can improve the likelihood of the Partnership meeting its goals.

History

The 21st Century Truck Partnership was announced by Vice President Gore April 21, 2000, as a heavy-duty counterpart of the Partnership for a New Generation of Vehicles (PNGV).[1] The PNGV was a cooperative program, launched in 1994, that sought to develop and demonstrate the technology to triple the fuel economy of U.S. passenger vehicles (see, for example, NRC, 2001), and continues today as the FreedomCAR and Fuel Partnership (involving the DOE, a number of vehicle and fuel companies, and a nonprofit corporation representing the Detroit-based auto manufacturers), discussed later in this chapter.

The launch of the 21CTP was welcomed by an earlier NRC committee (NRC, 2000, p. 11):

> If this new initiative moves forward as planned, it will have a major impact on OHVT [the DOE Office of Heavy Vehicles Technology]. 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; (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.

Those goals have been updated twice since the launch of the program. The details of today's goals are set out in technical white papers on engine systems, heavy-duty hybrids, parasitic losses, idle reduction, and safety (DOE, 2006a, pp. 2-3). The committee comments on the research and development (R&D) in each of those areas in each of following chapters.

Lines of Authority

The 21CTP was apparently expected to have a single stream of funds to support its research, so that it could set research projects according to their likely return.[2] In practice, it has not been so simple. The Partnership was at first under the command of the DOD (the U.S. Army Tank-Automotive Research and Development Command). In November 2002, that authority passed to the Department of Energy (DOE, 2006b, p. 4-7), specifically to the FreedomCAR and Vehicle Technologies (FCVT) Program under the Office of Energy Efficiency and Renewable Energy (EERE).

The other agencies have simply moved their own existing programs under the 21CTP umbrella, so DOE has little influence over the research programs of its DOT, DOD, or EPA partners. DOE staff organize meetings and conference calls, maintain the information-flow infrastructure (such as Web sites and e-mail lists), and have led the discussions for and preparation of the updated 21CTP roadmap and white papers laying out Partnership goals. The management of individual projects under the 21CTP umbrella rests with the individual federal agencies that have funded the work. These agencies use the 21CTP information-sharing infrastructure to coordinate efforts and ensure that valuable research results are communicated and that overlap of activities is reduced.

According to the official roadmap and technical white papers of the 21st Century Truck Partnership (DOE, 2006a, p. 6):

[1] James Eberhardt, Director, Office of Heavy Vehicle Technologies (OHVT), DOE, "The 21st Century Truck, a Government-Industry Research Partnership," Presentation to the Committee on Review of DOE's Office of Heavy Vehicle Technologies, Washington, D.C., June 15, 2000; Paul Skalny, U.S. Army Tank-Automotive Command, "The 21st Century Truck Initiative: Developing Technologies for 21st Century Trucks," Presentation to the Committee on Review of DOE's Office of Heavy Vehicle Technologies, Washington, D.C., April 26, 2000.

[2] Personal statement to the committee by Kenneth Howden, Director, 21st Century Truck Partnership, April 18, 2007.

> DOE has been assigned to lead the federal R&D component of this program because of the close alignment of the stated 21st Century Truck Program goals and research objectives with DOE's mission "to foster a secure and reliable energy system that is environmentally and economically sustainable. . . ." Since early 1996, DOE's FreedomCAR and Vehicle Technologies Program (and predecessor offices), in collaboration with trucking industry partners and their suppliers, has been funding and conducting a customer-focused program to research and develop technologies that will enable trucks, buses, and other heavy vehicles to be more energy-efficient and able to use alternative fuels while simultaneously reducing emissions. DOT brings to this program its mission-oriented intelligent transportation systems and highway transportation safety programs. DOD, as a major owner and operator of trucks, will define the military mission performance requirements and will fund appropriate dual-use and military-specific technologies so that national security will benefit by innovations resulting from this Program. R&D will be closely coordinated with EPA so that critical vehicle emissions control breakthroughs cost-effectively address the increasingly stringent future EPA standards needed to improve the nation's air quality.

Classes and Use Categories of Trucks and Buses

Industry classifies trucks and buses by weight based on the vehicle's gross vehicle weight rating (GVWR), or the maximum in-service weight set by the manufacturer, or—in the trucking industry—on the gross vehicle weight (GVW) plus the average cargo weight. The use categories of vehicles are not as well defined as weight classes, and depend on widely varying industry usage. For example, the same vehicle may be called heavy-duty by one segment of the industry and medium-duty by another.

Table 1-1 lists one often-used system of categories—the Vehicle Inventory and Use Survey (VIUS) of the DOT—alongside the "common categories" used by many manufacturers, insurance companies, service shops, and truck drivers; as can be seen, some category boundaries differ between the two lists.

Some truck classifications used by the EPA and the California Air Resources Board (CARB) for emissions regulations differ from those shown in Table 1-1 and are discussed in the emission-related sections of this report and in Appendix D. DOT, in its safety regulation, uses the term "heavy truck" for vehicles above 10,000 lb GVWR (as discussed in Chapter 7). In other cases in this report the VIUS categories are used, in which "heavy truck" is the term used for vehicles over 10,000 lb GVWR.

The number of medium-duty and heavy-duty trucks has increased substantially as the U.S. economy has grown. Over the period from 1970 to 2003, energy consumption by light-duty trucks (less than 10,000 lb GVWR) grew 4.7 percent annually, while that of passenger cars grew only 0.3 percent. Meanwhile, energy consumption by heavy trucks increased 3.7 percent per year. Figure 1-1 displays this divergence in growth. Figure 1-2 displays the underlying pattern here: it is not so much the change in fuel economy as a dramatic increase in annual miles driven by heavy vehicles.

ECONOMIC CONTRIBUTIONS OF TRUCKS AND TRUCKING

Trucks and trucking are important contributors to the national income. According to the Economic Census of 2002 (DOC, Census Bureau, 2005), the truck transportation industry consisted of more than 112,698 separate establishments, with total revenues of $165 billion. These establishments employ 1,437,259 workers, who take home an annual payroll of $47 billion. Truck and bus manufacturing also account for a significant share of national income. According to the same census, light-truck and utility-vehicle manufacturers have total shipments of $137 billion. Heavy-duty-truck manufacturing had sales of $16 billion. Another way to look at the trucking industry's economic contribution is to compare the revenue from trucks with other sectors in the transportation industry, in which case trucks account for about one-fourth of the industry's total revenues (Figure 1-3).

TABLE 1-1 Widely Used Truck Weight Classes and Categories

Weight Class	Minimum GVWR (lb)	Maximum GVWR (lb)	VIUS Category	Common Category
Class 1	NA	6,000	Light-duty	Light duty
Class 2	6,001	10,000	Light-duty	Light duty
Class 3	10,001	14,000	Medium-duty	Light duty
Class 4	14,001	16,000	Medium-duty	Medium duty
Class 5	16,001	19,500	Medium-duty	Medium duty
Class 6	19,501	26,000	Light-heavy	Medium duty
Class 7	26,001	33,000	Heavy-heavy	Heavy duty
Class 8	33,001	NA	Heavy-heavy	Heavy duty

NOTE: GVWR, Gross Vehicle Weight Rating; VIUS, Vehicle Inventory and Use Survey; NA, not available to the committee.
SOURCE: Used by permission of Charlie Kerekes, Changin' Gears, 2008. Available at http://changingears.com/rv-sec-tow-vehicles-classes.shtml. Accessed May 30, 2008.

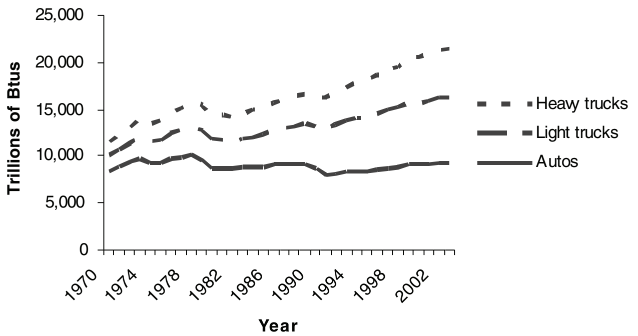

FIGURE 1-1 Energy consumption of heavy trucks (more than 10,000 lb gross vehicle weight rating [GVWR]) compared with that of light trucks and passenger vehicles, 1970-2003. Note that curves are additive. For context, 1 gallon of gasoline contains roughly 124,000 British thermal units (Btu), and 1 gallon of diesel fuel about 139,000 Btu. SOURCE: DOE, EERE, 2005.

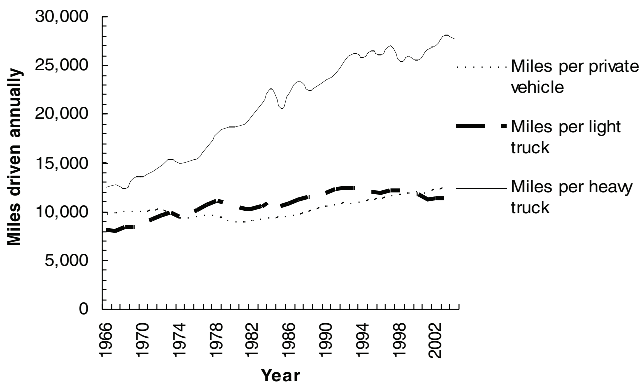

FIGURE 1-2 Trends in annual miles driven by three different classes of vehicle: heavy trucks, light trucks, and passenger vehicles, 1966-2005. SOURCE: DOE, EIA, 2007, Table 2.8.

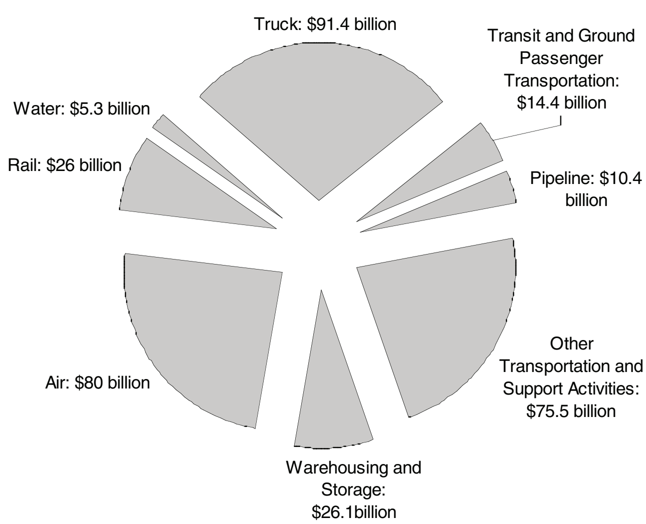

FIGURE 1-3 For-hire transportation services compared with other sectors of the transportation industry. SOURCE: DOC, Census Bureau, 2005.

THE NATIONAL OBJECTIVE OF REDUCING OIL IMPORTS

The president and the Congress have placed among the highest national objectives that of reducing fossil fuel imports (and in particular, petroleum). DOE's EERE, parent of the FCVT and 21CTP, has as its top priority: "Dramatically reduce or even end dependence on foreign oil" by spurring creation of a domestic biofuel industry; increasing the viability and deployment of renewable energy technologies; increasing the energy efficiency of buildings and appliances; leading by example through government's own actions; continuously improving the way EERE does business; reducing the burden of energy prices; increasing the energy efficiency of industry; and increasing the reliability and efficiency of electricity generation and use.[3]

While the fuel consumed per mile by light-duty vehicles improved substantially between 1966 and 2003, that of the average heavy-duty vehicle remained nearly constant (Figure 1-4). The flat fuel economy of heavy duty trucks was accompanied by a doubling of vehicle miles traveled per year (Figure 1-2). Fuel economy (miles per gallon) for passenger cars and light trucks such as sport utility vehicles and pickups rose from the late 1970s through the early 1990s. Fuel economy for passenger cars continued to rise through 2003 whereas the fuel economy of light trucks decreased from 2000 to 2003.

In fact, the U.S. transportation system relies nearly exclusively on petroleum, as shown in Figure 1-5 (DOE, EIA, 2006). That dependence grows more each year, despite attempts to substitute other fuels and energy sources.

The production of oil domestically, for its part, has declined continuously since 1985, so more and more of the nation's fuels are imported (Figure 1-6). That fact alone makes it increasingly vital to the national interest to reverse this trend. Trucks account for increasing highway transportation energy use.

TRENDS IN HEAVY-VEHICLE EMISSION REGULATIONS

Emission standards have become increasingly stringent since the passage of the Clean Air Act in 1963. Their evolution following the passage of the Clean Air Act is discussed in more detail in Appendix D, "Vehicle Emission Regulations." These increasingly stringent standards have dictated that new technologies be developed to comply with them. As an additional challenge, increasingly stringent emission standards for heavy-duty vehicles tend to adversely affect fuel economy at a time when there are challenges to *improve* fuel economy. Recognizing these dual challenges, the 21CTP adopted the simultaneous goals of improving the thermal

[3]Ed Wall, DOE Office of FreedomCAR and Vehicle Technologies, "DOE FreedomCAR and Vehicle Technologies Program," Presentation to the committee, Washington. D.C., February 8, 2007, Slide 3.

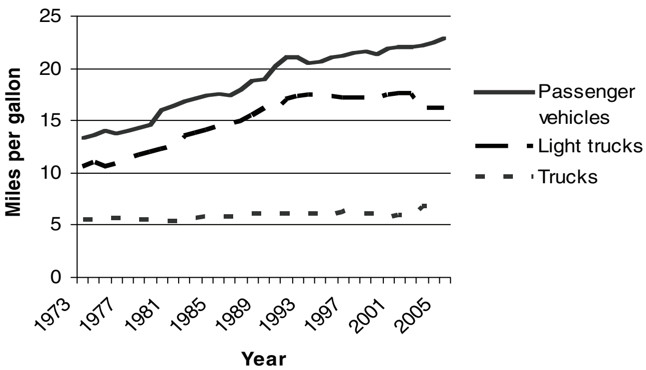

FIGURE 1-4 Fuel economy (miles per gallon) of passenger vehicles, light trucks, and heavy-duty trucks (more than 10,000 lb), 1973-2005. SOURCE: DOE, EIA, 2007.

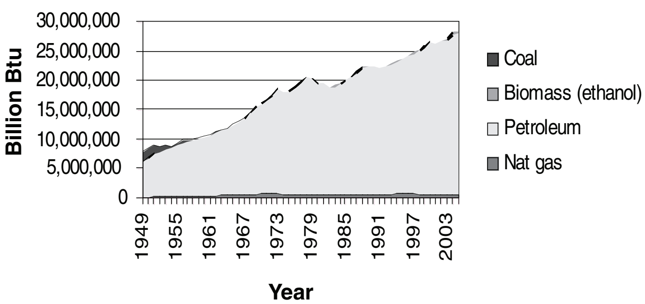

FIGURE 1-5 Energy use by the U.S. transportation sector, 1949-2005. SOURCE: DOE, EIA, 2007.

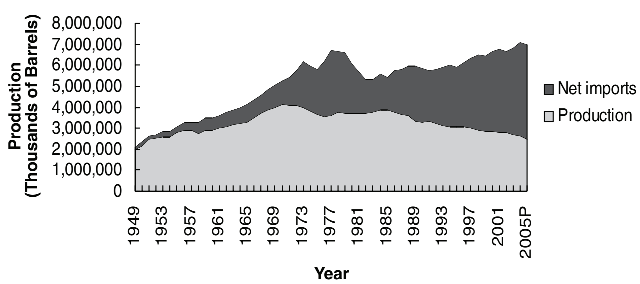

FIGURE 1-6 U.S. petroleum production and net imports, 1949-2005 (thousands of barrels per year). SOURCE: Data from DOE, EIA, 2006, Annual Energy Review 2006, Washington, D.C., Table 5.1

efficiency of heavy-duty diesel engines while, at the same time, achieving the increasingly stringent 2010 emission standards (discussed in Chapter 3 and in Appendix D).

Emission Standards

The progressively more stringent federal emission standards for light-duty vehicles are illustrated in Figure 1-7 (Ehlmann and Wolff, 2005). In the early 1960s, when exhaust emissions were unregulated, the subsequent exhaust emission regulations adopted by model year 2004 had reduced exhaust emissions from light-duty vehicles by the following amounts, based on certification-test emission levels (EPA, 2000):

- Hydrocarbons (HC), by 99 percent
- Carbon monoxide (CO), by 96 percent
- Oxides of nitrogen (NO_x), by 99 percent

The control of emissions from the engines of heavy-duty trucks with GVWR over 8,500 lb began in 1973 in California, and in 1974 in the United States as a whole (Johnson, 1988). As shown in Figure 1-8, the progressively more stringent emission standards for heavy-duty diesel engines followed trends similar to those for light-duty vehicles.

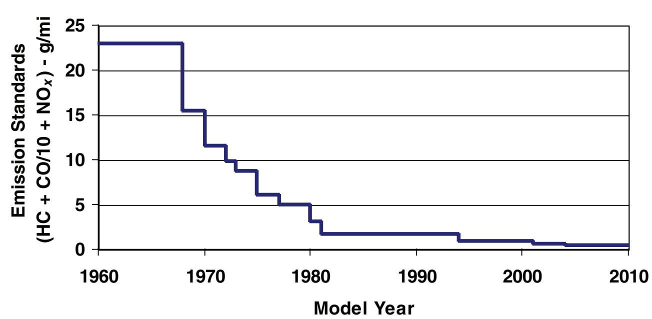

FIGURE 1-7 Historical trend in exhaust emission standards for light-duty vehicles, by model year. (The committee combined individual emission standards for hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) for illustration purposes.) SOURCE: Data from Ehlmann and Wolff (2005).

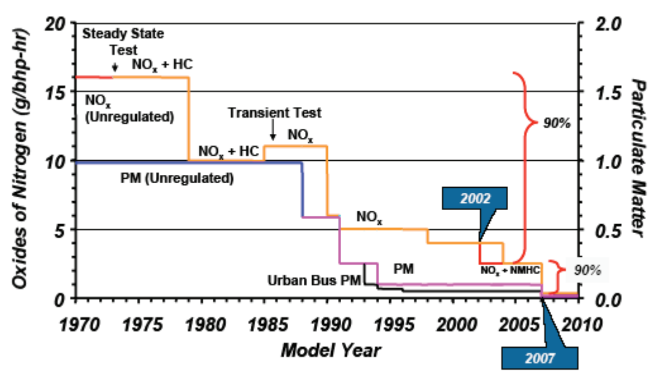

FIGURE 1-8 Historical trend in federal exhaust emission standards for heavy-duty diesel engines, by model year (in grams per brake-horsepower-hour (g/bhp-h), 1970-2010. HC, hydrocarbons; NMHC, nonmethane hydrocarbons. SOURCE: DOE, 2006a.

The federal emissions standards for highway trucks were harmonized with California standards beginning with model year 2004. Emission standards that apply to model year 2007 and later heavy-duty highway engines are given in Table 1-2. Federal regulations do not require that complete heavy-duty diesel vehicles be chassis certified, instead requiring the certification of their engines. Consequently, the emission standards are expressed in grams per brake-horsepower-hour (g/bhp-h) and require emission testing over the transient Federal Test Procedure (FTP) engine dynamometer cycle. The useful lives of the engines are also shown in Table 1-3. The required useful life of an engine for a Class 8 truck (heavy heavy-duty diesel engines in trucks over 33,000 lb) is 435,000 miles, or 10 years, or 23,000 hours (EPA, 2006).

Additional emission testing requirements, first introduced in 1998 (Table 1-4) include the following:

- Supplemental Emission Test (SET)
- Not-to-Exceed (NTE) limits

The SET is a 13-mode steady-state test that was introduced to help ensure that heavy-duty engine emissions are controlled during steady-state type driving, such as the operation of a line-haul truck on a freeway. The NTE limits have been introduced as an additional instrument to ensure that heavy-duty engine emissions are controlled over the full range of speed and load combinations commonly experienced in use. The NTE requirement establishes an area (the "NTE zone") under the torque curve of an engine where emissions must not exceed a specified value for any of the regulated pollutants.

Emission Standards Not Addressed by the 21CTP

In addition to the previously discussed exhaust emission standards that were incorporated as part of the 21CTP, several other emission standards that affect heavy-duty trucks which are not among the goals of the 21CTP are as follows:

- *Evaporative emissions*—Federal and California standards control evaporative emissions to stringent levels in gasoline passenger cars and light-duty trucks. In recognition of the high temperatures that diesel fuel can experience in modern common rail fuel systems, evaporative emission standards for diesel fuel vehicles have also been adopted.
- *On-board diagnostics*—On-board diagnostic (OBD) systems on vehicles ensure that the emission control system and other engine-related components are operating properly (Dieselnet, 2005; EPA, 2006). Table 1-5 shows the timetable for implementation of OBD II for heavy-duty vehicles.

TABLE 1-2 Heavy-Duty Emission Standards: Model Year 2007 and Beyond

Non-Methane Hydrocarbons (NMHC) (g/bhp-h)	Carbon Monoxide (CO) (g/bhp-h)	Nitrogen Oxides (NO_x) (g/bhp-h)	Particulate Matter (PM) (g/bhp-h)
0.14[a]	15.5	0.20[a]	0.01

[a]Phased in between 2007 and 2010 on a percentage sales basis: 50 percent for 2007-2009, 100 percent for 2010.

TABLE 1-3 Service Classes Used by EPA

Service Class	Required Useful Lives of Engines
Light heavy-duty diesel engine (LHDDE): Under federal regulations, between 8,500 and 19,500 lb gross vehicle weight rating (GVWR); in California, between 14,000 and 19,500 lb GVWR[a]	8 yr or 110,000 mi
Medium heavy-duty diesel engine (MHDDE): 19,500 lb to 33,000 lb GVWR	8 yr or 185,000 mi
Heavy heavy-duty diesel engine (HHDDE) (including those for diesel buses): heavier than 33,000 lb GVWR	10 yr or 435,000 mi or 23,000 hr

[a]Under federal light-duty Tier 2 regulations, vehicles of GVWR up to 10,000 lb used for personal transportation are reclassified as medium-duty passenger vehicles (MDPV—primarily SUVs and passenger vans) and are subject to light-duty vehicle legislation.

TABLE 1-4 Additional Emission Requirements

Test	Limits
Supplemental Emission Test (SET)	Federal Test Procedure (FTP) Standards
Not-to-exceed (NTE) Limits	1.5 × FTP Standards

TABLE 1-5 Timetable for Implementation of On-Board Diagnostic (OBD) II Systems for Heavy-Duty Vehicles (more than 14,000 lb GVWR)

Regulatory Body	Model Year	Comments
California Air Resources Board (CARB)	2007	Basic Engine Manufacturer Diagnostic (EMD) system
CARB	2010 Proposed	Comprehensive OBD II system
U.S. Environmental Protection Agency	2010 Proposed	Notice of Proposed Rule

- *Defeat devices*—Manufacturers must ensure that vehicle emission control systems operate in-use as they do on the prescribed test cycles. If, without the manufacturer's properly informing EPA, an emission control system operates differently when in use than it did in the test cycles, the emission control system is considered "defeated" and is called a "defeat device." EPA may seek judicial penalties for each vehicle sold containing a defeat device.[4]

Carbon Dioxide and Greenhouse Gases

Carbon dioxide does not absorb energy radiated from the Sun to Earth (high-temperature, short-wavelength radiation), but absorbs radiation in the infrared region (low-temperature, long-wavelength radiation). Consequently, long-wavelength heat radiated from Earth to space is absorbed by the atmosphere with increasing concentrations of carbon dioxide, thus raising the average temperature of the atmosphere (Obert, 1973).

Recently, a Supreme Court ruling declared carbon dioxide and greenhouse gases as air pollutants under the Clean Air Act and empowered the EPA to regulate vehicle emissions. As a result, EPA began a regulatory process aimed at promulgating final rules, possibly as soon as 2008 (EPA, 2007b). For engines using carbon-based fuels, potential carbon dioxide regulations will directly affect allowable vehicle fuel-economy levels. For every pound of typical hydrocarbon fuel burned, 3.1 pounds of carbon dioxide are generated.

In addition to potential carbon dioxide regulations, future greenhouse gas regulations may also target other gases, such as methane, (CH_4), nitrous oxides, (N_2O), and halogenated fluorocarbons (HFCs). Such regulations could affect heavy trucks by requiring additional emission control systems and by requiring new or modified air conditioning systems that may impact fuel economy.

Recent Fuel Regulations Affecting Future Vehicle Emissions

Ultra-low-sulfur diesel (ULSD) fuel has been regulated by EPA through a new standard for sulfur content in on-road diesel fuel sold in the United States since October 15, 2006. California had required it since September 1, 2006. The allowable sulfur content for ULSD is 15 parts per million (ppm), which is much lower than the previous U.S. on-highway standard for low-sulfur diesel (LSD) of 500 ppm. The rules mandate the use of ULSD in diesel engines. The move to lower sulfur content not only reduces the emissions of sulfur compounds, which are blamed for acid rain, but also allows the application of advanced emission control systems that would otherwise be poisoned by these compounds. These systems, which will greatly reduce emissions of oxides of nitrogen and particulates, will begin phasing in to diesel engines for highway applications in 2007(EPA, 2006).

The Need to Develop Nonpetroleum Fuels

The Energy Policy Act of 2005 (Public Law No. 109-058) amended the Clean Air Act to establish a Renewable Fuel Standard (RFS) program. The U.S. Congress gave EPA the responsibility to coordinate with DOE, the U.S. Department of Agriculture, and stakeholders to design and implement this first-of-its-kind program. Three months after the Energy Policy Act of 2005 was signed by President George W. Bush, in December 2005, EPA set a statutory default standard that required 2.78 percent, which is 4.0 billion gallons, of the gasoline sold or dispensed in calendar year 2006 to be renewable fuel. In April 2007, EPA finalized the regulations for the RFS program for 2007 and beyond. These regulations require nationwide volumes of 7.5 billion gallons of renewable fuel annually by 2012 (EPA, 2007a).

Owing to the certainty provided to investors by the RFS program, production capacity for ethanol and other renewable fuels has significantly increased since the passage of the Energy Policy Act. The construction of new and expanded facilities is projected to continue. By 2012, nationwide volumes are projected to reach over 11 billion gallons, compared to the 7.5 billion gallons required (EPA, 2007a).

A renewable fuel is defined in the Energy Policy Act of 2005 as a motor fuel that is produced from plant or animal products or wastes, as opposed to having fossil fuel sources. Renewable fuels include ethanol, biodiesel, and other motor vehicle fuels made from renewable sources. The RFS program grants credit for both renewable fuels blended in to conventional gasoline or diesel and those used in their neat (unblended) form as motor vehicle fuel (EPA, 2007b).

[4]See http://www.epa.gov/compliance/civil/caa. Accessed September 7, 2007.

SAFETY OF HEAVY-DUTY TRUCKS

Highway safety remains a problem in the United States. In spite of continued improvement in the crashworthiness of cars and trucks, the annual number of fatalities has remained nearly constant for the past decade, at more than 41,000, according to the National Highway Traffic Safety Administration (NHTSA).[5] In 2005 the number of fatalities reached 43,443. However, the fatality rate (per 100 million miles driven) has declined from 1.73 in 1995 to 1.47 in 2005. Still, it remains vital that the United States continue to strive to reduce the number of fatalities and injuries due to highway accidents.

Accidents involving large trucks account for about 12 percent of the total number of fatalities due to highway accidents, generally as many as 5,000 each year during the past decade. Some improvement was observed in 2006, as the fatality number dropped to 5,018 from 5,212 the previous year (Anonymous, 2007). According to the Federal Motor Carrier Safety Administration (FMCSA) of the DOT, large trucks pulling semi-trailers (Class 8) accounted for almost two-thirds of the truck-involved fatal crashes in 2005 (DOT/FMCSA, 2007).

Compared with the number of people who die in accidents involving Class 8 trucks and tractor-trailer combinations, substantially fewer people are killed in accidents involving medium-duty single-unit trucks (300 fatalities in 2005 for Classes 5 and 6 combined) due to the fact that these medium-duty trucks typically operate at lower speeds, in urban areas, and during daylight (DOE, 2006a, p. 59). Thus, the focus of DOE and DOT safety programs in the 21CTP has been on Class 8 trucks.

The number of fatalities associated with bus accidents is also quite low compared with those related to large trucks. In 2005, there was a total of 278 bus-related fatalities. Moreover, the safety record of school buses is very good. On average, from 1995 through 2005, 21 school age children died each year as a result of school transportation accidents (NHTSA, 2007).

Truck accidents have a direct impact on fuel consumption and the environment. Accidents involving large trucks and buses create significant highway traffic delays, particularly in congested areas, with consequent increases in fuel usage due to travel at low speeds and sitting in traffic at idle. There is a corresponding increase in exhaust emissions during these times. In some cases, the accidents involve vehicles carrying hazardous materials, creating an even more dangerous situation.

The Department of Transportation is responsible for standards, rules, and regulations governing all vehicles, including large trucks. DOT's National Highway Traffic Safety Administration is responsible for promulgating safety standards for new vehicles.[6] Many of the standards apply to all vehicles, inclusive of cars, light trucks, and heavy trucks. These rules, for example, include standards for controls and displays, transmission shift lever sequence, windshield defrosting and defogging systems, lamps and reflective devices, rearview mirrors, seat belt assembly, flammability of interior materials, and other automotive systems.

There are also NHTSA standards specifically for large trucks and for buses. For example, an important standard issued in January 1998, is FMVSS 233, which describes the required characteristics of under-ride guard structures used at the rear of trailers to prevent smaller vehicles from driving under the trailer when striking it from the rear. As noted earlier, this type of accident, the smaller vehicle rear-ending the trailer, is fairly common (causing 16 percent of truck related fatalities). FMVSS 232 describes standards for school bus seating and crash protection. Again, the NHTSA standards specify new vehicle requirements. For vehicles that are in service, DOT's FMCSA is responsible for setting requirements for maintenance and inspection and for licensing the drivers.

As noted in Chapter 7, in spite of these new vehicle design standards and in-service operating requirements, substantial reductions in heavy truck related fatalities and injuries have not been realized. For that reason, the 21CTP includes goals for improving large-truck safety, and in particular, goals for reducing fatalities and injuries associated with large-truck accidents. In support of those goals, DOE and DOT have initiated a number of programs aimed at improving the safety of large trucks.

Previously the focus of vehicle safety has been crash protection, including improvements in structural crush resistance, door and window retention during a crash, and occupant protection systems such as air bags. However, it has become clear that in order to make significant reductions in injuries and fatalities, it will be necessary to develop technologies, systems, and training programs to prevent crashes from occurring in the first place. More recently, research at DOE and DOT has been directed at crash avoidance technology for large trucks, including advanced braking systems, rollover warning and prevention systems, lane departure warning, drowsy driver detection systems, and collision warning systems.

Many of these systems have been tested on the highway as part of Field Operational Tests, several of which are currently ongoing. Moreover, several of these advanced safety systems have been put into production, including the following:

- Roll stability control systems,
- Electronic stability control systems,
- Lane-departure systems, and
- Collision warning systems.

[5]See http://www-fars.nhtsa.dot.gov. Accessed April 29, 2008.

[6]See http://www.nhtsa.gov/cars/rules/standards/FMVSS-Regs/index. Accessed May 12, 2008.

A major DOT safety program is the Intelligent Transportation Systems (ITS) program. The ITS program is broad in scope, touching on road design and operation, vehicle technologies, human factors research and in-vehicle as well as intervehicle communications.[7] The ITS programs involve not only federal government agencies, but also heavy- and light-vehicle manufacturers, state and local governments, and contract research groups including universities.

In summary, safety is an important part of the 21CTP, with support from both DOE and DOT, with DOT providing the majority of the budget. As crash protection measures have not substantially reduced highway fatalities during the past decade, the main objective going forward will be to prevent crashes using a myriad of crash avoidance technologies and in-vehicle communication systems. Because driver error is the cause of most highway accidents (Volpe Center Highlights, 2002), it will be necessary to focus on driver education, training, and law enforcement as well as advanced vehicle technologies.

PARTNERSHIP ACTIVITIES OF THE FREEDOMCAR AND VEHICLE TECHNOLOGIES PROGRAM

The FreedomCAR and Vehicle Technologies (FCVT) program is the home of two industry-government "partnership" activities; one of these, the FreedomCAR and Fuel Partnership, is described as follows on the program's Web site:[8]

- *FreedomCAR and Fuel Partnership.* "The Partnership is a collaborative effort among DOE, energy companies—BP America, Chevron Corporation, ConocoPhillips, Exxon Mobil Corporation, and Shell Hydrogen (US) and the U.S. Council for Automotive Research (USCAR) and partners—Chrysler Corporation LLC, Ford Motor Company, and General Motors Corporation.

  "The FreedomCAR and Fuel Partnership [FCFP] examines and advances the precompetitive, high-risk research needed to develop the component and infrastructure technologies necessary to enable a full range of affordable cars and light trucks, and the fueling infrastructure for them that will reduce the dependence of the nation's personal transportation system on imported oil and minimize harmful vehicle emissions, without sacrificing freedom of mobility and freedom of vehicle choice."[9]

  The term "Freedom" refers to "Freedom from dependence on imported oil . . . and from pollutant emissions" as well as "Freedom for Americans to choose the kind of vehicle they want to drive, and to drive where they want, when they want"; and "Freedom to obtain fuel affordably and conveniently." The Office of FreedomCar and Vehicle Technologies (OFCVT) works with a variety of industry partners to identify goals and timetables for research and development. The overall objective is "to accelerate advancements in technologies that enable reduced oil consumption and increased energy efficiency in passenger vehicles."

  The Partnership addresses a wide range of advanced automotive technologies, including fuel cells, hydrogen production and storage systems, lightweight materials, electrical storage systems, and advanced combustion and emission controls.
- *21st Century Truck Partnership*. As explained in this chapter, the 21st Century Truck Partnership includes four federal agencies (DOE, DOD, DOT, and EPA) and 15 industry partners. Partnership activities are summarized in the introduction to this chapter.[10]
  - The 21CTP is a cooperative research and development effort launched in 2000, in which the partners work together to reduce fossil fuel imports and to improve the physical environment by increasing vehicles' energy efficiency, promoting use of alternative fuels, and reducing emissions of particulate matter, oxides of nitrogen, sulfur dioxide, and other pollutants.
  - The 21CTP is more complex in its decision-making structure than is the FCFP. It includes not only the 15 partners identified earlier, but also four federal agencies whose interests may not always coincide.

BUDGET TRENDS OF THE 21ST CENTURY TRUCK PARTNERSHIP

The 21CTP itself has only a small (and apparently diminishing) research budget at DOE (Table 1-6). (Details of the research and development funding of the 21CTP and its parent organization are given in Appendix C.) Appropriations to the 21CTP from fiscal year (FY) 2003 through FY 2007 (shown in Figure 1-9 as "Heavy Duty") represent a declining proportion of the FCVT program (DOE, 2007, pp. 265ff).[11]

The challenge of analyzing multiagency "partnerships" is underscored by the fact that no one can tell the committee how much the various non-DOE parts of the 21CTP spend on their activities. Even the DOE parts are clouded by "proprietary" restrictions imposed by industrial partners.

The 21CTP effort centers on research and development to increase engine efficiency, improve the performance of hybrid powertrains, reduce fatalities through advanced safety

[7]Michael F. Trentacoste, Director, Office of Safety R&D, Federal Highway Administration, Turner Fairbank Highway Safety Center. "Federal Highway Administration Safety R&D Overview," Presentation to the committee, Washington D.C., February 8, 2007.

[8]See http://www1.eere.energy.gov/vehiclesandfuels/about/partnerships/freedomcar/index.html. Accessed May 22, 2008.

[9]See http://www1.eere.energy.gov/vehiclesandfuels/about/partnerships/freedomcar/fc_partners.html. Accessed May 22, 2008.

[10]See http://www1.eere.energy.gov/vehiclesandfuels/about/partnerships/21centurytruck/index.html. Accessed May 22, 2008.

[11]Ken Howden, DOE, FCVT, "21st Century Truck Partnership," Presentation to the committee, Washington, D.C., February 8, 2007.

TABLE 1-6 Funding of the 21st Century Truck Partnership (Department of Energy Funds Only), FY 1999-2008 (dollars in millions)

FY	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
FY 2004 Revised Structure					Appropriation ($ in millions)					Requested
Advanced Combustion Engine										
Combustion and Emission Control	3.400	3.200	3.668	4.176	4.705	3.333	8.312	3.317	3.680	3.000
Light-Truck Engine	14.800	17.411	17.783	15.778	14.734	12.495	0.000	0.000	0.000	0.000
Heavy-Truck Engine	NA[a]	4.830	5.914	9.396	12.174	11.831	13.832	9.270	14.490	3.519
Waste Heat Recovery	NA	NA	1.000	0.500	0.488	2.469	3.435	1.500	3.806	2.521
Health Impacts	NA	1.000	1.497	1.471	1.463	0.988	1.951	2.413	2.479	2.479
Off-highway Engine R&D	NA	NA	NA	0.500	3.414	3.457	0.000	3.369	0.000	0.000
Vehicle Systems										
Heavy Vehicle Systems R&D										
Vehicle System Optimization	1.500	2.915	4.230	9.369	9.555	10.187	8.764	8.457	5.922	5.913
Truck Safety Systems	NA	NA	0.500	0.400	0.397	0.395	0.099	0.096	0.000	0.000
STICK Program	NA	NA	NA	0.100	0.596	0.000	0.000	0.000	0.000	0.000
Hybrid and Electric Propulsion										
Subsys. Integ. & Dev. — Heavy Hybrid	NA	3.881	3.938	4.941	3.99	4.976	5.353	1.815	0.000	0.000
Fuels Technology										
Advanced Petroleum Based Fuels										
Heavy Trucks	2.700	3.873	4.854	5.853	7.996	6.321	5.876	3.375	3.511	2.623
Non-Petroleum Based Fuels & Lubes										
Heavy Trucks	3.300	2.743	3.241	3.695	1.408	1.383	0.690	0.000	0.000	0.000
Medium Trucks	4.700	2.712	3.266	3.903	1.316	1.284	1.282	0.000	0.000	0.000
Fueling Infrastructure	0.200	2.000	1.979	1.966	0.906	0.889	1.183	0.000	0.000	0.000
Renewable & Synthetic Fuels Util.	NA	NA	NA	NA	NA	0.395	1.367	2.940	3.059	4.031
Environmental Impacts	NA	2.000	2.973	2.789	2.282	1.975	0.986	0.000	0.000	0.000
Materials Technologies										
Propulsion Materials Technology										
Heavy Vehicle Propulsion Matls.	5.300	5.871	6.009	5.756	5.705	5.778	4.858	4.258	3.900	4.885
Lightweight Materials Technology										
High Strength Wt. Redc'n Matls.	4.200	5.781	8.804	9.574	8.731	8.840	7.690	2.766	0.000	0.000
High Temp. Matls. Lab (HTML)[b]	5.500	2.000	5.588	5.502	5.463	5.531	6.015	7.217	4.374	4.375
Technical Support Services			0.733	0.979	1.141	1.142	0.925	1.188		
TOTAL Heavy Vehicle Technologies	45.600	66.476	76.017	86.648	80.950	78.588	66.603	44.765	40.847	28.971

[a]NA, information not available to the committee.
[b]HTML became a separate line item in FY 2003.
SOURCE: Kenneth Howden, DOE, FCVT, "21st Century Truck Partnership," Presentation to the committee, Washington D.C., March 28, 2007, Slide 13.

systems, reduce parasitic and idling losses, and validate and demonstrate these technologies.

There is no single source of funds for the 21CTP, as was probably intended by its creators (according to the presentation of Paul Skalny at the committee's second meeting).[12] Instead, each of the four agencies has its own stream of funds. Agency personnel in the 21CTP meet frequently and industrial partners meet frequently to ensure communication about new technologies and new industrial needs. That is the extent of the coordination.

[12]Paul Skalny, U.S. Army Tank-Automotive Command, "The 21st Century Truck Initiative: Developing Technologies for 21st Century Trucks," Presentation to the committee, Washington, D.C., March 28, 2007.

In the part of the program administered by DOE/EERE, for example, the total appropriation each year is divided on the basis of several "technical areas," which correspond to engines, lightweight technology, idle reduction, and so on. In addition, they must maintain funding to companies with multiyear cooperative agreements and with Cooperative Research and Development Agreements (in the DOE laboratories).

ORIGIN AND SCOPE OF THIS STUDY

In response to a request from the director of the DOE's Office of FreedomCAR and Vehicle Technologies, the National Research Council formed the Committee to Review

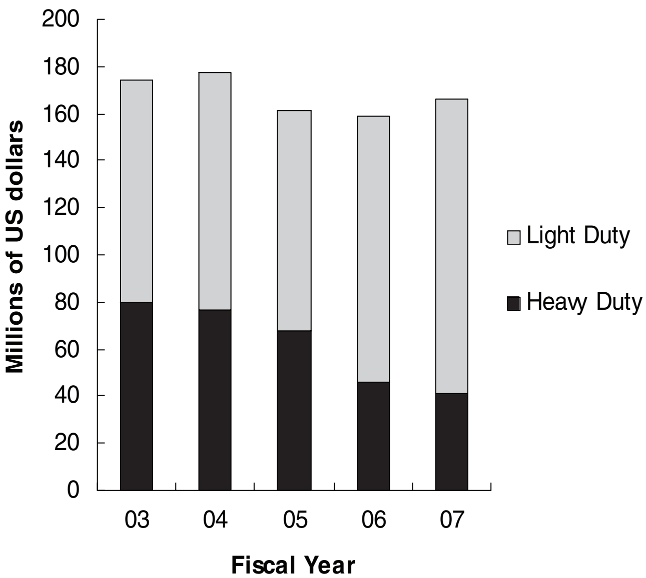

FIGURE 1-9 Appropriations to the 21CTP, FY 2003-2007 (shown as "Heavy Duty") represent a declining proportion of the FCVT Program. FY 2008 request is not meaningful for comparison, because several major subprograms are being reprogrammed. SOURCE: Kenneth Howden, "21st Century Truck Partnership," Presentation to the committee, Washington D.C., March 28, 2007, Slide 13. FY 2005-2008 FCVT funding data from DOE, 2007, FY 2008 Congressional Budget Request, Vol. 3, Office of Chief Financial Officer, Doc. No. DOE/CF-016, February. Available at http://www1.eere.energy.gov/vehiclesandfuels/about/printable_versions/ fcvt_budget.html. Accessed May 12, 2008.

the 21st Century Truck Partnership (see Appendix A for biographical information on committee members). The committee was asked to fulfill the following statement of task:

> The committee will conduct an independent review of the 21st Century Truck Partnership. In its review, the committee will critically examine and comment on the overall adequacy and balance of the 21st Century Truck Partnership to accomplish its goals, on progress in the program, and make recommendations, as appropriate, that the committee believes can improve the likelihood of the Partnership meeting its goals. In particular, the committee will:
>
> 1. Review the high-level technical goals, targets, and timetables for R&D efforts, which address such areas as heavy vehicle systems; hybrid electric propulsion; advanced internal combustion engines (ICEs); and materials technologies.
> 2. Review and evaluate progress and program directions since the inception of the Partnership toward meeting the Partnership's technical goals, and examine ongoing research activities and their relevance to meeting the goals of the Partnership.
> 3. Examine and comment on the overall balance and adequacy of the 21st Century Truck Partnership's research effort, and the rate of progress, in light of the technical objectives and schedules for each of the major technology areas.
> 4. Examine and comment, as necessary, on the appropriate role for federal involvement in the various technical areas under development.
> 5. Examine and comment on the Partnership's strategy for accomplishing its goals, which might include such issues as (a) program management and organization; (b) the process for setting milestones, research directions, and making Go/No Go decisions; (c) collaborative activities within DOE, other government agencies, the private sector, universities, and others; and (d) other topics that the committee finds important to comment on related to the success of the program to meet its technical goals.

STUDY PROCESS AND ORGANIZATION OF THE REPORT

The committee held four meetings. Information-gathering sessions included presentations on 21CTP activities by representatives of the four federal agencies involved in 21CTP, as well as individuals outside the program with expertise in the measurement and control of engine emissions, on issues related to light-duty and heavy-duty trucks, and on development needs relevant to the 21CTP program (see Appendix B for a list of the presenters and their topics). To clarify some aspects of the 21CTP, the committee also sent written questions to 21CTP representatives. The committee's conclusions and recommendations are based on the information gathered during the study and on the expertise and knowledge of committee members.

Chapter 2 assesses the strategy for managing the 21CTP and also identifies management and process issues. Chapter 3 reviews research and development programs in the engine systems area. The topics addressed include engine thermal efficiency, fuels, exhaust aftertreatment systems, the High Temperature Materials Laboratory of Oak Ridge National Laboratory, and health effects of diesel exhaust.

Chapter 4 discusses programs in the area of heavy-duty hybrid vehicles, and Chapter 5 reviews programs covering parasitic losses, such as aerodynamic drag, friction, and rolling resistance. Chapter 6 reviews programs in the technology area of idle reduction, aimed at minimizing fuel consumption of utility systems such as air conditioning and power steering. Chapter 7 covers the safety research programs, including braking, rollover stability, visibility, and crashworthiness, of all of the 21CTP partners.

Appendix A presents biographical sketches of the committee members. Appendix B lists all of the public presentations at the committee's four meetings. Appendix C contains funding details of the research and development of the FCVT program—that is, the parent program of the 21CTP. Appendix D is a brief account of trends in federal and state regulation of light- and heavy-duty vehicle emissions. Appendix E is a list of abbreviations and acronyms used in the report. Appendix F compiles engineering data on light duty electric vehicles. Appendix G provides complete and up-to-date information on the 21CTP membership.

The committee obtained a copy of the working draft of EPA's new "Smart Way Fuel Efficiency Test Protocol for Medium and Heavy Duty Vehicles" (EPA, 2007c), but did not review or discuss it in detail, since it was not released until after the committee's final meeting.

It should be noted that the Energy Independence and Security Act of 2007 (Public Law No. 110-140) includes a variety of measures that may affect the technology of heavy-duty vehicles. It was enacted too late to be considered by the committee.

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2

Management Strategy and Priority Setting

INTRODUCTION

The official technology goals of the 21st Century Truck Partnership (21CTP), set out in the official Roadmap and Technical White Papers document (DOE, 2006, pp. 1, 54), cover Engines, Heavy-Duty Hybrids, Parasitic Losses, Engine Idle Reduction, and Safety.

As part of its review, the committee received presentations by participating agencies (DOE, DOT, DOD, and EPA) and industrial partners. These presentations raised concerns about the program's overall effectiveness, funding variations, priority setting, partnership performance, etc. The committee decided to further explore these management and process issues. Information requests were submitted to the partnership participants. In addition, a detailed questionnaire was prepared, and private interviews were conducted to develop a better understanding of three areas:

- 21CTP Program Management
- Prioritization of Projects
- Performance of Industry Partnership

In this chapter the committee reviews each of these areas and reports its findings and recommendations.

PROGRAM MANAGEMENT

Overall management for the Partnership currently rests with the FreedomCAR and Vehicle Technologies (FCVT) Program of DOE, in the Office of Energy Efficiency and Renewable Energy. DOE personnel organize meetings and conference calls, maintain the information flow infrastructure (Web sites, e-mail lists, etc.), and lead the discussions for and preparation of the updated 21CTP Roadmap and White Papers, laying out Partnership goals (DOE, 2006). Management for individual projects under the 21CTP umbrella rests with the individual federal agencies that have funded the work. These agencies are intended to communicate among one another through the 21CTP information sharing infrastructure to coordinate efforts and ensure that valuable research results are communicated and that overlap of activities is reduced.

Figure 2-1 illustrates the interrelation among the key parties in setting research programs. Government agencies request funding from Congress through the administration, and work with the industrial partners and research organizations (including universities and federal laboratories) to establish research programs that meet national priorities and the interests of industry partners. However, final funding levels are determined by congressional appropriations.

In the case of the DOE, technology programs are developed to meet a cascading series of goals that begin at the President's National Energy Plan and culminate (at the program level) with specific technology goals. Figure 2-2 illustrates that pattern schematically.

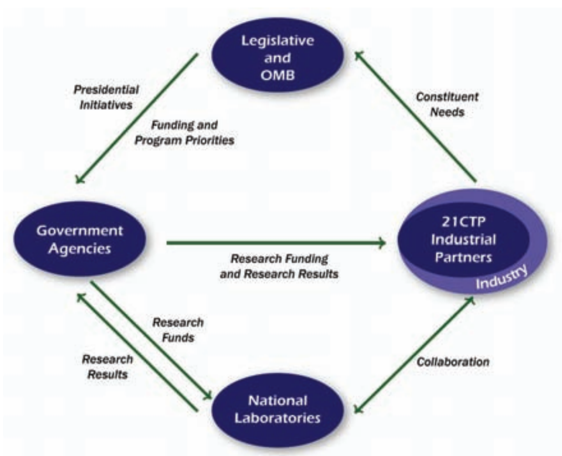

FIGURE 2-1 Interrelationships among 21CTP participants. SOURCE: DOE, FCVT, Responses to Committee Queries on 21CTP, Management and Process Issues, transmitted via e-mail by Ken Howden, March 27, 2007, p. 2.

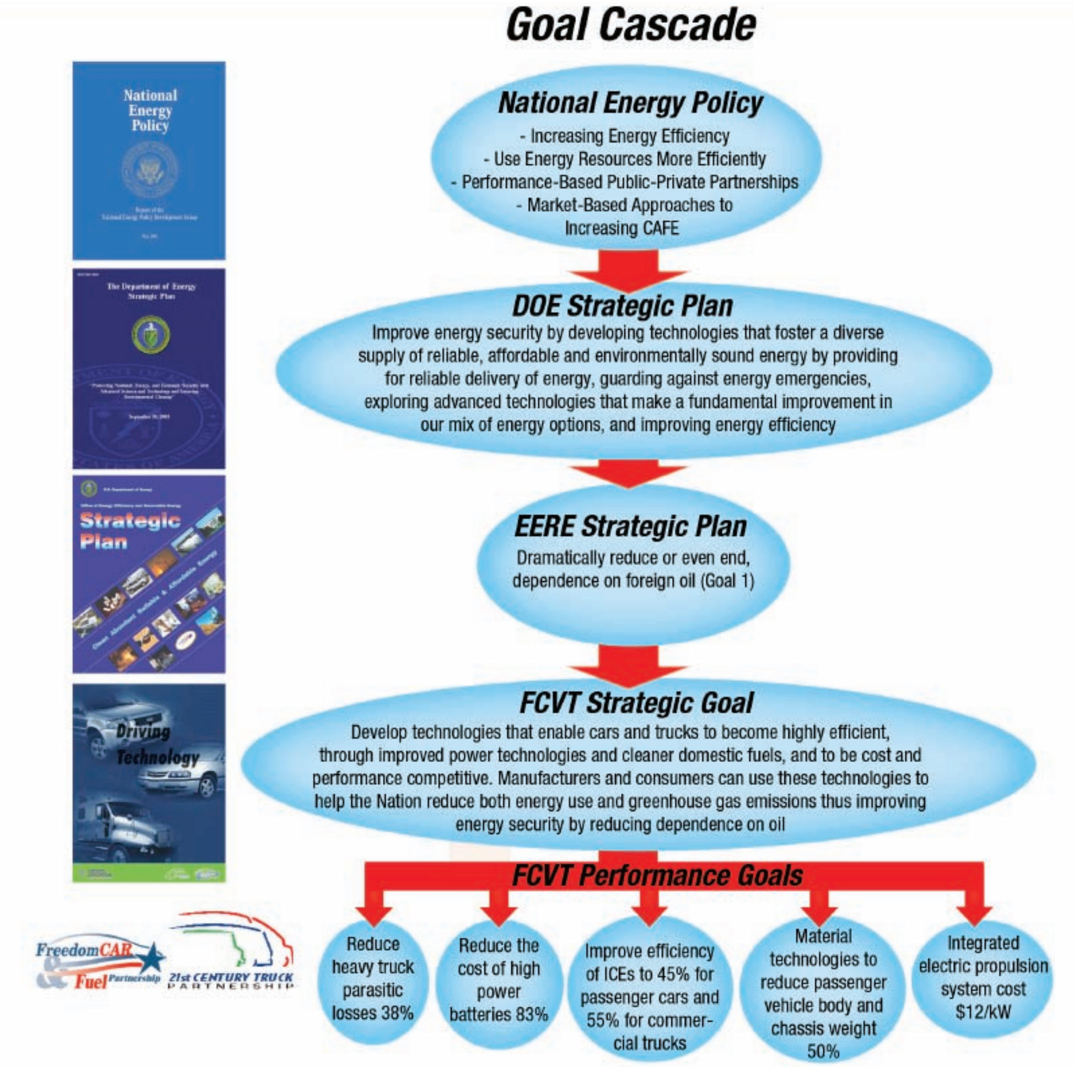

FIGURE 2-2 DOE goal-setting process. SOURCE: DOE, FCVT, Responses to Committee Queries on 21CTP, Management and Process Issues, transmitted via e-mail by Ken Howden, March 27, 2007, p. 2.

DOE focuses its technology research and development (R&D) investments specifically in high-risk areas or activities with uncertain or long-term outcomes that are of national interest but would most likely not be pursued by industry alone. Program activities include research, development, testing, technology validation, technology transfer, and education. These activities are aimed at developing technologies that could achieve significant improvements in vehicle fuel consumption and displacement of oil by other fuels that ultimately can be produced domestically in a clean and cost-competitive manner.

In DOE vehicle research, which specifically addresses the national issue of energy security and the increasing pressures of rising global consumption of oil, the FCVT Program has involved the affected industries in planning the research agenda and identifying technical goals that, if met, will provide the basis for commercialization decisions. The government's approach is intended to allow industry-wide collaboration in precompetitive research, which is then followed by competition in the marketplace.

The Partnership provides a forum for technical information exchange among the industry and government partners involved in heavy-duty transportation. At present, coordination of initiatives takes place as part of this information exchange. 21CTP holds regular meetings and conference calls to exchange information and hold productive discussions on technical topics. Specific areas in which the government partners have already coordinated initiatives include diesel fuel sulfur standard development (with coordination between DOE and EPA on appropriate sulfur levels for low-sulfur diesel), idle reduction activities (cooperation between EPA/DOT and their focus on deployment and DOE with a focus on technology R&D), truck aggressivity (with the National Transportation Safety Board (NTSB) using 21CTP as a forum for approaching all key government and industry participants involved with the issue), and hybrid powertrains (with DOE and EPA pursuing different technologies for hybridization, e.g., hydraulic hybrids at EPA and electric hybrids at DOE). Figure 2-3 illustrates the general collaborative structure of the four government agencies and some areas of interest among them.

The Partnership meets by conference call twice each month, and meets face-to-face about eight times per year. Agendas for the conference call typically include discussion of open funding opportunities (to bring these to the attention of members who may wish to apply), discussion of budget activities in the federal sector (where appropriate), discussion of technical accomplishments or plans for individual areas of interest to the heavy-trucking industry, discussion of news articles of interest to the industry, discussion of industry/government events (i.e., Society of Automotive Engineers International [SAE] Government Industry Meeting, SAE Commercial Vehicle Congress, and so forth) and any Partnership participation plans, discussion of other Partnership activities (such as face-to-face meetings, special visits to laboratories or other facilities, and reviews such as the National Academies/National Research Council review), and planning and participation in Diesel Engine-Efficiency and Emissions Research (DEER) conferences. These meetings typically last no more than two hours, with time reserved for industry partners to speak among themselves, for government personnel to speak among themselves, and for industry and government to speak together.

Face-to-face meetings are typically more focused on a specific topic or topics of interest to the group, rather than on general Partnership business. For example, the Partnership has conducted a meeting at DOT to discuss truck-related activities, a meeting at DOD, several meetings at various DOE national laboratories to tour their facilities and bring lab capabilities to the attention of the government and industry participants, and a meeting of the full Partnership with an industrial partner with international ties to discuss Partnership structure and activities with their overseas representatives. The agenda for these meetings focused on the topic or topics of interest, but a certain period of time was reserved for general Partnership business. These meetings typically last not more than one day, and are held chiefly at the convenience of the individual partners.

The Executive Committee is made up of three industry members, one from each of three industrial sectors: truck original equipment manufacturers (OEMs), engine manufacturers, and hybrid/system component manufacturers. It is thus a subset of the industrial membership of the 21CTP, that is, a subset of the fifteen participating companies. The Executive Committee is charged with organizing the business of the industrial partners in a manner consistent with the wishes of their constituencies. It is representative of a consensus of the full membership. It is responsible for meeting once per month to discuss partnership business, and it can represent the industrial sectors in discussions with government agencies or other external parties. The Executive Committee structure has proven to be a convenient way for issues to be brought to the partnership through the Executive Committee that can then take these issues off-line for consensus-building discussions within their sectors, so that final consensus on an issue can be reached more quickly, with less time spent in full Partnership discussions.[1]

Although the above discussion indicates a considerable amount of interaction among the government and industrial participants, no evidence was ever presented to the committee that these interactions included a rigorous go/no go process for evaluating individual projects. This may have been difficult to accomplish because, as described below, there was no central funding source for the 21CTP, and each of the government agencies involved runs its own programs.

As confirmed by representatives of DOE and other agencies, there is no single source of funds for the 21CTP, as perhaps intended by its creators. Instead, each of the four agencies has its own stream of funds, deriving from congressional appropriations. DOE, DOT, DOD, and EPA budget and optimize funding based upon their own priorities. In

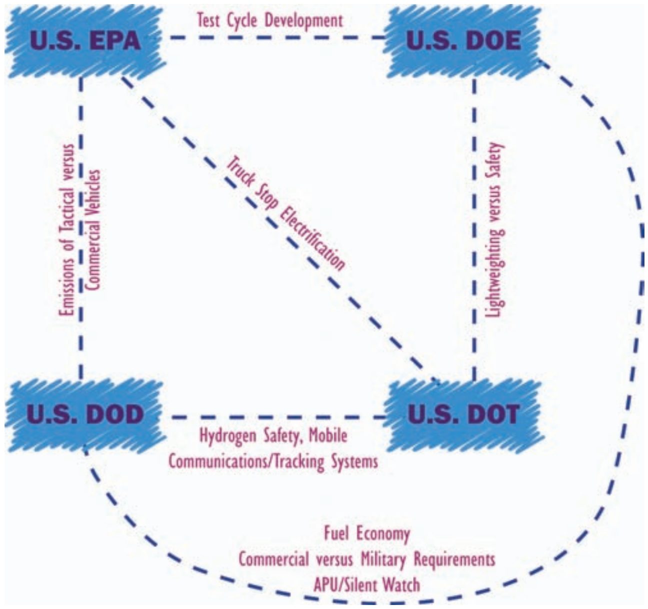

FIGURE 2-3 Government agency relationships. SOURCE: Responses to committee queries on 21CTP, Management and Process Issues, transmitted via e-mail by Ken Howden, March 27, 2007, p. 1.

[1]Ken Howden, DOE, FCVT, "Partnership History, Vision, Mission, and Organization," Presentation to the committee. Washington, D.C., February 8, 2007, Slide 3.

addition, they must maintain funding to companies with multi-year cooperative agreements.[2] (This does not allow for good project management or prioritization from a 21CTP programmatic perspective.)

The 21CTP is operated as a virtual network of agencies and government labs. Agency personnel meet frequently and industry partners meet periodically for limited sharing and communication. This has been the extent of the coordination. Both government agencies and industry partners believe that improvements in program management are possible and necessary. For example, the management process seemed more effective when a full-time person from industry was assigned as an Executive Director to coordinate the cross-agency efforts.

In summary, the 21CTP's effectiveness could be improved by:

- Adhering to the agreed-upon program budget spanning the agencies;
- Providing a full-time executive director to provide project management and set unified priorities;
- Setting realistic programmatic goals and objectives with stretch targets; and
- Empowering the 21CTP Executive Committee with authority to act collaboratively across agencies on program decisions and implementation, using a rigorous go/no go process.

PRIORITIZATION OF PROJECTS

The organizational structure of the 21CTP program precludes any systematic prioritization of research projects for the total program. Each of the four agencies included in 21CTP—DOE, DOT, DOD, and EPA—has separate budgets and priorities. The industrial partners also have their own needs, priorities, and resources. As a consequence, the program-wide prioritization that does occur is the result of a complex interaction (summarized in Figures 2-1 through 2-3) among government agencies, the industrial partners, the national laboratories, and the Congress and the Office of Management and Budget (OMB). 21CTP's primary function is to promote and facilitate interaction among the participants to enhance the sharing of information, discussion of common problems and the elimination of duplication.

A roadmap has been developed (DOE, 2006) that clearly states the goals of the program, with a listing of the many barriers to the accomplishment of the goals. However, there is little information in the roadmap document from modeling, expert opinion, or basic scientific analysis that would guide researchers to the most promising areas for research or to those with the greatest payback. The program would benefit greatly by an analysis similar to the one done for light vehicles by the National Research Council (NRC) in 2002.[3] In this analysis, estimates of the potential for fuel economy improvements and the associated costs were made for approximately twenty technologies and the results summarized in a single table. This approach highlighted the areas where substantial energy savings could be made, and at what cost, while facilitating a quick and easy comparison of the various candidate technologies. For example, engine cylinder deactivation was projected to improve fuel efficiency by 3 to 6 percent at a retail cost increase between $100 and $230 per vehicle, while a continuously variable transmission was projected to improve fuel efficiency by 4 to 8 percent at a retail cost of $150 to $325 per vehicle. Heavy vehicles would likely have a different cost-benefit structure, but such an analysis would provide a basis for setting research priorities.

It is difficult to assess the industrial partners' views on the establishment of research priorities. Generally, industry representatives gave 21CTP credit for help in meeting 2007 emissions standards, development of the light-duty diesel engine, and developing clean combustion technology. Some felt DOE's role was to develop high risk, high-payback technologies, but others complained that DOE did not do enough to help commercialize new technology. Some of the companies have successfully lobbied to obtain congressional earmarks to support their programs, bypassing peer review and program prioritization procedures. While many, if not all, of the industrial partners appreciated the cost sharing by the government, they expressed displeasure with the time and money it took to win and negotiate the contracts.

Prioritization of research within the DOE portion of the program is influenced by many factors. Under the Government Performance Results Act of 1993 (GPRA), the agency uses objective processes in strategic planning (and must estimate quantitatively the potential of its proposed research to help reach program goals). The Program Assessment Rating Tool (PART), overseen by the OMB, is a diagnostic tool for assessing the performance of federal programs and to drive improvements in program performance by making agencies accountable for improvement plans, for each of their programs.

21CTP uses the model VISON to forecast the effect of a successful research program on energy use, the model GREET (Greenhouse Gas, Regulated Emissions, and Transportation) on environmental impacts and PSAT (Powertrain Systems Analysis Toolkit) for vehicle simulation. In addition, DOE conducts project-level reviews and uses outside technical experts to review their research portfolio. However, each Administration has its priorities and special projects, and it expects the agencies to be responsive. In addition, congressional earmarks in effect establish priorities. As a consequence the research undertaken by DOE is influenced by many factors: scientific opportunity, engineering

[2]Personal communication to the committee from Ken Howden, 21st Century Truck Partnership, April 18, 2007.

[3]DOE responses to committee queries on 21CTP Management and Process Issues, transmitted via e-mail by Ken Howden, March 27, 2007.

needs, national priorities, congressional mandates, industry requests.

In summary, the primary role of 21CTP is to facilitate communication among the many partners to avoid duplication of effort, to communicate technical achievements, and to provide financial support to assist in moving new technology through development to commercialization.

PERFORMANCE OF THE PARTNERSHIP WITH INDUSTRY

The 21CTP was organized to reduce fuel consumption and emissions while improving the safety of heavy vehicles. To fully assess the performance of the industry partnership, the committee collected information using a questionnaire sent to the fifteen industrial partners and held discussions with a selected few. A questionnaire was distributed seeking their input on:

- Overall program management and organization
- The process for setting milestones, research directions, and making Go/No Go decisions
- Collaborative activities within the DOE, other government agencies, the private sector, universities, and others
- Other topics deemed important to the success of the partnership

Two approaches were used by the committee.

- One-hour conference calls were held with each of the three company representatives serving on the 21CTP Executive Committee.
- Written questionnaire requests were provided to the other twelve companies. Five responded.

The same set of questions was used in both instances. This resulted in a total response of eight from the original fifteen companies. The set of nine questions was as follows:

1. Has your organization's involvement with the 21CTP provided sufficient progress to consider commercialization of the technology on which you were involved? If yes, explain how the 21CTP helped. If no, explain what is preventing commercialization in terms of technology development, economics, market, etc.
2. Was there sufficient "sharing" of technology among the industrial partners and the government agencies? If not, why not?
3. Would your organization like to continue in the 21CTP? If yes, why? If no, why not?
4. Based on your organization's experience with the 21CTP would you recommend for or against its participation in a similar future government technology partnership? If for, why? If against, why?
5. Was there sufficient cooperation and coordination among the government agencies involved with your project? Please explain.
6. Was sufficient attention given to technological "show stoppers" in terms of technical support and funding? Please explain.
7. Regarding development of hybrid systems for trucks, does your organization believe that the specialized duty cycles for trucks and their limited production volumes are impediments regarding their commercialization? Please provide support for your answer. If you consider them impediments, can you provide input on how they can be overcome?
8. If you had the latitude to double the current program budget, where would you invest the additional funds?
9. Given your assessment of the program, do you support its continuance? If not, why?

In general, industry responded to these questions to indicate its appreciation and encouragement of the 21CTP. Its funding allowed progress to be made in solving technological issues and in moving advanced systems closer to commercialization. For example, meeting the 2007 heavy-duty emissions standards without loss in fuel economy was possible with DOE support.

However, significant frustration was voiced relative to the funding variance which was experienced from year to year. As evidenced in Table 1-6, funding for the heavy-duty vehicle programs has declined steadily in the past few years, while light-duty vehicle technology has held its own. Industry viewed this as placing undue pressure on the programs resulting in the reduction of program budget or elimination of some programs (NRC, 2002; Bezdek and Wendling, 2005).[4]

Although there was some sharing across agencies, the promise of interagency partnership has not been borne out. When asked to provide cross-agency budgets for programs relevant to the 21CTP, only some of the agencies were willing and able to do so. Industry partners felt that their continuance in the 21CTP was contingent on there being adequate funding, the agencies cooperating among themselves on technological issues and budgets, simpler contracting procedures, and a strong leader to represent the industrial partners. The consensus opinion was that the program made the most progress when a full-time leader was in place to handle cross-agency issues and interactions.

The 21CTP has become a communications channel for agency members. But, it is less relevant to industry or to senior policy makers in government. The sources of funding are not apparent to industry.

In the process of moving a new concept from research idea to commercial product, DOE research organizations use the general process shown in Figure 2-4. The "Basic Research"

[4]DOE, FCVT, response to committee queries, delivered via e-mail by Ken Howden, March 27, 2007.

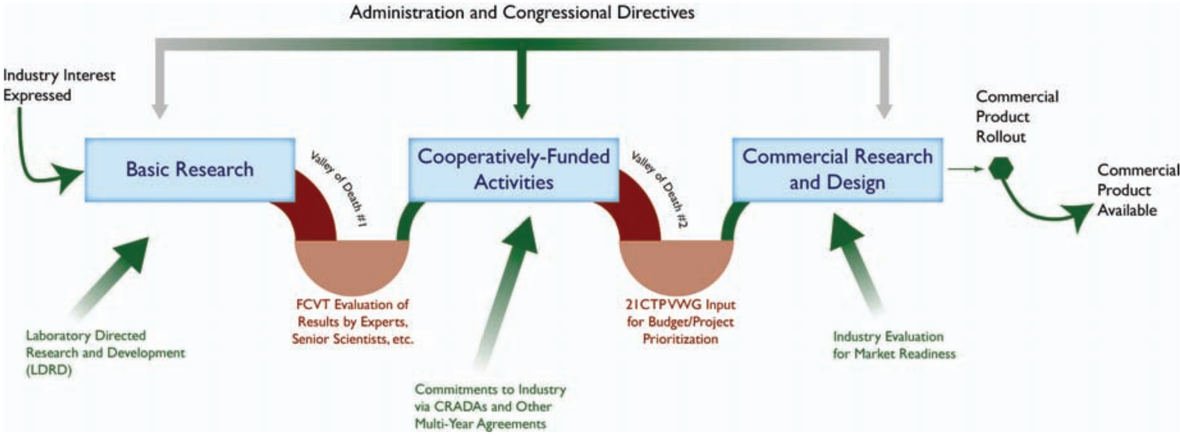

FIGURE 2-4 DOE project management and innovation process. SOURCE: DOE, 2006.

steps are clearly dominated by DOE laboratories and "Commercial Research and Design" by industry. Research results and budget proposals are thoroughly reviewed. Those not approved or having marginal benefit go into the "Valley of Death" where they remain until there is a change in circumstances.

The industry assessment is that more funding should be directed toward "Cooperatively-Funded Activities." This would focus more resources on the eventual commercialization of technologies, which was the goal of the program. The technical showstoppers would get sufficient funding to address and commercialize them. In general, industry responses were favorable toward the 21CTP and would support its continuation if improved funding, discipline, coordination, and cooperation are provided.

Finding 2-1. The 21CTP is operated as a virtual network of agencies and government laboratories, with an unwieldy structure and budgetary process. Agency personnel meet frequently and industry partners meet periodically for limited sharing and communication. This has been the extent of the coordination. Both government agencies and industry partners, per their remarks to the committee, have found the arrangement less than effective. The program was most productive when a full-time person from industry was assigned to coordinate the cross-agency efforts. Oversight of the 21CTP is provided through an Executive Committee with representation from DOE, DOT, EPA, DOD, and the industry partners. Although that committee lacks authority to make cross-agency decisions and implement firm actions, it has been most effective when chaired by a full-time executive. This seemed to be an effective measure to ensure cooperation among agencies and address program challenges.

Recommendation 2-1. A full-time, technically capable leader with consensus-building skills should be appointed to coordinate the 21CTP program among industry partners and government agencies. This person could chair the Executive Committee and would be authorized to make recommendations to the committee on behalf of the entire program on stopping or redirecting existing research, on setting research priorities, and on future funding levels.

Finding 2-2. As confirmed in meetings with the DOE and other agencies, there is no single source of funds for the 21CTP, as perhaps intended by its creators. Instead, each of the four agencies has its own stream of funds. DOE, DOT, DOD, and EPA budget and optimize funding based on their own priorities. In addition, they maintain funding to companies with multiyear cooperative agreements. Thus, managing the 21CTP program and projects across multiple agencies has been challenging, and there have been difficulties in setting program priorities, especially in aligning budgets to programmatic requirements. A result has been difficulty in balancing between near- and long-term projects and setting appropriate metrics and measures. In addition, variation in funding levels from year to year has diminished the impact of project achievements and results and reduced the probability of success and commercialization. The result of this complexity and lack of transparency is that some federal funds were spent by industry partners and by other federal agencies in ways that cannot be accounted for in the funding structure by fiscal year.

Recommendation 2-2. A portfolio management process that sets priorities and aligns budgets among the agencies and industrial partners is recommended. A proposed table of project priorities (Figure 2-5) would provide an objective way of ranking research and development projects according to their expected outcomes. This could evolve into a budgeting process that ensures support for programs of merit beyond a single year. Precompetitive, collaborative technol-

Priority	Goals	Project Name	Project Start and End Dates	FY 2007 Funding (US$)	Total Funding Over Life of Project (US$)	Estimated Likelihood of Meeting Goal	If Goal Is Reached: Projected Fuel Savings (gal/yr)	If Goal Is Reached: Estimated Cost of Implementation (per vehicle)	If Goal Is Reached: Estimated Likelihood of Implementation (high, medium, or low)
1									
2									
3									
4									
5									
6									
Etc.									

FIGURE 2-5 Proposed table of project priorities. Each agency involved with the 21st Century Truck Partnership would identify each project considered part of the 21CTP, rank it by priority, and provide the information requested.

ogy and concept development could receive proper focus for successful programs.

REFERENCES

Bezdek, Roger, and Robert Wendling. 2005. Fuel efficiency and the economy. *American Scientist,* Vol. 93, No. 2, p. 135.

DOE (U.S. Department of Energy). 2006. 21st Century Truck Partnership Roadmap and Technical White Papers. Document No. 21CTP-003. Washington, D.C. December.

NRC (National Research Council). 2002. Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, Table 3-3, Fuel Consumption Technology Matrix, p. 44. Washington, D.C.: National Academy Press.

3

Engine Systems and Fuels

INTRODUCTION

The 21st Century Truck Partnership (21CTP) includes specific goals in the areas of engine systems and fuels. This chapter contains comments on the goals and the related research programs, including aftertreatment systems, the High Temperature Materials Laboratory of the Oak Ridge National Laboratory (ORNL), and health concerns related to diesel emissions.

Three specific goals were set for engine systems and fuels (DOE, 2006, p. 2), which can be summarized as follows:

- Achieve 50 percent thermal efficiency, while meeting 2010 emission standards, by 2010;
- Research and develop technologies to achieve 55 percent thermal efficiency by 2013; and
- By 2010 identify and validate fuel formulations making possible 5 percent replacement of petroleum fuels.

The goals discussed in this chapter are exclusively focused on heavy-duty diesel engines. Prior to the formation of the 21CTP, the responsibilities for heavy-duty and light-duty truck technology were merged within the U.S. Department of Energy (DOE) Office of Heavy Vehicle Technologies (OHVT). One of the objectives that the OHVT inherited, and which was subsequently included in the 21CTP, was the development of diesel engine enabling technologies, to support large-scale industry dieselization of Class 1 and 2 light-duty trucks capable of achieving 35 percent fuel efficiency improvement over comparable gasoline-fueled trucks, while meeting applicable emission standards (National Research Council, 2000, p. 14). Because this program was a legacy of earlier vehicle research at DOE, none of the objectives of the 21CTP were associated with this program, although the accomplishments of this program were frequently cited by DOE officials in presentations to the committee. DOE believed that this program was beneficial for the heavy-duty diesel programs due to the synergy from light-duty to heavy-duty diesel engines.[1] No further discussion of the light-duty diesel program will be presented here, even though it was funded in fiscal years (FY) 2000 through 2004 (as shown in Table 1-6 in Chapter 1 and in more detail in Appendix C).

GOAL OF THERMAL EFFICIENCY OF 50 PERCENT

Introduction

The first overarching technology goal of the 21CTP is stated as follows:

> Develop and demonstrate an emissions compliant engine system for Class 7-8 highway trucks that improves the engine system fuel efficiency by 20 percent (from approximately 42 percent thermal efficiency today to 50 percent) by 2010. (DOE, 2006, p. 14)

This goal was further defined in terms of Major Activity and Milestone 3 as follows:

> Demonstrate engine efficiency of 50 percent with 2010 emissions compliance through integration of advanced fuel injection, new combustion regimes, exhaust-heat recovery, aftertreatment, advanced controls, low-friction features, air handling, thermal management, and advanced materials. (DOE, 2006, p. 21).

Background and Analysis

The 21CTP developed an energy audit of a typical Class 8 tractor-trailer combination vehicle traveling on a level road at a constant 65 miles per hour (mph) with a gross combination weight (GCW) of 80,000 lb, as shown in Figure 3-1. Baseline

[1]Personal communication to the committee from Ken Howden, U.S. Department of Energy, Office of FreedomCAR and Vehicle Technologies, August 29, 2007.

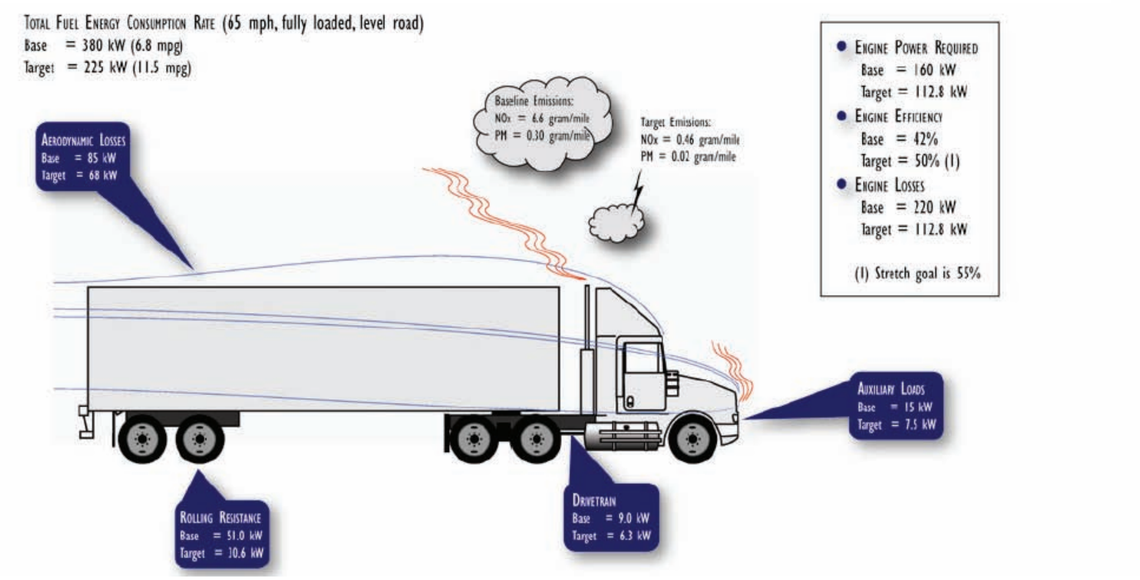

FIGURE 3-1 Energy audit of a typical Class 8 tractor-trailer combination on a level road at a constant speed of 65 mph and a GVW of 80,000 lb. SOURCE: DOE, 2006, p. 7.

TABLE 3-1 Baseline and 21CTP Target Values from the Energy Audit Shown in Figure 3-1

	Base	Target	Percentage Reduction
Total Energy Consumption	380 kW	225 kW	40%
Engine Power Required	160 kW	112.8 kW	30%
Thermal Efficiency	42%	50%	—
Auxiliary Loads	15 kW	7.5 kW	50%
Drivetrain	9 kW	6.3 kW	30%
Rolling Resistance	51 kW	30.6 kW	40%
Aerodynamic Losses	85 kW	68 kW	20%

and 21CTP target values from the energy audit shown in Figure 3-1 are also listed in Table 3-1.

The following observations can be derived from this energy audit:

1. Improvements in engine efficiency offer the largest potential reductions in fuel usage. Reductions in rolling resistance and aerodynamic losses offer lesser reductions in fuel usage.
2. The engine power output of 160 kilowatts (kW), which is required by the vehicle at 65 mph, is about 42 percent of the total fuel energy consumption rate of 380 kW (which equates to 6.8 mpg). Therefore, the thermal efficiency is 42 percent, which is representative of today's typical diesel engine thermal efficiency at the 65 mph road load operating condition.
3. A 20 percent improvement in engine thermal efficiency from the current baseline of 42 percent will yield the 50 percent thermal efficiency objective.

Increases in fuel economy, expressed in miles per gallon (mpg), will be directly proportional to improvements in thermal efficiency. However, fuel usage in gallons is inversely proportional to miles per gallon. Therefore, a 20 percent improvement in thermal efficiency will result in only a 16.7 percent reduction in fuel usage, as shown below.

Thermal efficiency =
(work output)/(fuel energy input) ~ miles/gal ~ mpg
Fuel usage ~ 1/mpg
Percentage change in fuel usage =
$(1/\text{mpg}_{\text{improved}} - 1/\text{mpg}_{\text{base}}) \times 100$
Percentage change in fuel usage =
$(1/1.2 - 1/1.0) \times 100 = -16.7$ percent

This result illustrates an inconsistency in a presentation to the committee,[2] which erroneously suggested that a 20 percent improvement in engine thermal efficiency would yield a 20 percent reduction in fuel usage.

For consistency with DOE, the following terminology is used in this report:

- Individual vehicle fuel consumption is expressed as gallons per mile (gpm). (Note: Alternative units such

[2]Vinod K. Duggal, Cummins Engine Company, Inc., "Diesel Engine R&D and Integration," Presentation to the committee, Washington, D.C. February 9, 2007, Slide 11.

as liters/100 km or gallons/ton-mile may be more descriptive, but the committee did not use them.

- Individual vehicle fuel economy is expressed as miles per gallon (mpg).
- Total annual vehicle fuel consumption is expressed in total gallons consumed and is equal to total vehicle miles traveled divided by the average mpg.

Program Status

The 21CTP selected the engine manufacturers Cummins, Caterpillar, and Detroit Diesel as the industry partners for the demonstration of 50 percent thermal efficiency at 2010 emissions. Although Volvo/Mack was also identified by DOE as another industry partner in the 21st Century Truck Partnership Roadmap, Volvo/Mack does not appear to have been funded and has not reported any results. Work on the 50 percent thermal efficiency objective began with the initiation of the 21CTP in 2000 and continued until 2007, when DOE concluded this activity.

The 21CTP funding for the demonstration of 50 percent thermal efficiency at 2010 emissions is shown in Table 3-2. A total of $116 million was spent on the program for demonstration of 50 percent thermal efficiency at 2010 emissions, with $55 million provided by DOE and $61 million provided by the industry partners. The industry partners performed all of the work in this program. DOE did not provide the committee with a breakdown of specifically how the government money and the industry money were spent.

Although it was not clearly stated by the 21CTP, the committee assumed that achieving this goal required testing a complete engine system on an engine dynamometer and demonstrating that the resulting thermal efficiency and emissions, measured according to standardized test procedures, met the specified goals. To assess the status of this goal, the committee summarized the results reported by each industry partner in Table 3-3.[3]

These results show that none of the industry partners achieved the goal of measuring 50 percent thermal efficiency at 2010 emissions from a complete engine system. With respect to the 50 percent thermal efficiency goal, each partner either failed to test a complete engine system on an engine dynamometer and used analysis to project results, or failed to achieve the 50 percent thermal efficiency goal with a complete engine system.

The technologies used in the demonstration engines, which were modified from production baseline engines, are listed in Table 3-4. These technologies were identified by the industry partners and are categorized according to the features that were intended to be used for this demonstration and are listed under Major Activity and Milestone 3 (DOE, 2006, p. 21).

TABLE 3-2 21CTP Funding for the Demonstration of 50 Percent Thermal Efficiency (U.S. dollars)

	DOE	Participant	Total
Cummins	19,032,087	20,471,307	39,503,394
Caterpillar	19,353,158	22,854,337	42,207,495
Detroit Diesel	16,906,376	17,496,651	34,403,027
Total	55,291,621	60,822,295	116,113,916

SOURCE: Ken Howden, DOE, FCVT, DOE responses to committee queries on 21CTP engine systems and fuels, March 28, 2007.

Although the details of the technology features are vague in many cases, significantly different approaches were taken in several areas. Cummins used a high-pressure (HP) common rail fuel, system while Caterpillar and Detroit Diesel did not specify the fuel injection system. Another possible significant difference is that Caterpillar used variable intake valve actuators while Cummins and Detroit Diesel did not specify this feature. Exhaust Gas Recirculation (EGR) systems differed, with Cummins using high pressure loop EGR while Caterpillar used low-pressure (LP) EGR. Detroit Diesel did not specify the EGR system. Turbocharging systems also differed. Cummins used variable geometry turbocharging while Caterpillar used a series LP compressor, HP compressor, HP turbine, and LP turbine. Detroit Diesel did not specify the turbocharging system.

Each of the industry partners used a waste heat recovery (WHR) system in an effort to approach 50 percent thermal efficiency. Cummins applied a Rankine cycle WHR system with a turbine-driven generator, which would ultimately drive an electric motor geared to the engine-output shaft. In contrast, Caterpillar and Detroit Diesel used turbocompounding WHR systems.

The Cummins results, which indicated that 50 percent thermal efficiency could be achieved when a Rankine cycle WHR system with a power output of 57 hp was added to the engine power output of 378 hp, are questionable due to two key technical issues.

1. The “Rankine cycle WHR System Test Block” schematic provided by Cummins shows 60ºF cooling water provided for the Rankine cycle WHR system. This unrealistically low temperature cooling water, which would not be available on Class 7 or 8 trucks, would improve the efficiency of the Rankine cycle WHR system (Van Wylen, 1961, pp. 282-284).

   An appropriate heat sink for such a Rankine cycle system might be air at an 80°F temperature. Such a heat sink temperature would require the design of special heat exchange systems and a system to provide the air for cooling. Thus, the change in Rankine cycle heat sink temperature would be accompanied by addi-

[3]Ken Howden, DOE, FCVT, DOE responses to committee queries on 21CTP engine systems and fuels, March 28, 2007.

TABLE 3-3 Reported Results of Thermal Efficiency Testing

Measured Test Results	Cummins	Caterpillar	Detroit Diesel
Engine alone	43.2% at 378 hp	Not Specified	Not Specified
WHR	57 hp at 60°F cooling water for Rankine Cycle	Not Specified	Not Specified
System (Engine + WHR)	Not tested (WHR device was not integrated with engine-output shaft)	47.4% Thermal Efficiency	48.4% Thermal Efficiency
Analytical Projections (Reported as Peak Efficiency)	50% Brake Thermal Efficiency	50.5% Thermal Efficiency (Nelson, 2006a)	50.2% Thermal Efficiency
Baseline Engine			
Engine Model	MY2000ISX 450	2007 C15 15L Engine	Not Specified
Rated Power	450 hp @ 2000 rpm	550 hp @ 1800 rpm (est.)	
Peak Torque	1650 ft-lb @ 1200 rpm	1850 ft-lb @ 1200 rpm and 1850 ft-lb @ 1100 rpm	1534 ft-lb @ 1237 rpm
Thermal Efficiency	42%	Not Specified	Not Specified
Test Speed/Load Condition	"Typical Cruise"[a]	"Key fuel economy point"[a]	Not Specified
Test Conditions	SAE J1349 (Net Power)	SAE J1995 (Gross Power)	EPA Certification Procedures
Technology Demonstration Engine			
System Tested	Engine and Rankine cycle WHR System were not mechanically connected	Implied to be total engine and turbocompound system	Implied to be total engine and turbocompound system
Test Speed/Load Condition	Peak Torque	Peak Torque (1200 rpm, 1,850 ft-lb)	Not Specified
Test Condition Power	435 hp	Not Specified	Not Specified
Issues with Results	Rankine cycle is used to produce electricity. Losses in the conversion of electricity to engine shaft power do not appear to be included Rankine cycle used 60°F cooling water. Significantly higher temperatures would be expected in a vehicle, with subsequent deterioration of the Rankine cycle efficiency		

[a]Gurpreet Singh, DOE, FCVT, "Overview of DOE/FCVT Heavy-Duty Engine R&D," Presentation to the committee, Washington, D.C., February 8, 2007.

tional energy losses required for cooling the system condenser.

2. A driveline electric motor consuming the electric power generated by the Rankine cycle WHR system and geared to the engine-output shaft would be required to utilize the WHR power in a Class 7 or 8 truck. Instead of testing a driveline electric motor and gear set to transmit the electric motor power to the output shaft of the engine, a load bank (i.e., resistors) was used to consume the electric power generated. The efficiency of the electric motor and the gear set do not appear to have been included in the calculation of the power that the WHR system could add to the engine shaft power.

Several features identified in the Major Activity and Milestone 3 were not included in the test engines, as shown in Table 3-5, and were not addressed by the industry partners. The most notable features not included were "new combustion regimes" and "advanced materials." This was of significant concern because DOE had funded extensive research work in the 21CTP focused on low-temperature combustion within the category of "new combustion regimes" and high-temperature materials within the category of "advanced materials."

Other features were not applied consistently by the industry partners; selected features were used by some partners and were not used by other partners. These areas included "advanced fuel injection," "advanced controls," "low-friction features," "air handling," and "thermal management." Several examples illustrate this issue:

TABLE 3-4 Technologies in Demonstrator Engines for Thermal Efficiency Testing

Features	Cummins	Caterpillar	Detroit Diesel
Engine	MY2000 ISX 450	2007 C15 15L Engine	Not Specified
Advanced Fuel Injection	High-pressure common rail fuel system replaced the HPI fuel system	NA	NA
New Combustion Regimes	NA	NA	NA
Exhaust-Heat Recovery	Rankine cycle with load bank to simulate a driveline motor consuming electric power	Turbocompound	Turbocompound
Aftertreatment	Simulated by increasing back pressure on the exhaust	High efficiency aftertreatment includes dual DPF and dual NRT	High-efficiency NO_x aftertreatment
Advanced Controls	Engine calibration was tuned with the hardware set to achieve target emission levels	Variable intake valve actuators	NA
Low-Friction Features	Optimized lube and water pumps	Low-friction components	NA
Air Handling	NA	Reduced flow restriction, High-Efficiency air systems (series turbocharging)	NA
Thermal Management	NA	Reduced heat rejection	NA
Advanced Materials	NA	NA	NA
Other Features			
Compression Ratio		Increased compression ratio	Increased compression ratio
Cylinder Pressure	NA	Increased peak cylinder pressure capability	NA
Charge Cooling	NA	High efficiency compact Intercooler and Aftercooler	NA
EGR	High-pressure loop EGR with EGR cooler	Low pressure (LP) EGR picked up after DPF; includes CGIC (EGR cooler)	NA
Turbocharging	Variable geometry turbocharging instead of fixed geometry turbocharging	High Efficiency Air System with series LP compressor, HP turbine and LP turbine	NA
Other	Exhaust—WHR cooler	System optimization (peak cylinder pressure, CR, etc.)	NA
	CAC—WHR cooler		
	Coolant—WHR cooler		
	WHR system boost and feed pumps, turbine/generator		
	Test cell coolers to control engine coolant and IMT to target conditions		

NOTE: CAC, charge air cooler; CGIC, clean gas induction cooler; DPF, diesel particulate filter; IMT, intake manifold temperature; NRT, NO_x reduction trap; WHR, waste heat recovery.

1. Variable valve actuation was used only by Caterpillar. The role of this feature for improving thermal efficiency was not defined. Furthermore, the committee was not informed of the extent to which the absence of this feature on the engines of the other two industry partners contributed to their failure to achieve the 50 percent thermal efficiency goal.
2. Only Caterpillar stated that it incorporated reduced heat rejection in its engine, but the means by which this was achieved was not defined and the role of this feature for improving thermal efficiency was not provided. Caterpillar subsequently reported to the committee that it had prepared air gap pistons and exhaust port liners, but that they had not been tested. The committee did not receive an explanation of why, after nearly 7 years with thermal management as a key feature to be included in this project, these items were not included in the Caterpillar test engine. In contrast, the engines of the other two partners did not include this feature and the committee did not receive an explanation of why this feature was not included in their programs. Likewise, the committee was not informed of the extent to which the absence of this feature contributed to their failure to achieve the 50 percent thermal efficiency.

TABLE 3-5 Status of Achieving 2010 Emissions Standards at 50 Percent Thermal Efficiency

	Cummins	Caterpillar	Detroit Diesel	Emissions Standards
Test Conditions	Assumed to be the same single point used to measure thermal efficiency	—	—	EPA FTP Heavy Duty Transient Test Cycle, Supplemental Emission Test (SET) consisting of the 13 mode ESC (European Stationary Cycle), and NTE (Not to Exceed) Limits.
Engine-Out Emission Test Results				
NMHC (nonmethane hydrocarbon)	—	—	—	—
CO	—	—	—	—
NO_x	1.39 g/bhp-h	2.5 g/bhp-h	—	—
PM (particulate matter)	<0.1 g/bhp-h	—	—	—
Exhaust Emission Test Results				
NMHC	—	—	—	0.14 g/bhp-h
CO	—	—	—	15.5 g/bhp-h
NO_x	—	—	—	0.20 g/bhp-h
PM	—	—	0.006 g/bhp-h	0.01 g/bhp-h
Exhaust Emission Analytical Calculations				
NMHC	—	—	—	—
CO	—	—	—	—
NO_x	0.209 g/bhp-h	0.17 g/bhp-h	0.2 g/bhp-h	—
PM	<0.01 g/bhp-h	<0.01 g/bhp-h	—	—
Assumptions for Analytical Calculations				
NO_x	85% effectiveness with urea-SCR aftertreatment	93-97% conversion efficiency demonstrated with SCR aftertreatment (Nelson, 2006a)	95.3% urea SCR efficiency assumed, but higher efficiency has been measured	—
PM	90% effective PMI filter	—	—	—
Aging Used for Aftertreatment System	Above Performance assumptions “consistent with an aged cycle.”[a]	“The effect of aging was accounted for by only using a 5% degradation factor for the NO_x aftertreatment” [a]	“These are technology evaluation/demonstration projects, and hence, did not require the protocol of durability or aging required for product development.” [a]	—
DPF Loading	Assumed to have average loading	—	—	—
Fuel Economy Penalty	Reflected in base engine performance. Aftertreatment system was simulated by increased back pressure on the exhaust.	The fuel economy penalty for the back pressure of 13 kPa of the aftertreatment system was accounted for by actually having the aftertreatment installed	“The fuel economy information is competitive information, and, therefore, not public domain.”[a]	—
DPF Regeneration	—	Passive regeneration ability of the DPF allows it to be self-regenerating	—	—

NOTE: —, no information provided to the committee.

[a]Gurpreet Singh, DOE, FCVT, “Overview of DOE/FCVT Heavy-Duty Engine R&D,” Presentation to the committee, Washington, D.C., February 8, 2007.

TABLE 3-6 Improvements Proposed for Reaching 50 Percent Thermal Efficiency

Feature	Cummins[a]	Caterpillar[b]	Detroit Diesel[b]
Breathing	NA	NA	Variable breathing
Fuel Injection	NA	Higher injection pressure	
Heat Insulation	NA	Add air gap pistons	NA
		Add exhaust port liners	
Parasitic Losses	NA	NA	Parasitic loss reduction
Turbocharger	NA	Redesign the LP stage turbine to reach the 80% analytical predictions	Increased efficiency
		Add the redesigned HP stage compressor to reach 80% analytically predicted level	
WHR	NA	Redesign turbocompound mechanically to eliminate rubbing friction caused by undamped shaft dynamics	NA
Aftertreatment	NA	NA	Backpressure reduction

[a]Cummins analytically projected 50 percent thermal efficiency, but it did not demonstrate 50 percent thermal efficiency with one complete engine system. Improvements are likely to be required by Cummins to resolve issues noted in Table 3-3 in order to achieve 50% thermal efficiency.
[b]Improvements provided by each company.

In defining the goals of the 21CTP, DOE indicated that all of these areas would have a significant role in improving engine thermal efficiency, yet several of the features received little or no attention in the attempted demonstration of 50 percent thermal efficiency. Although DOE has provided significant funding in several of these areas in the 21CTP in addition to the funding for the achievement of 50 percent thermal efficiency at 2010 emissions, the results from this work were not included in the unsuccessful attempts by the three industry partners to achieve the important goal of 50 percent thermal efficiency. Advanced development within companies usually lags national laboratory research. However, not including many advanced features in the test engines was of particular concern, because the engine manufacturers were known to have had past experience and development activities in most of these areas.

DOE should review the original features expected to be included in the 50 percent thermal efficiency engine and determine the justification for omitting some of the features from the demonstration engines. DOE should also determine how the results of their funding of research in several of these areas, especially in the categories of "new combustion regimes" and "advanced materials" could have been incorporated in an engine that might have had a greater potential to achieve 50 percent thermal efficiency.

None of the industry partners demonstrated compliance with the 2010 emissions regulations. Meeting the 2010 standard while achieving the 50 percent thermal efficiency goal implied that any thermal efficiency penalty incurred by meeting the 2010 emissions standard would inherently be included in the thermal efficiency measurement. Comparisons of the test procedures used to confirm that the demonstrator engines met the 2010 emissions standard and the emission control systems used, as reported by the industry partners, are shown in Table 3-5.[4] "Meeting the 2010 emissions standard" implies that: (a) emission levels from the test engine and aftertreatment system, when tested on the EPA FTP Heavy Duty Transient Test Cycle, the Supplemental Emission Test (SET) and the Not To Exceed (NTE) tests, are adequately below the applicable standards to account for the statistical variability of emission results from in-use production engines, and (b) the complete test engine and aftertreatment system has been aged on a durability cycle to simulate 435,000 miles for HHDDE as prescribed by the EPA regulations. The table indicates that an inconsistent approach was taken by the three industry partners in demonstrating 2010 emissions.

As described earlier, none of the partners achieved the goal of 50 percent thermal efficiency at 2010 emissions standards. Instead, the industry partners presented discussions on potential improvements that might be used to reach the stated goals. These potential improvements, as reported by the industry partners, are summarized in Table 3-6.[5] As indicated in the table, Caterpillar and Detroit Diesel projected that significant design changes would be required to reach the goal of 50 percent thermal efficiency at 2010 emissions. In contrast, Cummins analytically projected 50 percent thermal efficiency, but it did not demonstrate 50 percent thermal efficiency with one complete engine system. Improvements are also likely to be required by Cummins to resolve the issues noted in Table 3-3. EPA test procedures are the industry standard and should be used for emissions testing, in order to achieve 50 percent thermal efficiency with one complete engine system.

[4]Ken Howden, DOE, FCVT, DOE responses to committee queries on 21CTP engine systems and fuels, March 28, 2007.
[5]Ken Howden, DOE, FCVT, DOE responses to committee queries on 21CTP engine systems and fuels, March 28, 2007.

Finding 3-1. Although DOE has concluded that the 50 percent thermal efficiency goal has been achieved, the experimental test results show that none of the industry partners achieved the goal of 50 percent thermal efficiency at 2010 emissions standards with a complete engine system. Each partner either failed to test a complete engine system on an engine dynamometer and used analysis to project results or failed to achieve 50 percent thermal efficiency at 2010 emissions standards with a complete system. Details of the analytical projections were proprietary and were not provided to the committee. Moreover, the work that was accomplished was at the intrinsically more efficient peak torque condition rather than at an engine speed and load representative of 65 mph road load.

Recommendation 3-1. Objective and consistent criteria should be used to assess the success or failure of achieving a key goal of the 21CTP such as the attainment of 50 percent thermal efficiency. Detailed periodic technical reviews of progress against the program plan should be conducted so that deficiencies can be identified early and corrective actions implemented to ensure success in accomplishing program goals. DOE should continue to work toward demonstrating 50 percent thermal efficiency at the peak efficiency condition as well as representative 65-mph road load engine speed and torque condition. DOE should also consider reducing the number of industry contracts on specific engine projects that are funded so that only the engine systems most likely to meet the goal, based on system modeling and analytical projections, will be developed and tested experimentally.

Finding 3-2. The goal of achieving 50 percent thermal efficiency at 2010 emissions was not clearly specified by the 21CTP. Each of the three industry partners used a different test procedure for measuring thermal efficiency (see Table 3-4). Likewise, none of the industry partners demonstrated 2010 emissions using the required EPA test procedures with aged engine and aftertreatment systems. A goal of this importance should be specified by standard test procedures so that the results are verifiable and compatible with industry standards.

Recommendation 3-2. Future work to achieve the goal of 50 percent thermal efficiency at 2010 emissions should be specified by industry standard test procedures. SAE J1349 Engine Power Test Code is the industry standard for net power ratings and should be specified for the thermal efficiency portion of this goal (SAE, 2004). Test results should clearly provide all of the engineering details required to interpret the results.

Finding 3-3. Some of the technical features used to approach the goal of 50 percent thermal efficiency, as shown in Table 3-4, differed among the three industry partners, and no explanation or technical analysis was provided to justify the different approaches. Furthermore, the effectiveness of the individual features used on the demonstration engines could not be determined due to the lack of analysis or system modeling. A validated system model should have been used to compare test data with analytical projections to determine if each feature was performing as expected.

Recommendation 3-3. Prior to beginning future test phases of this program to achieve 50 percent thermal efficiency, *system modeling* should be used so that the preferred technical approaches could be selected and test data could be compared with analytical projections to determine if the expected results have been obtained.

Finding 3-4. Although DOE stated that the 2010 emissions standard was achieved in the demonstrator engines attempting to achieve 50 percent thermal efficiency, only steady-state emissions at one test condition were reported rather than test results from the EPA specified test procedures for the 2010 emissions standard. In some cases, the emissions were estimated from engine-out emissions and assumed aftertreatment efficiency.

Recommendation 3-4. Achieving compliance with 2010 emissions with a "one-off" prototype engine designed to demonstrate 50 percent thermal efficiency may be too stringent a goal for the 21CTP. The emission objective levels should be revised to be the demonstration of emissions at a single point, where the emission level selected to be demonstrated should have the potential for meeting the 2010 emissions as specified by EPA test procedures.

Finding 3-5. Although industrial partners reported on their progress, the presentations were high level summaries with critical engineering information omitted, thereby making the assessment of accomplishments relative to goals difficult.

Recommendation 3-5. DOE should work to develop a review process that will allow future review committees to evaluate "sensitive" information so quantitative assessments of progress can be made.

Engine System Life and Durability

Tests with single, one-off demonstration engines fail to demonstrate the system life required for introduction into the heavy-duty truck marketplace. The demonstration of system durability for a 400,000- to 1,000,000-mile system life target represents a serious "real world" hurdle for the introduction of such hardware.

DOE and the industry partners will need to address the system life target of heavy-duty diesel engines as they are developing experimental, one-off demonstration engines with improved thermal efficiency. At a minimum, a roadmap of required technical actions to achieve system life targets after demonstrating thermal efficiency objectives in a one-off, demonstration engine should be provided.

A Novel Potential Energy Recovery Concept

In reviewing the Cummins WHR concept of the Rankine cycle using a turbine generator to provide electric power to supplement the main engine shaft power, the committee found that an interesting, and potentially relevant, extension of this concept was contained in a Cummins presentation on exhaust energy recovery at the 2006 Diesel Engine Emission Reduction (DEER) Conference (Nelson, 2006b). This presentation suggested the following features for a potential energy recovery concept:

- An on-vehicle high-voltage bus, departing from the typical 12 VDC systems
- Incorporating technology common with Hybrid Electric Vehicles (HEV), including battery storage and power conditioning.
- Opportunities for high voltage accessories, including:
  —Driveline motor/generator
  —Coolant pump(s)
  —Power steering
  —Electric fans
  —Air compressor, and
  —Heating, ventilation, and air conditioning (HVAC)

This brief presentation suggested that a significant revision of the entire propulsion system and its accessories could potentially yield fuel savings from the following techniques:

- Using the HEV concept could allow the main diesel engine to be downsized and peak power demands could be supplied by the electric motor and battery storage system
- Extensive use of high voltage, electrically driven accessories on an on-demand basis
- Elimination of a separate engine-driven alternator

This significant revision of the entire propulsion system and its accessories should be studied for its potential in providing fuel savings as a means for meeting the goal of the 21CTP. The study should include analysis of the cost-benefit of each of the opportunities listed above. These opportunities are discussed further in Chapter 4, under the heading "Hybridization of Long-Haul Trucks."

Fuel Economy Losses Related to Oxides of Nitrogen (NO_x) and Particulate Control

One of the key challenges with regard to maintaining and improving fuel economy for heavy-duty truck engines is to minimize the fuel economy losses associated with adding NO_x and particulate control systems to these engines to meet future emissions standards. The impacts on fuel economy associated with the addition of these emission control systems are difficult to quantify for specific engines from the data that were presented to the committee. The industry partners indicated that the details of these emission control systems are proprietary and have chosen not to specify their configurations or their performance explicitly.

Several of the slides presented indicate the general trends of the adverse impact on fuel economy that can occur due to the additional emission control systems without further improvements in the thermal efficiency of the engine. Engine efficiency improvements, which had been occurring at the level of one half a percent per year, decreased significantly as the model year 2002 was approached.[6] Figure 3-2, which is reproduced from Duggal, shows trends for the impact of emission standards for model year 2002 and beyond on engine efficiency.[7] A 3 percent decline in absolute engine efficiency is associated with the introduction of cooled EGR to meet the 2002 emissions standard. An additional 1.5 percent degradation in engine efficiency is forecasted to occur with increased EGR to meet the 2007 emissions standard. Improvements in the engine configuration were portrayed as having the capability to recover this absolute $4^1/_2$ percent engine efficiency decrease at the 2007 emissions standard. Figure 3-2 also predicts a 2 percent absolute engine efficiency degradation because EGR levels will again be increased to meet the 2010 emissions standard.

Because of the lack of detailed information, it is not possible to determine the precise fuel economy degradation that had been encountered by the engine manufacturers as they changed their configurations to meet the emission standards. DOE should ask the manufacturers to supply this information to assist in determining the size and cause of these fuel economy degradations associated with the successive changes in required emission standards (such as increases in back pressure before regeneration and quantity of fuel used to regenerate the diesel particulate filter [DPF]). Such information would allow the DOE to evaluate the potential beneficial impact of the technologies being developed by the 21CTP program.

An additional concern is associated with the cost and energy content/requirements (because urea is made from natural gas) of reagents for reducing NO_x levels with Selective Catalytic Reduction (SCR) NO_x removal systems. It is not clear how the cost or energy content/requirements of such reagents is being related to the efficiency targets for the 21CTP. Because the reagent use is directly proportional to the pre-SCR NO_x levels in the exhaust, one must know these details to outline reagent use and cost. Discussion with regard to SCR reagent usage was absent from the presentations and

[6]Vinod K. Duggal, Cummins Engine Company, Inc., "Diesel Engine R&D and Integration," Presentation to the committee, Washington, D.C., February 9, 2007, Slide 8.

[7]Vinod K. Duggal, Cummins Engine Company, Inc., "Diesel Engine R&D and Integration," Presentation to the committee, Washington, D.C., February 9, 2007, Slide 16.

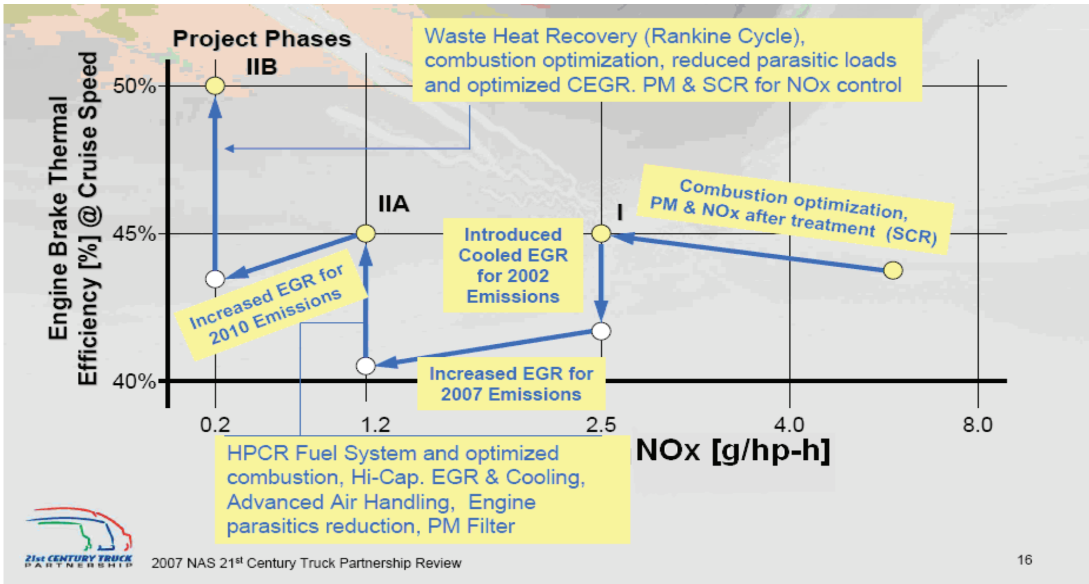

FIGURE 3-2 Heavy truck engine technology roadmap showing the effects of emission regulations on thermal efficiency. SOURCE: Vinod K. Duggal, Cummins Engine Company, Inc.,"Diesel Engine R&D and Integration," Presentation to the committee, Washington, D.C., February 9, 2007, Slide 16.

only the NO_x removal effectiveness was discussed in information presented for the SCR systems. If DOE determines that reagent costs or energy is significant, it should specify a procedure to include these effects in thermal efficiency and vehicle fuel economy goals and economic assessments.

The data presented for the 50 percent thermal efficiency goal by the industry partners projected the performance of such emission control systems for the configurations used in the specific engine tests. In some cases, the operating condition chosen for the test caused exhaust temperatures to be sufficiently high to continuously regenerate the DPFs. Thus, no fuel economy degradation was associated with the level of fuel economy demonstrated. This circumstance appears to be an optimistic assumption with regard to overall usage of a heavy-duty truck. It appears reasonable that DPFs would require periodic regeneration, especially in city use or operating without a loaded trailer, and thus the potential for degradation in overall engine efficiency.

A January 31, 2007, Associated Press article (Robertson, 2007) quoting Freightliner executives highlighted additional costs associated with meeting new emissions standards. In that article, Freightliner Corporation stated that some fuel economy penalties were associated with meeting the 2007 emissions standards. These fuel economy degradations were not quantified in their corporate statement.

Thermal Efficiency Goal at Full Load Versus Road Load

The 21CTP goal for the three industry partners was to demonstrate 50 percent thermal efficiency. Although the specific engine speed and load conditions for this demonstration were not specified, each of the industry partners reported that their best thermal efficiency was measured at, or near, the peak torque condition of the engine, as indicated in Table 3-3.

The peak torque condition where the best thermal efficiency was demonstrated is not consistent with the typical 65 mph road load engine operating condition that was specified as the focus of Class 8 trucks for the 21CTP. This discrepancy in operating conditions is illustrated in the energy audit of a typical Class 8 tractor-trailer combination on a level road at a constant speed of 65 mph and a GVW of 80,000 lb as shown previously in Figure 3-1.

To meet the goals of the 21CTP goal, this audit shows that the 50-percent thermal efficiency goal is required at the road load power at 65 mph rather than at the peak torque condition. The road load power required at 65 mph is 214 hp (160 kW), as shown in Table 3-7. At the peak torque condition for these engines, approximately the same power is generated as at the rated power condition, which is attributed to the significant torque rise of these engines.

The decrease in thermal efficiency at the 65 mph road load power condition versus the peak torque condition can be significant. This reduction is illustrated on a typical fuel consumption map for a production DDC Series 60 12.7L engine shown in Figure 3-3 (from Merrion, 1994). The 65 mph road load operating condition (speed and power) for typical drivetrain parameters for a fuel-efficient Class 8 truck is shown on this fuel consumption map. As indicated in the figure, a 2.5 percent decrease (1.1 percentage point

TABLE 3-7 Comparison of Engine Rated Power and Road Load Power

Engine	Rated Power	Road Load Power	Road Load Power as Percent of Rated Power
Cummins ISX	450 hp	214 hp	48%
Caterpillar C15	550 hp	214 hp	39%
Detroit Diesel	NA	NA	NA

NOTE: NA, Not available to the committee.

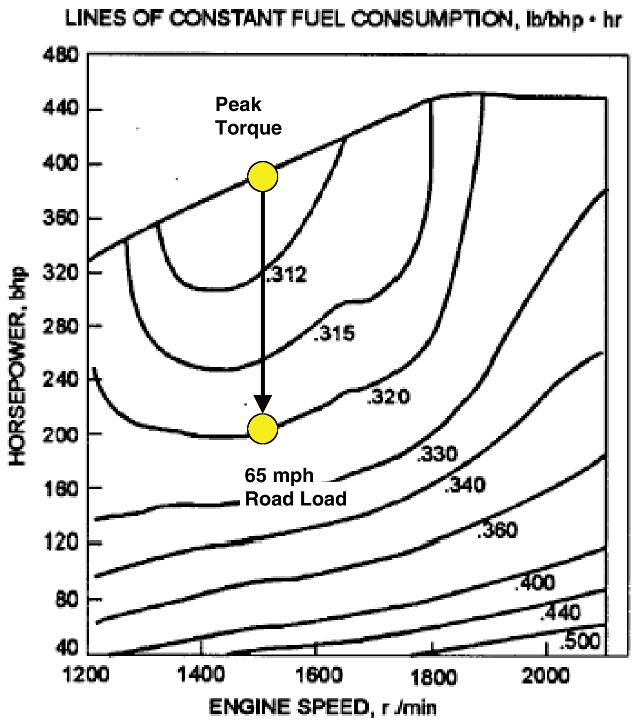

FIGURE 3-3 DDC Series 60 12.7L brake-specific fuel consumption map. SOURCE: Based on Merrion, 1994, modified by the committee. Reprinted with permission from SAE paper 940130. Copyright 1994 by SAE International.

decrease) in thermal efficiency occurs from the peak thermal efficiency condition to the road load condition, as shown in Table 3-8.

The 21CTP stated that "difference in peak thermal efficiency and road-load thermal efficiency is common, [but] it is not a universal rule."[8] However, subsequent data provided by several of the industry partners, also shown in Table 3-8, indicated that the decrease in thermal efficiency at the 65 mph road load engine operating condition versus the peak thermal efficiency can be significant. The available data from the 21CTP as well as published data indicate that up to a 7 percent decrease (3.4 percentage point decrease) in thermal efficiency can be expected at the 65 mph road load condition versus the peak thermal efficiency condition.

A convenient method for defining the road load condition would be to use one of the operating conditions from the SET (Supplemental Emission Test) which is the 13-mode steady-state emission test established to help ensure that heavy-duty engine emissions are controlled during steady-state type driving, such as a line-haul truck operating on a freeway. This test is based on the European Union's 13-mode ESC (European Stationary Cycle) schedule, commonly referred to as the "Euro III cycle." This cycle is shown schematically in Figure 3-4.

Because road load power required at 65 mph is approximately half of the rated power, and rated torque of the engine, 13-mode test point A50 (60 percent engine speed, 50 percent load) would appear to be an appropriate choice to approximate the 65 mph road load condition, although this would need to be confirmed for each engine under consideration. The 60 percent of rated engine speed for test point A50 is similar to the speed for the peak torque condition that had been used for the demonstration of peak thermal efficiency by the industry partners.

Finding 3-6. Achieving the 21CTP's goal of 50 percent peak thermal efficiency is not expected to result in the Partnership's goal of 50 percent thermal efficiency for a typical Class 8 tractor-trailer combination on a level road at a constant speed of 65 mph and a GVW of 80,000 lb. Even if 50-percent thermal efficiency were to be achieved at, or near, the peak torque condition, up to a 7 percent improvement (3.4 percentage point improvement) task would still remain to achieve 50 percent thermal efficiency at the 65 mph road-load condition.

Recommendation 3-6. The 21CTP should clearly define, in addition to the peak thermal efficiency condition, the specific 65-mph road-load condition for demonstrating 50 percent thermal efficiency. The committee suggests using one of the 13-mode steady-state emission test points for approximating the 65-mph road load condition. For typical engines, drivetrains, and vehicles, emission test point A50 (60 percent engine speed, 50 percent load) would be appropriate, although the most appropriate point (or multiple points, if necessary) should be determined for the specific engine, powertrain, and vehicle configuration under consideration. The 21CTP should request each of the three current industry partners to test their experimental demonstration engines according to this recommendation.

A recent CRC study has proposed new cycles under development that may correlate better with actual in-use emissions and, possibly fuel usage, for heavy-duty diesel trucks (Tennant, 2007). This study found that their in-use operation

[8]DOE, FCVT, 21CTP, response to committee query, transmitted via e-mail by Ken Howden, March 27, 2007.

TABLE 3-8 Change in Thermal Efficiency (BSFC) from Peak Thermal Efficiency to 65 mph Road Load Condition

Source	Condition	BSFC	Thermal Efficiency[a]	Change in Thermal Efficiency Road Load vs. Peak
DDC Series 60	Peak Thermal Efficiency	0.312 lb/bhp-h	43.9%	Peak
12.7L BSFC Map	400 hp			
	1,500 rpm			
	(71% maximum engine speed)			
	Road Load (65mph)	0.320 lb/bhp-h	42.8%	–2.5%
	214 hp			
	1,500 rpm			
Cummins ISX	Peak Thermal Efficiency	NA[c]	50%	Peak
50% Thermal Efficiency	A100 point: 1,168 rpm, 1,650 ft-lb, 367 hp		Analytical Projection	
Test Engine	Road Load (65 mph)	NA	Inadequate Data	Inadequate Data
	B63 point: 1,456 rpm, 1020 ft-lb, 283 hp		Provided	Provided
Caterpillar	Peak Thermal Efficiency	NA	47.4%	Peak
50% Thermal Efficiency	1,200 rpm, 1,850 ft-lb, 420 hp			
Test Engine	(peak torque)			
(Gear Fast, Run Slow Strategy)	Road Load (65 mph)	NA	Avg = 45.7%	–3.6%
	Approximately 250 hp			
	Average of A50 and B50 points[b]			
	A50 point: 1,200 rpm, 925 ft-lb, 210 hp		A50 pt = 46.6%	
	B50 point: 1,500 rpm, 925 ft-lb, 265 hp		B50 pt = 44.8%	
Detroit Diesel	Peak Thermal Efficiency	N/A	48.4%	Peak
50% Thermal Efficiency	A100 point: 1,237 rpm, 1,548 ft-lb, 364 hp			
Test Engine	Road Load (65 mph)	NA	About 45%	–7.0%
	Average of B50 and B75 points			
	A50 point: 1,506 rpm, 782 ft-lb, 224 hp			
	B75 point: 1,506 rpm, 1,172 ft-lb, 336 hp			

[a]Thermal efficiency % = (1/BSFC) × 13.7.
[b]Points refer to 13 mode emission test points.
[c]NA, not available to the committee.

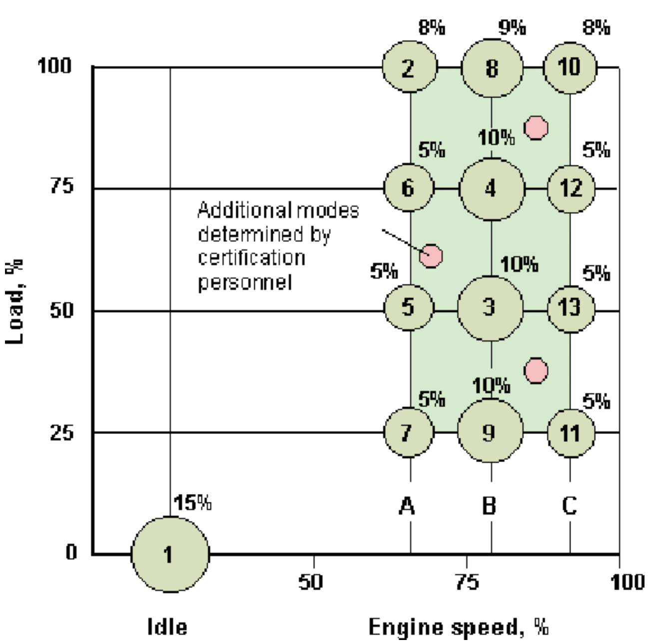

FIGURE 3-4 Thirteen-mode steady-state emission test conditions. SOURCE: DieselNet Online information service on clean diesel engines and diesel emissions. Available at www.dieselnet.com/standards/cycles/esc.html. Accessed August 6, 2007.

could be partitioned into the following four modes (with associated maximum speeds noted): creep (9 mph), transient (48 mph), cruise (59 mph), and high-speed cruise (65 mph). Each mode was highly transient, and only the high-speed cruise mode reached 65 mph. The 21CTP should monitor this work and consider the possible future application of these cycles for assessing thermal efficiency improvements for HHDDEs.

Commercial Viability

The ultimate purpose of DOE's 21CTP is to develop technology that will ultimately be used in widespread commercial applications so that the demonstrated fuel savings in the laboratory can be achieved across all Class 7 and 8 trucks. For this to occur in the free marketplace, the ultimate cost of the technology used to achieve the fuel savings must be recovered by the savings in fuel costs within a period of several years. The status of the system costs required to achieve 50 percent thermal efficiency, as reported by the industry partners, is summarized in Table 3-9. As indicated by the lack of cost information in the table, the issues of system costs and commercial viability do not appear to have been suitably addressed by DOE and the industry partners.

TABLE 3-9 Commercial Viability

	Cummins	Caterpillar	Detroit Diesel
Hardware Status	Lab-based technology demonstration One-off, prototype devices	NA	Technology demonstration projects
Vehicle Packability of Engine System	Lab demonstration not constrained by on-vehicle packaging limits	System package able to be installed in Class 8 truck	
Hardware Costs	NA	NA	Costs of laboratory or prototype hardware do not reflect on their costs when available in commercial use.
Commercial Potential	NA	Several of the technology building blocks are being considered for inclusion on the 2010 Heavy Duty on highway engine offering from Caterpillar. Production viability and the ability to package the system were vital in the Caterpillar demonstration.	NA
Cost of Key Elements to be Considered Commercially Viable from an Economic Perspective	These details are proprietary. However, a cost-payback analysis considering fuel cost versus the performance and price of the waste heat recovery (WHR) system components would determine its viability from an economic perspective. Any analysis should also include the potential benefit of WHR to reduce overall vehicle cooling system loadings.	NA	NA
Work Planned to Achieve Costs Required to Make the Key Features of the Engine Commercially Viable	Ongoing WHR project seeks to demonstrate this concept in-vehicle which may also demonstrate its commercial viability.	NA	Some work is planned. However, DOE role in these efforts has not yet been determined.

NOTE: NA, no information provided to the committee.

Cummins addressed this issue at the August 2006 DEER Conference in a presentation titled “Achieving High Efficiency at 2010 Emissions” (Nelson, 2006a). This presentation showed that a 10 percent fuel savings for a truck operating for 120,000 miles per year and with \$3.00/gal fuel would provide a savings of \$9,000 over an 18-month period (assuming 6.0 mpg). Cummins stated that \$9,000 would be the target cost for 10 percent fuel savings. Because the 21CTP goal is to reduce fuel consumption by 17 percent, the Cummins estimates would indicate that, at \$3.00/gal fuel cost, approximately \$15,000 might be a suitable cost target for the improvements added to the base engine.

An additional cost related to major modifications to the base engine and the addition of an energy recovery system is associated with the required durability of heavy-duty diesel engines. Engine lifetimes for heavy-duty diesel engines are typically 400,000 to 1,000,000 miles. To achieve this level of durability, significant development cost and time are incurred. None of the analyses of fuel savings required to pay back initial costs highlighted the development costs for demonstrating the high mileage life of these modified engines and energy recovery systems. The work to guarantee a system life comparable to those of current engines will represent very significant investment of time and cost for the introduction of modified engines and energy recovery systems into production.

Finding 3-7. DOE and the industry partners did not appear to address the potential commercial viability of the technologies or the potential costs required to achieve cost-effective solutions, as illustrated in Table 3-10.

Recommendation 3-7. DOE should request the industry partners to make an assessment of cost objectives required to achieve commercial viability.

GOAL OF THERMAL EFFICIENCY OF 55 PERCENT

Introduction

The 55 percent goal has been proposed by DOE in the 21CTP Roadmap document (DOE, 2006, p. 2) to follow the goal of demonstrating the 50 percent efficiency goal. It should be noted that the work toward the 55 percent goal, if it has started at all, is very much in its beginning.

In assessing the research programs in support of this goal, the committee identified two general issues of concern:

1. The appropriateness of the recent shift of focus toward component development to achieve a prototype emissions-compliant engine system thermal efficiency of 55 percent by 2013; and
2. Effectiveness of the number of engine companies to be funded, i.e., one or two versus five.

Appropriateness of Shifting Focus Toward Component Development to Achieve an Engine System Thermal Efficiency of 55 Percent by 2013

The pertinent strategy as stated the 21CTP Roadmap document (DOE, 2006, p. 10) is as follows:

> Research and develop technologies which will achieve a stretch thermal efficiency goal of 55 percent in prototype engine systems by 2013, leading to a corresponding 10 percent gain in over-the-road fuel economy over the 2010 goal. (2010 goal was 50 percent thermal efficiency.)

This goal has to be taken in the context that the DOE budget for Engine Systems work starting in FY 2008 could be severely reduced (see Table 1-6 and Appendix C for the details of the appropriations to the 21CTP and the parent program's research budgets). The extent of this reduction is illustrated by the budget for Heavy Truck Engines of $14.49 million in FY 2007 dropping to a requested budget of $3.519 million for FY 2008, i.e., a 76 percent reduction. Lesser reductions are present in supporting areas such as Combustion and Emissions, and Waste Heat Recovery. Only Propulsion Materials Technology for Heavy Vehicles shows a modest budget increase of roughly 25 percent.

As noted earlier in this chapter, the 2010 efficiency goal of 50 percent was not demonstrated by any of the program participants, even with the relatively large funding base that was available from the initiation of the 21CTP until 2007 when DOE concluded this activity. Therefore, it is obvious that the funds to be allocated for FY 2008 and onward will have to be used in a very prudent manner, which may mean fewer projects of greater scope and potential, in order to have any chance of achieving meaningful technical progress.

On pages 16 and 17 of the 21CTP Roadmap (DOE, 2006), what appears to be a "laundry list" of technical barriers to achieving this goal is presented under the separate categories of efficiency, emissions, and fuels. It is well known that the interactions among these elements are fundamental and complex. For example, a new aftertreatment component such as a NO_x trap or SCR catalyst cannot be effectively considered in a systematic manner without knowledge of the "engine-out" emissions, particularly from the new combustion regimes that are being investigated.

It does not appear that any formalized systems engineering analysis was done to determine (1) the relative importance of these barriers, (2) the interactions among them, and (3) the overall effect of each on the entire system. This would be required to determine realistic improvements that would be needed for each of the barriers identified to achieve the 55 percent thermal efficiency goal. To do so quantitatively would require a well-developed total system simulation, which the authors of the Roadmap state is immature or not available. However, a top-down qualitative approach, starting with the overall system goals, subgoals, and technical requirements to achieve them would provide at least some understandable framework for allocating the reduced amount of funding that is available. Inspection of the Quad Sheet submissions of 2007 (DOE, 2007) appears to show a collection of projects, albeit in important areas, but absent any estimate of what success in any of the projects would mean to the achievement of the system goal. This type of funding and organization is more appropriate to basic research than it is to applied research with a specific system goal.

However, a planned major enabler of the attainment of the 55 percent thermal efficiency goal appears to be low-temperature combustion (LTC), in its various forms. LTC is heavily supported by the FreedomCAR and Vehicle Technologies light duty program with expected "spill-over" benefits in the heavy-duty engine sector. Therefore, in reviewing the appropriateness of the shift to component research, it is important to assess LTC as a "component" technology for the attainment of 55 percent thermal efficiency in heavy-duty truck engines. This discussion follows.

Issues Related to Low-Temperature Combustion

The committee is concerned about the research program to develop LTC, i.e., homogeneous charge compression-ignition (HCCI) or premixed charge compression-ignition (PCCI). In particular, recognizing the present status and future outlook for this technology, the committee believes it to be unlikely that it will enable heavy-duty diesel engines to achieve the thermal efficiency goal and emission standard with a more effective emission control system having little or no aftertreatment.

Traditional spark-ignited (SI) and diesel engines both rely on a source of positive ignition. In SI engines, this is accomplished by means of a high-voltage discharge across the electrodes of a spark plug that is immersed in a fuel and air mixture within the engine cylinder that is capable of supporting flame kernel development and subsequent flame propagation. The timing of the spark event is a control variable, which can be set optimally for fuel efficiency or delayed (retarded) to control in-cylinder phenomena such as NO_x formation or to eliminate the occurrence of engine knock. The rate at which the flame propagates is highly correlated to the turbulence level in the cylinder and the cylinder geometry.

In diesel engines, positive ignition is obtained by injecting fuel of sufficient cetane rating into air, which has already been compressed to high temperature and pressure within the cylinder of a high compression ratio engine before the injection event. After a short delay associated with droplet atomization, vaporization and early-stage chemical reactions, a flame process is initiated that spreads to the remainder of the fuel that has already been injected or is continuing to be injected in jet-like fashion through the nozzle(s) of the high-pressure diesel fuel injection system. The rate of combustion is tied to the injection rate, the fluid motion in the cylinder, and the rate at which the individual droplets vaporize and burn. The timing of the injection event is a control variable that has an effect on the thermal efficiency of the cycle and the formation of pollutants such as NO_x and particulate matter.

Diesel combustion, in many ways, is more complex than SI engine combustion. (Flynn et al., 1999). Even though the air-fuel mixture is lean overall (excess air with respect to the stoichiometric requirement for complete combustion), the combustion process is not homogeneous. Some of the energy release process takes place in a very rich condition as the fuel enters the injector's spray plume. This region is where particulate precursors are formed and particulates are created which must be subsequently burned before the combustion process is completed. In addition to the very rich process taking place in the fuel air mixture that enters the spray plume, there is a very high temperature in the nearly stoichiometric diffusion flame that forms around the spray jet periphery. This high-temperature diffusion flame is the source of the nitrogen fixation process within the diesel combustion chamber. Despite the major advances in high-pressure diesel fuel injection technology, which has reduced both emissions and noise through pulse injection and droplet size reduction, the process is still inherently nonhomogeneous. Consequently both NO_x and particulates from the engine are well in excess of tailpipe standards and significant, and complex aftertreatment is required to lower them to acceptable levels.

The basic concept of LTC, in its various forms, is to carry out the combustion process in an ultra-lean or dilute mixture, the temperature of which is low enough to forestall the fixation of nitrogen and oxygen, i.e., reduce NO_x formation to levels capable of meeting 2010 emission levels without aftertreatment, and whose lean composition avoids the formation of particulate matter. The fundamental technical issue or barrier to LTC combustion in diesels (and SI) engines is that there is no longer a source of positive ignition, which is easily controlled. The fuel is injected very early in the case of HCCI to achieve homogeneity or is premixed before entry into the cylinder in the case of PCCI. In either case, the mixture is so dilute that combustion has to occur through the natural chemical kinetic mechanisms between the fuel and the surrounding air and residual gases (i.e., burned gases containing nitrogen, oxygen, carbon dioxide [CO_2] and water [H_2O] as major species) as the mixture is compressed to higher temperatures during the compression stroke of the engine. This reliance on gas-phase chemical kinetics results in major control and operational issues because the kinetic rates do not scale with engine speed (measured in revolutions per minute [rpm]), are variable at different loads, are dependent on engine thermal condition and are a function of the diesel fuel composition, which can vary across a significant range and still be acceptable for traditional diesel combustion.

Many papers and articles have been written about LTC and homogeneous charge compression-ignition (HCCI) engines (see, for example, SAE, 2007), but most describe single-cylinder steady-state engine operation and initial attempts at modest transient operating states. As such, many of the conclusions about the potential of such combustion approaches are still quite speculative and not based on solid documented technical results.

HCCI, PCCI, or LTC cannot be used in engine starting and cold-engine light load operation due to the very low temperature and the correspondingly low rates of the controlling kinetic reactions. The processes require a warmed-up engine and the attainment of appropriate operating temperatures within the engine system. This primary issue must be overcome in any practical implementation of an LTC concept.

LTC processes depend on the ignition quality of the fuel used in their operation. Fuels with high cetane numbers such as those typically used for diesel fuels have significant low temperature reactivity and thus ignite easily at modest overall engine compression ratios. These low compression ratios limit the maximum thermal efficiency obtainable from such cycles. Fuels with lower cetane, or higher octane ratings, have a smaller amount of low temperature reactivity and thus require higher compression ratios to obtain ignition. DOE's present fuels research activity is investigating the optimization of fuel composition for such approaches to obtain combustion at appropriate compression ratios and engine operating temperatures. Again, most of this effort is undertaken on single-cylinder engine tests, and not transient multicylinder engine operation. Thus, the data obtained to date are far removed from those required to demonstrate the true viability of such approaches for real multicylinder heavy-duty engines. Furthermore, it is likely that no single fuel composition optimizes efficiency under all conditions of speed and load. As discussed below in the section "Goals Involving Fuels," the committee does not recommend assuming that specialized fuels will be commercially available for advanced combustion engines.

Experience has shown that the overall thermodynamic efficiency of optimized HCCI or PCCI combustion processes can be similar to those of normal optimized diesel engines

(Kuzuyama et al., 2007). This is true even though the best of such cycles would have significant unburned hydrocarbon (HC) and carbon monoxide (CO) emissions due to the relatively low temperatures and the tendency for the reactions to terminate quickly before the entire combustion process is complete, especially during the expansion stroke when the temperature is decreasing rapidly. Analysis usually indicates that the incomplete hydrocarbon combustion in the best of such cycles yields combustion efficiencies of about 95 percent compared to the normal diesel combustion efficiency of 99-plus percent. This lower combustion efficiency is counteracted by the lack of radiant emissions and heat loss from particulates that occurs in the traditional diesel combustion process. These radiant heat losses typically amount to 5 percent of the fuel energy and they occur near top dead center of the cycle and thus represent nearly a 5 percent loss in engine efficiency (Flynn et al., 1999). The combination of poor combustion efficiency and lower heat losses can yield similar indicated engine efficiencies for conventional diesel and LTC combustion processes. Combustion efficiency losses accompany even the most efficient LTC (HCCI or PCCI) operating points, even those with most of the energy release occurring rapidly near top dead center.

These rapid energy releases are also accompanied by significant noise emissions similar to those occurring during knock in an SI gasoline engine. A great deal of effort has been placed on slowing these rapid heat release rates to control noise and rapid rates of pressure-rise within the cylinder. A wide variety of approaches have been used to slow these combustion processes. Approaches such as the introduction of diluents to the combustion chamber and the stratification of fuel/air ratios within the combustion chamber have been successfully used to lengthen heat release durations and reduce combustion noise. These processes, though, also lead to delaying combustion into the later part of the expansion cycle, thus increasing the portion of unburned HC and CO that remain in the engine's exhaust and a corresponding loss in thermal efficiency. The level of HC and CO emissions in the exhaust of such HCCI and PCCI combustion processes far exceeds the allowed level of tailpipe HC and CO. With combustion efficiency in the range of 95 percent versus 99 percent for conventional diesel engines, LTC engines will experience a four- to fivefold increase in unburned HC and/or CO emissions. Thus, catalytic oxidation of these combustion products will be required if HCCI or PCCI combustion processes are used in operating modes of a production engine configuration. These emissions occur at conditions of low exhaust temperature and thus will require catalysts of very high efficiency and systems to promote oxidation at operating points with very low exhaust temperature. It is unknown whether sustained operation at these types of conditions would require the addition of fuel or some other means to heat the oxidation catalysts.

Transient engine operation is also a problem with HCCI and PCCI combustion processes. Because the chemical kinetic ignition process, and therefore the resulting combustion placement, is dependent on the integrated thermal state within the engine, special adaptations are required to manage combustion processes during transient operation where the engine thermal and heat transfer conditions can change drastically and rapidly. To date only modest rates of engine-output increase or decrease have been demonstrated with actual engine tests. The severity of required engine operation transients is well demonstrated by the transients required during the transient emissions certification process for heavy-duty engines, i.e., the FTP. This test was statistically derived from analysis of actual engine operation in in-city environments. Thus, the transients represented in the cycle depict the required level of transient operations necessary for in-city operation of a heavy-duty truck. Because the rates of transient load excursion on the cycle are almost an order of magnitude greater than any transient load excursion rates demonstrated for LTC in the open literature, the development of such transient capability remains a significant roadblock to the application of such combustion processes to real engines (SAE, 2007).

These LTC processes, as intended, do produce engine exhaust with virtually no particulates or NO_x emissions. Thus, engines that could use such processes over their complete operating range could have exhaust emission control systems that are much simpler than those being presently proposed for heavy-duty applications, i.e., regenerative particulate filters and either regenerative NO_x traps, lean NO_x catalyst or SCR. No researcher has demonstrated that LTC processes could be used to cover the entire engine operating map from engine startup through high load and transient operation. The current operating range for LTC, as shown in Figure 3-5, is confined to low loads, while diffusion combustion dominates at high loads. Thus, it remains unclear as to the actual emission control benefits of applying such combustion processes. Some authors, such as Duffy (2004), proclaim success at operation from light load to very high load with low temperature combustion processes, but examination of their test results indicate that these experiments really use combinations of multiple combustion modes. The resulting exhaust gas constituents include unburned HC and CO, (normal LTC emissions) plus particulates and NO_x emissions in excess of upcoming standards that would require exhaust aftertreatment devices for each of these pollutants complicating the exhaust aftertreatment system greatly.

As indicated above, most of the research presented in the open literature to date is from single-cylinder and simple multi-cylinder engine experiments. These experiments presently have shown no way of dealing with the range of load variation that is required for heavy-duty engine operation or the transient characteristics necessary for real vehicle operation. It presently appears that there is little potential for the application of such low temperature combustion processes over the range of engine operation in heavy-duty engines.

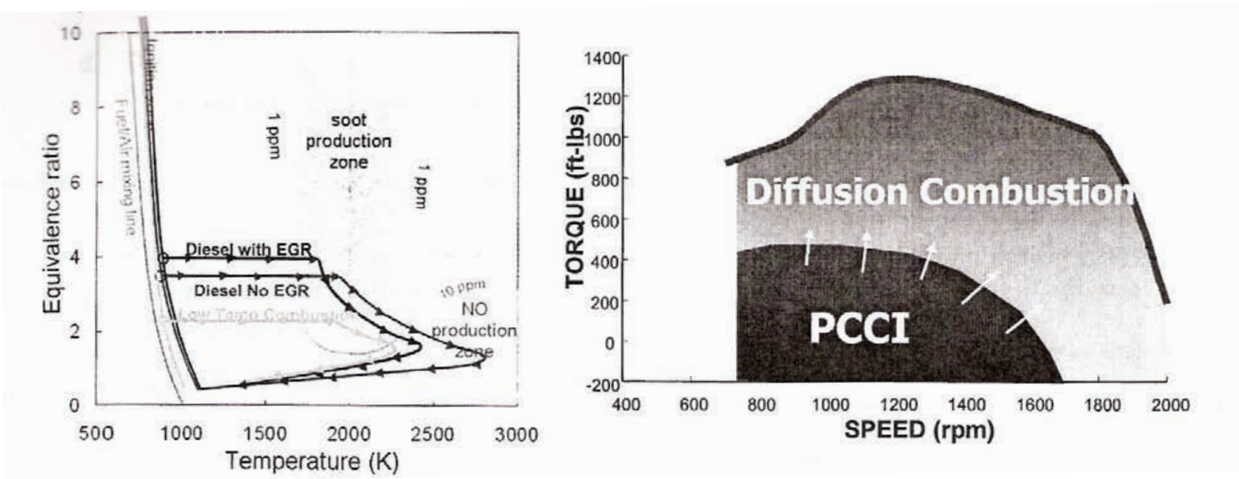

FIGURE 3-5 Illustration of the operating range for LTC combustion. SOURCE: Vinod K. Duggal, Cummins Engine Company, Inc., "Diesel Engine R&D and Integration," Presentation to the committee, Washington, D.C., February 9, 2007, Slide 14.

Further, if LTC is ultimately able to operate successfully at the maximum engine load, the lean or dilute nature of this combustion process (to achieve NO_x levels capable of meeting 2010 emission levels without aftertreatment) will require significant increases in engine maximum cylinder pressures or engine displacement to achieve output similar to those of engines currently used in on highway trucks. If these changes in engine cylinder pressure requirements or displacement are introduced into the market, these product introductions would require major changes in engine design and require a research and development cycle of over five years to demonstrate appropriate engine life targets. Higher cylinder pressures may also introduce significantly higher friction losses, which should be considered. Early discussions by DOE with potential contractors and/or suppliers for such efforts to obtain their perspective on how such product change would be implemented, the time requirements for such product introductions and their overall effect on efficiency and emission controls are considered by the committee as highly desirable.

Finding 3-8. DOE is shifting prematurely to component research to support the 2013 stretch goal of 55 percent thermal efficiency before completely demonstrating the earlier 2010 goal of 50 percent. Importantly, after analyzing the results of the lengthy and extensive efforts carried out in the area of low-temperature combustion (LTC), it is considered unlikely that this technology will be a successful enabler of the 55 percent stretch goal at any time in the near term because it cannot be adequately controlled over the full range of operating conditions of heavy-duty engines and has not demonstrated inherent fuel-consumption advantages. Based on the open literature, the chances for success of LTC as a practical technology appear limited.

Recommendation 3-8. DOE should complete the demonstration of the 50 percent thermal efficiency goal before embarking on the 55 percent goal. With respect to ongoing work on low-temperature combustion, DOE should objectively analyze the potential viability of this combustion concept for heavy-duty engine applications, recognizing the many issues that would need to be resolved to achieve commercial viability.

Finding 3-9. Information on the effects of fuel formulations on LTC operation was not presented to the committee by the 21CTP. However, the committee's opinion is that any single diesel fuel formulation is unlikely to optimize LTC over all modes of operation. The optimum fuel for light-load operation will likely have different properties than the optimum fuel for heavy-load operation.

Recommendation 3-9. DOE should try to specifically confirm whether or not a single non-specialty diesel fuel formulation will optimize LTC over all modes of operation and modify its priorities accordingly based on the data.

Finding 3-10. Even if LTC is successful at light loads, traditional diesel operation will likely be necessary at cold start and higher loads. Due to the different emission issues at light loads and heavy loads, it is very implausible that heavy-duty diesel engines will require no aftertreatment.

Recommendation 3-10. DOE should undertake an analysis of a mixed-mode scenario to determine whether unburned HC and CO control in the LTC regime and DPF and NO_x control in the traditional diesel combustion regime is not more complex and costly than aftertreatment for traditional diesel alone.

Number of Companies to Be Funded

At the level of the proposed funding for FY 2008 and future years, it is unlikely that five heavy-duty engine manufacturers can be funded adequately as major participants in the component area. This number should be reduced to one or, possibly two, based on the merits of the proposals submitted.

Finding 3-11. At the reduced budget levels for FY 2008 and beyond, the inclusion of five engine manufacturers as cost-sharing participants reduces the ability of funding projects of "critical mass," which is not in keeping with the national interest.

Recommendation 3-11. DOE should fund only one or, possibly, two manufacturers during the next phase of the program so that only the most promising projects of a significant scope can be accomplished.

Thermoelectric Energy Conversion Systems

A subsidiary issue related to the goal of thermal efficiency of 55 percent is DOE's decision to investigate thermoelectric energy conversion technology as a major opportunity for improved waste heat recovery systems.

There are only two references to this work in the documentation provided to the committee. Experimental work at NREL is described in Quad Sheet B-1 and FEA analysis work at ORNL is documented in Quad Sheet A-53. Other work may have been presented at other forums such as the DEER conferences of 2002 through 2007. The work described seems to still be at a very basic stage of development for it to merit inclusion in an applied program such as the 21CTP at this time. Further, it is hard to envision that a thermoelectric device could absorb a significant amount of exhaust energy without imposing an undue backpressure on the engine system.

Finding 3-12. The thermoelectric conversion systems are at a very basic stage and seem to have been "lumped" into the 21CTP as a matter of budgetary convenience for more basic work going on primarily at the National Laboratories.

Recommendation 3-12. The thermoelectric conversion research should be removed from the 21CTP program until a more advanced level of technical maturity is attained. At the very least, a technical analysis of the candidate waste energy recovery systems is needed to determine if future efforts on thermoelectric conversion systems within the framework of the 21CTP are justified.

GOALS INVOLVING FUELS

Introduction

The fuel-related goals of the 21CTP were as follows:[9]

1. By 2010, identify and validate fuel formulations optimized for use in advanced combustion engines exhibiting high efficiency and very low emissions, and facilitating at least 5 percent replacement of petroleum fuels.
2. By 2010, identify and exploit fuel properties that could increase efficiency and reduce overall tailpipe emissions through (1) lower engine-out emissions, including new low-temperature combustion regimes, and (2) enhancement of aftertreatment performance for 2010 emissions regulations.
3. By 2013, identify non-petroleum fuel formulations (i.e., renewables, synthetics, hydrogen-carriers) for advanced engines and new combustion regimes for the post 2010 time frame that enable further fuel economy benefits and petroleum displacements while lowering emissions levels to near zero, thus adding incentives for using non-petroleum fuels.

The meaning of the dates specified in the above goals, 2010 and 2013, were unclear to the committee. For Goal 1, the committee assumed that 2010 was the date by which the research work required to identify and validate the fuel formulations specified would be completed and 5 percent replacement of petroleum fuels would actually be achieved in-use. For Goals 2 and 3, the committee assumed that the dates, 2010 and 2013, respectively, were the dates by which the research work would be completed. The basis by which DOE selected these dates was not provided to the committee.

The engines referred to in the above goals were assumed by the committee to mean the following:

- *Advanced Combustion Engines.* These are engines that are currently being researched by the 21CTP with the goal of achieving 50 percent thermal efficiency at 2010 emissions. These engines are being developed for the current specification for No. 2 diesel fuel.
- *New Combustion Regimes and Low Temperature Combustion Regimes.* Both of these terms are assumed to refer to the process of more thoroughly premixing the fuel and air prior to combustion at very lean air/fuel ratios to achieve low combustion temperatures.

Diesel fuel has been the primary truck fuel in the United States, and around the world, for many years. Currently, heavy trucks and buses, almost all of which use diesel fuel, consume 21 percent of the total surface transportation fuel

[9]Kevin Stork, DOE, FCVT, "Fuel Technologies R&D for Heavy Trucks," Presentation to the committee, February 9, 2007, Washington, D.C., Slide 3.

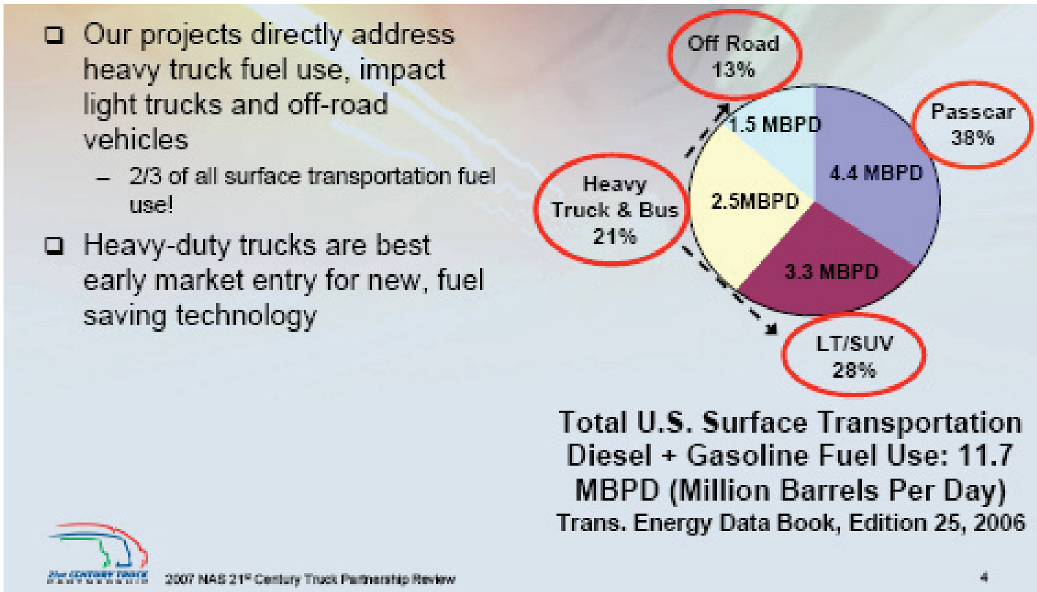

FIGURE 3-6 Surface transportation fuel use. SOURCE: Vinod K. Duggal, Cummins Engine Co., Inc., "Diesel Engine R & D and Integration," Presentation to the committee, Washington, D.C., February 9, 2007, Slide 4.

used in the United States, as shown in Figure 3-6.[10] Off-road vehicles are also significant consumers of diesel fuel while light-duty vehicles predominately use gasoline. Overall, approximately 40 percent of the total surface transportation fuel used is diesel fuel. Very little diesel fuel is used in the United States for light-duty vehicles. That may change if, as expected, fuel economy standards (CAFE) are increased, and the use of light-duty diesel engines increases because of their inherently higher fuel economy.

The United States has a very extensive and well-developed refining, distribution and storage system for providing low-sulfur diesel fuel, essentially all of it derived from domestic and imported petroleum. Engines and diesel fuels have been designed to work well together in terms of vehicle operation and performance, fuel economy, and emissions control. ASTM fuel specifications help to ensure that available engines and fuels are compatible. The extensive work that has been required to ensure engine and fuel compatibility will have to be taken into consideration when developing advanced combustion engines and replacements for petroleum fuels.

A considerable portion of the freight movement in the United States is by truck. The trucking industry is very sensitive to fuel cost. Thus, any efforts to modify fuel for use in diesel engines by either changing the composition of the basic hydrocarbon portion obtained from petroleum, or supplementing it with bio-derived or other non-petroleum-derived diesel fuel, must be sensitive to the impacts of fuel cost.

Nonpetroleum Fuels for Advanced Combustion Engines—Goal 1

DOE recently clarified to the committee that this goal deals with advanced nonpetroleum-based fuels and that future engine designs should operate cleanly and efficiently on fuels with a range of fuel properties, regardless of fuel feedstock.[11] Because the entire truck fleet takes many years to replace, existing engine designs will be in operation for many years to come. Therefore, properties of fuel available in-use must be within the range of the diesel fuel specifications that were used in the design of these engines in prior years. In addition, current engines as well as future engine designs will need to operate cleanly and efficiently on fuels independent of the fuel feedstock.

The first part of Goal 1 deals with advanced combustion engines exhibiting high efficiency and very low emissions. As noted earlier in this section, these engines are currently being researched by the 21CTP with the goal of achieving 50 percent thermal efficiency at 2010 emissions. As

[10] Vinod K. Duggal, Cummins, Inc., "Diesel Engine R & D and Integration," Presentation to the committee, Washington, D.C., February 9, 2007.

[11] DOE responses to committee queries on engine systems and fuels, delivered by Ken Howden via e-mail, March 27, 2007.

TABLE 3-10 Comparison of ASTM Specification for No. 2 Diesel Fuel and 100 Percent Biodiesel

	D975-No.2 Diesel Fuel	D6751-Biodiesel (B100)	Units	ASTM Method
Applicability	Diesel fuel suitable for use in on-highway engines	Blend component up to 20 percent in any diesel fuel or home heating oil	°C	D93
Flash point	52 min.	130 min.	°C	D93
Water and Sediment	0.050 max.	0.05 max	percent volume	D2709
Distillation Temperature, 90% Recovered	282-338	Not Specified	°C	D86
Distillation Temperature, Atmospheric Equivalent, 90% Recovered	Not Specified	360 max.	°C	D1160
Kinematic Viscosity, 40°C	1.9-4.1	1.9-6.0	mm²/sec	D445
Ash	0.01 max.	Not Specified	percent mass	D482
Sulfur	0.0015 max.	0.0015 max.	percent mass (ppm)	D5453
Copper Strip Corrosion	No. 3 max.	No. 3 max		D130
Cetane Number	40 min.	47 min.		D613
One of the following:				
Cetane Index	40 min.	Not Specified		D976
Aromaticity	35 max.	Not Specified	percent volume	D1319
Cloudpoint	Report	Report	°C	D2500
Ramsbottom Carbon on 10% Distillation Residue	0.35 max.	Not Specified	percent mass	D524
Carbon Residue 100% Sample	Not Specified	0.05 max.	percent mass	D4530
Lubricity, HRFF@60C	520 max.	Not Specified	microns	D6079
Calcium/Magnesium combined	Not Specified	5 max.	ppm (ug/g)	EN14538
Sulfated Ash	Not Specified	0.02 max.	percent volume	D874
Acid Number	Not Specified	0.50 max.	mg KOH/gm	D664
Free Glycerin	Not Specified	0.020 max.	percent mass	D6584
Total Glycerin	Not Specified	0.240 max.	percent mass	D6584
Phosphorus Content	Not Specified	0.001 max.	percent mass	D4951
Sodium/Potassium combined	Not Specified	5 max.	ppm	EN14538
Oxidation Stability	Not Specified	3 min.	hours	EN14112

SOURCE: DOE responses to committee queries on engine systems and fuels, delivered by Ken Howden, DOE, FCVT, via e-mail, July 27, 2007.

explained in this chapter, these engines are modifications of existing production diesel engines with conventional combustion systems using high pressure, common-rail fuel injection systems, advanced turbocharging systems and cooled EGR, along with PM and NO_x aftertreatment systems. The production engines were originally developed for the current ASTM specification for No. 2 diesel fuel and the modified versions of these engines for the 21CTP program were tailored for the same fuel specification.

The second part of Goal 1 deals with 5 percent replacement of petroleum fuels with non-petroleum fuels. DOE explained that their Fuel Technologies R&D program consists of two components: Advanced Petroleum-Based Fuels (APBF) and Non-Petroleum-Based Fuels (NPBF).[12] The specific activity of the NPBF component that applies to this objective is research to resolve barriers pertaining to use of non-petroleum fuels as direct replacements of conventional fuels. Fuels and fuel sources under consideration by DOE include:

- Biodiesel primarily, but also biomass-to-liquids (BTL)
- Oil sands and shale oil

Biodiesel is a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils such as soybeans or animal fats, designated B100 and meeting the requirements of ASTM International Specification D6751. This standard specification for biodiesel was issued in 2002. The specification for biodiesel fuels does not depend on the feedstock and/or processing method. The specification is designed to ensure safe operation in a compression-ignition engine (Hoar, 2007). Biodiesel is not raw vegetable oil; it must be produced by a chemical process that removes glycerin from the oil. Table 3-10 show a comparison of the biodiesel specification, ASTM 6751, with ASTM 975 for conventional No. 2 diesel fuel.

As noted in Table 3-10, many of the physical properties considered in these specifications for biodiesel meet or exceed the stringency of the conventional No. 2 diesel fuel specification. However, several physical properties specified for No. 2 diesel fuel, such as T90, aromaticity and ash, are not specified for biodiesel, thereby making transparent operation in current diesel engines problematic. Experience

[12]Kevin Stork, DOE, FCVT, "Fuel Technologies R&D for Heavy Trucks," Presentation to the committee, February 9, 2007, Washington, D.C.

to date with biodiesel has shown some favorable properties (lubricity, sulfur content and lower particulate matter emissions) compared with conventional diesel fuel.

To date, EPA has considered biodiesel fuel as "substantially similar" to diesel fuel, which precludes producers from having to go through the laborious EPA fuel waiver request program.

Another potential shortcoming is that the biodiesel specification does not specify composition. Biodiesel fuel composition will depend on the source (rapeseed oil, soy oil, palm oil, coconut oil, waste cooking oil, etc.), and the production technology. Thus, the chemical composition of biodiesel fuels will vary greatly, and their composition will determine their effects on engine operation, deposits, emissions, etc., when blended into conventional diesel fuel. To eliminate some of these potential problems, refinery-based processes, such as Neste Oil's Next Generation Biomass to Liquids (NExBTL) process (Schill, 2007) have been developed to process the biofuels feedstock in the refinery along with the petroleum. This could help ensure more uniform fuels with consistent properties when biodiesel is a refined component of diesel fuel.

In the United States and around the world, biodiesel production facilities are being built in large numbers. The Renewable Fuels Standard (RFS) of the Energy Policy Act of 2005 has had, and will continue to have a role in the increase in production facilities in the United States. Currently in the United States, there are more biodiesel production facilities than refineries making diesel fuel, and many more are being built and planned. However, their fuel production capacities are very small compared with refineries. In 2005, biodiesel production was less than one percent of refinery production of 2.8 million barrels per day of diesel fuel (EIA). The National Biodiesel Board estimated that 16,000 barrels per day would be produced in 2006 (Moran, 2006), which is significantly less than the several million barrels per day of refinery production of diesel fuel.

Hart's International Fuel Quality Center/Global Biofuel Center recently projected that the world's biofuel capacity could increase threefold from its current capacity of 5 billion gallons per year. Even if U.S. biofuels capacity increased similarly by 2010, it would only reach less than 3 percent of refinery production of diesel fuel, which would be insufficient to replace 5 percent of petroleum-derived diesel fuel. Therefore, it is highly unlikely that the goal of at least 5 percent replacement of petroleum fuels could be achieved by 2010 using biodiesel alone.

An additional and increasing concern with biofuels is the competition between biomass use for food and for fuel. This is already evident in the United States with the increased production of corn for ethanol taking away cropland from other products, such as soybeans, and resulting in increased prices for both soy and corn dependent food products.

The controversy over biofuels and ethanol continues to grow. As reported in the Ethanol and Biodiesel News of Sept. 11, 2007, a report by the Organization for Economic Cooperation and Development (OECD) unequivocally recommended that governments around the globe phase out their biofuels subsidies (Ngo, 2007). It characterized them as simply ushering in inefficient new sources of energy supply. The OECD report said biofuels would cut energy-related emissions by 3 percent at most, and that their cost greatly outweighs their benefits. The report's authors stated, "When acidification, fertilizer use, biodiversity loss and toxicity of agricultural pesticides are taken into account, the overall environmental impacts of ethanol and biodiesel can very easily exceed those of petrol (gasoline) and diesel fuel."

The authors of this report take no stance on the future of biofuels in the United States. However, as pointed out here and elsewhere in this section, there are many issues involving biodiesel that have to be resolved before it can become a viable commercial success. It is incumbent that the DOE stay in the mainstream regarding all of these issues.

DOE, especially at NREL, together with biodiesel suppliers and users are actively exploring the compatibility of biodiesel fuels with current and future engines. Potential biodiesel performance concerns that are being evaluated are:

1. Deposit control, especially in the fuel system and at the injector tips
2. Filter plugging and water separator performance, especially the influence of low temperature properties
3. Oxidation stability
4. NO_x emissions
5. Impact of particulate properties on DPF performance, ash loading in the DPF and EGR cooler fouling
6. Impacts on lubricant performance

DOE did not report on the status or timetable of their efforts to resolve these concerns.

A major exploration of biodiesel fuel issues is currently being conducted by the Japanese Clean Air Program (JCAP), with which NREL has maintained close contact. DOE should explore more joint activities on biofuels with JCAP.

With modern diesel engines moving toward hot fuel circulation (via common rail systems), potential oxidation stability issues will need to be resolved. It is generally accepted that palm oil derived biodiesel (from Southeast Asia) has better oxidation stability than either rape methyl ester (from Western Europe) or soy methyl ester (from the United States). However, a recent study published by SAE (Goto and Shiotani, 2007) pointed out that oxidation stability worsens as the palm oil-derived methyl ester biodiesel fuel content increases, or the fuel temperature increases, with consequent loss of oxidation stability and fuel system corrosion.

The impact of biodiesel on exhaust NO_x emissions is not clear. EPA's position is that biodiesel increases NO_x emissions; NREL's position is that it has little or no effect. A recent paper (Sobotowski et al., 2007) supports EPA's position. This issue will need to be resolved. The discrepancy may be related to the chemistry of the biodiesel fuels used in the various studies. To resolve the impasse between DOE and EPA, an independent body should look at all of the biodiesel studies to see if the chemistry of the fuel can be related to its impact on NO_x emissions.

Today's diesel fuel can be improved by blending with gas-to-liquid (GTL) components. This approach is used in Europe for premium quality diesel fuel. However, DOE did not comment on any work on diesel fuel blended with GTL components.

Independent of their source and the process for generation, biodiesel fuels should be characterized by their chemical and physical properties. These properties should be used to correlate with the fuel's performance in engines and impacts on emissions.

A biodiesel blend, as distinguished from biodiesel fuel, is a blend of biodiesel fuel meeting ASTM 6751 with petroleum-based diesel fuel designated B*XX*, where *XX* is the volume percent of biodiesel. DOE is focused on ensuring that B20 is compatible with engines with diesel particulate filters/selective catalytic reduction/NO_x absorber catalysts that will enter the market in the 2007-2010 timeframe.[13] However, to date, the diesel engine manufacturers, through the Worldwide Fuel Charter, have recommended a maximum of five percent biodiesel (fatty acid methyl ester) blended in diesel fuel, and that ASTM Standard D6751 be followed. DOE must allay the engine manufacturers' concerns about blends containing more than 5 percent biodiesel fuel before such blends can be accepted.

DOE has stated that they are not aware of operational issues for B20 or lower blends prepared from B100 that meets D6751, with one exception. Some biodiesel blends can cause cold temperature filter plugging even when the cloud point of the blend indicates it should be satisfactory. This may be caused by an impurity that is not currently limited in D6751. NREL and other participants at ASTM are working on this issue and expect to ballot a new requirement for the ASTM specification during 2008. DOE acknowledges that experience is still being gained, especially with 2007 and later on-highway engines. As more information is acquired, a further update to the specification may be required.[14]

DOE did not provide the committee with plans for achieving the goal of replacing 5 percent of petroleum fuel with non-petroleum fuels by 2010. This goal is highly dependent on three factors:

1. Biodiesel availability
2. Compatibility with existing engines
3. Fuel cost

[13]Kevin Stork, DOE, FCVT, "Fuel Technologies R&D for Heavy Truck," Presentation to the committee, Washington, D.C., February 9, 2007.

[14]DOE responses to committee queries on third meeting, delivered by Ken Howden via e-mail July 27, 2007.

Replacement of 5 percent petroleum fuel by 2010 is a very aggressive, if not unrealizable goal, especially considering that the most optimistic increase in biodiesel production capacity could only achieve replacement of 3 percent of petroleum fuels by 2010, as previously discussed. Regarding compatibility of the fuel with existing engines, DOE did not provide the committee with a timetable for the resolution of the issues associated with the use of biodiesel fuels or blends. Achieving this goal is also highly contingent on the acceptance of biodiesel blends by the diesel engine and trucking industries, especially from a cost and operational performance perspective. Current and proposed federal and state legislation contain tax incentives for the biodiesel industry that could assist with the acceptance of biodiesel fuels. Without these incentives it is unlikely that biodiesel will have a major impact.

Biodiesel fuels are in vogue because of their presumed benefits regarding greenhouse gases, especially carbon dioxide (CO_2), reduction. A recent study from Wetlands International (Max, 2007) in the Netherlands has challenged that assumption regarding palm oil. It concluded that the CO_2 reduction benefits of palm oil were overwhelmed by the CO_2 released when swamps in Southeast Asia were drained to provide land for planting the palm trees. Although this will not apply in the United States, it lends a note of caution, and suggests that rigorous "well-to-wheel" analyses, especially in the generation of the crops providing the biodiesel feedstocks, are needed to thoroughly explore the benefits of biofuels. Land use issues must be incorporated into the "well-to-wheel" analyses.

The Low Carbon Fuel Standard (LCFS) concept is likely to be implemented in the United States and Europe.[15] It essentially calls for a 10 percent reduction in carbon intensity of transportation fuels by 2020. Biofuels, including biodiesel, are one of the most likely near term options. DOE, EPA, and industry should work closely together on this standard as it is being implemented.

In addition to biodiesel as a potential replacement for petroleum fuels, DOE is also investigating oil sands and shale oil sources of fuel as part of its Non-Petroleum-Based Fuels (NPBF) efforts. DOE did not provide additional information on work directed toward these fuel sources, and did not provide any indication of the potential extent of the commercial use of these fuels by 2010.

Oil shale for many years has been a prominent potential source of oil. The resource base, primarily in arid Utah and Colorado, is very large. But it has not been commercially tapped to any extent because of environmental concerns related to water availability and surface mining. To lessen the concerns over surface mining, attention is being given to in-situ retorting to generate the shale oil.

In recent years, fuels made from Canadian tar sands have been commercialized and blended into diesel fuel. More than

[15]See http://www.energy.ca.gov/low_carbon_fuel_standard/index.html.

one million barrels per day of fuels from Canadian tar sands are now being used in the United States. That volume was expected to grow; however recent environmental concerns in Alberta may limit the growth.

Finding 3-13. It is unlikely that the goal of identifying and validating non-petroleum fuel formulations, optimized for use in advanced combustion engines, will be achieved by 2010. DOE's nonpetroleum fuels effort is focused on resolving biodiesel operational issues and commercialization barriers, but DOE did not provide a timetable for successful resolution of these efforts. DOE is also investigating oil sands and shale oil as other sources of petroleum fuel replacement. DOE did not present a plan for 5 percent replacement of petroleum fuels. The Renewable Fuels Standard of the Energy Policy Act of 2005 is likely to have a role in accelerating the availability of nonpetroleum fuels.

Recommendation 3-13. DOE should continue to work with biodiesel developers and users to ensure compatibility when biodiesel is blended with conventional diesel fuel and problem-free use of biodiesel fuels in diesel engines. Successful deployment will require resolving operational issues and updating the biofuel specifications. Development of refining technology to make acceptable diesel from shale oil or tar sands is not high-risk research suitable for federal funding and should be left to the private sector. DOE should develop specific plans, including key actions and timetables, for 5 percent replacement of petroleum fuels.

Fuels for Low-Temperature Combustion Regime Engines—Goal 2

The committee interpreted Goal 2 as being directed toward fuel properties of petroleum-based fuels that could have beneficial effects on engine efficiency and emissions, including aftertreatment performance with emphasis on engines with new low temperature combustion regimes. Directly addressing this goal is the other component of DOE's fuel technology R&D program identified as Advanced Petroleum-Based Fuels (APBF).[16]

A key DOE project focused on this goal is the FACE (Fuels for Advanced Combustion Engines) project. This project, which operates under a Coordinating Research Council working group, was formed to better understand the fuel effects on LTC (low temperature combustion) engines. The fuel variables being investigated are cetane number, aromatic content, and T90 point. Fuels with variations in these properties are being distributed to teams researching multiple approaches to advanced combustion engines and aftertreatment systems. DOE stated that the engine hardware in these studies "may remain undisclosed," which severely limits the usefulness of this project. Furthermore, because the committee is concerned about the viability of low temperature combustion (discussed in this chapter), the applicability of the results of this project may be limited.

Furthermore, the implication of the FACE project, which is exploring fuels significantly beyond today's ASTM specification for No. 2 diesel fuel, is of serious concern. DOE did not address the concern that the FACE project may define optimum fuel properties for an engine with a new combustion regime that are not consistent with the properties of conventional diesel fuel defined in the ASTM specification for No. 2 diesel fuel. A potential implication of such a result is that an engine with a new combustion regime may require a separate fuel, which would entail significant problems in the refining, distribution, storage, availability and cost of a special diesel fuel for these engines. Additionally, if the emissions performance of vehicles with engines having a new combustion regime is contingent on use of specialized fuels, it is unlikely that the EPA would grant approval without guarantees of fuel availability.

The history of liquid fuel (both gasoline and diesel fuel) use in the United States shows little or no success for highly specialized fuels with limited sales potential. An example of this is the very limited availability of E85 fuel (85 percent ethanol, 15 percent gasoline) for the millions of recent model year vehicles that can utilize this fuel. Even assuming success of engines with low temperature combustion regimes, there will be very few vehicles in the marketplace with them for many years. Trucking companies are unlikely to buy vehicles with these engines without widespread availability of the specialized, reasonably priced fuel needed for these engines.

Refiners do not like to make small quantities of specialized fuels, especially if it requires capital expenditures. Production, distribution and storage of these fuels will cost more per gallon than for conventional diesel fuels. Refueling stations will not readily either give up an existing tank and pump, or install a new tank and pump, for a specialized fuel with small demand.

While it is important to continue with R&D to understand the optimum fuel properties for current and future engines, it will be more critical to be able to make the future engines operate on the conventional diesel fuel or gasoline that will be readily available for many years. The committee does not believe that specialized fuels will be commercially available for advanced combustion engines, especially with the low volume that will be required for many years for vehicles with these engines. To gain a better appreciation for the issues involved with use of a specialized fuel with advanced combustion engines, DOE should meet with at least several major oil companies to explore the practical realities of providing a special fuel.

With respect to the emission reduction portion of this objective, the difficulty in defining the properties of fuels

[16]Kevin Stork, DOE, FCVT, "Fuel Technologies R&D for Heavy Trucks," Presentation to the committee, Washington, D.C., February 9, 2007, Slide 4.

for engines with new combustion regimes was pointed out in a recent paper published by SAE (Kalghatgi et al., 2007). The authors said that the debate over reducing engine-out emissions from diesel engines is tied to whether or not future engines, especially light-duty diesel engines, will require higher cetane number than currently is sold in the United States. If such engines need to promote premixed combustion, higher cetane number fuels will not help. These engines are expected to require lower cetane number fuel to allow time for thorough premixing of the air and fuel prior to the initiation of combustion.

Finding 3-14. DOE is exploring fuel properties of petroleum-based fuels that could have beneficial effects on engine efficiency and emissions, including aftertreatment. The committee is concerned about the viability of low temperature combustion regimes used in this effort, and that the applicability of the results of this project may be of limited value. The committee is also concerned that DOE's work may define optimum fuel properties for an engine with a new combustion regime that are not consistent with the properties of conventional diesel fuel defined in the ASTM specification for No. 2 diesel fuel. A potential implication of such a result is that a future engine with a new combustion regime may require a separate fuel, which would entail significant problems in the refining, distribution, storage, availability and cost of a special diesel fuel for these engines.

Recommendation 3-14. The committee recommends against assuming that specialized fuels will be commercially available for future engines with new combustion regimes. Due to the issues concerning the viability of low temperature combustion regimes and commercially available specialized fuels, DOE should consider redirecting these efforts toward work with greater probability of contributing to the overall goals of the 21CTP.

Nonpetroleum Fuels for the Post 2010 Timeframe—Goal 3

The committee assumed that Goal 3 was intended to emphasize the development of nonpetroleum fuel formulations beyond biodiesel, previously addressed by Goal 1. The goal also addresses benefits of these fuels in providing additional fuel economy improvements and emission reductions. The discussion below will first address the potential fuel formulations followed by the potential functional benefits in fuel economy and emissions.

DOE's report on their work on this objective to the committee provided little insight into the scope and magnitude of the effort. DOE briefly mentioned that they planned to investigate fuels with properties that capture synthetic fuels. Also briefly mentioned was their effort to resolve barriers pertaining to fuels derived from oil sands and shale oil. DOE has established a synergistic team with the Canadian Center for Upgrading Technology (NCUT) to improve the understanding and development of future fuels. The focus of this effort appears to be on oil sands.

There are many potential sources of non-petroleum derived diesel fuel, including; oil shale, coal, tar sands, natural gas and biomass. Technology exists to make diesel fuel with excellent properties from coal and natural gas. Some gas-to-liquids facilities have been commercialized outside the United States. None has been announced for construction in the United States.

Extreme caution has to be exercised when using diesel fuels made from these sources. For example, engine and fuel system failures have been reported (Peckham, 2007) with light-duty pickup trucks using diesel fuel derived entirely from tar sands. DOE's Pacific Northwest National Lab is investigating this problem. Although it is unlikely that future diesel fuel will be produced entirely from tar sands, this failure indicates that a thorough investigation of this issue is required. James Eberhardt of DOE has cautioned that more attention needs to be paid to the molecular structure of these new fuels, rather than only the ASTM D-975 diesel fuel specifications.

The goal of identifying fuel formulations that will improve fuel economy and reduce emissions is optimistic, perhaps to the point of being unrealistic. The synthetic fuels being mentioned for this goal are all hydrocarbon-based fuels that would be expected to have combustion characteristics similar to conventional diesel fuel. It appears unlikely that the fundamental mechanisms that control the formation of HC, NO_x, and particulate emissions in a diesel engine can be dramatically altered with a change in the fuel formulation to the extent that the emissions could approach zero.

Finding 3-15. DOE provided little insight into the scope and magnitude of the effort to address the goal of developing non-petroleum fuel formulations beyond biodiesel that could provide additional fuel economy improvements and near-zero emissions. DOE did not report any specific work plans, results, or timetables addressing this objective.

Recommendation 3-15. DOE should reaffirm that this goal should continue to be pursued. If the goal is considered to strongly contribute to the overall 21CTP goals, DOE should develop specific work plans and timetables for addressing this goal.

In 2005, Reaction Design of San Diego, Calif., a developer and licensor of commercial simulation software used for modeling the kinetics of fuel combustion, formed the Model Fuel Consortium (MFC).[17] The activities of the MFC are directed toward the creation of new test-fuel formulations as well as the establishment of a database for certified fuel models that will be accessible by the various

[17] Available at http://www.reactiondesign.com/support/open/mfc.html. Accessed May 30, 2007.

members of the consortium. Model fuels are a unique mix of a few pure chemicals that are intended to reproduce the combustion behavior of more complex commercial fuels. The main computer codes used by the MFC are CHEMKIN and KINetics, both of which are commercially supported by Reaction Design.

It should be noted that this type of work has been going on in government and industry laboratories and academic institutions for many years and that it is exceedingly difficult to capture the detailed and complex kinetics of realistic fuels and their performance in actual engine combustion systems. Success is far from guaranteed. Nevertheless, improvements in this capability offer the promise of faster and more cost-effective evaluation of current and future fuel formulations in existing and new engine designs as well as in new combustion concepts.

In addition, the MFC and Reaction Design, with partners from Chevron and the University of Southern California, has been recently awarded a grant from the U.S. Department of Energy's FCVT to study the combustion of various biofuels. The program is aimed at developing efficient, environmentally friendly transport fuels that will lessen the U.S.'s dependence on petroleum. The goals of the program are generally consistent but more aggressive than DOE's 21CTP goal to optimize fuel formulations for current-generation diesel engines that incorporate some non-petroleum-based biofuel-blending components. A 5 percent replacement of petroleum fuels is an initial target with an additional 5 percent set for 2010 diesel engines. However, based on the impacts on refinery operations and fuel blending facilities, it is unlikely that this program will be able to influence the introduction of commercial fuels in time to impact 2010 diesel engines.

AFTERTREATMENT SYSTEMS

Introduction

The three goals discussed above in this chapter address exhaust emissions and aftertreatment, in terms such as "2010 emission compliant," "emission-compliant, engine system thermal efficiency of 55 percent by 2013," "reduce overall tailpipe emissions," "lower engine-out emissions," enhancement of aftertreatment performance for 2010 emission regulations," and "lowering emission levels to near zero." The following material discusses aftertreatment in the context of these statements.

Discussion

The 21CTP program on aftertreatment systems is vague and does not define the priority for exhaust aftertreatment. For instance, the Ed Wall presentation does not mention exhaust emissions as part of the top R&D objectives.[18] Ken Howden, program director of the 21CTP, mentioned the phrases, "emit little or no pollution," and "develop and demonstrate an emissions-compliant engine system"[19] and stated that among the program's significant accomplishments, "collaboration has enabled production diesel engines to meet stringent 2007 emissions while maintaining high efficiency."[20]

Jim Eberhardt, Chief Scientist of the FCVT, said "DOE with industry is developing more sulfur tolerant catalysts under Combustion and Emission Control and Advanced Petroleum-Based Fuels-Diesel Emission Control (APBF-DEC) activities."[21]

Gurpreet Singh listed, under barriers, "emissions: inadequate simulation capabilities, lack of readily implemented sensing, robust process control system" and "Fuels: need understanding of fuel property effects on NO_x and particulate emission characteristics and implications on DPF operation." Thus, the 21CTP and DOE's role in the exhaust aftertreatment arena is not very well defined, and measurement against specific objectives is not possible. In spite of these statements, some significant contributions have been made, as outlined by Singh.[22]

Ron Graves's presentation thoroughly reviewed the status of several emissions treatment projects. The "Overview of Goals and Status of Major Engine Technology Projects with Industry" outlines several emissions and aftertreatment accomplishments and future goals.[23]

Duggal stated that the heavy-duty engine technology roadmap included potential improvements of "elimination of NO_x aftertreatment."[24] and Kevin Stork stated that "balance point temperature (for DPF regeneration) decreased with B20- and B100-significant differences in regeneration rate, with blend levels as low as 5 percent (biodiesel)."[25]

The most significant review of aftertreatment programs was presented by Ron Graves[26] in "Emission Control R&D

[18]Ed Wall, DOE, FCVT, "DOE FreedomCAR and Vehicle Technologies Program," Presentation to the committee, Washington. D.C., February 8, 2007.

[19]Ken Howden, DOE, FCVT, "Partnership History, Vision, Mission, and Organization," Presentation to the committee, Washington. D.C., February 8, 2007, Slide 2.

[20]Ken Howden, DOE, FCVT, "Partnership History, Vision, Mission, and Organization," Presentation to the committee, Washington. D.C., February 8, 2007, Slide 14.

[21]James Eberhardt, DOE, FCVT, "Review of Findings from Previous Heavy Vehicle Review," Presentation to the committee, Washington, D.C., February 8, 2007.

[22]Gurpreet Singh, DOE FreedomCAR and Vehicle Technologies Program, "Overview of DOE/FCVT Heavy-Duty Engine R&D," Presentation to the committee, Washington, D.C., February 8, 2007.

[23]Ron Graves, DOE, ORNL (Oak Ridge National Laboratory), "Emission Control R&D for Heavy Truck Engines," Presentation to the committee, Washington, D.C., February 8, 2007.

[24]Vinod K. Duggal, Cummins, Inc., "Diesel Engine R & D and Integration," Presentation to the committee, Washington, D.C., February 9, 2007.

[25]Kevin Stork, DOE, FCVT, "Fuel Technologies R&D for Heavy Trucks," Presentation to the committee, Washington, D.C., February 9, 2007.

[26]Ron Graves, DOE, ORNL, "Emission Control R&D for Heavy Truck Engines," Presentation to the committee, Washington, D.C., February 8,

TABLE 3-11 Sectoral Breakdown of CRADA Partners in Emission Control Research

Sector	Share of Total Held by That Sector (percent)
Engine/Auto	28
Catalyst Suppliers	18
Labs and Government	21
Software/Consulting	18
Universities	15

SOURCE: Ron Graves, DOE, Oak Ridge National Laboratory, "Emission Control R&D for Heavy Truck Engines," Presentation to the committee, Washington, D.C., February 9, 2007, Slide 7.

for Heavy Truck Engines," which included the following statements:

1) Expected lower limits of engine-out emissions dictate aftertreatment requirements for NO_x.
2) Progress in NO_x control via in-cylinder processes has delayed need for exhaust aftertreatment until after 2007.

He also detailed the activities of CLEERS, DCT (Diesel Crosscut Team), and DOE labs use of CRADAs. Much has been accomplished through these cooperative groups, perhaps in part, because they are made up of the components shown in Table 3-11.

Finding 3-16. No specific goals have been outlined for 21CTP diesel engine aftertreatment systems but some goals have been set for eliminating aftertreatment. However, as discussed in this chapter, the goal of eliminating aftertreatment does not appear to be achievable in the foreseeable future.

Recommendation 3-16. Specific goals should be set for aftertreatment systems (improved efficiency, lower fuel consumption, lower cost of substrates, lower cost catalyst, etc.).

Finding 3-17. The CLEERS, DCT, and CRADAs have contributed to many successful projects and programs.

Recommendation 3-17. The 21 CTP should continue with the CLEERS, DCT and CRADA activities for aftertreatment systems.

HIGH TEMPERATURE MATERIALS LABORATORY

Introduction

The High Temperature Materials Laboratory was established 20 years ago as a National User Facility to provide specialized, in some cases one-of-a-kind (for example, aberration-corrected electron microscope with sub-Angstrom resolution) instruments for materials research and characterization. Its facilities have been utilized by participants of the 21CTP. Examples are given below.

The replacement value of the instruments in the facility is approximately $47 million. It is located at the Oak Ridge National Laboratory occupying a space of 37,511 square feet, which houses six centers:[27]

- Materials Analysis Center
- Mechanical Characterization and Analysis Center
- Residual Stress Center
- Thermography and Thermophysical Properties Center
- Friction, Wear, and Tribology Center
- Diffraction Center

The Laboratory makes available to researchers from universities, U.S. industries, and governmental agencies a skilled staff providing support in the use of the specialized equipment in the six centers. On average, 90 user projects are supported each year with projects lasting from a few days to as long as a few weeks. Access is available to qualified users through either proprietary or non-proprietary agreements. In the case of non-proprietary work, the results must be published in the open literature; in that case there is no cost to the user. Users who conduct proprietary work there are charged for total recovery of costs associated with time and resources. At one time, funding for work at the facility was included in the budgets of various DOE programs, such as the 21CTP. However, since FY 2003 it has been treated as a separate line item in the DOE budget. Funding for the User Program is allocated on an annual basis and is not prorated for each user project. The budget for FY 2007 is $4.1 million.[28]

21st Century Truck Projects[29] That Rely on the High Temperature Materials Laboratory

Active 2007 Projects

1. Austenitic Stainless Steel Alloys for Exhaust Manifolds and Turbochargers.
   The objective is to develop new materials to permit an increase in engine-out temperatures to improve engine efficiency. This is a CRADA between ORNL and Caterpillar. The DOE budget for 2007 is $185,000 with a cost share of $185,000 from Caterpillar.

2007, Slide 1.

[27]Edgar Lara-Curzio, "The High Temperature Materials Laboratory," Presentation to the committee, Washington, D.C., May 31, 2007.

[28]Personal communication, Edgar Lara-Curzio, Re: 21st Century Truck Partnership Project Quad Sheets, to the committee, Washington, D.C., May 21, 2007.

[29]As listed in DOE, 2007.

2. Catalyst Characterization.

   The objective is to develop catalyst devices that will meet diesel emissions regulations with minimal impact on fuel economy. The DOE budget for 2007 for this area is $230,000.
3. Catalyst via First Principles.

   The object is to use theoretical models to help develop optimum catalyst systems. The DOE budget for 2007 is $195,000.
4. Characterization of Catalyst Microstructures and Deactivation Mechanisms.

   The objective is to develop a better understanding of mechanisms that control aging and poisoning behavior of exhaust emission reduction catalyst materials. The DOE budget for 2007 is $200,000.
5. Friction and Wear Reduction in Diesel Engine Valve Trains.

   The objective is to develop a high-temperature, repetitive impact test system and associated test methods, and apply them to the investigation of candidate materials and surface treatments for diesel engine valve train components. The DOE budget for 2007 is $130,000. This project is planned to continue through 2009.
6. Life Prediction of Diesel Engine Components.

   The objective is to develop methods to assess and improve the durability (life) of advanced ceramic and titanium/aluminum diesel engine components (valves). Such advanced materials provide better engine efficiency through improved thermal management and reduced mass. The DOE budget for 2007 is $95,000.
7. Lightweight Valve Train Materials (Titanium).

   The objective is to develop and validate by in-engine tests, the performance of advanced ceramic and titanium valves. This project is in cooperation with Caterpillar. The DOE budget for 2007 is $175,000.
8. Mechanical Reliability of Piezo-Stack Actuators.

   The objective of the project is to evaluate piezoceramic materials and stack actuator designs for diesel fuel injectors and develop methods for improving system performance. The project is planned to continue through 2008. The DOE budget for 2007 is $305,000.
9. Micro-structural Changes in NO_x Trap Materials.

   The objective is to develop an understanding of the changes that occur in NO_x trap materials during various modes of operation. There is no continuing DOE budget in 2007.
10. Nano-crystalline Materials by Machining.

    The objective is to develop high performance metal matrix composites to reduce rotating mass in diesel engine components. The DOE budget for 2007 is $50,000.
11. Integrated Approach for Development of Energy-Efficient Steel Components for Heavy Vehicle and Transportation Applications.

    The objective is to develop tools to simulate the formation and influence of non-homogeneous microstructures in steel processing for truck applications. Validation of the tools using production components is being carried out at Caterpillar. There is no DOE budget for 2007.
12. Thermomechanical Processing of Titanium and Titanium/Aluminum Sheet and Plate.

    The objective is to develop new low cost titanium powder processing methods for application to large truck components (e.g., leaf springs) for weight reduction. There is no DOE budget for 2007.

Completed Projects

NO_x Sensor Development
Advanced Machining and Sensor Concepts
Deformation in Ceramics
Durability of Diesel Engine Materials
Durability of Particulate Filters
High Density Infrared Technology for Surface Treatments
High Toughness Materials
Low Cost Manufacturing of Precision Diesel Engine Components
Mechanical Behavior of Ceramic Materials
Titanium Turbocharger Development
Walker Process for Stress Relief
Advance Materials for Friction Brakes
Attachment Techniques for Heavy Truck Composite Chassis Members
Basic Studies of Ultrasonic Welding for Advanced Transportation Systems
Counter Gravity and Pressure-Assisted Lost Foam Magnesium Casting
Effects of Ice Clearing Treatments on Corrosion of Heavy Vehicle Materials and Components
Friction Stir Welding and Processing of Advanced Materials
High Conductivity Carbon Foam for Thermal Control in Heavy Vehicles
Improved Friction Tests for Engine Materials
Research on Next Generation Truck Brake Materials
Brake Lining Coding and Marking
Finite Element Truck Crash Modeling
Integrated Braking Systems Analysis–Laboratory Efforts

Finding 3-18. The High Temperature Materials Laboratory is a valuable resource, providing specialized instrumentation and professional expertise in support of materials research. 21CTP projects have utilized the laboratory extensively; it has provided support to 35 different 21CTP projects since 2001. Whereas few advanced materials were actually utilized in the 21CTP project to demonstrate the major 50 percent thermal efficiency goal, it is expected to contribute to the 21CTP in valuable ways in the future.

Recommendation 3-18. The DOE should continue to provide 21CTP projects access to the HTML. Although HTML's budget is not explicitly linked to the 21CTP, DOE should make every effort to maintain a stable budget for the HTML, in order to keep it at the "state of the art" level, and able to respond to the needs of the broader research community.

HEALTH CONCERNS RELATED TO EMISSIONS FROM HEAVY-DUTY VEHICLES

Introduction

The FreedomCAR and Vehicle Technologies (FCVT) program of the Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, conducts research to illuminate the health effects of emissions from heavy-duty vehicles. Its goals are twofold: (1) to provide a sound scientific basis underlying any unanticipated potential health hazards associated with the use of new powertrain technologies, fuels, and lubricants in transportation vehicles; and (2) to ensure that vehicle technologies being developed by FCVT for commercialization by industry will not have adverse impacts on human health through exposure to toxic particles, gases, and other compounds generated by these new technologies. In all, 105 papers from the FCVT Health Impacts Activity have been published in peer-reviewed literature since 1999 (Eberhardt, 2007).[30]

Discussion

The database upon which the health impact of diesel particulate is evaluated is generally recognized to be in need of updating. The pollutants of major concern are nitrogen oxides (NO_x) and particulate matter (PM)—both PM_{10} (particles smaller than 10 millionths of a meter [micrometer] in diameter) and especially $PM_{2.5}$ (those smaller than 2.5 micrometers). Both of these classes of pollutants will be reduced with new engine and aftertreatment technologies used with cleaner, low-sulfur diesel fuel. In terms of health impacts, there is the need for data about the health impacts associated with the mass and the precise chemical components of particles for engine systems designed to meet the 2007 and 2010 standards.

A major new study is underway to address the data gaps identified above. The Advanced Collaborative Emissions Study (ACES) is a multiyear, multisponsor program designed to investigate potential health effects of emissions from heavy-duty vehicles meeting the 2007 and 2010 US EPA emissions standards. DOE is a major funder of this program.[31]

ACES recognizes that any study must address emissions from the combined technologies of new heavy-duty diesel engines, aftertreatment, lubricants and fuels designed to meet the new standards. It is an animal study using rats and not focusing on the direct effects in humans.

The committee endorses the DOE funding of this study and recommends that this continues for the remainder of the study until results become available in the 2012-2013 period.

ACES is a cooperative, multi-party effort to characterize the emissions and assess the safety and potential health effects of these new, advanced engine systems and fuels. The ACES program is being carried out by the Health Effects Institute (HEI) and the Coordinating Research Council (CRC). Key stakeholders and funders of the effort include representatives of engine manufacturers, the petroleum industry, emission control manufacturers, EPA, DOE, CARB, and the Natural Resources Defense Council. ACES will utilize established emissions characterization and toxicological methods to assess the overall safety and potential health effects of production-intent engine and control technology combinations that will be introduced into the market during the time period.

The characterization of emissions from representative advanced diesel engine systems will include comprehensive analyses of the gaseous and particulate material, especially those species that have been identified as having potential health significance. This study will include a chronic bioassay of cancer end points similar to the standard National Toxicology Program (NTP) bioassay utilizing one rodent species (rats) and assessing cancer and noncancer end points (including respiratory, immunologic, and other effects for which there are accepted toxicological tests). These end points will also be measured in a short-term exposure study after completion of the bioassay using the then aged engine. It is anticipated that these studies will assess the potential health effects of these advanced diesel engines systems, will identify and assess any unforeseen changes in the emissions and effects as a result of the technology changes, and will contribute to the development of a data base to inform future assessments of the potential health risks relating to these advanced engine and control systems.

Major Project Elements and Timing

ACES is taking place in three phases:

- In Phase 1, extensive emissions characterization (by the Southwest Research Institute) of four production-intent heavy heavy-duty diesel (HHDD) engines and

[30]James Eberhardt, Chief Scientist, DOE, FCVT, "Overview of the Health Impacts of the Office of FreedomCAR and Vehicle Technologies Program," Presentation to the committee, Washington, D.C., February 8, 2007.

[31]Brent Bailey, "Diesel Emissions Research at CRC" (the ACES Diesel Project), Presentation to the committee, Washington, D.C., May 31, 2007.

control systems designed meet 2007 standards for PM and NO_x are being conducted and will be the basis for selecting one heavy-duty diesel engine/aftertreatment system for health-related studies (Phase 3). No results were available at the time of this report.

- In Phase 2, extensive emissions characterization of a group of production-intent engine and control systems meeting the 2010 standards (including more advanced NO_x controls) will be conducted.
- In Phase 3, the selected 2007-compliant engine system would be installed in a specially-designed emissions generation and animal exposure facility (Phase 3A) and will be used in chronic inhalation study with health measurements at several time periods to form the basis of the ACES safety assessment (Phases 3B and 3C). This is will include a core 24-month chronic bioassay of cancer and noncancer end points in rats similar to the standard NTP bioassay. In addition to assessing potential carcinogenicity of whole diesel exhaust, this chronic bioassay would provide information on chronic toxicity through histopathological analyses of multiple organs at interim sacrifices and at the end of the study, on mutagenicity, inflammation, and other noncancer health end points that have been associated with exposure to diesel exhaust (Phase 3B). In addition, a short-term study (3 months exposure duration), measuring the same noncancer end points as in the chronic bioassay will be conducted in a different set of animals after completion of the chronic bioassay to determine whether the exhaust of the 2007 engine (Phase 3C) will produce emissions that are of concern from the human health standpoint. Due to program slippage, animal studies are now expected to start in the Fall of 2008 and may slip further.

Subsequently, subject to full evaluation of the 2007 engine tests, one (or possibly two) selected 2010-compliant engine system could be installed and characterized (Phase 3D) and evaluated in short-term health effects studies (Phase 3E) measuring the same end points measured after comparable exposure duration in the chronic bioassay and the subsequent short-term study with the 2007-compliant engine, as well as other established end points that require specific animal models or interventions. The schedule and organization of the study are shown on Figures 3-7 and 3-8, respectively. With respect to the ACES program, the committee supports

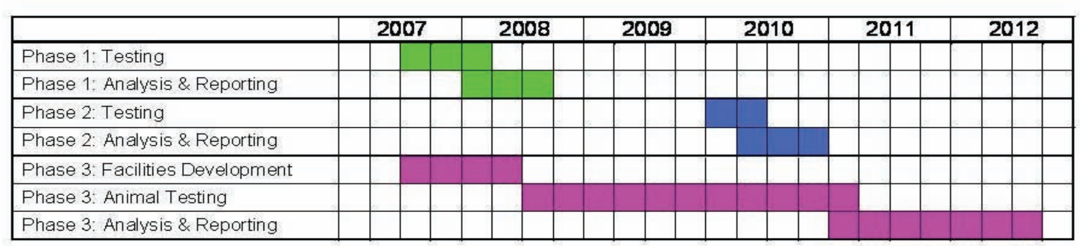

FIGURE 3-7 Overall schedule, CRC ACES study. SOURCE: Brent Bailey, Health Effects Institute, "Diesel Emissions Research at CRC" (the ACES Diesel Project), Presentation to the committee, Washington, D.C., May 31, 2007, slide 21.

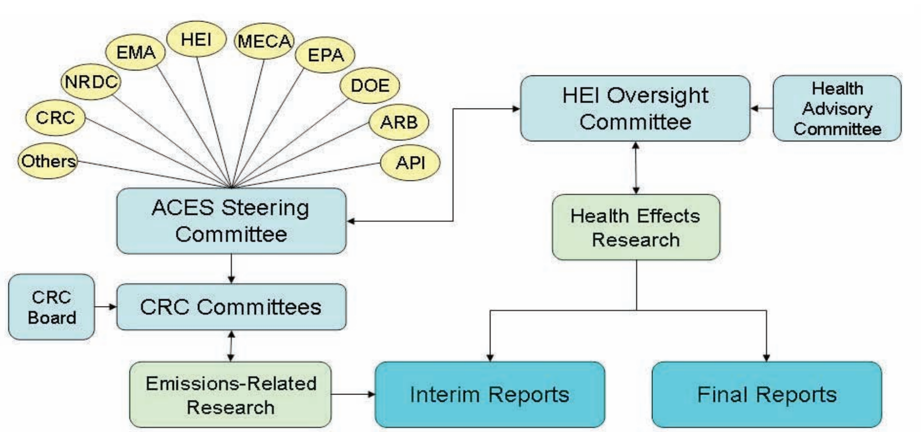

FIGURE 3-8 Project organization, CRC ACES study. SOURCE: Brent Bailey, Health Effects Institute, "Diesel Emissions Research at CRC" (the ACES Diesel Project), Presentation to the committee, Washington, D.C., May 31, 2007, slide 21.

continuation of this study, because of the vital information it provides.

Finding 3-19. ACES is a cooperative, multi-party effort to characterize the emissions and assess the safety and potential health effects of new, advanced engine systems, aftertreatment, fuels and lubricants. It is an animal study using rats and not focusing on the direct effects on humans. DOE is providing the major funding for this program.

Recommendation 3-19. The committee endorses the DOE funding of this study and recommends that this continue for the remainder of the study until results become available in the 2012-2013 time period.

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4

Heavy-Duty Hybrid Vehicles

INTRODUCTION

The objectives for introducing hybrid architectures into the powertrains of heavy-duty trucks and buses are much the same as those for introducing them into passenger vehicles and light-duty trucks. More specifically, the introduction of either electric or hydraulic propulsion equipment makes it possible to operate the diesel engine at or near its conditions for maximum efficiency and/or lowest emissions to spend more of its operating time while under conditions of reduced fuel consumption and emissions. In addition, the electric/hydraulic equipment is used for acceleration and the recovery of braking energy, making it possible to reduce the required engine rating and, in some cases, to turn the engine off during idling conditions. In addition to the opportunities for improved fuel economy, heavy-duty hybrid trucks also are capable of delivering significant reductions in emissions (Barker and Hitchcock, 2003).

The architectures developed for hybrid heavy-duty vehicles (HHV) have much in common with the configurations adopted for passenger vehicles and light-duty trucks. For hybrid-electric powertrains, both parallel and series hybrid configurations have been developed for different applications. In parallel hybrid systems, the electric or hydraulic motor is coupled to the same driveshaft as the engine so that the motor can add torque when needed to assist with acceleration. The motors can also act as generators or as hydraulic pumps in the case of hydraulic systems to provide regenerative braking force that recovers energy to help recharge the system batteries or as accumulators respectively. In series hybrid architectures, all of the mechanical power from the engine is converted to electricity or pressurized hydraulic fluid which is then delivered to one or more electric or hydraulic motors that drive the wheels.

During the past several years up to and including FY2007, funding has been dedicated to the development of hybrid truck components and systems as part of the 21CTP initiative. This investment has resulted in the completion of several prototype heavy-duty hybrid vehicles in a variety of classes for a range of applications. Tests to date with these vehicles have confirmed that these trucks are capable of delivering significant improvements in fuel economy falling predominantly in the range of 40 to 60 percent depending on the truck class and the specific technologies that have been applied (Table 4-1). The reports straddle the 21CTP target of 60 percent fuel economy improvement that will be discussed in more detail later in this chapter. However, larger increases in fuel economy exceeding 100 percent have already been demonstrated in some special applications such as the Class 6/7 hybrid utility trucks that are particularly good candidates for this technology[1] (van Amburg, 2006).

Funding agencies for hybrid truck projects under the 21CTP umbrella have included DOE, DOD, and EPA.[2] The DOE-funded projects have focused on trucks with hybrid-electric powertrains, while the EPA-funded effort has been devoted to hybrid-hydraulic configurations as shown in Table 4-1. The DOD-funded projects are distinguished from the DOE and EPA projects by the special requirements associated with military vehicles, often including significant amounts of auxiliary electric power.

In the face of changing priorities in the larger FCVT program, DOE has diverted nearly all of its hybrid-electric technology investments to light-duty vehicles since FY2006. As a result, the requested R&D budget for heavy-duty hybrid development in the DOE budget for 21CTP activities was reduced to zero in both FY2007 and FY2008.[3] The only remaining research projects on heavy hybrid propulsion systems are two congressionally directed activities (DOE, 2006b). The committee was advised that this termination

[1]Kevin Beaty, Eaton Corp., and V.K. Sharma, International Truck, "Hybrid Technology Program Review," Presentation to the committee, Washington, D.C., February 8-9, 2007.

[2]Ken Howden, DOE, FCVT, "21st Century Truck Partnership," Presentation to the committee, March 28, 2007, Washington, D.C.

[3]Ken Howden, DOE, FCVT, "21st Century Truck Partnership," Presentation to the committee, March 28, 2007, Washington, D.C.

TABLE 4-1 Reported HHV Fuel Economy Improvements

Developer and Vehicle	Fuel Economy Improvement (percent)
Eaton Electric Hybrid	
UPS P100 Delivery Van[a]	36 (in field)
Adv. Technology HEV[b]	47 (on dynamometer)
HTUF Utility Truck[c]	67-150 (in field)
Oshkosh Electric Hybrid	
AHHPS Refuse Truck[d]	36 (in field)
EPA Hydraulic Hybrid	
Urban Delivery Van[e]	39-74 (in field)

[a]Data from Kevin Beaty, Eaton Corp., and V.K. Sharma, International Truck, "Hybrid Technology Program Review," Presentation to the committee, Washington, D.C., February 8, 2007, Slide 5.

[b]Data from Beaty and Sharma presentation, Slide 20.

[c]Data from Beaty and Sharma presentation, Slide 8.

[d]Data from Nadr Naser, "Oshkosh Truck Corporation–AHHPS," Presentation to the committee, Washington, D.C., February 8, 2007, Slide 16.

[e]Data from Charles Gray, Jr., "EPA's Transportation R&D," Presentation to the committee, Washington, D.C., March 28, 2007, Slide 24.

of funding was necessitated by the sharp reduction in the total 21CTP initiative funding that was enforced beginning in FY2007, requiring deep cuts in even successful project areas. In contrast, funding has continued for hybrid truck projects supported by DOD and EPA, although this hybrid work apparently falls outside of the 21CTP initiative.[4]

The 21CTP Roadmap (DOE, 2006a) identifies the major challenges for hybrid truck commercialization to be:

- System reliability
- System cost
- System integration into the vehicle.

Based upon these commercial issues, it identifies the top priority areas for HHV funding to achieve the 21CTP goals as:

- Drive unit reliability
- Drive unit cost
- Energy storage system reliability
- Energy storage system cost
- Demonstrated ability to meet heavy-duty 2007 emission standards
- Demonstrate 60 percent improvement in fuel economy, compared to current production heavy duty vehicles.

The 2012 goals stated in the 21CTP 2006 Roadmap for heavy-duty hybrid vehicles are as follows:

- Develop a new generation of drive unit systems that have higher specific power, lower cost and durability matching the service life of the vehicle. Develop a drive unit that has 15 years of design life and costs no more than $50/kW by 2012.
- Develop an energy storage system with 15 years of design life that prioritizes high power rather than high energy, and costs no more than $25/kW peak electric power rating by 2012.
- Develop and demonstrate a heavy hybrid propulsion technology that achieves a 60 percent improvement in fuel economy, on a representative urban driving cycle, while meeting regulated emissions levels for 2007 and thereafter.

However, summary presentations by government staff have shown significant changes in program goals over time. Skalny presented information which showed that the original fuel economy improvement targets when 21CTP was established, following the earlier Review of the DOE Office of Heavy Vehicle Technologies (National Research Council, 2000) were between 100 and 200 percent improvements for heavy-duty hybrid vehicle demonstrations, depending upon the application.[5] Rogers reported a goal of "up to a 100 percent improvement" in fuel economy without reference to a driving cycle.[6] The current official 21CTP goal of demonstrating 60 percent improvement in fuel economy on a representative urban driving cycle neither defines the cycle nor does it identify the vehicle class or intended use. This gradual reduction in the fuel economy improvement target during the past seven years has the effect of aligning the goal more closely with what available electric or hydraulic hybrid technology can achieve in Class 5/6 urban delivery vehicles, as summarized in Table 4-1.

Some insight into the background of these changing program objectives was provided by the 21CTP management in response to a question posed by the committee. The committee was informed that "the change in goals is mainly attributable to a change in focus at the government level soon after the development of the 2000 roadmap, in which government agencies (DOE in particular) were encouraged by the Administration to focus more on component technologies and less on vehicle/system technologies."[7]

The timetable for hybrid truck development is very brief (truncated beyond 2007) as a result of the decision to terminate further research in the heavy hybrid propulsion area.

[4]Charles Gray, Jr., "EPA's Transportation R&D," Presentation to the committee, March 28, 2007, Washington, D.C.; Paul Skalny, "Briefing to the National Academies' Committee to Review the 21CTP," Presentation to the committee, March 28, 2007, Washington, D.C.

[5]Paul Skalny, DOD (U.S. Department of Defense), U.S. Army Tank Automotive Research and Development Command, "Briefing to the National Academies' Committee to Review the 21CTP," Presentation to the committee, March 28, 2007, Washington, D.C.

[6]Susan Rogers, DOE, FCVT, "Heavy Hybrid Propulsion Overview," Presentation to the committee, February 21, 2007, Washington, D.C.

[7]DOE, FCVT, Response to committee query on "Partnership History, Vision, Mission, and Organization" section of "Responses to NAS Queries on 21CTP Management and Process Issues," transmitted via e-mail by Ken Howden, March 27, 2007.

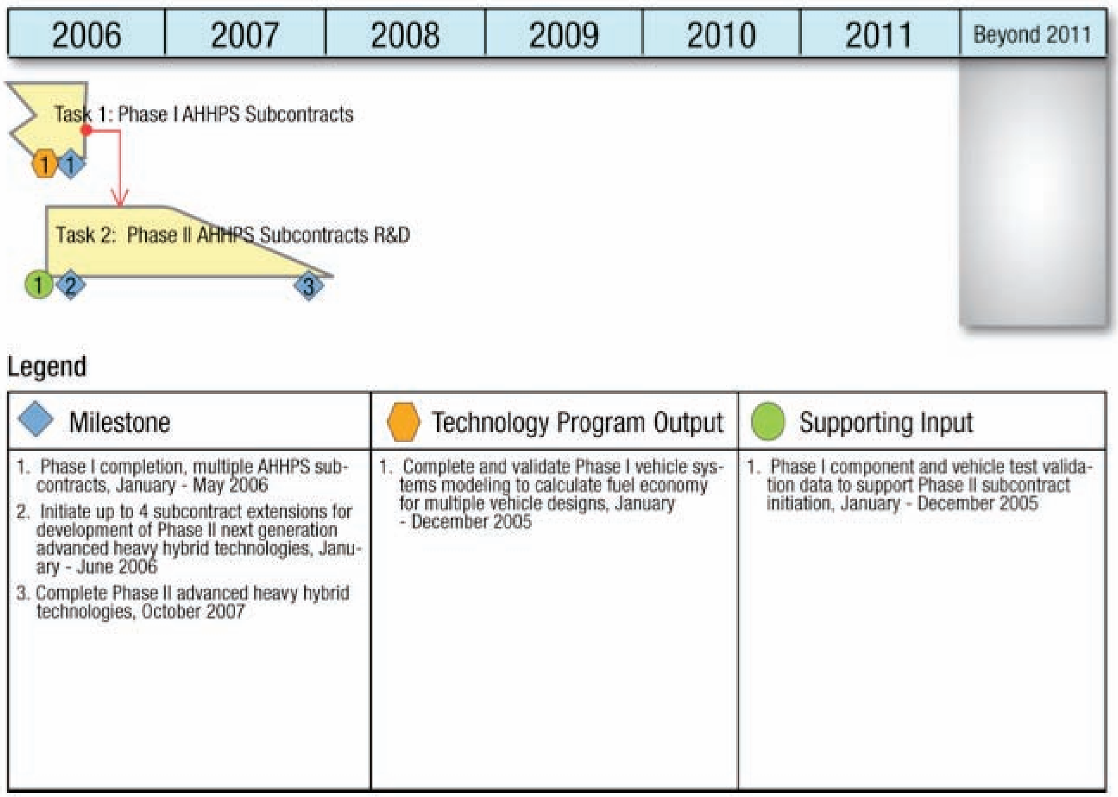

FIGURE 4-1 Network chart for heavy hybrid propulsion. SOURCE: DOE, 2006b, Figure 3.1-4.

The Heavy Hybrid Propulsion Network Chart (Figure 4-1) for the heavy-duty hybrid truck program provided in the FreedomCAR and Vehicle Technology (FCVT) Multi-Year Program Plan (MYPP) document (DOE, 2006b, Fig. 3.1-4) shows that heavy-duty hybrid R&D efforts supported by DOE are being brought to a close in early 2008.

GOAL 1: DEVELOP A NEW GENERATION OF DRIVE UNIT SYSTEMS

This goal's full title is "Develop a new generation of drive unit systems that have higher specific power, lower cost, and durability matching the service life of the vehicle. Develop a drive unit that has 15 years design life and costs no more than $50 kW by 2012." Goal 1 and Goal 3 (60 percent improvement in fuel consumption) are identified by 21CTP as separate goals, but they are closely interrelated. That is, the achievement of a commercially-viable hybrid truck for any application depends on achieving significant improvements in both fuel economy and emissions at a cost that is low enough to justify the associated cost premium. In addition, the equipment must be sufficiently rugged and durable to perform reliably during the full design life of the truck in adverse environmental conditions.

Demonstrating the cost-effectiveness of a heavy-hybrid vehicle within a specific period (typically, the objective is a payback period less than two years) is a major factor in determining the commercial success of heavy-duty hybrid trucks. Key obstacles to achieving cost effectiveness include (1) high costs of the non-optimized, hybrid components used in the demonstration vehicles to date; (2) the large variety of potential low-volume applications (buses, garbage trucks, delivery trucks, etc.) that result in high initial development and investment costs; and (3) the lack of a recognized procedure/standard for demonstrating the fuel savings, which are highly dependent on the vehicle duty cycle.[8]

Meeting the aggressive cost target of $50/kW is proving to be one of the most difficult challenges for the developers of heavy hybrid propulsion systems. On the positive side, information presented to the committee indicates that 21CTP funding has helped manufacturers to reduce the produc-

[8]Arthur McGrew, GM Allison Transmission, "AH2PS: Motor and Power Electronics Development," Presentation to the committee, February 8-9, 2007, Washington, D.C.; Kevin Beaty, Eaton Corp., and V. K. Sharma, International Truck, "Hybrid Technology Program Review," Presentation to the committee, February 8, 2007, Washington, D.C., Slide 20; Nadr Naser, "Oshkosh Truck Corporation—AHHPS," Presentation to the committee, February 21, 2007, Washington, D.C.

tion cost of the hybrid propulsion equipment. For example, a representative of Allison Transmission reported to the committee that the company's DOE-supported project had yielded component improvements that could achieve a 40 percent decrease in electric machine costs and a 50 percent reduction of power electronics costs, yielding an aggregate cost reduction of 14 percent for the hybrid-electric drivetrain system. Furthermore, it is likely that increases in the annual production of hybridized versions of passenger vehicles and light-duty trucks will help to bring the cost of hybrid-electric drivetrain equipment down the learning curve in ways that will directly benefit heavy-duty truck hybrid powertrain equipment as well.

Despite this progress, the 21CTP management reported to the committee that, as of 2006, industrial partners working on electric-based hybrid propulsion systems "had achieved costs of between $600 and $1,000 per kilowatt with the energy storage system as the major cost item."[9] This same document reports that ". . . industry may be able to achieve a target of $300 per kilowatt by 2012" and that the threshold for achieving high-volume sales is expected to be "in the range of $100 to $200 per kilowatt." If this threshold is correct, it suggests that the official 21CTP goal of reaching $50/kW may be more ambitious than necessary to achieve commercial success. Regardless of the ultimate cost objective, it is clear that significantly more progress is required in the area of cost reduction in order to achieve dollar-per-kilowatt values that would make hybrid powertrains attractive to buyers of heavy-duty trucks in the absence of direct subsidies or appropriately targeted tax credits.[10]

One notable exception to the cautious pronouncements about the cost of heavy-duty hybrid truck technology was the more optimistic outlook articulated by representatives of Eaton Corp. and International Truck and Engine indicating that series hydraulic hybrids can be sufficiently low in cost to achieve a payback period of two to three years.[11] EPA has indicated that the cost premium for installing a hydraulic-hybrid drivetrain into a Class 6 urban delivery van on a mass production basis could be as low as $600 (Nikkel, 2006). However, this promising news is tempered by the fact that the limited energy storage capacity of hydraulic accumulators constrains the usefulness of hybrid-hydraulic technology in heavy-duty trucks primarily to those with significant start-stop duty cycle requirements, such as refuse trucks.[12]

[9]DOE/FCVT, response to question 1 in "Additional Hybrid System Questions" section of "Responses to NAS Queries on 21CTP," transmitted via e-mail by Ken Howden, August 28, 2007.

[10]DOE, FCVT, Response to committee query on "Partnership History, Vision, Mission, and Organization" section of "Responses to NAS Queries on 21CTP Management and Process Issues," response to committee query, transmitted via e-mail by Ken Howden, March 27, 2007.

[11]Kevin Beaty, Eaton Corp., and V.K. Sharma, International Truck, "Hybrid Technology Program Review," Presentation to the committee, February 8, 2007, Washington, D.C.

[12]Charles Gray, Jr., "EPA's Transportation R&D," Presentation to the committee, March 28, 2007, Washington, D.C.

Looking beyond the cost targets, DOE contractors have reported progress toward achieving substantial increases in the power density of the hybrid-electric drivetrain hardware. For example, Allison Transmission reported that their engineers had succeeded in improving the power of their Dual Power Inverter Module (DPIM) by 200 percent compared to the previous generation of power electronics. A 30 to 40 percent improvement in the motor power density was also reported in the same presentation.

Very little evidence was presented to the committee to substantiate any significant progress made by 21CTP-funded researchers toward achieving the desired reliability target of 15 years design life for the hybrid propulsion powertrain equipment. In fairness, the number of prototype heavy hybrid trucks currently in the field is very low, making it particularly difficult to gather any meaningful reliability data. However, there are promising reports indicating that hybrid powertrain equipment can be designed to operate reliably over long periods of time under adverse environmental conditions. For example, a 2006 NREL-funded study of the maintenance records of hybrid passenger buses used in regular revenue service in New York City indicated that the hybrid buses delivered approximately 5,000 Miles Between Road Call (MBRC), exceeding the New York City Transit minimum requirement of 4,000 MBRC (Barnitt and Chandler, 2006).

GOAL 2: DEVELOP AN ENERGY STORAGE SYSTEM WITH 15 YEARS OF DESIGN LIFE THAT PRIORITIZES HIGH POWER RATHER THAN HIGH ENERGY, AND COSTS NO MORE THAN $25/KW PEAK ELECTRIC POWER RATING, BY 2012

Current State of Electrical Storage Technology for Transportation Use

The ideal electrical energy storage system for heavy-duty hybrid trucks would have the following characteristics:

- High Volumetric Energy Density (energy per unit volume)
- High Gravimetric Energy Density (energy per unit of weight, Specific Energy)
- High Volumetric Power Density (power per unit of volume)
- High Gravimetric Power Density (power per unit of weight, Specific Power)
- Low purchase cost
- Low operating cost
- Low recycling cost
- Long useful life
- Long shelf life
- Minimal maintenance
- High level of safety in collisions and rollover accidents
- High level of safety during charging

- Ease of charging method
- Minimal charging time
- Storable and operable at normal and extreme ambient temperatures
- High number of charge-discharge cycles, regardless of the depth of discharge
- Minimal environmental concerns during manufacturing, useful life, and recycling or disposal

Unfortunately, every commercially viable battery technology being pursued must trade off compromises of these attributes. The optimal electrical energy storage system for a given application will highly depend on the weighted values of these attributes as they relate to the specific application.

Trading Off Attribute Priorities for an Application

Battery-only electric vehicles (EVs), hybrid electric vehicles (HEVs), and plug-in HEVs (PHEVs) have somewhat distinct requirements. An EV developer might place the highest priority on an energy storage system that has the highest energy density or specific energy, to assure maximum range between charges for a given size of system. The instantaneous power available would likely be less important than mileage or range to the EV developer, but the relative priorities would be reversed for the HEV developer. However, systems with higher energy capacity also tend to have higher available power for acceleration but with more mass than is desired for HEV applications.

The EV developer might also interpret system safety and environmental concerns somewhat differently from an HEV developer. Because a battery-only vehicle usually has a much larger battery than an HEV, and because it carries more electrical energy and caustic chemicals on-board, it may carry higher battery-related safety risks than an HEV with a smaller battery. However, the HEV includes an internal combustion engine (ICE) that carries additional safety risks associated with its energy storage system (i.e., gasoline fuel tank) that drivers of conventional ICE-based vehicles have lived with for many years.

An HEV seeks to recover as much of the braking energy as possible to recharge the battery. If the battery system has insufficient ability to be rapidly charged, the friction brakes will be used and significant energy will be lost to heat. Because regenerative braking is a primary method to charge the battery in an HEV, the efficiency is critically important to an HEV's performance characteristics. Because the electric motor is also used significantly to assist the internal combustion engine during acceleration, specific power and power density will become important considerations. PHEVs have battery energy storage characteristics that can have more in common with either typical EV or HEV requirements, dependent on whether the PHEV powertrain design is dominated by the electric motor or by the internal combustion engine.

Comparing Published Energy Storage Data

Metrics for energy storage components vary quite significantly in published data, making accurate comparison of energy storage technologies difficult. For example, capacity specifications, often expressed in ampere-hours (Ah), vary with the interval used to discharge the battery during testing. Testing with longer intervals typically exhibits much higher capacities than with shorter intervals for the same battery. The interval used for a capacity test is usually expressed by the time used during testing to discharge the battery, and is often expressed as a "C-rate." 1C represents discharge of the rated energy capacity in one hour, 2C corresponds to discharge in 0.5 hours, and 0.5C (or C/2) corresponds to discharge in two hours. For example, if a battery is rated with an energy capacity of 5 Ah, the 1C rate would be 5 amps, the C/2 rate would be 2.5 amps, and 2C would be 10 amps.

In addition to the inconsistencies associated with the C-rate, the amp-hour rating does not usually allow easy analysis of the instantaneous power available for acceleration or the ability of the battery to store energy quickly to recover braking losses.

Power density specifications are suitable for comparison of the short-term power delivery capability for an energy storage system, as a function of its mass or volume. In contrast, energy density specifications are suitable for comparison of long-term available stored *energy capacity* of an energy storage system, as a function of its mass or volume. However, even these metrics (when provided) possess variability in how they are derived, particularly the percentage and rate of discharge over the measurement interval. This measurement renders the task of comparing energy storage device technologies difficult at best, based upon the information provided to the committee.

Appendix F of this report reviews the state-of-the-art in batteries for light-duty vehicles.

Battery Technology for Heavy-Duty Applications

Unique challenges exist for the application of energy storage components in heavy-duty hybrid trucks, including batteries, ultra-capacitors, hydraulic accumulators, or flywheels. Light-duty EVs and HEVs focus on energy capacity for long battery range, or rapid power charging and discharging capabilities for acceleration and braking energy recovery, or a combination of both. It is currently impractical for heavy-duty vehicles and trucks to carry sufficiently large battery packs or electric power sources (e.g., fuel cells) to provide the required power levels for an all-electric powertrain (without ICE). Therefore, vehicle manufacturers and researchers are focusing on hybrid powertrains based on diesel-electric architectures that require batteries with high power capability to assist in vehicle acceleration, rapid charging, and efficient recovery of braking energy.

TABLE 4-2 Current Status of FreedomCAR Energy Storage Goals and NRC Evaluation

FreedomCAR Energy Storage Goal (units)	2010 Goal (end of life)	2005 NRC Review	Current Status
Discharge Power (kW)	25 (18 sec)	25	25
Available Energy (Wh)	300	300	300
Calendar Life, years	15	10	10-15
Cost Goal (at 100,000 units/year)	500	1,200	750-900
Regen Pulse, kW	20 (10 sec)	20	20
Cycle Life, cycles	300 k	300 k+	300 k+
Maximum System Weight, kg	40	32	25
Maximum System Volume, liter	32	33	20
Cold Cranking Power, kW at –30°C	5 for 2 sec	3-5	3-5
Operating Temperature Range, °C	–30 to +52	+10 to +40	–10 to +40

SOURCE: National Research Council, 2005.

The charge rate and level of charge acceptance needed to maximize the capture of braking energy in a heavy-duty vehicle is much greater than the comparable requirements for a light-duty vehicle, due to the difference in vehicle mass and inertia. A popular way to reach the higher power capacity required for heavy-duty truck applications is to over-size the battery. For light-duty hybrid vehicles there are storage systems available with sufficiently high charge rates that avoid the need to over-size the battery. Over-sizing the energy storage system to obtain the necessary power capacity is undesirable in several regards including the unnecessary expenses of additional mass, volume, and heightened environmental and safety concerns.

The additional mass in the heavy-duty vehicle makes them less practical as battery-only EVs due to the required battery size for reasonable performance, given the current state of the art, while battery-only power remains more viable for the light-duty vehicle.

21CTP Goals

During meetings with DOE and 21CTP management, the committee was informed that essentially all DOE-sponsored effort associated with batteries and other forms of energy storage is focused on light-duty vehicles under the FreedomCAR and Fuel Partnership.[13]

Based upon materials submitted to the committee (Howell and Habib, March 2007), the FreedomCAR Program charter related to energy storage is to:

- Research and develop electrochemical energy storage technologies which support the commercialization of (light-duty) hybrid and electric vehicles, with the following target applications:
  - — HEVs (power-assist hybrid electric vehicles)
  - — PHEVs (plug-in hybrid electric vehicles)
  - — FCVs (fuel cell hybrid vehicles)
  - — EVs (battery electric vehicles)

The stated 2010 FreedomCAR research goals associated with energy storage (Table 4-2) are intended to enable reliable HEVs that are durable and affordable, with an electric drivetrain energy storage system that exhibits:

- 15 year life
- Capacity of 300 Wh
- Discharge power of 25 kW for 18 seconds
- Cost of $20/kW
- 100 Wh/kg by 2012
- 150 Wh/kg by 2015

The DOE PHEV battery goal is focused on cost reduction with a target of $200 to $300 per kWh by 2014.

TARDEC Program Goals and Activities

TARDEC Program Goals.[14] The energy storage program goals established by the US Army Tank-Automotive Research, Development and Engineering Center (TARDEC) are to:

- Reduce the current $115,000 per 30 kWh pack cost to $58,000
- Accelerate the technology and automate the manufacturing process
- Improve the temperature stability and safety
- Develop enhanced materials
- Produce affordable battery packs for HEV dash mobility, silent watch, and pulse power for weapons

[13]Personal communication, Rogelio Sullivan, Ken Howden, and Ed Wall, DOE, FCVT, during committee meeting, August 28, 2007.

[14]DOD, TARDEC (U.S. Army Tank-Automotive Research, Development, and Engineering Command), “Energy Storage Research Projects, TARDEC Ground Vehicle Power & Mobility,” received by the committee from Ken Howden, DOE, FCVT, August 31, 2007.

- >3 kW/kg by 3/2009
- 150 Whr/kg by 3/2009

TARDEC ManTech Objective (MTO) Program. Within the MTO program, TARDEC is pursuing opportunities to encourage battery technology suppliers, especially Li-ion cell and battery manufactureres, to produce safer, more reliable, lower-cost cells and batteries for heavy-duty HEB applications. Included in these goals is earlier demonstration of higher energy capacity compared to that currently being demonstrated under the FreedomCAR program.

TARDEC desires to achieve the goal of 150 Wh/kg by March 2009, whereas the FreedomCAR goal is to achieve 150 Wh/kg by 2015. TARDEC reports that it has demonstrated more than 100 Wh/kg in FY2008,[15] whereas the FreedomCAR program has targeted the demonstration of 100 Wh/kg by 2012.

FreedomCAR Electrochemical Storage Program

The FreedomCAR program appears to be exploring a greater breadth of technologies than the Army TARDEC program. Because the focus is light-duty vehicles, all of the stated goals seem to be extremely cost-driven, because the energy storage system remains a significant percentage of the cost of an HEV, and an even higher percentage of PHEV and EV cost.

15 Year Life. Battery life is critically important to avoid the replacement of the energy storage system before the end of the useful life of the vehicle which would represent a very significant repair/replacement cost and increase the recycling challenges. The need to replace the energy storage system once in a vehicle's life would more than double its effective cost. Therefore, the goal of achieving battery lifetimes that match or exceed that of the vehicle may be necessary for owner acceptance in large volume production.

Capacity Goals. The FreedomCAR energy capacity goals of 300 Wh and power capability goal of 25 kW for 18 seconds may be appropriate for the anticipated battery-only range of a light-duty HEV, but they may fall short of the needs for heavy-duty HEVs, unless two or more of the target battery packs are used for the application.

Costs. The targeted energy storage system for 2010 has a cost target of $20/kW pack so the battery pack would cost $500, making the cost reasonable for a light-duty HEV. The achievement of this goal opens the door for energy storage packs with peak power ratings higher than 25 kW. However, if the light-duty HEV industry adopts a 25 kW, 300 Wh storage pack as a standard, economy-of-scale would suggest the opportunity to further reduce cost by using multiple 25kW packs for heavier-duty vehicles. However, the shift in focus toward technologies that favor high power over high energy is not currently a high priority in the light-duty segment where cost reduction and reliability are the driving factors at this time. In principle, a shift toward higher power capability would not detract from the normal use of battery pack in full hybrid light-duty applications.

However, for PHEVs, the DOE target of $200-300 per kWh re-emphasizes the need for energy capacity optimization, as expected for PHEVs. The market expectation for battery-only range with a PHEV will be much higher than 2010 expectations for HEVs. Although these cost goals are founded on reasonable market expectations, they may prove to be difficult to achieve by the targeted dates.

Specific Energy. Specific Energy goals of 100 Wh/kg by 2012 and 150 Wh/kg by 2015 seem achievable, considering the rapid pace of development, the high levels of public and commercial business interest, and that TARDEC has already achieved the 2012 goal.

Shift to High Power from High Energy. During the period when California initially imposed its zero emission vehicle standards, battery-only EVs received significant development attention by the auto industry. In those cases, gravimetric energy density was a primary concern because acceptable vehicle range was one of the most important EV attributes being addressed, due to the battery limitations at the time. Advancements in Ni-metal-hydride battery technology in the late 1990s allowed light-duty EVs such at the electric-powered Toyota RAV4 to achieve reasonably acceptable range. Gravimetric power density is a focus of light-duty HEV electrical storage system. Heavy-duty HEVs require even higher power so the shift in priority for improved gravimetric power density for such applications is quite appropriate.

Higher power density will support further improvements in light-duty HEV fuel efficiency as less reliance on the internal combustion engine for transient power is achieved, enabling further engine downsizing. As power density increases, the maximum charging rate and charge acceptance tend to increase as well, facilitating greater ability to recover brake energy. Therefore, progress made toward higher power density, which is necessary for efficient heavy-duty HEV applications, will also benefit light-duty HEVs. Li-ion technology appears to be the leading candidate for significant progress in energy storage system power density, but significant cost, durability and safety issues exist.

Durability and Safety Issues for Li-ion Battery Systems. Safety remains a significant issue for Li-ion battery systems. Overcharging, fast charging, fast discharging, crushing, projectile penetration, external heating, or external short-circuiting, can cause the battery pack to heat up. If heat gen-

[15] DOD, TARDEC (U.S. Army Tank-Automotive Research, Development, and Engineering Command), "Energy Storage Research Projects, TARDEC Ground Vehicle Power & Mobility," received by the committee from Ken Howden, DOE, FCVT, August 31, 2007.

eration exceeds heat dissipation capability, thermal runaway can occur. Elevated temperatures can cause leaks, gas venting, smoke, flames, or even "rapid disassembly" to occur.

Intelligent monitoring and control of the charging and discharging processes is being developed to manage many of the concerns associated with thermal runaway. However, vehicle collisions and projectiles that can cause the battery case to be breached are inspiring the need for new construction materials that are less prone to mechanical and thermal issues.

Other battery technologies, such as LiFePO4 and Li-titanates, are also being pursued because they offer some advantages over Li-ion approaches, but have other features which render them less attractive than Li-ion. Some new technologies are becoming available that offer promise for greater safety with fewer environmental concerns.

Future Development Trends. There are several promising new technologies which are currently under development and will be evaluated to determine the extent to which they can provide improvements over conventional Li-ion approaches. The features that allow these technologies to be directed toward higher power density for use in heavy-duty hybrids should be explored.

Lithium Nano Titanate. Altair Nanotechnologies, Inc., is marketing a battery called NanoSafe® that offers extremely fast charging without thermal runaway, along with other safety improvements. NanoSafe® is a lithium nano titanate battery system. Altair Nanotechnologies recently demonstrated a 10-minute charge cycle for an 18-kWh pack, using a 125-kW-rated, high-voltage charging station from AeroVironment, Inc.

50°C lithium titanate batteries under development by the company Enerdel are identified in the FreedomCAR summary.

Ultracapacitors. Ultracapacitors represent an alternative way to achieve the desired power density levels in combination with other batteries. Ultracapacitors are inherently high in instantaneous power availability, compared to batteries. Currently, ultracapacitors are very expensive, but the technology is advancing quickly and production costs are continuing to decrease.

Ultracapacitors offer more than 10× the power density of today's batteries, but far less energy density, making them unsuitable as battery replacements. However, hybrid energy storage packs containing both batteries and ultracapacitors are under development. Practical production vehicle systems must trade off the associated costs of system with both high energy density and high power density. However due to the high factor of fuel in the operational cost of heavy-duty vehicles, the use of ultracapacitors may prove to be cost effective. Ultracapacitors have extremely long useful life and are inherently safer than most practical batteries.

Enhanced Lead-acid Batteries. Enhanced Lead-acid batteries are also under development. The company Firefly® Energy, Inc., is introducing a new carbon-graphite foam-based construction that significantly reduces the volume, mass, and cost of a lead acid battery, while reportedly improving its cycle life, durability, recycle ability, and temperature range. TACOM is currently evaluating this advanced lead-acid solution for potential heavy-duty hybrid applications.

Assessment of 21CTP Energy Storage Research Programs

FreedomCAR Light-Duty Energy Storage Effort. Review of the material provided by DOE on the ongoing FreedomCAR research and development effort for light-duty vehicles suggests that the program is addressing the needs, goals, and sizing for light-duty HEVs. However, it is clear that the capabilities needed for heavy-duty use may differ significantly from light-duty applications. Therefore, a clearer assessment by DOE as to how the technology may be transitioned from light- to heavy-duty is needed.

TARDEC Energy Storage Research Projects. TARDEC's Energy Storage Research Projects appear to be focused on incremental improvements in lead-acid, Ni-metal-hydride, Li-ion, and Ni-Zn batteries that can be introduced into planned military-specific hybrid electric applications. Power density and energy density trade-offs appear to be appropriately considered. The near-term focus is to address durability and safety issues related to Li-ion batteries, due to the specific requirements of military applications. The urgency of this matter as well as the need for Li-ion-type energy and power density characteristics for next-generation military combat and tactical vehicles underscores the need for significant financial support in the future.

Allison and Eaton Heavy-Duty Hybrid Programs under 21CTP. The Allison Two Mode Hybrid Bus Program and the International/Eaton Advanced Technology HEV were identified as examples of successful developments conducted under the 21CTP programs. The Allison Two-Mode system incorporates a lead-acid battery system and the International/Eaton system uses a 70 kW NiMH battery. Based upon materials provided to the committee, it appears that the successful development effort was targeted more toward advanced motor, drive and power electronics systems, although early Eaton plans call for Li-ion batteries. However, future cooperative programs have identified the desire for Li-ion battery systems.

Energy Storage Funding

The annual energy storage funding under the DOE FreedomCAR budget has been fairly stable (~$17 million) in FY2005, FY2006, the FY2007 request and the FY2008 request, related to High Power Energy Storage. However, significant increases in Advanced Battery Development have been requested for FY2007 ($7.6 million, up from $1.4 million in FY2006) and FY2008 ($18.2 million, up from $1.4 million in FY2006). These increases are targeted toward higher energy storage capacity systems that would be necessary for PHEVs.

No information was provided to the committee concerning the funding allocations that have been directly attributable to the energy storage system development under the TACOM budget line items.

Appropriateness of the 21CTP Research Areas of Focus

The committee agrees that the following issues need to be addressed to advance the state of the art in energy storage systems for heavy-duty vehicle applications:

- Cost, both procurement and life cycle
- Weight and space claim
- Life expectancy in a specific heavy-duty drive cycle
- Energy and power capacity for a heavy-duty hybrid application
- Suitability for the heavy-duty vehicle environment and cooling techniques
- Architecture/modularity
- Safety/failure modes
- Maintainability
- Supplier base for the energy storage components.

Continued focus on solving the cost, durability, safety, battery management system, and reliability issues associated with Li-ion batteries appears to be appropriate. However, due to the unique requirements for very high power capacity for certain heavy-duty applications, additional focus on ultracapacitors or other very high power capable technologies seems appropriate.

Although the stated intent for transfer of technology from light-duty to heavy-duty appears logical, the unique requirements for heavy-duty application may require significantly different trade-offs. This appears to be the focus of the TACOM programs, but the cost issues for military acceptance may be significantly different than commercial heavy-duty service.

Progress Toward Achieving the Stated Goals. TARDEC appears to have established more aggressive technical goals than those stated in the 21CTP 2006 Roadmap. For instance, TARDEC reports that it has already achieved and exceeded the 2012 FreedomCAR goal of 100 Wh/kg. However, the cost and durability targets have not yet been confirmed.

The Roadmap stated goal is to develop an energy storage system with 15 years of design life that prioritizes high power rather than high energy, and costs no more than $25/kW peak electric power rating by 2012. It is difficult to extrapolate the progress made in the light-duty sector with respect to the achievement of goals in a heavy-duty environment. In general, it appears that as a minimum, lithium-ion technology is necessary to achieve the stated heavy-duty roadmap goals. However, until sufficient effort is conducted to truly evaluate the light-duty progress in a commercial heavy-duty environment, the committee cannot gauge the real progress.

Findings and Recommendations

Finding 4-1. Challenges with lithium-ion anode/cathode materials and chemical stability under high power conditions will likely preclude achieving the 15-year durability targets by 2012.

Recommendation 4-1. Much closer interaction between military and commercial suppliers is recommended to identify the highest-priority areas for further research in an attempt to expedite the development of commercially viable battery or battery/ultracapacitor systems that can accomplish the unique high-power needs of heavy-duty vehicles.

Finding 4-2. There are significant differences associated with the use of battery energy storage systems in heavy-duty vs. light-duty applications.

Recommendation 4-2. Due to these differences and the much lower production volumes for heavy-duty applications, it is appropriate to continue funding and conduct sufficient research and development to demonstrate prototypical success in heavy duty applications, or identify areas for continued research.

Finding 4-3. The information exchange between DOD, DOT, DOE appears to be rather casual due to completely separate funding mechanisms, priorities, and testing methods.

Recommendation 4-3. Jointly funded programs that prioritize research, build on the success of each agency's programs, and thereby necessitate technology transfer between the partners would significantly improve the technology transfer and reduce the chance for "reinventing the wheel" or duplicating others' mistakes.

Finding 4-4. The metrics used for comparing battery technologies differ from manufacturer-to-manufacturer, agency-to-agency, and even for different evaluations within a given agency. Terminologies also vary in definition. Many existing standards for measuring battery parameters are technology specific, making accurate comparison of different technologies difficult or impossible.

Recommendation 4-4. Metrics should be standardized or modified to enable more accurate comparisons across different battery technologies for transportation use. Universal terminologies should be defined, published, and recommended for adoption by the various battery manufacturers.

Finding 4-5. Very little data are published about batteries when used in conjunction with ultracapacitors for heavy-duty HEV applications in this program. Recent developments show great promise with this technology, especially for heavy-duty applications requiring high power output for acceleration and fast charging for braking energy recovery.

Recommendation 4-5. Expanded research effort and associated funding focus should be focused on ultracapacitors or supercapacitors as "hybrid" storage systems, in combination with batteries.

GOAL 3: DEVELOP AND DEMONSTRATE A HEAVY HYBRID PROPULSION TECHNOLOGY THAT ACHIEVES A 60 PERCENT IMPROVEMENT IN FUEL ECONOMY, ON A REPRESENTATIVE URBAN DRIVING CYCLE, WHILE MEETING REGULATED EMISSIONS LEVELS FOR 2007 AND THEREAFTER

The hybrid truck development projects funded by DOE as part of the 21CTP initiative have demonstrated significant progress toward achieving the 60 percent fuel economy improvement target for some specific truck classes and applications. In order to evaluate this progress, it is important to recognize that heavy-duty trucks experience a much wider range of driving cycles than passenger vehicles or light-duty trucks. For example, a Class 6 urban delivery van experiences typical driving cycles that are much different from those of Class 8 long-haul commercial trucks. Because large numbers of accelerations and braking decelerations associated with truck applications such as delivery vans or refuse trucks are well-suited to demonstrating the advantages of hybridization, most of the 21CTP-funded development of hybrid trucks has been focused on these applications.[16] In fact, even Goal 3 itself has been formulated in terms of an "urban driving cycle" to highlight these applications.

An example of a heavy-duty hybrid truck that has demonstrated greater than 60 percent improvement in fuel economy is a Class 6/7 utility truck developed using Eaton parallel hybrid-electric drivetrain technology. In tests conducted by the Hybrid Truck Users Forum (HTUF), the prototype hybrid utility truck demonstrated higher-than-expected fuel economy improvement of between 62 and 150 percent on four different mission duty cycles. As a second example, a series hydraulic hybrid system installed in a Class 6 UPS delivery van by Eaton and International Truck and Engine achieved an improvement in fuel economy between 60 and 70 percent during lab testing using an EPA city driving cycle.

One of the most aggressively developed applications for heavy-duty hybrid truck technology has been urban transit buses. Tests conducted by the U.S. National Renewable Energy Laboratory (NREL) on the hybrid-electric buses developed by Orion Bus and BAE Systems demonstrated that the buses achieved an average fuel economy improvement of 45 percent compared to conventional diesel engines when driving over the city's most severe duty cycles (Green Car Congress, 2006).

It is also worth noting that Eaton has reported progress in the development of parallel hybrid-electric powertrains for Class 8 heavy-duty commercial highway trucks that have demonstrated fuel economy improvements of 5 to 7 percent over long-haul routes during independent tests (Eaton Corp., 2006). Although this percentage improvement is not as high as for the other heavy-duty trucks and buses cited above, it is still noteworthy because of the much higher annual fuel consumption associated with Class 8 long-haul trucks compared to any other type of heavy-duty truck (Eaton Corp., 2006). Eaton claims that the fuel savings provided by their hybrid drivetrain can deliver a cost savings of approximately $9,500 per long-haul truck per year. Overall, the progress achieved by truck manufacturers and suppliers toward meeting the 60 percent fuel economy improvement objective in Goal 3 is substantial.

Past DOE-supported heavy-duty hybrid truck development efforts appear to have been almost completely biased toward achieving improved fuel economy with comparatively little attention being given to opportunities for major reductions in emissions. Despite references to emissions reductions in the basic mission of the truck partnership, the briefings that the committee received summarizing the accomplishments of recent hybrid truck development projects made almost no mention of targets or achievements in the area of emissions reductions.

In response to a question about this apparent omission, the committee was informed that "the emissions of heavy-duty vehicles are not measured on a chassis dynamometer and regulated on a grams/mile basis like passenger cars and light trucks."[17] This is unfortunate, because features such as electric creep (movement under electric power alone) are expected to make it possible to turn off engines for extended periods during congested traffic or loading queue conditions, creating opportunities for substantial emission reduction during these conditions. The limitations imposed by existing procedures for certifying truck engines make it difficult to fairly evaluate the full benefits of heavy-duty hybrid trucks,

[16]Susan Rogers, U.S. Department of Energy, "Heavy Hybrid Propulsion Overview," Presentation to the committee, February 8, 2007, Washington, D.C.; Arthur McGrew, Allison Transmission, General Motors Corporation, "AH2PS: Motor & Power Electronics Development," Presentation to the committee, February 8, 2007, Washington, D.C.; Kevin Beaty, Eaton Corp., and V.K. Sharma, International Truck, "Hybrid Technology Program Review," Presentation to the committee, February 8, 2007, Washington, D.C.; Nader Nasr, Oshkosh Truck Corporation, "Advanced Products–AHHPS," Presentation to the committee, February 8, 2007, Washington, D.C.

[17]DOE, FCVT, 21CTP, response to committee query (Question 15 in "Hybrid Electric Vehicle Systems" section), transmitted via e-mail by Ken Howden, March 27, 2007.

providing the basis for a separate recommendation (4-8) presented later in this section.

In summary, there is an acknowledged risk that heavy-duty truck hybrid propulsion technology will not be successfully commercialized on a broad scale without continuing coordinated governmental support at both the federal and state levels. As stated by the 21CTP management team: "Currently, the development of hybrid technology for various vehicle platforms represents a high technical risk and is cost-prohibitive. Government-industry sharing of these risks and costs may accelerate introduction of these vehicles. This evaluation is consistent with the stated 21CTP "Strategic Approach" that calls for efforts to "promote research focused on advanced heavy-duty hybrid propulsion systems" as well as to "promote the validation, demonstration, and deployment of advanced truck and bus technologies" (DOE, 2006a).

Finding 4-6. R&D on heavy-duty hybrid trucks and buses has demonstrated significant progress, achieving 35 to 47 percent fuel economy improvements in hybrid-electric delivery vans and urban buses, with specialized applications and the hydraulic hybrid delivery van in the 50 to 70 percent range (60 percent is the present 21CTP target). Commercial success has already been achieved with hybrid electric urban buses, albeit with major governmental subsidies. Despite the promising progress, significant hurdles still remain to achieving the fuel economy improvement targets for a broader range of heavy-duty hybrid vehicle (HHV) applications, reducing the cost, and improving HHV reliability sufficiently to achieve broader commercial success. In addition, there are opportunities for achieving significant system-level improvements that would make HHVs more attractive to OEMs and users, such as the merging of hybrid propulsion and idle reduction features, including start-stop operation and creeping under all-electric power.

Recommendation 4-6. Development and demonstration of heavy-duty hybrid truck technology should be continued as part of the 21CTP program in order to reduce barriers to commercialization. These development projects should include efforts to capitalize on opportunities for system-level improvements made possible by HHV technology in order to extract the maximum possible value from any new hybridized propulsion equipment that is installed in future trucks and buses.

SYSTEMS DEVELOPMENT AND PROJECT COORDINATION

The decision by the government to focus 21CTP development efforts on component technologies has resulted in a reduction of emphasis on coordinated systems development. For example, there is little indication that any significant portion of the substantial 21CTP investment in advanced combustion engine development has been directed to optimizing the engine design for integration into a hybrid powertrain.[18] This is noteworthy in view of the major impact that engine performance characteristics have on the achievable fuel economy and emissions of heavy hybrid trucks and buses.

Progress toward the successful development of hybrid truck technology would benefit from improved coordination among the governmental agencies that are funding this work—DOE, DOD, and EPA—as well as among the national labs, universities, and subcontractors who are carrying out this R&D. Although it has been pointed out to the committee that some communication and technical interactions already occur as part of 21CTP activities and technical conferences,[19] the overall development program would benefit from closer technical coordination among the various projects. In light of the limited resources that are available to support R&D projects in this area, the importance of gaining the highest value from these investments by sharing information wherever possible and avoiding unnecessary duplication takes on added urgency.

Looking elsewhere among the 21CTP programs for best practices in developing system approaches, the idle reduction program reviewed in Chapter 6 deserves special attention. In particular, the nighttime idle reduction initiative has been particularly successful in demonstrating how several agencies and stakeholders can coordinate their activities to aggressively move new technology developments out of the laboratory and into marketplace.[20] This has been accomplished using an effective combination of technology development, field validation, certification testing, and tax credit incentives. In addition, this initiative has included customer education and incentive programs that have involved governmental agencies at both the state and federal levels working together with equipment manufacturers.[21]

The considerable progress achieved in the idle reduction area deserves to be studied to determine whether its success can be replicated in other areas such as hybrid trucks using some of the same techniques. This approach makes particular sense for the hybrid truck area because hybrid drive and idle reduction technologies directly overlap in some key areas such as creep idle.

There is also a need for this coordination to extend beyond the agencies to Congress itself. For example, the tax credits

[18]Gurpreet Singh, DOE, FCVT, "Overview of DOE/FCVT Heavy-Duty Engine R&D," Presentation to the committee, Washington, D.C., February 8, 2007.

[19]Ken Howden, DOE, FCVT, "Partnership History, Vision, Mission, and Organization," Presentation to the committee, February 8, 2007, Washington, D.C.

[20]Mitchell Greenberg, EPA (U.S. Environmental Protection Agency), "EPA SmartWay Transport Program: Overcoming Technology Deployment Challenges," Presentation to the committee, March 28, 2007, Washington, D.C.

[21]Glenn Keller, Linda Gaines, and Terry Levinson, DOE, Argonne National Laboratory, Center for Transportation Research, "Idle Reduction Technologies," Presentation to the committee, February 8, 2007, Washington, D.C.

specified for hybrid trucks in the Energy Policy Act of 2005 (Public Law 109-58, August 8, 2005) are due to expire on December 31, 2009. There is a high likelihood that the timing of this expiration and uncertainty about its renewal will complicate the market acceptance of hybrid trucks introduced by manufacturers during the coming years unless early action is taken to clarify renewal plans. A very similar problem has afflicted the wind power industry because of the series of expirations and renewals of tax incentives in that industry, creating a "feast-or-famine" market environment (Pellerin, 2005). Closer coordination between the agencies and Congressional offices would help to prevent this problem from harming the hybrid truck market in a similar fashion.

Industry also has an important role to play in order to ensure that an appropriate systems perspective is maintained in the 21CTP programs. In 2006, DOE established a subgroup activity named the Validation Working Group made up of 21CTP member volunteers. The purpose of this subgroup is to focus attention on vehicle system technologies that are evaluated as having the greatest potential for positive impact on fuel economy and emissions combined with high cost effectiveness. The Validation Working Group is intended to actively seek out opportunities to conduct in-service demonstrations of these promising technologies in order to encourage their commercial adoption. The Hybrid Truck Users Forum (HTUF) established with the support of the U.S. Army National Automotive Center (NAC) and the Hewlett Foundation is playing a similar role.[22]

Finding 4-7. Progress in the development of HHV technology under the 21CTP program has been hindered by the decision to focus on component-level technology rather than systems. Successful development and commercialization of HHV technology requires coordinated, customized development of the combustion engine, electrical/hydraulic drive equipment, mechanical powertrain, and controls as components of an integrated system, in order to realize its full potential. In addition, the coordination of HHV project activities among the 21CTP's federal partners (DOD, EPA, and DOE) has not matched the level achieved in other 21CTP programs such as nighttime idle reduction, making it more difficult to achieve ambitious HHV technology targets.

Recommendation 4-7. Coordination of all 21CTP heavy-duty hybrid truck development and demonstration activities should be strengthened across components, programs, and agencies to maximize the system benefits of this technology and to accelerate its successful deployment in commercial trucks and buses. In addition to improved cross-agency coordination, HHV stakeholder-based organizations including the Validation Working Group and the Hybrid Truck Users Forum should be engaged more aggressively to assist in identifying and overcoming key hurdles to the successful commercialization of HHV technology.

HHV CERTIFICATION TEST PROCEDURES

Lack of fuel economy and emission certification test procedures for heavy-duty hybrid trucks has been a deterrent to their commercialization. Although the U.S Energy Policy Act of 2005 provided direct tax credits for hybrid trucks that deliver improved fuel economy, there was no practical way for truck purchasers to derive these direct tax credits until mid-2007.[23]

EPA is aware of the lack of fuel economy and emissions test and certification procedures for heavy-duty hybrid trucks. Currently, EPA is developing a procedure to directly measure fuel economy and emissions of complete heavy-duty vehicles, including hybrids; when finalized, this procedure is expected to provide a measurement method and certification procedure for obtaining tax credits for heavy-duty hybrid trucks.[24] Unfortunately, EPA's development of fuel economy and emissions test procedures for heavy-duty hybrid trucks is expected to be a time-consuming process, requiring vehicle-level testing on heavy-duty chassis dynamometers. This process is particularly challenging because the number of large chassis dynamometers available in the United States that are suitable for heavy-duty trucks is quite limited.

EPA, in response to a U.S. Supreme Court ruling in a lawsuit brought by the state of Massachusetts in April 2007, is developing programs to utilize its experience with fuel economy and CO_2 measurement protocols as part of its ongoing deliberations on potential greenhouse gas regulations for vehicles under the Clean Air Act. Whether this program will accelerate the development of fuel economy and emissions test procedures for heavy-duty hybrid trucks is not known at this time.

[22]HTUF is available at http://www.calstart.org/programs/htuf/. Accessed June 2, 2008.

[23]Note added in proof—Following the public release of this report, the following information came to the committee's attention: In 2007, the Internal Revenue Service set forth interim guidance that provides a means to obtain tax credits for new qualified heavy-duty hybrid motor vehicles, based on their improved fuel economy. Internal Revenue Service Notice 2007-46, issued June 4, 2007, and entitled "Credit for New Qualified Heavy-Duty Hybrid Motor Vehicles," provides procedures for a vehicle manufacturer to certify to the IRS that the city fuel economy of a heavy-duty hybrid vehicle was measured in a manner that is substantially similar to the manner in which city fuel economy is measured under 40 CFR (Code of Federal Regulations) Part 600 (in effect August 5, 2005). This notice allows the manufacturer to use any procedure that the manufacturer reasonably determines to be substantially similar to procedures under 40 CFR Part 600. In addition, the IRS will not challenge a manufacturer's determination of city fuel economy. A manufacturer following this procedure still needs a certificate of conformity that the vehicle's internal combustion engine meets the EPA emission standards for heavy-duty engines. Therefore, no credit is available for possible reductions in actual vehicle emissions with hybrid operation. As a result, simplified emission control systems cannot be considered for hybrid heavy-duty vehicles.

[24]Note added in proof—The committee was unaware of this fact at the time of the report's public release.

Finding 4-8. Emissions of heavy-duty trucks are currently measured and certified by EPA for each engine type rather than for any truck as a complete unit. Current procedures do not allow either the fuel economy or emissions of complete hybrid propulsion systems to be certified, and so neither the fuel economy improvements nor emissions reductions of hybrid trucks are appropriately recognized. Prior to mid-2007, these procedures served as deterrents to commercialization of HHV technology since there was no practical way for truck purchasers to derive any direct tax credits for buying hybrid trucks as called for in the U.S. Energy Policy Act of 2005, which expires in 2009. Developing the necessary test procedures is expected to be a complex and lengthy process, and EPA has not been able to devote sufficient resources to developing such procedures in a timely manner.[25]

Recommendation 4-8. Since tax credits for hybrid trucks established in the Energy Policy Act of 2005 expire at the end of 2009, and there are not established engineering test procedures, DOE should work with EPA and stakeholders to accelerate the development of fuel economy and emissions certification procedures for heavy-duty hybrid vehicles so that the actual benefits of hybridization can be recognized and rewarded to further encourage commercial adoption.

HYBRIDIZATION OF LONG-HAUL TRUCKS

21CTP investments in heavy-duty hybrid truck development activities have been predominantly focused on truck types other than Class 8 long-haul trucks because stakeholders originally identified long-haul trucks as poor candidates for significant fuel economy improvements in comparison to other truck types and classes.[26] However, as noted earlier in this chapter, recent statements by some truck manufacturers and OEM suppliers are suggesting that the potential fuel economy benefits of hybridization for Class 8 long-haul trucks may be much larger than previously expected (Eaton Corp., 2006).

Some opportunities for fuel-economy improvement in long-haul trucks can be derived from engine-off operation under idle and low-speed creep conditions, as well as energy recovery from regenerative braking. Additional improvement has been proposed using waste heat recovery (WHR) from a Rankine cycle using a turbine generator to provide electric power to supplement the main engine shaft power, providing a predicted fuel efficiency boost of 15 to 20 percent to the diesel engine (Regner et al., 2006).

As discussed in Chapter 3, Cummins engineers have reported that, in addition to the WHR technology, a revision of the entire heavy-duty vehicle propulsion system and its accessories could potentially yield significant fuel savings from the following techniques beyond those achievable with WHR alone. These revisions include the following:

- Application of the basic hybrid-electric vehicle concept, allowing the main diesel engine to be downsized and peak power demands to be supplied by the electric motor and battery storage system.
- Extensive use of high-voltage, electrically driven accessories on an on-demand basis.
- Elimination of a separate engine-driven alternator.

In light of these developments, the 21CTP management has made statements indicating that they are reconsidering some of their earlier conclusions about the benefits of hybridization for heavy-duty Class 8 long-haul trucks.[27] However, there is no indication that any documented study is yet available in the public literature to prove that opportunities for significant fuel economy/emissions improvements in hybrid Class 8 long-haul trucks really exist.

Finding 4-9. Recent statements by representatives of some heavy-duty truck OEMs have reported that there are opportunities for fuel economy improvements between 5 and 7 percent in hybridized versions of Class 8 long-haul trucks, yielding annual fuel cost savings exceeding $9,000 per year. This result runs counter to generally-held opinions about the low potential of hybrid versions of Class 8 long-haul trucks for substantial fuel savings, and no documented study results have been made available to the committee to firmly substantiate the recent claims.

Recommendation 4-9. The committee recommends that the potential benefits of hybrid Class 8 long-haul trucks be evaluated as part of the 21CTP program by conducting a documented study using a combination of analytical simulation and experimental data. If the results of the study confirm the recent claims of substantial fuel economy opportunities in hybrid long-haul trucks, the 21CTP program management is encouraged to find ways to contribute directly to the accelerated development of the necessary hybrid technology and its successful demonstration in prototype vehicles.

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[25]Note added in proof—Currently, EPA is developing a procedure to directly measure fuel economy and emissions of complete heavy-duty vehicles, including hybrids.

[26]DOE, FCVT, 21CTP, response to committee query (Question 2 in "Hybrid Electric Vehicle Systems" section), transmitted via e-mail by Ken Howden, March 27, 2007.

[27]DOE, FCVT, response to Question 14 in "Hybrid Electric Vehicle Systems" section of "Responses to NAS Queries on 21CTP Idle Reduction, Hybrid Vehicles, and Parasitic Losses," forwarded via e-mail by Ken Howden, 21CTP program director, March 27, 2007.

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5

Parasitic Losses of Energy

INTRODUCTION

The role of parasitic losses of energy has been important throughout the history of the 21st Century Truck Partnership (21CTP). The latest statement of overall goals for reduction of parasitic energy loss is in the Partnership's updated roadmap (DOE, 2006a). The goals in this area have been refined substantially since the version of the year 2000 (DOE, 2000).

The energy audit data for the parasitic loss elements for the baseline and the target goals is given in Table 5-1, listed by goal.

GOALS AND OBJECTIVES

The technical goals and milestones for parasitic losses given in the latest versions of the 21CTP Roadmap (DOE, 2006a):

- **Goal 1:**
  —Develop and demonstrate advanced technology concepts that reduce the aerodynamic drag of a class 8 highway tractor-trailer combination by 20 percent (from a current average drag coefficient of 0.625 to 0.500).
- **Goal 2:**
  —Develop and demonstrate technologies that reduce essential auxiliary loads by 50 percent (from current 20 hp to 10 hp) for class 8 tractor-trailers.
- **Goal 3:**
  —(21CTP-003)—Develop and demonstrate lightweight material and manufacturing processes that lead to a 15 to 20 percent reduction in tare weight (for example, a 5,000-lb weight reduction for class 8 tractor-trailer combinations).
- **Goal 4:**
  —A. Increase heat-load rejected by thermal management systems by 20 percent without increasing radiator size to accommodate future increased engine power requirements or allow reduced radiator and cooling system size at constant power.
  —B. Develop and demonstrate technologies that reduce powertrain and driveline losses by 50 percent, thereby improving class 8 fuel efficiencies by 6 to 8 percent.
- **Goal 5:**
  —Reduce tire rolling resistance values relative to existing best-in-class standards by 10 percent without compromising cost or performance. (This has not been an active area of research.)

The five goals are discussed in the text that follows.

GOAL 1: DEVELOP AND DEMONSTRATE ADVANCED TECHNOLOGY CONCEPTS THAT REDUCE THE AERODYNAMIC DRAG OF A CLASS 8 TRACTOR-TRAILER COMBINATION BY 20 PERCENT (FROM A CURRENT AVERAGE DRAG COEFFICIENT OF 0.625 TO 0.5)

Background

The 21CTP's efforts in the area of aerodynamic drag reduction followed directly from activities undertaken under the DOE Heavy Vehicle Aerodynamics Multiyear Program Plan (MYPP) (DOE, FCVT, 2006a), which had its beginning at the First DOE Workshop on Heavy Vehicle Aerodynamic Drag, held in Phoenix, Ariz., on January 30-31, 1997 (McCallen et al., 1998). The goal of the group as stated in the MYPP was as follows (DOE, 2006b):

> The goal of the proposed activities is to develop and demonstrate the ability to simulate and analyze aerodynamic flow

TABLE 5-1 Energy Audit—Baselines and Targets (80,000-lb Gross, 65-mph Level Road)

Goal/Technical Area	Baseline	Target	Delta	Improvement (percent)
		Primary Technology Goals		
Goal 1: Aerodynamic losses	85 kW/114 hp	68 kW/91 hp	17 kW/23 hp	20
Goal 2: Auxiliary loads	15 kW/20 hp	7.5 kW/10 hp	7.5 kW/10 hp	50
Goal 3: Reduce tare weight	12,245 kg/ 27,000 lb	9,795 to 10,410 kg/ 21,600 to 22,950 lb	1,837 to 2,450 kg/ 4,050 to 5,400 lb	15 to 20
		Other Technology Goals		
Goal 4: Thermal management and friction and wear				
Goal 4a: Waste heat rejection	Increase in cooling heat rejection by 20 percent without increasing radiator size.			
Goal 4b: Powertrain losses	9 kW/12 hp	4.5 kW/6 hp	4.5 kW/6 hp	50
Goal 5: Rolling resistance	10 percent reduction relative to existing best in class			

SOURCES: DOE, 2000; DOE, FCVT, 2006.

> around heavy truck vehicles using existing and advanced computational fluid dynamics (CFD) tools. The final products are validated CFD tools that can be used to reduce aerodynamic drag of heavy truck vehicles and thus improve their fuel efficiency.

The team included participants from DOE national laboratories, universities, and the National Aeronautics and Space Administration (NASA). Visits were made to truck and trailer manufacturers to get their views on the issues to overcome in order that lower drag heavy vehicles would be commercially viable. Workshops were held and reports on the work of the various participants were issued on a regular basis through 2005. These reports are available at the DOE Scientific and Technical Information web site.[1] In each working group report the project goals were reaffirmed in the following form through 2003 (with some variation in the items listed in parentheses in the last line):

- Perform heavy vehicle computations to provide guidance to industry
- Using experimental data, validate computations
- Provide industry with design guidance and insight into flow phenomena from experiments and computations
- Investigate aero devices (e.g., boattail plates, side extenders, . . .)

In the report of the July 2004 meeting of the working group (the last line was changed as follows including the bold type for the last part of the statement).

- *Investigate aero devices* ***with emphasis on collaborative efforts with fleet owners and operators***.

The reports for 2005 reaffirm this statement of goals. Reports on the work on aerodynamic drag from 2006 appear in a different form as parts of the annual progress report of the Heavy Vehicle Systems Optimization Program (DOE, FCVT, 2005a) and the 2000 Heavy Vehicle System Review (NRC, 2000a).

The work began, as the goal statement reflects, with a primary focus on computational tools and with experiments expected to serve the purpose of supporting the computational tool developed, as opposed to the experimental program being a parallel path for development of drag reducing design features. The computational tools on which the majority of resources were expended were codes that had their origins at the national laboratories. By 2001 a number of truck manufacturers were invited to the working group meetings and made presentations on their approaches to aerodynamic development. The principal manufacturers all had small in-house teams who had a history of doing experimental development in wind tunnels and who had recently begun evaluating and using commercial computational fluid dynamic (CFD) codes. Although the truck manufacturers were somewhat interested in the claims of the team about the potential power of their CFD codes, their opinion was that the only way the features would become feasible for industry use would be if the features were incorporated into commercial codes that would be accessible to all and maintained for customers over time.

The DOE heavy vehicles team organized a conference on the aerodynamics of heavy vehicles (DOE, 2004). Kevin Cooper of the National Research Council, Canada, gave the keynote paper, "Commercial Vehicle Aerodynamic Drag Reduction: Historical Perspective as a Guide" (Cooper, 2004). Cooper gave a concise history of prior work on truck aerodynamics and demonstrated that data were already available to allow assessment of the potential of a number of drag reducing devices including tractor-trailer gap closure, trailer skirting, and boat-tailing, and had been available for several

[1]Available at http://www.osti.gov/.

decades. He cited a number of important sources that do not appear in any references in the reports on the DOE HV program. Cooper challenged the following claims, which appeared in the then-current version of the MYPP (McCallen et al., 1998).

> At present the aerodynamic design of heavy trucks is based largely upon wind tunnel estimation of forces and moments, and upon qualitative streamline visualization of flow fields. No better methods have been available traditionally, and the designer/aerodynamicists are to be commended for achieving significant design improvements over the past several decades on the basis of limited quantitative information.
>
> The trucking industry has not yet tapped into advanced design approaches using state-of-the-art computational simulations to predict optimum aerodynamic vehicles. Computational analysis tools can reduce the number of prototype tests, cut manufacturing costs, and reduce overall time to market.

Cooper went on to report on a case study undertaken over a three-week period (which again validated the size and plausibility of the existing program goals) leading up to his presentation in which the Canadian National Research Council took an existing truck model, fabricated tractor and front trailer skirts, fabricated beveled base panels to emulate a simple boat tail, fabricated skirts for the area behind the trailer wheels, fabricated a gap seal between tractor and trailer, and fabricated a filler block to completely close and fill the gap. Design had to be done before the fabrication. In one 8-hour shift of wind tunnel time the effect of these parts singly and in selected combinations on drag was measured over yaw angles from –20 to +20 degrees. The results get close to the Technology Roadmap target of a drag coefficient of 0.5, even though the tractor itself is not as streamlined as a number of currently available tractors.

Another project carried out under the Heavy Vehicle Aerodynamic Drag Program is quite distinct and has been an active project for almost the entire period from the initial MYPP. The project explored the potential for pneumatic devices to actively control flow separation in critical regions to reduce drag. This project has provided some substantial drag reductions. However, the methodology remains questionable for practical use because of the complexity of the active devices. The project team from the Georgia Tech Research Institute continues to develop the systems.

As mentioned earlier, input from truck manufacturers beginning about 2001 indicated that commercial CFD codes were more likely to become useful tools for industry than the codes developed in the national laboratories due to ease of use issues and code maintenance. A project was added to the program led by Argonne National Laboratory to evaluate commercial codes by applying selected ones to the same geometries that were the subject of simulation in the ongoing projects using national laboratory codes.

Around 2004, a project was initiated under a contract with the Truck Manufacturers Association, with the title “Test, Evaluation, and Demonstration of Practical Devices/Systems to Reduce Aerodynamic Drag of Tractor/Semi-trailer Combination Unit Trucks.” The participants were Freightliner LLC, International Truck and Engine Corp., Mack Trucks, Inc., and Volvo Trucks NA. Reports on this project appear in the 2005 and 2006 annual progress reports on the Heavy Vehicle Systems Optimization Program (DOE, FCVT, 2005a, 2006). Each of the companies focused on a different aspect of the tractor-trailer aerodynamics. The combined results in 2006 indicate a potential for meeting the 20 percent reduction in drag that has been the target since the first technology roadmap.

Goals, Targets, and Timetables

The goal for aerodynamic drag reduction has been a 20 percent reduction of drag coefficient from 0.625 to 0.5 since the first technology roadmap (DOE, 2000). Although mention has been made from time to time of achieving the target by a particular date, the working documents have not included timetables as part of the primary goals and objectives.

In fact, the frequently restated goals of the program appearing in every report of a workshop meeting as quoted in the background section do not mention the technology roadmap goal for drag coefficient or a timeline, but instead are stated in terms of process. DOE should make sure that truck manufacturers have commercial CFD codes that are usable for making aerodynamic drag calculations.

Progress Toward Objectives

As reported by McCallen, devices have been identified that will reduce drag to the target levels.[2] A reading of the reports and related information as cited in the background section indicates that methods and devices capable of achieving the target levels were already available as the MYPP was being put together. Practical problems of implementation were and remain major barriers to application of known techniques. Since the barriers to implementing modified aerodynamic designs are potentially different for each fleet owner or operator, CFD design tools may prove to be helpful to truck and trailer manufacturers in exploring the multitude of design changes to address the needs of individual fleet owners. It appears that these CFD programs have been developed to handle aerodynamic design issues, because they are currently used by race car builders.

[2]Rose McCallen et al., “DOE’s Effort to Reduce Truck Aerodynamic Drag through Joint Experiments and Computations.” Presentation on work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract W-7405-ENG-48. April, 2006. Available at http://www1.eere.energy.gov/vehiclesandfuels/pdfs/hvso_2006/02_mccallen.pdf. Accessed June 2, 2008.

GOAL 2. DEVELOP AND DEMONSTRATE TECHNOLOGIES THAT REDUCE ESSENTIAL AUXILIARY LOADS BY 50 PERCENT (FROM CURRENT 20 HP TO 10 HP) FOR CLASS 8 TRACTOR-TRAILERS

Background

In all modern vehicles powered by internal combustion engines, there are auxiliary components and subsystems that are necessary to operate the vehicle. Examples of these auxiliaries are the alternator, power steering pump, air conditioning compressor, and pneumatic air compressor. Additional power requirements which consume energy that otherwise would propel the vehicle and are closely associated with the powertrain but nonetheless reduce the overall efficiency of the vehicle include the oil pump, coolant pump, fuel injection pump, fuel supply pump, transmission, and differential gear sets. This group of components and subsystems are addressed in the chapter under Goal 4: Thermal Management and Friction and Wear.

Engine Accessories

The parasitic losses associated with auxiliary loads are approximately 20 hp for a typical heavy-duty vehicle (DOE, FCVT, 2006). To minimize additional power transfer losses, these components are normally directly driven by the engine crankshaft or camshaft through a series of the serpentine belts, chains or gear sets. The decision to drive these auxiliaries off the crankshaft or camshaft is influenced by in-vehicle packaging constraints, rotational speed ranges of the individual components and other system dynamic factors such as torsional excitation, system natural frequencies, and under-hood heat sources.

Besides the actual design and internal mechanical losses of the auxiliaries themselves, a condition that directly impacts their efficiency of operation is their direct connection to the engine. This results in many non-optional compromises that reduce operational efficiency over the engine and vehicle duty cycle. One example of this compromise is the power steering pump; where sufficient pressure to navigate the vehicle under low speed conditions results in excess pressure at high vehicle speeds, where limited power steering assistance is needed.

Under the 21CTP program, several projects directed toward the optimization of operational parameters for auxiliaries have been conducted. The most noteworthy of these has been the More Electric Truck (MET) program conducted by Caterpillar.

The MET program focused on the design, development, and demonstration testing of electrically powered auxiliary components and systems that would allow anti-idling operation (main engine shut-off, yet offering auxiliary power for accessories and/or cabin heating/cooling). The subsystems included:

- Modular HVAC Unit
- Shore Power Electrical Converter
- Integrated Starter-Generator
- Electric Oil Pump
- Electric Compressed Air Module
- Electric Water Pump

In addition, the necessary power distribution architecture was developed, integrated and tested, as were the supervisory control algorithms. The removal of these auxiliaries from the engine system loads also reduces the radiator heat loading, since less fuel is consumed by the main engine for the same propulsion energy.

Caterpillar reported a demonstrated fuel economy improvement of 1 to 2 percent in over-the-road operation. Assuming an average operational power of 250 hp, this represents a reduction in auxiliary loading of about 2.5 to 5 hp.

The anti-idling of the main engine was offset by the use of a small diesel powered auxiliary power unit (APU) and a shore-power converter for use in an electricity-enabled overnight parking center. This strategy demonstrated the potential to provide an additional 5 to 7 percent yearly fuel savings. A more detailed discussion concerning idle-reduction technologies and programs conducted under the 21CTP program are included in Chapter 6 of this report.

Other Parasitic Loss Reduction Program

During the period FY 2005-FY 2007, many other programs were classified under the general heading of "Reducing Essential Power Loads by 50 Percent." Although some of these may tend to cross over into other technical areas of focus, such as secondary energy recovery through turbocompounding, they all are associated with increasing the percentage of fuel energy that is used to propel the vehicle. A partial list of these programs includes:

- Advanced Brake Systems for Improved Undercarriage Aerodynamic Flow
  —Evaluated impact of new brake materials and designs on undercarriage aerodynamic flow
  —Assessed effect of design and material improvements on necessary brake cooling, under-hood temperature and overall vehicle thermal management
- Evaluate Autothermal Diesel Reformer
  —Assessed fuel injection technology that could allow autothermal diesel reformation that would produce hydrogen to be used by on-board fuel cell APU
- Optimize Boundary Layer Lubrication Mechanisms for improved friction characteristics and component life
  —Developed a model for scuffing mechanism based upon adiabatic shear instability
  —Established and validated performance and failure prediction methodologies for lubrication systems

—Applied X-ray-based techniques to characterize tribofilms
—Eaton Corporation demonstrated methods to improve drivetrain efficiency achieving a 2.5 percent improvement in vehicle fuel efficiency

- Reduce Engine Friction by Advanced Tribological Concepts
—Evaluated potential friction reduction through the use of advanced lubricants, additives, and low-friction engineered surfaces
—Developed engine/vehicle models to predict fuel economy savings
—Predicted fuel economy improvement of 0.5–1.4 percent with low friction surfaces
- Improved Cooling Fan and System Performance and Efficiency
—Designed and demonstrated 5 percent flow and 10 percent efficiency improvement of large axial fan
—Demonstrated improvements of aerodynamic fan shroud
—Demonstrated high pressure air fine debris filtration for high performance radiators
- Determine Feasibility of Nanofluid Application in Heavy Vehicle Engine Cooling for Improved Efficiency
—Designed, fabricated and tested experimental test facility
—Quantified experimental test section heat losses
- Evaluate boiling critical heat fluxes and pressure drops of nanofluids Efficient Cooling in Engines with Nucleate Boiling
—Reduced cooling system size by development of more efficient heat transfer method
—Developed two-phase flow engine cooling heat transfer rates and pressure drops
—Determined practical limits of engine coolant boiling
- Develop Nanofluids with Ultra-high Thermal Conductivity
—Developed gold-based nanoparticle-water suspension that increased thermal conductivity by 10 percent over water
—Conducted laminar flow experiments and developed analytical model for effective viscosity of nanofluids
- Determine Erosive Effects of Nanofluids for High Efficiency Radiator Systems
—Analyzed and developed predictive models for erosion of radiator systems caused by the use of nanofluids
—Measured baseline data on erosion of aluminum radiator systems due to use of Cu-based nanofluid
—Evaluated tribological effects of nanofluids
- Develop Integrated Under-hood Thermal Analysis for Cooling System Optimization and Radiator Size Reduction
—Developed predictive capability in cooperation with Cummins to identify hot-spots inside divided engine compartments of off-road machine
—Prototypical test rig constructed at Caterpillar and experiments conducted to validate 1D and 3D simulation methods
—Validated integrated system analysis methodology for effects of ventilation on heat rejection and component temperatures
- Powertrain System Efficiency Improvement through Reduction of Friction and Wear
—Cooperative program conducted with Eaton Corporation to reduce friction and parasitic energy losses in truck transmissions and axles
—Conducted friction predictions utilizing a range of surface characteristics, lubricants and surface topographies of gears
—Demonstrated significant potential for parasitic energy loss reduction
—Calibrated rough surface contact model using test data
—Developed and calibrated in-situ boundary film analysis capability

Finding 5-1. The More Electric Truck program demonstrated an integrated system to reduce idling emissions and fuel consumption. The test program showed significant progress toward achieving the objectives of Goal 2 in Chapter 5 ("Develop and demonstrate technologies that reduce essential auxiliary loads by 50 percent, from the current 20 hp to 10 hp, for Class 8 tractor-trailers") and Goal 6 in Chapter 6 ("Produce by 2012 a truck with a fully integrated idling-reduction system to reduce component duplication, weight, and cost"). It did so by demonstrating 1 to 2 percent estimated reduction in fuel use including significant truck idling reductions. According to DOE, this translates into an overall annual fuel savings for the U.S. fleet of 710 million to 824 million gallons of diesel fuel (about $2 billion per year at $2.75 per gallon).

Recommendation 5-1. Given the potential of this program to save fuel, the committee recommends that the 21CTP continue the R&D of the identified system components that will provide additional improvements in idle reduction and parasitic losses related to engine components that are more efficient and provide better control of energy use. The program should focus also on the cost-effectiveness of the technologies.[3]

[3]Finding and Recommendation 5-1 are identical to Finding and Recommendation 6-7 (in Chapter 6, "Engine Idle Reduction").

GOAL 3: DEVELOP AND DEMONSTRATE LIGHTWEIGHT MATERIAL AND MANUFACTURING PROCESSES THAT LEAD TO A 15 PERCENT TO 20 PERCENT REDUCTION IN TARE WEIGHT (FOR EXAMPLE, A 5,000-LB WEIGHT REDUCTION FOR CLASS 8 TRACTOR-TRAILER COMBINATIONS)

Background

An important objective of the program was to explore vehicle weight reduction opportunities through the applications of lightweight materials, including high strength steels, aluminum, and advanced composites. Previous demonstration programs have shown the potential to reduce the weight of light vehicles by over 20 percent using high strength steels, and by as much as 50 percent using carbon reinforced composites (NRC, 2000b), and similar opportunities were cited for application to U. S. Army trucks (NRC, 2003). The primary barriers to weight reduction in vehicles are the costs not only of the raw material but also of the manufacturing technology required for production. Most vehicles today, including heavy trucks, utilize mild steel for body applications—the fabrication, assembly, and joining technologies for mild steel are well developed and optimized for low cost. Nevertheless, the transition to high strength steels from mild steel is relatively straightforward and has been progressing well in the automobile industry because, while there is a modest premium for the higher-strength steels, existing fabrication and body assembly processes need little modification. Aluminum presents more of a challenge because of its inherently higher raw material cost, and also because of differences (from steel) in fabrication and joining. Carbon reinforced composites, while offering the greatest weight reduction potential, require special methods for fabrication and assembly, and are only now being used by a commercial aircraft manufacturer for extensive application in the fuselage and wing structures.[4] In addition, carbon fiber costs are very high (several dollars per pound compared with mild steel at well under a dollar a pound), and carbon fiber costs may remain high as demand grows in the aircraft industry.

Goals, Targets, and Timetables

The overall goal for the program was to develop and demonstrate, by 2012, lightweight material and manufacturing processes that would enable a reduction in vehicle weight of from 10 percent to 33 percent depending on vehicle type (DOE, 2006a). For Class 8 trucks, the goal was a weight reduction of from 15 percent to 20 percent in tare weight, which is equivalent to a 5,000 lb weight reduction for a Class 8 tractor-trailer combination. Cost targets associated with the weight reduction targets were not cited in DOE (2006a). The approach included the application of lightweight materials to specific vehicle components and systems, resulting in hardware demonstration projects. Materials under consideration included aluminum, high strength and stainless steels, and composite materials including carbon reinforced composites. The total lightweight materials budget averaged from $8 million to $9 million from 2000 through 2005, and was reduced to $2.7 million in 2006. As a result of the reduction of the total 21CTP budget in FY 2007, the lightweight materials program was discontinued. Nevertheless the committee has reviewed the program to date.

Progress Toward Objectives

Numerous separate projects were initiated to support the program, spanning the application of steel, aluminum, titanium, magnesium, and glass and carbon reinforced composites. A number of different partners from industry, notably involving major truck manufacturers, participated in the program. Several of the projects (taken from 21CTP Project Quad Sheets (DOE, 2007) and the 2005 merit review (DOE, FCVT, 2005b) are listed below:

- Carbon fiber composite hoods and fairings for class 8 trucks
- Ultralight (stainless steel) transit bus
- SPF (super plastic forming) aluminum vehicle body panels
- Cast magnesium metal matrix composites for components (e.g. transmission case)
- Friction stir joining (FSJ) in application to using tailor welded blanks for aluminum panels
- Titanium processing development for application to truck leaf springs
- Investigation of non-homogeneous microstructures due to heat treatment of steel
- Equal channel angle extrusion processes development for aluminum alloy metal matrix composites
- Lightweight diesel engine components (cylinder and liner)
- Development of graphite foams for lightweight heat exchangers
- Advanced materials for friction brakes
- Lightweight trailer project
- Basic studies of ultrasonic welding

While this is not the complete list of lightweight projects, it serves the committee's purpose of discussing the strategy employed in the lightweight materials program. Evaluating a number of different materials is a good approach to use early in this type of program, as it enables identification of "best applications," in order to "down-select" the best material for a specific application. And indeed, certain materials are likely to be the most promising for specific components and subsystems. In addition it is important to fund supporting projects such as joining and materials processing for

[4] See www.boeing.com/commercial/787family/background.html.

advanced materials. On the other hand, funding so many disparate projects seriously constrains the budget allotted to each individual project, and therefore the progress of the weight reduction program.

Nevertheless, good progress was made on the individual projects, and in many cases the results demonstrated the potential for achieving significant weight reduction in various components and subsystems. However, it was not possible to determine whether or not the program would likely meet the objective of 15 percent to 20 percent weight savings because a full system analysis of a truck incorporating the various lightweight components was not presented. In addition, the issues of material costs and costs of developing new fabrication, joining, and assembly systems for production remain to be resolved. Of course, it is appropriate that the truck manufacturers, rather than the federal government, be responsible for both full system integration and production implementation; nevertheless it would have been instructive to have had a preliminary analysis of the net weight reduction of a heavy truck due to the integrated application of the individual component projects (as was attempted for the steel bus project).

Due to the aforementioned reduction in the 21CTP budget, the lightweight materials program has been terminated. Yet it might be instructive to consider logical next steps. Prior to production, an original equipment manufacturer (OEM) would develop prototype vehicles with the new materials technology fully integrated into the vehicle. The prototype vehicles would undergo stringent validation schedules to ensure durability, corrosion resistance, resistance to ultraviolet exposure for painted surfaces, reliability, and maintainability. At the same time, the OEM would begin a cost analysis to predict the finished cost of a production vehicle. The cost analysis would include the investment required to establish, if necessary, a new body shop (where the body panels are fabricated and joined), a new paint shop (new painting process for lightweight materials), and a new assembly line. Production technologies and systems are considered to be important competitive assets, and therefore manufacturing technologies are sometimes treated as company confidential. For this reason, it would be expected that the truck manufacturers would pursue scale up and production individually.

In summary, the initial strategy and goals of the lightweight program were sound. Many of the individual projects made good technical progress resulting in a number of options for truck manufacturers to consider for further development and deployment. Indeed, a few projects were carried to production (e.g., composite truck bed for pickups). Clearly as these technologies mature and as they move into production, the responsibility should shift from the 21CTP to the individual original equipment manufacturers.

Due to the 2007 budget reduction, DOE management elected to terminate the lightweight materials project in order to maintain as much resource as possible focused on engine and emissions technology. The committee agrees with that decision for several reasons. First of all, improvements to the engine have greater potential for reducing fuel consumption than do technologies associated with vehicle weight reduction.[5] In addition, many of the materials under consideration have been used in commercial automotive application; therefore, the opportunity for new discovery through research seems less likely than is the case for engine and emissions technology. Finally, as previously mentioned, further development and production implementation of the vehicle materials technology should be the responsibility of the manufacturers rather than that of the federal government.

Finding 5-2. The 21CTP lightweight materials research was terminated as a result of the 2007 budget reduction.

Recommendation 5-2. The committee agrees with the decision to terminate lightweight materials research in order to provide as much budget resource as possible to continue research in engine efficiency and emissions reduction technologies, as improvements in engine efficiency offer greater potential for overall gains in vehicle fuel efficiency.

Finding 5-3. Prior to termination of the lightweight materials program, several lightweight material projects demonstrated weight reduction potential for truck components. However, the program did not achieve the longer term objective (planned for 2012) of demonstrating a 5,000-pound weight reduction for a complete class 8 tractor trailer combination.

Recommendation 5-3. Due to the termination of the project in 2007, it will be the responsibility of truck manufacturers to take the next steps of system integration, product validation, and ultimately production of a lightweight truck. Although an interim step of system integration at the pre-production stage would have been useful, it is not inappropriate that the OEMs now assume responsibility for continuation of the work, as the next steps will require development of a business case which comprehends material costs and the costs of modifying existing manufacturing systems to accommodate the introduction of advanced materials.

GOAL 4A: THERMAL MANAGEMENT AND FRICTION AND WEAR—INCREASE HEAT-LOAD REJECTED BY THERMAL MANAGEMENT SYSTEMS BY 20 PERCENT WITHOUT INCREASING RADIATOR SIZE

The background and approach for Goal 4A are described in the 21st CTP Roadmap and Technical White Papers (DOE, 2006a) and are discussed and summarized below.

The focus of this goal is to reduce truck radiator size through efficient cooling systems, advanced nanofluid cool-

[5] Ken Howden, DOE, FCVT, "Partnership History, Vision, Mission, and Organization," Presentation to the committee, Washington, D.C., February 8, 2007, Slide 21.

ants and improved under-hood design through the use of advanced modeling techniques. Exhaust gas recirculation (EGR) is the most common near-term strategy for reducing NO_x emissions, but is expected to add 20 to 50 percent to the coolant heat-rejection requirements. Thus, there is a need to package more cooling capability into a smaller package space without increasing cost. Benefits in fuel efficiency are projected to be achieved through the development of high-performance heat exchangers and cooling media (fluids) which will reduce the need for high-output engine water pumps.

Longer term, the trend toward hybrid vehicles is expected to further increase the demand on coolant heat rejection systems. In diesel hybrid vehicles, there are up to five separate cooling systems (for the engine, batteries, motors, electronics, and charge air).

These demands for improved thermal management systems have created a need for new and innovative thermal management technologies that will require long-term R&D. Several research areas were identified by DOE and industry that could provide both near-term and long-term solutions to these thermal management challenges. The research areas identified were as follows:

- Intelligent thermal management systems
  —Use of higher electrical bus voltage to enable the use of variable speed electric pumps and fans
  —Variable shrouding
  —Integration of thermal management components into the vehicle structure
- Advanced heat exchangers and heat-transfer fluids
  —Innovative, enhanced airside heat-rejection concepts
  —New materials, such as carbon foams, for cooling system components
  —Nanofluids for improving heat transfer properties of coolants and engine oils
  —Mitigation of heat exchanger fouling
- Advanced thermal management concept development
  —Heat pipes
  —Cooling by nucleate-boiling
  —Waste-heat recovery (e.g., thermoelectric generators)
- Simulation code development
  —CFD for airflow and temperatures of the powertrain, under-hood aerodynamics and airflow, lubricant cooling, vehicle-load predictions, cooling systems, and control systems
  —Experimental database
- Thermal signature management (the committee assumed that this area was focused on military applications)
  —Masking technologies to mask overall signature
  —Masking technologies to mask specific cargoes

Finding 5-4. The committee noted that the above list of research areas was extensive and comprehensive. However, the list appeared to be significantly more ambitious than the budget for the 21st CTP could fund. The committee assumed that this was the case since no projects or results from any of the above research areas were provided.

Recommendation 5-4. In addition to identifying a list of research areas that could provide solutions to thermal management challenges, DOE should develop, fund, and implement plans for pursuing the key areas that will lead to the successful accomplishment of the specific 21CTP Goal 4A. DOE's first step should be to assess the candidate technology or technologies that have the highest potential for meeting the requirements of Goal 4A.

This goal and its status were briefly discussed with the committee and the following information was provided: "Track and laboratory tests met or exceeded goals, validation test is underway."[6] Unfortunately, a description of the track and laboratory tests that had been performed, the engineering details and the results from these tests, or a description and timetable for the validation test reported to be under way were not described for the committee.

Finding 5-5. Based on the above observations, the committee was not able to accurately assess the progress on this goal or the expectation of whether this goal can be successfully achieved.

Recommendation 5-5. DOE should provide periodic status reports on the 21CTP goals that include the technical status vs. the program plan, funding vs. budget, and the expected future accomplishments vs. the program plan.

System changes for heavy duty trucks are always complicated by the fact that truck manufacturers are assemblers of components specified by the truck buyer. As such, cooperative engineering design and development relationships may not exist between the suppliers of the many different components assembled into the thermal management system. The engine supplier may specify the thermal loading requirement for radiators, after coolers, oil coolers, and the controls to manage their interactions.

Since the combinations of component characteristics and controls required to optimize such systems may span the capabilities of many supply companies, it may be necessary for DOE to sponsor new sets of relationships to attack these problems. Many of the suppliers required for such a cooperative effort are not presently participants in the 21CTP.

On the other hand, several elements in the thermal management systems, such as water and oil pumps, are key items in meeting engine life and reliability goals for the engine manufacturers. These components are matched to the engine to meet torque, speed, cylinder pressure and thermal

[6]Rogelio Sullivan, DOE, "Parasitic Energy Loss Reduction," Presentation to the committee, Washington, D.C., February 8, 2007, Slide 5.

load requirements. As such, the capacity and power use of the systems, which are usually direct drive from the engine, probably exceed the real requirements at speeds and loads away from the torque peak maximum load condition. This fact means that potential for system efficiency improvements may exist over a good portion of the engine operating map. Currently the engine builders use very reliable belt and gear drives for oil and water pumps to meet engine life and reliability goals. If newly developed systems such as variable speed drives with flexible controls are to be engineered in the truck systems, the long-term durability and reliability of the systems will have to be demonstrated to engine builders and truck buyers. These development demonstrations will be costly and take many years to complete. The Caterpillar "More Electric Truck" project and presentations by Cummins indicated that the engine manufacturers have begun to think along such lines but the present state of progress was difficult for the committee to assess.[7]

Finding 5-6. The achievement of present program targets would require the involvement of a wide range of new program participants and the sharing of responsibilities among new program partners, inherently incorporating higher technical and durability risks than the present approaches. Truck manufacturers are assemblers of components specified by the truck buyer, and cooperative design and development relationships may not exist between suppliers.

Recommendation 5-6. DOE should determine if the above approach for achieving Goal 4A is feasible within the scope of the 21CTP and containable within the available budget. DOE should take a strong leadership role with appropriate funds to bring manufacturers and suppliers together for systems research and development for Goal 4A and Goal 3.

GOAL 4B: THERMAL MANAGEMENT AND FRICTION AND WEAR—DEVELOP AND DEMONSTRATE TECHNOLOGIES THAT REDUCE POWERTRAIN AND DRIVELINE LOSSES BY 50 PERCENT, THEREBY IMPROVING CLASS 8 FUEL EFFICIENCIES BY 6 TO 8 PERCENT

The background and approach for Goal 4B were also described in the 21CTP Roadmap and Technical White Papers (DOE, 2006a) as discussed and summarized below. Friction, wear and lubrication are important considerations in many approaches for reducing energy consumption. Consequently, DOE identified the following opportunities for improvements:

1. *Engine efficiency.* Improved friction and piston/ring lubrication can improve engine efficiency.
2. *Driveline components (transmission, axles, etc.).* Advances in lubrication and friction can reduce the losses in driveline components.
3. *Engine emissions and aftertreatment systems.* Lubricant formulations and coatings can impact exhaust particulate matter as well as exhaust sulfur and phosphorous content, which can affect exhaust aftertreatment systems.

The 21CTP roadmap (DOE, 2006a, p. 1) states that the long-term objective of this goal is the development of tools and technology to reduce parasitic friction losses in the engine, driveline and auxiliary components. The following barriers and challenges in friction and wear reduction were identified:

- Although reducing the viscosity of drivetrain fluids will reduce viscous and windage losses, current designs, materials, and lubricant additives are inadequate to maintain component durability and reliability when used with low-viscosity fluids.
- The current levels of phosphorous-based additives (ZDDPs) used in engine lubricants will rapidly degrade the performance of emission-control devices. However, reducing the level of phosphorous and other metal-containing additives will accelerate the wear of critical engine components and degrade engine durability and reliability. Thus, a delicate balance must be maintained.
- Cost-effective technologies for high-volume manufacturing of low-friction, wear-resistant materials, surface treatments, and additives are lacking.
- Integration of component designs with advanced materials, engineered surfaces, and lubricants into complete systems is poor.

The following major topics addressing both short-term and long-term friction, wear, and lubrication technologies were identified by DOE and industry for improving fuel economy, while maintaining system durability and reliability:

- Integration of mechanistic friction and wear models into codes to predict and mitigate parasitic energy losses
- Advanced materials and coating technologies that lower friction, reduce wear and improve reliability
- Engineering surfaces to improve friction and lubrication properties
- Lubricant additives
- Boundary layer lubrication studies to control friction, durability and reliability

[7]Vinod K. Duggal, Cummins Engine Company, Inc., "Diesel Engine R&D and Integration," Presentation to the committee, Washington, D.C., February 9, 2007, Slide 8.

Finding 5-7. The committee noted that the DOE list of research topics in friction, wear and lubrication was extensive and comprehensive. However, the list appeared to be significantly more ambitious than the budget for the 21CTP could fund. The committee assumes that this was the case since no projects or results from any of the above research areas were provided.

Recommendation 5-7. In addition to identifying a list of topics addressing friction, wear, and lubrication technologies, DOE should develop, fund and implement plans for pursuing key areas that will lead to the successful accomplishment of the specific 21CTP Goal 4B. DOE's first step should be to conduct detailed friction testing of a range of heavy-duty diesel engines, transmissions, and final drives to determine those with best-in-class friction. With respect to engines, previous industry light- and heavy-duty engine friction reduction investigations that included lightweight-low friction piston and piston ring designs, low friction coatings and surface finishes, reduced engine bearing sizes and other design modifications should be reviewed to determine opportunities for reducing engine friction below best-in-class levels. From this assessment, other candidate technologies with the highest potential for meeting the requirements of the engine portion of Goal 4B should be identified. Likewise, the efficiencies of transmissions and final drives on heavy-duty trucks should be measured and compared with the efficiencies of best-in-class light-duty vehicles, normalized for load differences, thereby providing insight for friction reductions in heavy-duty truck transmissions and final drives. From this assessment, other candidate technologies with the highest potential for meeting the requirements of the driveline portion of Goal 4B should be identified.

The committee was not provided with the detailed approach and plans to achieve a 50 percent reduction in parasitic losses in the powertrain and driveline, which would yield a 6 to 8 percent improvement in fuel efficiency. However, some insights into this goal were provided by reviewing the following information, which was available to the committee:

1. *Driveline losses.* DOE has a target for reducing drivetrain losses from 9 kW (Table 5-1) by 50 percent to 4.5 kW. Reducing the fuel energy used by 4.5 kW (from a total fuel energy used of 380 kW as shown in Figure 3-1) would reduce fuel consumption by 1.2 percent.
2. *Powertrain losses.* Baseline engine losses are shown to be 220 kW in the energy audit of a typical Class 8 tractor-trailer combination at 65 mph road load (Figure 3-1). A further breakdown of these losses into coolant loss, exhaust heat loss and friction loss was not provided to the committee. However, by using a typical FMEP value for a direct injected diesel engine (Heywood, 1988, p. 724), the friction losses were estimated by the committee to be approximately 30 kW. The goal of a 50 percent reduction in engine friction would reduce the total fuel energy used by 15 kW (from a total fuel energy used of 380 kW), which would reduce fuel consumption by 3.7 percent.

The above insights indicate that, even if DOE can achieve a 50 percent reduction in powertrain and drivetrain losses, a reduction in fuel consumption of only 5 percent (sum of 1.2 percent for drivetrain and 3.7 percent for powertrain) could be achieved. This is a shortfall relative to the goal of 6-8 percent.

Furthermore, the engineering details of achieving 50 percent reduction in driveline and engine losses were not provided to the committee. However, past experience has indicated that major reductions in powertrain and drivetrain losses have not been achievable while retaining adequate durability and reliability. The committee concluded that due to the lack of an in-depth technical rationale and a plan to approach the goal, it is very unlikely that this goal can be achieved. The issues with the basis for calculating the percentage improvement must be resolved so that a realistic reduction in powertrain losses can be determined.

Having noted the above issues with this goal, the committee was concerned that "Track and laboratory tests met or exceeded goals, validation test is underway."[8] A description of the track and laboratory tests that had been performed, the engineering details and the results from these tests, or a description and timetable for the validation test which was reported to be under way were not described for the committee.

While the problems dealing with friction and wear inside the engine can be addressed by engine manufacturers associated with the 21CTP, the issues associated with the other driveline devices must be handled by other suppliers that are not currently participants in the 21CTP. Here again, the makeup of the truck building industry makes the required cooperative efforts difficult. The fact that the truck builders use components specified by the truck end-users means that the driveline efficiency responsibility may be shared by several manufacturers. A review of specifications on driveline components indicated that, although torque and speed specifications were readily available, specifications regarding power losses were not easily obtained. Thus, buyers presently make such decisions absent of efficiency information. Since lubricant viscosity and additives will have an impact on both the efficiency and life of the driveline components, decisions will have to be made carefully so as not to reduce driveline component life as efficiency is improved. Changes to driveline systems will have to demonstrate life characteristics similar to those that exist today, thus the introduction

[8]Rogelio Sullivan, DOE, "Parasitic Energy Loss Reduction," Presentation to the committee, Washington, D.C., February 8, 2007, Slide 5.

of such systems will be costly and require several years of life validation demonstration.

The improvement of driveline efficiencies presents a significant problem for DOE. The required involvement of new suppliers and the costly requirement to demonstrate long-lived components may be beyond DOE's budget limits.[9]

Finding 5-8. In contrast to the report by DOE to the committee, the analysis of the basis of this goal by the committee indicates that it is very unlikely that this goal can be achieved within the scope of the 21CTP. The achievement of the goal's projected fuel savings appears to be very unlikely with accompanying high risks relative to component life.

Recommendation 5-8. DOE should reassess the basis of this goal and determine if 50 percent reductions in powertrain and drivetrain losses are technically feasible. Based on this assessment of technical feasibility, DOE should determine if this goal should be pursued based on its potential fuel savings vs. other competing programs within the 21CTP. If DOE determines that this goal should be pursued, they should then develop specific program plans, timing and funding.

GOAL 5: ROLLING RESISTANCE TECHNOLOGY GOAL—10 PERCENT REDUCTION IN TIRE-ROLLING RESISTANCE VALUES RELATIVE TO EXISTING BEST-IN-CLASS STANDARDS WITHOUT COMPROMISING COST OR PERFORMANCE

Background

Rolling resistance of tires is one of the parasitic losses acting on trucks that increase fuel consumption. Although rolling resistance is generally considered a tire property, it is also recognized to be dependent on the texture and rigidity of the road surface. The 21CTP initially considered rolling resistance to be one of the areas warranting investigation inasmuch as it is estimated to consume about 51 kW of power during highway travel of a fully loaded Class 8 truck (DOE, 2006a, Table 3.1). The Partnership set a goal for 10 percent reduction relative to existing best-in-class standards (DOE, 2006a, Section 3.2). However, it failed to become an active area of investigation with the result that there has been little attention or discussion within the program.

Significance of Rolling Resistance

The 21CTP estimate of 51 kW of power to overcome rolling resistance of an 80,000 lb Class 8 truck operating at 65 mph on a level road corresponds to a rolling resistance force that is 0.6 percent of the vehicle weight. Of the total energy consumed (400 kW per hour) 12.75 percent is due to rolling resistance. However, of the mechanical energy needed to maintain the truck at speed arising from auxiliary loads, drivetrain losses, aerodynamic losses, and rolling resistance, rolling resistance constitutes 32 percent of the total. Thus, at stake is a loss equivalent to about one-third of the power needed to propel the truck. Consequently, the initial goal for a 10 percent reduction in rolling resistance at the outset of the Partnership would be expected to achieve a reduction in fuel consumption of about 3 percent. In terms of fuel savings at the national level, this 3 percent can be translated into gallons of fuel if it is assumed that the engine losses decrease in proportion to the reduction in power required. Using the Federal Highway estimate (DOE, 2006a, p. 5) that tractor-trailers consume 26.8 billion gallons of fuel annually, the savings would be about 800 million gallons per year just for tractor-trailers. For smaller trucks used in other vocational applications the savings are not well known, but are likely to be on the same order of magnitude. At the passenger car level it has been estimated (NRC, 2006, p. 4) that a 10 percent reduction in rolling resistance would translate into a fuel savings of 1 to 2 percent. Assuming a nominally conservative value of 2 percent savings from a 10 percent reduction in rolling resistance, U.S. petroleum consumption from trucks of class 3 through 8 trucks could be reduced by approximately 20 million barrels per year. (Note: This quantity was calculated based on the 2.6-million-barrel-per-day estimate for the year 2005 shown in the current 21CTP roadmap [DOE, 2006a, Figure 1-2].)

Suggestions for Government Initiatives

In the highly competitive tire market, the technology by which tires are designed to have specific attributes is proprietary to the manufacturers. Thus the opportunity for government agencies to develop partnerships and participate in developing improved tires is limited. Thus, it is not surprising that no tire manufacturers participated as partners in the 21CTP.

Designing tires for low rolling resistance is often in conflict with other performance objectives and hence falls under the purview of tire manufacturers. For example, using low-hysteresis materials in the tread to reduce rolling resistance directly conflicts with the need for tread hysteresis in order to maintain good wet traction. Similarly, reducing tread depth also reduces rolling resistance but at the cost of decreased tire life. Numerous other conflicts exist.

Recognizing that there is little opportunity for government agencies to participate in developing tire technologies, the question arises as to whether there is any mechanism for encouraging development and adoption of performance standards for rolling resistance. The industry itself supports standardization of tire and wheel related components through the Tire and Rim Association, Inc. In existence since 1903, the Association holds primary responsibility for establishing standards for dimensions, load ratings and inflation pressures

[9]Rogelio Sullivan, DOE, "Parasitic Energy Loss Reduction," Presentation to the committee, Washington, D.C., February 8, 2007, Slide 5.

for tires in the United States, in addition to standards for rim dimensions, tubes, valves and other components.

Two standard tests for measuring rolling resistance exist as SAE recommended practices—SAE J1269, "Rolling Resistance Measurement Procedure for Passenger Car, Light Truck, and Highway Truck and Bus Tires" (SAE, 2006) and SAE J2463, "Stepwise Coastdown Methodology for Measuring Tire Rolling Resistance" (SAE, 1999). Both tests are conducted in a laboratory with the tire loaded against a 1.7-meter-diameter drum. While these test procedures are not identical to each other or to on-road operating conditions, they can be expected to provide good relative measures of rolling resistance.

Since precedent and test procedures exist, the government could add grading requirements for rolling resistance to the UTQGS (Uniform Tire Quality Grading System) if there is promise of its effectiveness. At least two barriers exist:

- *Consumer acceptance*—Although the UTQGS was designed to assist consumers in making informed choices when buying passenger car tires, it is not universally effective. The effectiveness was evaluated in a 1992 telephone survey of individuals who buy tires for their own vehicles and individuals who buy tires for fleets of vehicles (Weiss, 1992). Approximately 80 percent of potential customers considered UTQGS information important to a purchase decision, although only about 30 percent of recent customers considered it in their last purchase. More than 50 percent of fleet buyers considered UTQGS information important in buying decisions.
- *Retread tires*—More than 50 percent of the tires on long-haul trucks are retreads. A retread is simply new tread molded on to an existing, pre-used tire carcass. Rolling resistance depends both on the design and materials of the tread stock as well as the underlying structure. Thus, each retread will have a different rolling resistance value. Therefore, it is less practical to expect rolling resistance values to be measured for retread tires than for those produced by OEM tire manufacturers.

Finding 5-9. There is a precedent for government to establish performance measures for tires as illustrated by the Uniform Tire Quality Grading System (UTQGS) adopted by NHTSA in 1980 [Part 575.104 of the Consumer Information Regulations]. The UTGS applies to passenger car tires and requires manufacturers to grade new tires for tread wear, wet traction and temperature resistance. Tread wear is graded on a numerical scale, while traction and temperature resistance are graded on an alphabetic scale. There is no current requirement for grading rolling resistance, or for grading truck tires.

Recommendation 5-9. DOE, EPA, and DOT should arrange to gather and report information on the influence of individual truck tires on vehicle fuel consumption; to convey such tire information to both buyers and sellers; and to periodically reassess the effectiveness of this consumer information and the methods used for communicating it.

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6

Engine Idle Reduction

INTRODUCTION

The stated 21CTP goal of the engine idle reduction activity is to promote the research, development, and deployment of technologies that substantially reduce energy consumption and exhaust emissions due to idling.

The objectives are as follows:

- Establish an industry/government collaboration to promote the research, development, and deployment of cost-effective technologies for reducing fuel use and emissions due to idling of heavy-duty diesel engines.
- Establish an educational program for truck and bus owners and operators to implement the most cost-effective enabling technologies and operational procedures to eliminate unnecessary idling.
- Develop a mix of incentives and regulations to encourage trucks and buses to find other more fuel-efficient and environmentally friendly ways to provide for their power needs while at rest.
- Facilitate the development of consistent electrical codes and standards that apply to both onboard and stationary electrification technologies.
- Develop and demonstrate add-on idling-reduction equipment that meets driver cab comfort needs, has a payback time of 2 years or less, and produces fewer emissions of NO_x and PM than a truck meeting 2010 emission standards, by 2009.
- Develop a truck with a fully integrated idling-reduction system to reduce component duplication, weight and cost, by 2012.
- Develop and demonstrate a viable fuel cell Auxiliary Power Unit (APU) system for on-road and off-road transportation applications in the 5-30-kilowatt (kW) range, capable of operating on hydrogen directly, or using a carbon-based fuel with a reformer.

According to the DOE, Class 7 and 8 trucks idle a significant portion of the time, accounting for the consumption of a billion gallons of diesel per year from overnight idling.[1] To understand the potential to reduce the time spent in the idle mode, one needs to understand the importance of keeping the engine running. DOE indicates that a variety of reasons account for this activity:

- To keep the cab or sleeper heated or cooled
- To keep the fuel warm in winter
- To keep the engine warm in the winter to permit easier startup
- To provide power to operate electrical appliances such as microwaves and TV sets
- To keep the batteries charged
- Because the other drivers do it!

Most activity has been focused on nighttime idling, but as Table 6-1 shows, daytime idling can surpass the fuel use during nighttime idling.

In addition to the waste of fuel, idling is a significant source of emissions and has been identified as playing a substantial role in exposure to diesel particulates. Such exposure has been estimated to cause thousands of premature deaths (Lloyd and Cackette, 2001). In this case, daytime idling particularly has more impact on human exposure than nighttime idling. The example of a school bus idling, exposing children to elevated diesel particulates, led the California Air Resources Board (CARB) to regulate the time of idling for school buses. Problems with noise during idling, as well as the associated air pollution, have led to communities placing significant restrictions on operations of trucks at idle.

The concern to limit fuel use and reduce emissions during idling has provided a logical opportunity for DOE and the

[1]Glen Keller, Linda Gaines, and Terry Levinson, U.S. Department of Energy, Center for Transportation Research, "Idle Reduction Technologies," Presentation to the committee, Washington D.C., February 8, 2007, Slide 3.

TABLE 6-1 Fuel Use During Idling as Percentage of Total Fuel Use (million gallons per year)

	Gasoline	Diesel	Total
Overnight Idling	0	700	700
Workday Idling (excluding vocational power take-off use)	1,400	1,000	2,500
Total Long-Duration Idling Fuel Use	1,400	1,700	3,200
Total Fuel Use for Commercial Trucks	14,000	23,000	37,000
Idling Percentage to Total Use by Fuel Type	10%	7%	9%

SOURCE: Glen Keller, Linda Gaines, and Terry Levinson, U.S. Department of Energy, Center for Transportation Research, Idle Reduction Technologies," Presentation to the committee, Washington D.C., February 8, 2007, Slide 3.

Environmental Protection Agency (EPA) to work together on reducing the time vehicles spend at idle.

Finding 6-1. Idle reduction is one of the most effective ways to reduce pollutant emissions (especially locally) and improve fuel economy. As a result of the Energy Policy Act of 2005, the authority for this effort now rests with EPA and DOT. Several important lines of research are carried on in the 21CTP. In addition, the EPA SmartWay Transport Partnership voluntary program is effective at promoting the use of electrified parking spaces. The 21CTP, in cooperation with several major shippers, has demonstrated a number of cost-effective technologies (such as fuel-fired cab heaters and coolers) that are being used by existing fleets. (One fleet is installing more than 6,000 heaters, and another is installing more than 7,000.) One trucking company reported that diesel-fired heaters provided 2.4 percent fuel savings and a payback in less than 2 years at $2.40 per gallon.

Recommendation 6-1. The 21CTP should continue to support R&D for the technologies that reduce idle time and address the remaining technical challenges (including California emission requirements, completely integrated APU/HVAC systems, and creep devices).

ASSESSMENT OF INDIVIDUAL GOALS

Goal 1. Establish an Industry/Government Collaboration to Promote the Research, Development, and Deployment of Cost-Effective Technologies for Reducing Fuel Use and Emissions Due to Idling of Heavy-Duty Diesel Engines

DOE has for at least a decade carried out cooperative research and development to characterize and address the reduction of fuel use and emissions during idling of heavy-duty engines. In 2002 it began a study of diesel truck engine idle-reduction technologies, called the Advanced Vehicle Testing Activity (AVTA).[2] The study identified several barriers to widespread use of existing idle-reduction technologies, including initial cost, driver education and receptiveness, reliability, and maintenance considerations. AVTA sponsored four idle reduction demonstration projects, each consisting of a team of a truck fleet, truck manufacturer, and idle-reduction technology manufacturer:

- *Engine-Off Cab Cooling and Heating.* Schneider National Inc. led a project to demonstrate engine-off cab cooling and heating.
- *Engine-Off Accessory Power.* Caterpillar Inc. is leading a project to demonstrate Caterpillar's MorElectric technology, which applies electrically driven accessories for cab comfort during engine-off stops and for reducing fuel consumption during on-highway operation.
- *Combined Cab Heating and Cooling.* Espar is leading a project to demonstrate combined cab heating and cooling systems. One system combines an air conditioner with a bunk heater. Another system combines an auxiliary power unit—which provides heating, cooling, and accessory power—with a bunk heater.
- *Factory-Installed Idle Reduction System for Sleeper Trucks.* International Truck and Engine Corporation is leading a project to develop and integrate onboard idle-reduction technology into heavy-duty sleeper trucks as an original-manufacturer, factory-installed equipment option. The idle-reduction system consists of an auxiliary power unit, electric air conditioner, cab and engine preheater, and improved cab insulation. In 2006, five trucks equipped with the system began field evaluation in fleets. The evaluation will conclude in 2007. In addition, production orders for the factory-built system—in hot-climate and cold-climate versions—are already being delivered to customers.

DOE took a leadership role in conducting meetings with the industry and a significant report on time idling and its consequences was released in 2000, and continued to work closely with industry to identify and demonstrate potential idle-reduction technologies as discussed later in the report.

Other federal agencies involved with these programs are the EPA, Department of Transportation (DOT), and

[2]Information is available at http://www.eere.energy.gov/afdc/vehicles/idle_reduction_research.html.

Department of Defense (DOD). Results of the cooperative demonstration projects are used to educate the truck drivers to reduce idling. The EPA SmartWay Transport Partnership is a highly successful example of government-industry partnership and is discussed later in this chapter.

Finding 6-2. An effective government-industry cooperative program has been established to examine idle-reduction technologies, which have been successfully employed for nighttime truck operation.

Recommendation 6-2. The success of the nighttime anti-idling measure and deployment should be the basis for expanding to technologies that can be applied for daytime operation, which will then lead to greater fuel savings than nighttime operation.

Goal 2. Establish an Educational Program for Truck and Bus Owners and Operators to Implement Enabling Technologies and Operational Procedures to Eliminate Unnecessary Idling

A very successful educational program was created following the DOE Conference on National Idling Reduction Planning held in May 2004 in Albany, New York: see the monthly publication "National Idling Reduction Network News."[3] This publication has a primary recipient list of about 1,500 and contains information on the following:

- Solicitation for funding and awards
- Presentations from meetings
- Upcoming meetings
- Awards from solicitations
  —Regulating news
  —Reports of interest
  —Manufacturers news
  —News about ports
  —Hybrid commercial vehicles
  —Truck stop electrification
  —Other news

Argonne National Laboratory prepares the monthly document for the DOE Office of Energy Efficiency and Renewable Energy (EERE). Review of a sample document indicates that this is an effective tool to educate stakeholders on the various aspects of idle reduction and the opportunities for funding at the federal, state, and local levels. The Clean Cities Program and events held by this organization is another effective way of distributing the message on the benefits of idle reduction.

[3]Available at http://www1.eere.energy.gov/vehiclesandfuels/pdfs/idling_news/apr07_network_news.pdf.

Finding 6-3. DOE has built an effective outreach instrument in its monthly publication, "The National Idling Reduction News." This publication and education through conferences and other agencies such as the EPA provides stakeholders with significant information and guidelines for idle reduction.

Recommendation 6-3. DOE should continue its current successful education and outreach program as currently operated.

Goal 3. Develop a Mix of Incentives and Regulations to Encourage Trucks and Buses to Find Other More Fuel-Efficient and Environmentally Friendly Ways to Provide for their Power Needs at Rest

This section addresses the various mechanisms being followed to address idle reduction—namely a market mechanism for incentives and the regulatory approach being implemented by various governmental agencies at the local, state, and national levels.

One of the most successful programs appears to be the EPA SmartWay Transport Partnership, which is a "collaborative effort between EPA and industry designed to create a demand for cleaner, more fuel efficient transportation."[4] This partnership includes idle reduction as part of its overall program objectives. EPA has provided $5 million in grants for 84 projects nationally to fund a variety of Truck Stop Electrification (TSE) and APUs. The advent of new regulations such as the CARB regulations for PM reduction on APUs installed on 2007 heavy-duty trucks may require R&D programs funded by DOE to develop additional technologies, which may be deployed in other states.

According to the EPA, there is a patchwork of anti-idling regulations across the United States, which is a disincentive to the industry to invest control equipment to reduce idling emissions. To address this issue, EPA developed a "model idle reduction" regulation, which could be applied nationally. This was a follow-up to a series of stakeholders meetings. It will be important for EPA to follow up on this initiative if it is to be successful.

EPA has also provided a mechanism for truckers to secure loans for installing devices such as APUs to reduce emissions and improve fuel economy. This has proven to be a successful program.

Finding 6-4. Progress on the incentive part of this goal has been excellent as evidenced by the SmartWay Transport Partnership between EPA and industry. The patchwork of anti-idling regulations nationally is an impediment to broader use of anti-idling measures.

[4]Mitchell Greenberg, EPA Office of Transportation and Air Quality, "EPA SmartWay Transport Program: Overcoming Technology Deployment Challenges," Presentation to the committee, Washington, D.C., March 28, 2007.

Recommendation 6-4. EPA should renew its efforts to promulgate national anti-idling regulations, and DOE should review whether additional R&D is needed to implement those regulations.

Goal 4. Facilitate the Development of Consistent Electrical Codes and Standards That Apply to Both Onboard and Stationary Electrification Technologies

EPA apparently passed the electrical codes and standards program on to industry in 2005 and does not have any type of ongoing summary of progress. The program was divided into two working groups: (1) truck codes and (2) ground codes using 120-volt power. The truck codes have been set up with two 20-amp ground-fault interrupter circuits (GFIC) protectors, and a draft SAE standard has been approved by the SAE Truck and Bus Electronics Committee. A full committee vote was due in the summer of 2007 with anticipated release of the new standard by September 2007. The committee obtained a draft copy of the new standard (J2698 SAE, September 2004).

Other activities in this area include plug-in refrigeration units utilizing 460V/30 amp links intended to start with port containers through the remainder of the shipping infrastructure. This is not part of the SAE standard but is being incorporated into the National Electric Code (NEC) (Article 26). This was approved in the NEC committee and is expected to be approved the NEC convention in July 2007. The working group is still addressing implementation issues across different manufacturers. New activities include an electrification demonstration site in New York State and a July 19, 2007, ribbon cutting ceremony in Portland, Oregon, for 160 truck electrified parking locations.

Goal 5. Develop and Demonstrate Add-On Idling-Reduction Equipment That Meets Driver Cab Comfort Needs, Has a Payback Time of 2 Years or Less, and Produces Fewer Emissions of NO_x and PM Than a Truck Meeting 2010 Emission Standards By 2009

DOE presented to the committee information which showed that it had supported two fleet validations of cab comfort devices that could be added to existing fleets of vehicles.[5] The study with Schneider National tested both cab heating and cooling appliances. The cab heaters provided 2.4 percent fuel savings and less than 2-year payback. Two cooling systems were tested—one based on a phase-change and the other on battery power. These were tested in 19 and 70 trucks, respectively, and both reduced idling time by 3 percent. However, it was concluded that the cooling systems need further work before they can be widely deployed. In contrast, Schneider has installed over 6,000 heaters and expects to have 80 percent of its fleet retrofitted by winter 2007/2008.

In separate fleet tests with Wal-Mart International and Espar utilizing combined diesel heating and electric cooling resulted in Wal-Mart retrofitting its entire fleet with Tri Pac units (these provide heating, cooling, and accessory power).

Finding 6-6. The DOE-sponsored demonstrations with two major trucking fleets resulted in deployment of several idle-reduction devices. Greater success was achieved with cab heating than with cab cooling. It appears that only one device met the goal of less than 2-year payback. It is unclear whether the emissions requirement of the goal was met.

Recommendation 6-6. Given that funding and responsibility for idle-reduction technologies was redirected in the Energy Policy Act of 2005 to EPA and DOT, there is no requirement for DOE to pursue this area. However, given the progress to date and potential attractive returns on investment, it would be desirable for DOE, EPA, and DOT to continue to advance this aspect of fuel reduction and environmental mitigation.

Goal 6. Produce by 2012 a Truck with a Fully Integrated Idling-Reduction System to Reduce Component Duplication, Weight, and Cost

The major effort under the goal to produce by 2012 a fully integrated idling-reduction system is the DOE program with a team headed by Caterpillar to create the More Electric Truck system.[6] Other industrial participants included Kenworth, Emerson, SR Drives, and EMP. The program was designed to reduce both emissions and fuel consumption by the use of onboard and off-board electricity. Specifically, the More Electric Truck was designed to:

- Reduce parasitic losses
- Reduce radiator heat load
- Improve cooling system performance, air systems management and advanced power management

These improvements were designed to facilitate more effective idle reduction applications. International and Cox joined DOE and Caterpillar in some real world fleet tests. Some salient results (provided by the DOE, February 2007) were that:

- Fuel savings were up to 2 percent on road plus 6 percent from idle reduction

[5]Glen Keller, Linda Gaines, and Terry Levinson, U.S. Department of Energy, Center for Transportation Research, “Idle Reduction Technologies,” Presentation to the committee, Washington, D.C., February 8, 2007, Slide 14.

[6]Glen Keller, Linda Gaines, and Terry Levinson, U.S. Department of Energy, Center for Transportation Research, 2007, Idle Reduction Technologies,” Presentation to the committee, Washington, D.C., February 8, 2007, Slide 13.

- The HVAC unit can be driven by the APU during rest periods
- The truck can be plugged into shore-power electrical service, where fuel consumption to serve these loads can be cut significantly.

Another overall result was that the More Electric Trucks idled less than control vehicles (12.8 versus 26.5 percent) resulting in fuel savings.

The program has achieved some significant results but additional work is anticipated to further reduce fuel consumption. Example areas are mild hybrid storage using nickel metal hydride (NiMH) batteries; advanced cooling system components (electric thermostat valve and cooling fan, high efficiency after cooler); and decoupling the air compressor from the engine.

Finding 6-7. The More Electric Truck program demonstrated an integrated system to reduce idling emissions and fuel consumption. The test program showed significant progress toward achieving the objectives of Goal 2 in Chapter 5 ("Develop and demonstrate technologies that reduce essential auxiliary loads by 50 percent, from the current 20 hp to 10 hp, for class 8 tractor-trailers") and Goal 6 ("Produce by 2012 a truck with a fully integrated idling-reduction system to reduce component duplication, weight, and cost"). By demonstrating 1 to 2 percent estimated reduction in fuel use including significant truck idling reductions. According to DOE, this translates into an overall annual fuel savings for the U.S. fleet of 710 to 824 million gallons of diesel fuel (about $2 billion per year at $2.75 per gallon).

Recommendation 6-7. Given the potential of this program to save fuel, the committee recommends that the 21CTP continue the R&D of the identified system components that will provide additional improvements in idle reduction and parasitic losses related to engine components that are more efficient and provide better control of energy use. The program should focus also on the cost-effectiveness of the technologies.

Goal 7. Develop and Demonstrate Viable Fuel Cell APU Systems for Military And Other Users, in the 5-30 kW Range, Capable of Operating on JP-8 fuel with 35-Percent Efficiency (Based on the Fuel's Heating Value) by 2015

Based on the information provided by DOE in presentations, work under this goal is being performed by the DOD. The DOD has two fuel cell APU programs under way: the U.S. Army CERDEC (Communications-Electronics Research, Development, and Engineering Center) fuel cell APU programs focus on diesel and JP-8 fuel reforming coupled with fuel cells in the 500 W to 5 kW auxiliary power range. The U.S. Army TARDEC (Tank Automotive Research, Development and Engineering Center) fuel cell programs focus on combat vehicles and APUs in the range > 5 kW.

The DOD is supporting a variety of companies with various fuel reformers and fuel cells (solid oxide [SOFC] and polymer electrolyte membrane [PEM]). These studies are ongoing, and definitive results toward meeting goal 7 are not available.

Finding 6-8. The work on fuel cell APU is being carried out by the DOD and a number of contractors are being supported. There is no evidence that goal 7 has been met at this time.

Recommendation 6-8. The DOE's 21CTP should continue to monitor and interact with the DOD program. As DOD reaches its goals, DOE should explore with major truck operators the possibility of bringing appropriate fuel cell APU technologies into commercial use.

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7

Safety of Heavy Vehicles

HIGH-LEVEL TECHNICAL TARGETS AND TIMETABLES

Introduction

The vision of the 21st Century Truck Partnership (21CTP) is that the nation's trucks and buses safely and cost-effectively move larger volumes of freight and greater numbers of passengers while emitting little or no pollution and dramatically reducing the dependency on foreign oil. Safety is a vital element of the program. The U.S. Department of Energy (DOE) transports hazardous materials across the nation in large trucks. Ensuring the safety of these special trucks is critically important to DOE's mission. However, the majority of the 21CTP budget is devoted to energy efficiency and vehicle emissions reduction, and only a relatively small portion has been dedicated to safety-related technology.

Recent reductions in the overall 21CTP budget (discussed in Chapter 1) have limited the funding provided by DOE for safety research going forward. As such, DOE relies on the Department of Transportation's (DOT's) initiatives for progress in the area of truck safety, since DOT has historically had responsibility for transportation safety. Indeed, although DOE and DOT have worked collaboratively in certain areas with respect to truck safety, DOT has established a number of specific commercial truck safety goals, but these goals have been established independent of the 21CTP. Furthermore, DOT budget allocations in support of commercial trucks come from the various DOT agencies including the National Highway Traffic Safety Administration (NHTSA), the Federal Motor Carrier Safety Administration (FMCSA), and the Federal Highway Administration (FHWA), and are also independent of the 21CTP. Each of these DOT agencies has broad responsibility well beyond the goals of the 21CTP.

Consequently, the committee encountered some difficulty in addressing the subject of commercial truck safety. By virtue of the future DOE budget allocation, the 21CTP includes very little on truck safety. Yet, DOT goals for commercial truck safety support the 21CTP's vision of truck safety. Therefore, as a compromise, the committee elected to use the DOT safety goals, and to review selected DOT projects that support them. Moreover, this review of DOT programs is at a high level, because it is beyond the scope of this study to provide an in-depth review of all the DOT programs covering commercial truck safety and safety regulation. The review is also restricted to projects related to on-board large truck technologies and systems. Nevertheless, the committee suggests future work and outlines areas in which DOE and DOT collaboration might lead to improvements in large truck safety. DOT defines a "large truck" as one with a gross vehicle weight rating (GVWR) of more than 10,000 pounds (which includes vehicles that may be known in other contexts as medium and heavy trucks).[1] Finally, the committee notes that its discussion focuses mainly on large trucks due to the fact that the number of bus accidents and fatalities is much smaller in comparison.

Goals and Timetables

DOT has established several specific goals for commercial truck safety:

- Reduce the fatality rate for heavy-duty trucks and buses to 0.160 fatalities per 100 million total vehicle miles of travel by 2011.[2]
- Develop and implement technologies for better braking, rollover protection, vehicle position, and visibility enhancement:
  —*Braking*. Advanced braking technologies will be sought with the research goal of achieving a reduction of stopping distances by 30 percent from operational

[1]Personal communication (e-mail), Tim Johnson, DOT, NHTSA, June 12, 2008.

[2]Michael S. Griffith, FMCSA, "Federal Motor Carrier Safety Administration Safety Research Overview," Presentation to the committee, Washington, D.C., February 9, 2007.

speeds in appropriate platforms. Improvement in retention of braking ability during grade descents is desired.

—*Rollover*. Reduce the incidences of heavy vehicle rollover through the application of advanced technology brake control systems and other complementing technologies.

—*Vehicle position*. Develop and implement driver aid systems that promote safe following distance and in-lane tracking.

—*Visibility enhancement*. Develop and implement systems that provide the operator with 360 degree visibility (direct and indirect) in day and night conditions.

- Work with tire manufacturers to improve truck tire performance and reduce tire debris. Incorporate tire advancements with improved braking technologies to achieve substantial vehicle handling improvements.
- Determine the feasibility of enhanced occupant survivability in collisions (offset, frontal, and angle/sideswipe) at differential speeds up to 35 mph between heavy vehicles and passenger vehicles weighing approximately 4,000 pounds. Also, improvements will be sought in truck occupant seat belt use rates by harmonizing restraint systems requirements to enhance comfort and, therefore, driver acceptability.

Research Priorities and Budget Allocation

The committee asked DOE and DOT to provide a list of projects and related funding, prioritized by potential impact on reducing fatalities and injuries relevant to large truck and bus accidents. This request yielded only partial project lists, prioritized at the agency level (NHTSA, FHWA, and FMCSA), with too little information to give an overall picture of the safety programs or their funding trends.[3] As a result, it was not possible for the committee to integrate the patchwork of information to produce a clear picture of DOT's safety programs relevant to the 21CTP. This is another reason the committee elected the approach of discussing the DOT safety program at a high level, as mentioned above.

The committee understands that individual agencies and departments have responsibilities far beyond the subject of large-truck safety. Yet it appears that there is no single integrated list of truck safety projects prioritized by potential benefit. The committee addresses that topic later in this chapter.

ACCIDENTS INVOLVING LARGE TRUCKS

Before discussing progress toward achieving these DOT safety goals, the committee first reviews heavy-duty truck and bus accidents, to characterize their general nature. It then discusses how such accidents lead to traffic congestion and slowdowns, whose ultimate impact is increased fuel consumption and vehicle emissions.

The Nature of Heavy-Duty Truck and Bus Accidents

The main focus of the committee's discussion is large trucks, because they contribute to an overwhelming majority of accidents compared to buses. For example, in 2005 there were 5,510 fatalities due to accidents involving large trucks and buses, but 5,212 of those fatalities were due to large trucks (DOT, NHTSA, 2006a).

In 2004, 12 percent of the total number of highway fatalities involved large trucks (over 10,000 pounds gross vehicle weight), resulting in the death of 5,190 people (DOT, NHTSA, 2005a). In 2005 the number of fatalities due to large-truck crashes rose to 5,212, while another 114,000 people were injured in large-truck accidents (DOT, FMCSA, 2007a). In 2006, the number dropped to 5,018 fatalities (*Transport Topics*, 2007). Although the most serious results of highway accidents are the fatalities and injuries, there is also a significant cost to society associated with large truck and bus accidents. In one study, the medical costs, emergency service costs, property damage costs, lost productivity costs, and the monetized value of the pain and suffering incurred by the families of those who die or are injured due to crashes were used to estimate the total cost of accidents. It was found that on average, the cost due to a large-truck crash was almost $60,000, while the average cost due to an inter city bus crash was over $32,000, based on 2000 dollars (Zaloshnja and Miller, 2002).

Large trucks pulling semi-trailers (Class 8) accounted for almost two-thirds of the truck-involved fatal crashes in 2005 (DOT, FMCSA, 2007a). The majority of fatal accidents involved vehicle–to-vehicle crashes rather than single-vehicle accidents. In 2005, the causes of fatal crashes were (1) large truck rear-ending passenger vehicle, 5 percent; (2) passenger vehicle rear-ending large truck, 16 percent; (3) large truck striking passenger vehicle (other than rear-ending), 35 percent; and (4) passenger vehicle striking large truck (other than rear-ending), 38 percent (DOT, FMCSA, 2007a). However, it is noteworthy that in 61.4 percent of the large truck fatality accidents, the initial point of impact with the large truck was the front of the truck (DOT, FMCSA, 2007b, Table 42).

In fatal accidents involving heavy trucks and lighter vehicles, the fatality is most often an occupant of the lighter vehicle, due, obviously, to the size and weight differentials. For example, in 2005, 92 percent of the fatalities due to such accidents were the occupants of the lighter vehicle (DOT, NHTSA, 2005a).

Although the number of heavy-duty trucks involved in fatal crashes per miles traveled declined, the total number of large trucks involved in fatal crashes increased from 4,472 to 4,932 from 1995 to 2005, and the total number of fatalities increased from 2004 to 2005 as noted above.

[3] DOE, FCVT, response to committee queries on safety issues, transmitted via e-mail by Ken Howden, March 27, 2007.

Studies suggest that in many cases the accidents between light and heavy vehicles are caused by the driver of the smaller vehicle. According to data collected by the Federal Motor Carrier Safety Administration (FMCSA), DOT, passenger vehicle drivers accounted for 66 percent of fatal accidents involving large trucks (DOT, FMCSA, 2007a). In a study of 210 accidents reported in 2002 by the University of Michigan's Transportation Research Institute (UMTRI) (Hanowski, 2002), the results suggested that 78 percent of the accidents were initiated by the light-vehicle driver. Further, the study concluded that "[a]ggressive driving on the part of the light vehicle driver was found to be the primary contributing factor for light vehicle driver initiated incidents. For heavy vehicle driver initiated incidents, the primary contributing factor was poor driving technique."

In another study of heavy truck accidents, Blower found that 70 percent of the truck-car accidents were cause by the driver of the car (De Groat, 1999). However, in a study of heavy truck accidents in North Carolina, Council et al. (2003) found a more even distribution of fault, reporting that across a broad spectrum of accident types, including accidents such as low-speed backing accidents, truck drivers account for slightly more accidents than car drivers: 48 percent for truck drivers and 40.2 percent for drivers of cars.

Accident causation has been a focus of research for many years. It is well known that for accidents leading to fatalities, considering all vehicle types—not just heavy trucks—alcohol or speeding are often causal factors, with alcohol involvement cited in about 40 percent of fatal accidents during the past 10 years, and speeding a factor in about 30 percent of fatal accidents over the same period of time (DOT, NHTSA, 2006a). However, alcohol and speeding are most often attributed to the driver of the vehicle other than the heavy truck (e.g., 22 percent of car drivers involved in fatal accidents were speeding while 7 percent of large truck drivers involved in fatal accidents were speeding). A recent report on large truck accident causation cites a variety of factors including driver fatigue, falling asleep, inattention, driving too fast for conditions, and physical impairment due to illness (DOT, NHTSA, 2006c).

Compared with heavy-duty trucks, the number of people killed in accidents involving medium-duty single-unit trucks is much smaller than the aforementioned case of large-truck accidents (300 fatalities in 2005 for classes 5 and 6 combined, for example) due to the fact that these medium-duty trucks typically operate at lower speeds, in an urban area, and during daylight (DOT, NHTSA, 2006c, p. 59).

Bus accidents account for a much smaller percentage of fatalities and injuries. For instance, in 2005, there were a total of 278 bus accident related fatalities, representing only 0.5 percent of all highway vehicle fatalities for that year (DOT, NHTSA, 2005a). Moreover, school-bus travel continues to be quite safe compared to travel in most other highway vehicles. Although any child fatality is a tragedy, from 1995 through 2005 on average only 21 school age children were fatalities in school transportation related crashes each year—of that 21, typically 6 were occupants of school transportation vehicles and 15 were pedestrians (DOT, NHTSA, 2005c, p. 1).

Impacts of Large-Truck Accidents on Fuel Consumption and the Environment

As described in the previous section, large truck crashes are a major cause of accident fatalities and injuries in the United States each year. That is reason enough for major efforts by industry and government to improve heavy truck highway safety. However, they also have direct impacts on fuel consumption and the environment. Accidents involving large trucks and buses create significant delays on our highways, particularly in congested areas. During these delays, there are increases in fuel usage due to travel at low speeds and while sitting in traffic at idle. There is a corresponding increase in tailpipe emissions during these times. In some cases, the accidents involve vehicles carrying hazardous materials, creating an even more dangerous situation, and in certain cases, potential issues related to national security.

Of course, accidents also contribute to costs associated with lost work time by commuters. Indeed, highway congestion, even in the absence of an accident, is a serious problem in the United States and in many large cities around the world. The Texas Transportation Institute (TTI) tracks congestion data for the 85 largest cities in the United States (http://tti.tamu.edu/). According to TTI, in 2003, in the combined total of the 85 cities, there was travel delay of about 3.7 billion hours, associated with which there was excess fuel consumption of 2.258 billion gallons of fuel. Elements contributing to congestion include heavy traffic, highway construction and repair, and roadway incidents including accidents (Texas Transportation Institute, 2007, Table 2).

A recent report prepared by the Volpe Center, DOT (Flieger et al., 2007), the authors provide estimates of the impact of commercial vehicle crashes on fuel economy and emissions. The authors project that each commercial motor vehicle (CMV) crash leads to additional fuel consumption of from almost 800 gallons to as much as 1,200 gallons depending on the level of congestion prior to the crash. Estimating extra emissions caused by CMV crashes is extremely difficult due to the variation of the factors involved. However, the Volpe report estimates that over a year, CMV crashes in the major metropolitan areas in the United States produce significant levels of emissions: CO on the order of 100,000 tons, and NO_x on the order of 14,000 tons. Perhaps of more consequence, most of these emissions are localized in urban areas, thereby aggravating local health issues. Clearly, improvements in CMV safety will contribute to reduction in fuel consumption and exhaust emissions.

GOAL 1: REDUCE THE LARGE-TRUCK AND BUS FATALITY RATE TO 0.160 PER 100 MILLION TOTAL VEHICLE-MILES BY 2011

The information in this section clearly shows that large truck accidents are a very serious problem in the United States, causing major loss of life, thousands of serious injuries, and substantial property damage. Moreover, although some improvement has occurred since the highs of 1997, 1998, and 1999, the total number of deaths due to large truck accidents seems to remain in the neighborhood of 5,000 per year, and was higher in 2004 and 2005 than it was as long ago as 1994, as is shown in Figure 7-1. This trend is not unique to large truck accidents; highway fatalities due to all types of accidents have remained constant over the past decade. In fact, although the number of fatalities per miles traveled has decreased, the total number of fatalities has increased slightly from 40,716 in 1994 to 43,443 in 2005 (FARS data online).

On the other hand, there has also been a decrease in the rate of large-truck-related accidents as the number of vehicle miles traveled has increased steadily. Thus, improvements in highway safety have been observed. Figure 7-2 shows the fatality rate for large truck and bus accidents from 1995 to 2005. The fatality rate has declined from 0.215 to 0.184 during that time period while the total vehicle miles traveled

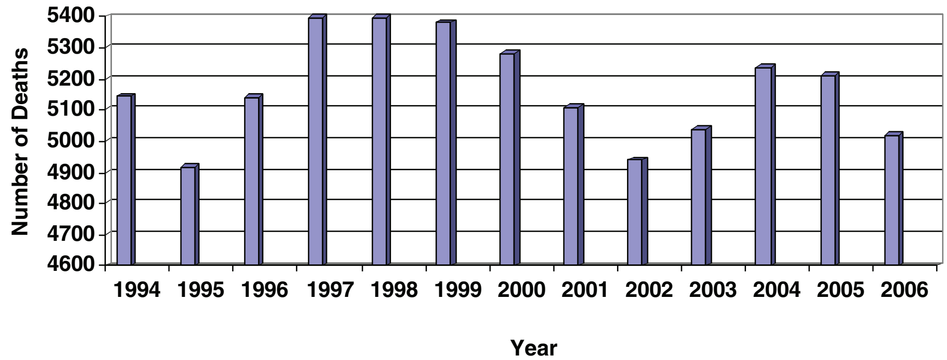

FIGURE 7-1 Deaths due to large-truck accidents. SOURCE: Data from DOT, NHTSA, Fatality Analysis Reporting System. Available at www.fars.nhtsa.dot.gov/ Accessed May 13, 2008.

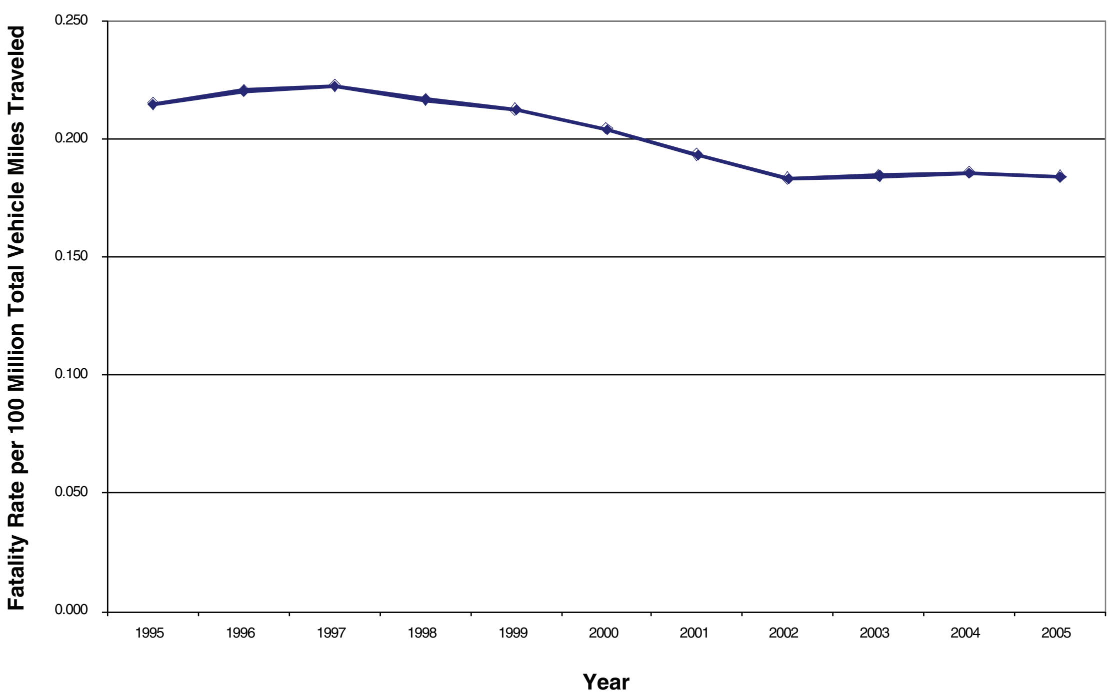

FIGURE 7-2 Large-truck and bus fatality rate (per 100 million total vehicle miles traveled). SOURCE: Michael Griffith, DOT, FMCSA, August 29, 2007. Large Truck and Bus Fatality Rates, 1995-2005. Personal communication to the committee.

has increased from 2,422,696 to 2,989,807, a 23 percent increase. As noted earlier, compared to bus accident related fatalities, large truck accidents contribute the most to highway fatalities by a large margin (~95 percent of fatalities).

Although the rate has improved, unfortunately, we have not seen a significant decrease in the number of large truck accident related fatalities in spite of the fact many resources have been directed at making improvements in vehicle safety. Earlier efforts were focused on crash protection, including improvements in structural crashworthiness and occupant protection. Increased usage of seat belts both in trucks and cars provides enhanced survivability. In light vehicles, the increased usage of air bags further enhances survivability in more severe crashes.

One might conclude that crashworthiness improvements have merely offset the increase in accidents due to the increase in total miles driven, and that we will have to reduce the number of crashes through accident avoidance technologies in order to significantly reduce the number of fatalities. To this end, DOT has been putting more focus on accident prevention. Crash avoidance topics relative to vehicle modifications include improvements in braking; rollover reduction; vehicle position (safe following, lane tracking); visibility enhancement; and tire safety.[4] However, as the committee noted earlier in this chapter, most accidents are due to driver error. Moreover, in 2005 there were 14,539 car and truck fatalities due to crashes in which alcohol was a factor (DOT, NHTSA, 2006a). Therefore it will be important to assess the potential benefit of vehicle modifications to determine whether or not DOT's goals for fatality rate reduction can be met.

Finding 7-1. The DOE program director of the 21st Century Truck Partnership has no direct authority for heavy-duty truck safety projects because there is no budget in the program itself to support safety projects. The program manager will need to continue to work with DOT, because DOT has several initiatives with the goal of making improvements in heavy-duty truck safety. They range from driver education to accident avoidance technology. However, the committee was unable to determine whether the goals would be met as a result of these initiatives.

Recommendation 7-1. DOT should develop a complete and comprehensive list of current and planned heavy-duty truck safety projects and initiatives, and prioritize them in order of potential benefit in reducing heavy-duty truck-related fatalities. The list should provide quantitative projections of fatality reduction potential attributable to each project. The list should also be used to prioritize budget and resource allocations, in order to expedite heavy-duty truck safety progress.

[4]Tim Johnson, DOT, NHTSA, "NHTSA Heavy Vehicle Research Overview," Presentation to the committee, Washington D.C., March 28, 2007, Slide 6.

GOAL 2: CRASH AVOIDANCE (E.G., BRAKING, ROLLOVER AVOIDANCE, VEHICLE POSITION CONTROL AND MONITORING, VISIBILITY IMPROVEMENTS, AND TIRE PERFORMANCE)

As mentioned above, it may be that we are seeing diminishing returns with respect to further improvements in crash protection; perhaps other, further benefits might come from 100 percent seat belt usage on the road. Crash avoidance has become, thus appropriately, the overarching next generation goal.

Programs

Braking

DOE and DOT are working toward improvements in braking to achieve a reduction by 30 percent in stopping distance, by considering the application of air disc brakes, more powerful front-axle brakes, and electronic control (DOE, 2006).[5] In addition, work is ongoing at DOE laboratories to develop improved properties in brake materials.

The Department of Transportation is sponsoring several studies at DOE laboratories (DOE, 2006, p. 52). NHTSA has initiated several brake related studies at Oak Ridge National Lab (ORNL). A study on standardizing the rating of brake friction materials is aimed at maintaining standard capabilities in new and replacement brakes. Additional research is focused on testing brake materials on test tracks to correlate material properties with brake performance.

The Federal Highway Administration (FHWA) has initiated a study at ORNL aimed at improving the accuracy of truck brake simulations by incorporating the effects of temperature, humidity and braking torques on brake performance.

Rollover Prevention

The objective is to reduce the incidences of heavy vehicle rollover through applications of advanced braking systems and other technologies. NHTSA is working with industry using currently available commercial hardware to determine the effectiveness of roll stability systems and yaw stability control systems on tractors, and roll stability systems on trailers (Evans et al., 2005). In addition, NHTSA has sponsored work at the University of Michigan Transportation Research Institute on a hardware in the loop simulation study of electronic control systems, and has recently awarded an electronic stability control (ESC) driving simulator study to the National Advanced Driving Simulator at the University of Iowa.[6]

[5]Tim Johnson, DOT, NHTSA, "NHTSA Heavy Vehicle Research Overview," Presentation to the committee, Washington D.C., February 8, 2007, Slide 6.

[6]Tim Johnson, DOT, NHTSA, "NHTSA Heavy Vehicle Research Overview," Presentation to the committee, Washington D.C., March 28, 2007, Slide 6.

Vehicle Position Control

Research in this area includes studies of both forward collision warning to prevent rear impacts, and side-to-side lane departure warning. Both NHTSA and FMCSA have been heavily involved in research in these areas.[7] In cooperation with industry, electronically controlled brake systems, collision warning systems, and adaptive cruise control systems are being evaluated to determine their effectiveness. In addition, on-board monitoring systems are being investigated to determine their effectiveness in alerting drivers who might become drowsy or distracted.

Visibility

According to NHTSA, one of the largest causes of large truck crashes results from lane changing and merging with other traffic. In many cases the accident is caused by the truck driver not being able to see areas that are blind spots. In cooperation with FMCSA, NHTSA is exploring the use of video mirrors to eliminate truck blind spots. Longer range potential research topics could include advanced night vision systems and head up displays, according to the 21CTP Roadmap (DOE, 2006).

Tire Performance

The objective is to work with tire manufacturers to improve truck tire performance and to reduce roadway tire debris (DOE, 2006). It will be important to couple tire behavior with improved braking technology to optimize vehicle stopping distance as well as handling. NHTSA plans to research improvements to FMVSS 119 relative to endurance and high speed tires, with emphasis on identification of the frequency and failure mode of both new and retread heavy vehicle).

Additional studies include methods for monitoring tire pressure and the effects of replacing standard dual tires with single tires on truck tractors.

In the area of tire mechanics, it is important for DOE and DOT to work closely together, to ensure that changes that lead to reduced rolling resistance don't compromise safety.

Other Focuses

Improving driver performance is, of course, an important approach to preventing accidents. Driver fatigue has been cited as an important factor leading to accidents, and the National Transportation Safety Board has proposed the use of on-board recorders to ensure that drivers comply with rules regarding hours of service.[8]

The committee noted in this chapter that 7 percent of heavy truck drivers were speeding in accidents that led to a fatality. Some trucking companies employ speed control governors to prevent speeding. Reduced speed also reduces fuel consumption.

DOT's Intelligent Transportation Systems Program (ITS) is broad in scope, touching on road design and operation, vehicle technologies, human factors research and in-vehicle as well as inter-vehicle communications.[9] The ITS programs involve not only federal government agencies, but also heavy and light vehicle manufacturers, state and local governments, and contract research groups including universities.

The ITS program is beyond the scope of this report. However, we note that many aspects of ITS support the objective of accident avoidance. Furthermore, ITS is broad in vehicle scope, potentially covering communications among all highway vehicles; this could be an important element in helping to prevent large truck crashes with light vehicles.

It is also beyond the scope of this study to evaluate the work being done in support of our roads, bridges, and road infrastructure. However, the road system and its condition critically influence highway safety.

Progress Toward Goals

Braking

Several high-technology tractor-trailer trucks have been built that have demonstrated stopping distance reduction on the order of 30 percent. This result has been achieved using air disc brakes. The use of these brakes will also improve the fade resistance of large truck brake systems. Cost will be an issue with respect to rapid deployment (DOE, 2006, p. 1). In a DOT Field Operational Test (FOT) involving Volvo, test results validated the improvement in stopping distance using disc brakes, and also showed that the disc brakes have longer useful life compared with drum brakes (Volvo Trucks North America, 2005).

Rollover Prevention

In a field operational test involving six Freightliner tanker trucks, an in-cab system was evaluated. The system indicates to the driver what the rollover threshold is of the combination truck-trailer, and how close to that threshold the vehicle is at any instant in time. As a result of data analysis, it was concluded that the driver advisor system reduced the overall chance of rollover by from 20 to 30 percent for "too fast around the curve" types of potential rollover (DOE, 2006, p. 61).

[7]Tim Johnson, DOT, NHTSA, "NHTSA Heavy Vehicle Research Overview," Presentation to the committee, Washington D.C., February 8, 2007, Slide 4.

[8]Mark V. Rosenker, "On-Board Recorders (EOBR's) and Truck Drivers Fatigue Reduction," Presentation to the U.S. Senate, May 1, 2007.

[9]Michael F. Trentacoste, DOT, FHWA, "Safety R&D Overview," Presentation to the committee, Washington, D.C., February 8, 2007, Slides 5 and 6.

Vehicle Position Control

Two different field operational tests have been completed and provide results relative to vehicle position control. A field operational test in cooperation with Mack Trucks studied the performance of on-board lane departure warning systems. The Volvo FOT mentioned earlier included systems for collision warning, adaptable cruise control, and electronically controlled braking systems.[10] According to DOT, the lane departure warning systems, under FOT conditions, provided a 21 percent to 23 percent reduction in accidents for single vehicle roadway departure, and a 17 to 24 percent reduction in rollovers (DOT, FMCSA, 2006). The Volvo FOT (Volvo Trucks North America, 2005) showed that it could be possible to reduce rear impacts by 28 percent by using a combination of collision warning, adaptive cruise control, and electronic braking.

Visibility

Performance specifications for camera/video imaging systems are expected to be completed in September 2007. In September 2008, the development and assessment of a 360 degree vision system capable of operating in all weather conditions should be completed.

Tire Performance

NHTSA is working with the American Society for Testing and Materials and tire companies on the aforementioned programs. Results are expected in 2007.

Researchers at ORNL have been studying the benefits of using a single tire to replace two thinner tires on heavy duty tractor trailer trucks. They have found that the single tire improves fuel economy by as much as 3 percent and also allows them to be run with more stability.[11]

Tire pressure monitoring systems are being developed to ensure proper pressures on truck tires. Keeping tires properly inflated maintains safety performance and improves fuel economy by reducing tire rolling resistance. In a study of light vehicle tires, it was found that a 10 percent reduction in average rolling resistance could yield a 1 to 2 percent improvement in fuel economy and that this could be done without sacrificing safety (NRC, 2006).

Summary of Performance

A number of programs are currently in progress to advance the individual goals of crash avoidance. These programs are in various states of completion, with some having reached milestones. During the past several years, large truck OEMs, working with suppliers, have developed on-board systems for enhancing roll and yaw stability, for improving straight line braking performance, for collision warning, and for alerting drivers relative to lane departure. In cooperation with DOT, many of these systems have been or are being evaluated in FOTs, and results are being reported.

Finding 7-2. Programs are underway to develop and implement technologies and vehicle systems to support safety goals. Indeed, private industry, through internal research and commercial product development, has produced commercially available systems for enhanced braking, roll stability, and lane departure warning. They are beginning to be used in the field. It is now important to determine to what extent these accident avoidance technologies will reduce the number of accidents and therefore fatalities and injuries.

Recommendation 7-2. DOT should continue programs in support of heavy-duty truck onboard safety systems, with an emphasis on accident avoidance and with priorities set by a comprehensive potential cost/benefit analysis (Recommendation 7-1). Particular emphasis should be placed on monitoring the accident experience of heavy-duty trucks as these systems begin to be deployed in the field (for example, as electronic stability control systems begin to penetrate the fleet). It is the role of the manufacturers to develop safety systems for commercial application. DOT can play important roles in (1) providing support for field tests (known to DOT as field operational tests), (2) monitoring field data to help substantiate benefit analyses used to prioritize resources, and (3) implementing regulations that would require the adoption of safety systems that were proved to be effective. With adequate field data, DOT should refine and more rigorously specify and prioritize goals for accident avoidance technologies.

Appropriate Roles for DOT in Accident Avoidance Technology Development and Deployment, and Other Areas of Vehicle Safety

The Department of Transportation plays an important role in large truck safety by establishing safety requirements for new vehicles, by licensing commercial drivers, and by ensuring that safe practices are used once the vehicles are in service. In addition to this regulatory role, DOT can promote highway safety by working with original equipment manufacturers, suppliers, other government agencies, including DOE, and others in helping to evaluate the effectiveness of newly developing large truck safety systems. The field operational tests are an example of how DOT is currently doing this. Furthermore, DOT can play an important and unique role by monitoring the field performance of truck safety systems to accurately assess the cost-benefit of such systems and by identifying any deficiencies in the systems. Finally, DOT can monitor safety initiatives and practices

[10] Tim Johnson, DOT, NHTSA, "NHTSA Heavy Vehicle Research Overview," Presentation to the committee, Washington D.C., March 28, 2007, Slide 6.

[11] See www.greencarcongress.com/2006/06/single_widebase.html.

around the world, and use this information along with its own studies to suggest future work that might further the goals of highway safety.

GOAL 3: CRASHWORTHINESS RESEARCH (SURVIVABILITY)

The crashworthiness of heavy duty trucks is an area in which close collaboration between DOE and DOT is critical. Structural changes to the truck for weight reduction might be suggested for fuel economy savings as part of the 21CTP. It must also comprehend how the application of lightweight materials would affect the structural crashworthiness of the vehicle. Any modification to the exterior shape for improvements in safety could also affect the aerodynamic performance of the vehicle and thus its fuel efficiency. As a specific example, it was noted (DOE, 2006) that the addition of the rear under-ride guard to truck trailers adversely impacted the aerodynamic performance by increasing vehicle drag.

In addition to considering the crashworthiness of the heavy truck for the sake of protecting the truck driver, DOT should further explore the truck design from the standpoint of its aggressiveness in a collision with smaller vehicles. As the committee noted in the section entitled "Accidents Involving Large Trucks," more than half of the fatal accidents in which a heavy truck collided with another vehicle involved contact with the front of the truck, suggesting this as an area for additional study with respect to alternate materials and under-ride guards.

Finding 7-3. In spite of extensive improvements in light vehicle crashworthiness made during the past decade, the number of fatalities caused by heavy-duty truck accidents has remained nearly constant, at approximately 5,000 per year, although the fatality rate has decreased showing that progress is being made. In most cases, the occupant(s) of the light vehicle is the one fatally injured. It appears that to make significant safety progress, it will be necessary to reduce the number of accidents substantially by implementing accident avoidance technologies as well as methods for improving driver behavior. In light of this need, DOT future plans have been directed largely at accident avoidance technologies.

Recommendation 7-3. The committee agrees with the apparent decision by DOT to put more emphasis on accident avoidance technologies than on additional crashworthiness research. In addition, DOT should continue to focus on driver education and law enforcement. Furthermore, DOE and DOT should work collaboratively, because there often are trade-offs between vehicle safety and fuel economy, for example, as new fuel efficient systems emerge. There are obvious trade-offs between safety and fuel economy in many areas of research such as tire mechanics and braking (especially with respect to hybrid vehicles). Of course, any additional work in aerodynamics or weight reduction might alter the vehicle configuration and therefore its crashworthiness. Moreover, as new fuel efficient systems emerge, such as hybrid electric systems, and vehicles using alternate fuels including, for example, hydrogen, it will be imperative that DOE and DOT work closely to ensure continued progress toward more fuel efficient vehicles but without compromising highway safety.

BENEFITS OF 21ST CENTURY TRUCK PARTNERSHIP SAFETY RESEARCH

Due to the relatively large number of fatalities and injuries suffered as a result of large truck accidents, it is entirely appropriate to consider many different safety technologies—in fact it may require an integrated system of technologies to make a large impact on the problem. For example, NHTSA has shown that a 30 percent improvement in stopping distance due to enhanced braking capability, could lead to a reduction of 257 fatalities.[12] Unfortunately, this represents only a 4.9 percent reduction in fatalities related to large truck accidents based upon the number of fatalities reported in 2005, illustrating the point that significant improvements in truck safety are still needed.

The aforementioned discussion raises the obvious need for the development of an analysis of the numerous safety technologies under consideration, to be used to prioritize projects and funding. FMCSA has provided a list of large truck safety systems being applied and their approximate retail prices.[13]

- Roll stability control systems
  —Tractor based system: ~$500 above cost of traction control
  —Trailer based system: ~ $1,000-$1,500
- Electronic stability control systems: ~$1,500-$2,100
- Lane departure systems: ~$700-$1,500
- Collision warning systems: ~$700-$5,000 depending on options

Continued development should bring down these costs over time. However, there is only cursory and incomplete information available at this time to indicate to what extent the incorporation of all of these and other safety technologies will lead to the overall safety goals for fatality reduction for large truck and bus accidents as set by DOT.

NHTSA has addressed the potential benefits of electronic stability control (ESC) systems applied to passenger cars, multipurpose vehicles, and trucks and buses with a gross vehicle weight rating of 4,536 kg (10,000 lb) or less. Based on crash data studies, NHTSA estimates that the use of ESC will reduce single-vehicle crashes of SUVs by 59 percent and

[12] DOE, FCVT, response to committee queries on safety issues, transmitted via e-mail by Ken Howden, March 27, 2007.

[13] DOE, FCVT, response to committee queries on safety issues, transmitted via e-mail by Ken Howden, March 27, 2007.

reduce rollovers by 84 percent. Overall, the annual potential benefit of ESC applied to these vehicles is estimated to be 5,300 to 10,300 lives saved and prevention of 168,000 to 252,000 injuries in all types of light vehicle crashes (DOT, NHTSA, 2006b). No comparable analysis of the potential benefit of ESC applied to heavy trucks has been found. However, the fact that there are over 15,000 rollovers of commercial trucks each year accounting for 12 percent of fatalities (UMTRI Research Review, 2000) suggests that there is a large potential benefit. It is encouraging at this time that heavy truck manufacturers and component suppliers are making stability control systems available on new trucks.

In addition to the aforementioned systems, it would be helpful to have similar analyses of other technologies under consideration. For example, the ITS technologies, including vehicle-to-vehicle communications, will permit communication between large commercial trucks and passenger cars and trucks, perhaps leading to substantial reduction in accidents. But it is important to know what improvements in safety will likely come from these technologies.

In conclusion, a benefit analysis for any system under consideration should be developed to help prioritize the work, and to help speed up the introduction of safety systems. A technology roadmap showing the benefit of all technologies under development would be very useful in generating support for the large truck safety effort.

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Appendixes

Appendix A

Biographical Sketches of Committee Members

John H. Johnson, *Chair,* is a Presidential Professor Emeritus, Department of Mechanical Engineering-Engineering Mechanics, Michigan Technological University (MTU), and a fellow of the Society of Automotive Engineers and the American Society of Mechanical Engineers. His experience spans a wide range of analysis and experimental work related to advanced engine concepts, diesel and other internal-combustion engine emissions studies, fuel systems, and engine simulation. Dr. Johnson had been previously Project Engineer, U.S. Army Tank Automotive Center, and chief engineer, Applied Engine Research, International Harvester Company before joining the MTU mechanical engineering faculty. In 1986-1993, he served as chairman of the MTU Department of Mechanical Engineering and Engineering Mechanics. He has served on many committees related to engine technology, engine emissions, and health effects—for example, committees of the Society of Automotive Engineers, the National Research Council (NRC), the Combustion Institute, the Health Effects Institute, and the Environmental Protection Agency—and has been a consultant to a number of government and private-sector institutions. In particular, he served on the NRC's Committee on Fuel Economy of Automobiles and Light Trucks and the Committee on the Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) and Standards and chaired the Committee on Review of DOE's Office of Heavy Vehicle Technologies. Presently, he is a member of the NRC Committee on the Fuel Economy of Light-Duty Vehicles. In 2002, Dr. Johnson was honored with the American Society of Mechanical Engineers' Soichiro Honda Medal. He was recognized with this medal for advancing the understanding of vehicle cooling problems and for research investigations into the origin of diesel exhaust pollutants and their impact on human health. He received his Ph.D. in mechanical engineering from the University of Wisconsin.

Jewel B. Barlow is director of Glenn L. Martin Wind Tunnel at the University of Maryland, College Park. His research areas include applied aerodynamics, experimental aerodynamics, flight mechanics and control, vehicle design process, and vehicle aerodynamics. Dr. Barlow is a member of the Society of Automotive Engineers' Road Vehicle Aerodynamics Committee. His publications include the book "Low Speed Wind Tunnel Testing," now in its third edition (Wiley 1999) and numerous papers. He holds a B.S. in physics and an M.S. in aerospace engineering, both from Auburn University, and a Ph.D. in aerospace engineering from the University of Toronto.

Paul N. Blumberg (NAE) is a consultant in the areas of engines and powertrain systems. His previous positions at Ford Motor Company include director, Physical Sciences and Systems Research Laboratory and Powertrain and Vehicle Research, Ford Research Laboratories; director, Task Force on Fuel Consumption Reduction, Research & Vehicle Technology, Product Development and Director, Global Product Development Information Technology Systems. Other positions that Dr. Blumberg has held include president/principal engineer, Ricardo North America Incorporated; and manager, Engine & Powertrain Systems Technology, Science & Technology Laboratory, International Harvester Company. He has extensive experience with engine systems analysis; hybrid powertrains; fuel economy technologies; internal combustion engines, including diesel, gasoline, compressed natural gas and hydrogen; emission control systems and catalysts, and aluminum alloy casting technology. Dr. Blumberg was elected fellow of the Society for Automotive Engineers. He serves on a number of advisory boards including as outside reviewer to some of the national laboratories work on advanced vehicle technologies, such as combustion engines and fuel cell power plants. He has a Ph.D. in chemical engineering from the University of Michigan, an S.M. in chemical engineering from the Massachusetts Institute of Technology (MIT), and an S.B. from MIT.

Andrew Brown, Jr. (NAE) is executive director and chief technologist, Delphi Corporation. Dr. Brown went to Delphi from the General Motors Research and Development Center in Warren, Michigan, where he was director of Strategic Futures. He served as manager of Saturn Car Facilities from 1985 to 1987. At Saturn, he was on the Site Selection Team and responsible for the conceptual design and engineering of this innovative manufacturing facility. Dr. Brown began his General Motors career as a project engineer at Manufacturing Development in 1973. He progressed in the engineering field as senior project engineer, staff development engineer, and manager of research and development for the manufacturing staff. During this period, he worked on manufacturing processes and systems with an emphasis on energy systems, productivity improvement, and environmental efficiency. Before joining GM, he supervised process development at Allied-Signal Corporation, now Honeywell, Incorporated, in Morristown, N.J. He earned a B.S. degree in chemical engineering from Wayne State University in 1971. He received an M.B.A. in finance and marketing from Wayne State University in 1975 and an M.S. degree in mechanical engineering with a focus on energy and environmental engineering from the University of Detroit–Mercy in 1978. He completed the Pennsylvania State University Executive Management Course in 1979. A registered professional engineer, Dr. Brown earned a Doctorate of Engineering in September 1992. He is currently serving or has served on the boards of the following organizations: Society of Automotive Engineers, Engineering Society of Detroit, Convergence Education Foundation, National Inventors Hall of Fame, Convergence Transportation Electronics Foundation, National Council of Engineering Examiners, State of Michigan Board of Professional Engineers, WSR College of Engineering Board of Advisors. Dr. Brown has been an adjunct professor at Wayne State University, the University of Michigan, and Tsinghua University (Beijing, China).

Joseph M. Colucci (NAE) is president, Automotive Fuels Consulting, Inc., and retired executive director, Materials Research, General Motors Research and Development Center. His previous positions included serving as head, assistant head, research engineer, and senior research engineer, Fuel and Lubricants Department, General Motors Research and Development Laboratories. His research interest focuses on vehicle emissions and fuel economy and on the interactions among the engine, fuel system, fuel, and emissions-control system. Conventional engines (spark-ignition and diesel) and fuels (gasoline and diesel fuel), alternative fuels, and new vehicle propulsion systems (hybrids and fuel cells) are also among his current interests. These research topics have societal benefits for improved air quality and reduced vehicular energy consumption. Mr. Colucci has served on numerous technical advisory committees. He has a B.S.M.E. from Michigan State University and an M.S.M.E. from the California Institute of Technology.

Patrick F. Flynn (NAE) is retired vice president for research at Cummins Engine Company, Inc. Among other professional associations, Dr. Flynn was on the executive advisory board of the U.S. Army University Research Initiative and was on the advisory board for the Department of Energy's combustion research facility at Sandia National Laboratories. Dr. Flynn is a member of the Combustion Institute and a registered professional engineer in Indiana. He has served on a number of National Research Council boards and committees, including as a member, Board on Army Science and Technology; chair, Committee on Portable Energy Sources for the Objective Force Warrior; member, Committee on the Future of Personal Transport in China; and member, Committee on Army After Next Logistics. He has expertise in diesel engine designs, mechanical engineering and integrated power systems. He received his bachelor's and master's degrees in agricultural engineering from the University of Minnesota, his M.B.A. from Indiana University, and his Ph.D. in mechanical engineering from the University of Wisconsin.

Thomas D. Gillespie is a Research Professor Emeritus and former director of the Great Lakes Center for Truck and Transit Research at the University of Michigan. He currently works part time at Mechanical Simulation Corporation in Ann Arbor, Michigan, as the director of product planning. His research is in vehicle dynamics and vehicle-roadway interaction. He was at the University of Michigan from 1976 to 2005, except for service in 1987-1988 as a senior policy analyst in the White House Office of Science and Technology Policy. From 1973 to 1976 he was with Ford Motor Company. Dr. Gillespie is the author of *Fundamentals of Vehicle Dynamics* (Society of Automotive Engineers, 1992). He was a member of Transportation Research Board's Committee for a Study of Consumer Automotive Safety Information. He holds a Ph.D. in mechanical engineering from Pennsylvania State University as well as an M.S. and a B.S. from the Carnegie Institute of Technology.

S. William Gouse is vice president of the Intelligent Transportation Society of America, a position that he has held since early 2006. He is also managing director, Sustainable Transport and Vehicle Systems. His previous positions include executive director, United States Council for Automotive Research; vice president of engineering, American Trucking Association; executive engineer for technology planning, Freightliner, LLC; and others. He has 25 years of experience in automotive/truck and vehicle systems as a product design and development engineer and manager, planning and executing domestic and international projects for research, testing, evaluation, prototyping, and production of safety, environmental, alternative, and conventional fuels, and of vehicle intelligence systems, as well as in regulatory and technology policy. He has also managed government-sponsored/cooperative research and development programs, technical communications, and program outreach. Mr. Gouse has published numerous technical papers and articles on vehicle technologies, emissions controls, and systems engineering and holds several patents for both products and processes. He holds a bachelor of mechanical engineering from the Georgia Institute of Technology and is a candidate for a masters of science in transport emissions at the University of Leeds, United Kingdom.

Larry J. Howell is a consultant to industry and government, specializing in the management of research and design for business innovation, automotive technology, telematics, and vehicle structures and materials. His previous positions include executive director, science, of the General Motors Research and Development Center, in which he served as chief scientist for General Motors (GM), overseeing of the company's R&D center's six science laboratories (Thermal and Energy Systems; Electrical and Controls Integration; Materials and Processes; Enterprise Systems; Chemical and Environmental Sciences; and Vehicle Analysis and Dynamics). Dr. Howell had global responsibility for joint research with universities, government agencies, and GM's alliance partners. He also served as secretary to GM's Corporate Science Advisory Committee, which reports on technology issues to the General Motors board of directors. Other positions that Dr. Howell held at GM included director of body and vehicle integration at GM Research; member of the General Motors Research Laboratories; and head of the Engineering Mechanics Department at GM Research. While head of the Engineering Mechanics Department at GM R&D, he had responsibility at the project level for research in vehicle crashworthiness and occupant protection, including air bag research. He sat on GM's Corporate Safety Committee for many years. His department had numerous joint projects with GM R&D's Biomedical Research Department (in-depth research on human injury mechanisms, the benefit of air bags, seat belts, and other topics.). Later, as executive director, he had overall responsibility for all of GM's safety research. The team helped GM develop StabiliTrak (a chassis system to prevent spinout and rollover), and more recently a number of accident avoidance systems such as adaptive cruise control. Prior to joining GM, Dr. Howell worked for General Dynamics Corporation as a principal investigator of research related to the structural dynamics of the space shuttle. In 1984, he completed the Executive Program at Dartmouth's Amos Tuck School of Business Administration. He is a member of the American Institute of Aeronautics and Astronautics, the American Society of Mechanical Engineers, the Society of Automotive Engineers, and Sigma Xi. He served on the National Research Council's study on *Use of Lightweight Materials in 21st Century Army Trucks* and on the Panel on Benefits of DOE's Light-Duty Hybrid Vehicle R&D Program, and has served on the College of Engineering advisory boards of the University of Illinois and Western Michigan University. He represented GM as a member of the Industrial Research Institute (IRI) and has served on the IRI board of directors. He is now an emeritus member of IRI. Dr. Howell earned his bachelor's, master's and doctorate degrees in aeronautical and astronautical engineering at the University of Illinois, Urbana.

Thomas M. Jahns, Grainger Professor of Power Electronics and Electrical Machines at the University of Wisconsin, Madison, has been a driving force behind the development of high-performance, permanent-magnet synchronous machine drives, distinguished by magnets in their spinning rotors. Since early in his professional career at General Electric, Dr. Jahns has made important technical contributions leading to successful applications of permanent-magnet drives in machine tools, home appliances, and aerospace actuators. Making use of these principles, all hybrid-electric passenger vehicles in high-volume commercial production today have adopted permanent-magnet synchronous machines for their electric propulsion systems. An IEEE fellow, Dr. Jahns' many honors include the IEEE Power Electronics Society's William E. Newell Award. He has served as president of the IEEE Power Electronics Society and as Division II director on the IEEE board of directors. Both the IEEE Industry Applications Society and the IEEE Power Electronics Society have recognized him as a Distinguished Lecturer. He has a Ph.D. in electrical engineering from the Massachusetts Institute of Technology.

Alan C. Lloyd is president of the International Council on Clean Transportation. His previous positions include serving as secretary of the California Environmental Protection Agency, chair of the California Air Resources Board (CARB), executive director of the Energy and Environmental Engineering Center at the Desert Research Institute, and chief scientist at the South Coast Air Quality Management District, California. His research interests involve greenhouse gas reductions, alternative fuels, renewable energy and advanced technologies such as hybrid electric vehicles and fuel cell vehicles. While at CARB, he led the initiative of California's diesel risk reduction efforts. He has served on many advisory committees, including as chair of the Hydrogen Technical Advisory Panel. He is a member of the Air and Waste Management Association and of the National Hydrogen Association, and is a recipient of the 2005 Fuel Cell Seminar Award and the 2005 Grove Medal. He received his Ph.D. in gas kinetics from University College of Wales, Aberystwyth.

David F. Merrion is chair of David F. Merrion LLC; chair of Green Vision Technology LLC; and a member of the board of directors of Clean Diesel Technologies, Inc. and Hy-Drive Technologies, Ltd. He is the retired executive vice president of engineering for Detroit Diesel Corporation (DDC). His positions at DDC included staff engineer, Emissions and Combustion; staff engineer, Research and Development;

chief engineer, Applications; director, diesel engineering; general director, Engineering (Engines and Transmissions); and senior vice president, Engineering. Mr. Marrion has extensive expertise in the research, development, and manufacturing of advanced diesel engines, including alternative-fueled engines. He is a Society of Automotive Engineers fellow and a member of American Society of Mechanical Engineers. He served as president of the Engine Manufacturers Association, a member of Environmental Protection Agency's (EPA) Mobile Sources Technical Advisory Committee, a member of the Coordinating Research Council, and a member of the U.S. Alternate Fuels Council. He served on the National Research Council's Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles. He is a consultant to DDC, which includes Compliance Auditor for the Consent Decree signed with EPA/California Air Resources Board/Department of Justice in 1998. Mr. Merrion is the co-inventor on a patent for a diesel-electric hybrid vehicle. He has a bachelor of mechanical engineering degree from General Motors Institute (Kettering University) and a master's of science degree in mechanical engineering from the Massachusetts Institute of Technology.

Gary W. Rogers is president and chief executive officer, FEV Engine Technology, Inc., and executive vice president (Geschäftsführer), FEV Motorentechnik, GmbH. He is also president, FEV Test Systems, Inc. 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 homogeneous and direct-injected gasoline engines, high-speed direct injection passenger car diesel engines, heavy-duty diesel engines, hybrid vehicle systems, gas turbines, pumps, and compressors. Mr. Rogers provides corporate leadership for a multinational research, design, and development organization specializing in engines and energy systems. He is a 25-year member of both the Society of Automotive Engineers and the American Society of Mechanical Engineers and sits on the advisory board of the College of Engineering and Computer Science, Oakland University, Rochester, Michigan. He served as a member of the National Research Council (NRC) Committee on Review of DOE's Office of Heavy Vehicle Technologies Program, the NRC committee on the Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) standards, and the NRC Panel on Benefits of DOE's Light-Duty Hybrid Vehicle R&D Program. He also recently supported the Department of Transportation, National Highway Traffic Safety Administration (NHTSA) by conducting a peer review of the NHTSA CAFE Model. Mr. Rogers has a B.S.M.E. from Northern Arizona University.

Yang Shao-Horn is assistant professor of mechanical engineering at the Massachusetts Institute of Technology. Before that she was a National Science Foundation International Research Fellow at the Institute of Condensed Matter Chemistry in Bordeaux, France (2000-2002). Prior to that, Dr. Shao-Horn spent 3 years (1998-2000) as a staff scientist at the Eveready Battery Company. Her areas of interest include electrochemically active materials for batteries and fuel cells, electrocatalysis, application of transmission electron microscopy techniques, intercalation chemistry, and solid-state ionics. She holds a B.S. degree in metallurgical engineering from Beijing University of Technology and a PhD in metallurgical and materials engineering from Michigan Technological University.

Dale F. Stein (NAE) 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 is an elected fellow of the American Society of Metals, The Metallurgical Society (TMS), and American Association for the Advancement of Science. He has served on numerous National Research Council committees, including as the chair, Committee for the National Tire Efficiency Study, and member of the Committee on Review of DOE's Office of Heavy Vehicle Technologies. He previously was a member of the U.S. Department of Energy's Energy Research Advisory Board. He is also an internationally known authority on the mechanical properties of engineering materials. He received his Ph.D. in metallurgy from Rensselaer Polytechnic Institute and a B.S. in metallurgy from the University of Minnesota.

Wallace R. Wade was chief engineer and technical fellow, Powertrain Systems Technology and Processes, Ford Motor Company, Dearborn, Michigan, where he served for 32 years before retiring in 2004. He was responsible for the development, application, and certification of emission and powertrain control system technologies for all Ford Motor Company's North American vehicles. Today he is a consultant to industry and government in the areas of engine research and development, emission control systems, powertrain electronic control systems, powertrain calibration, and systems engineering. He holds the M.S.M.E. degree (awarded by the University of Michigan, Ann Arbor, in 1964); and the B.M.E. degree from Rensselaer Polytechnic Institute (1963), both in mechanical engineering.

Appendix B

Presentations and Committee Meetings

FIRST COMMITTEE MEETING: FEBRUARY 8-9, 2007, WASHINGTON, D.C.

Ed Wall, U.S. Department of Energy: DOE FreedomCAR and Vehicle Technologies Program

Ken Howden, U.S. Department of Energy: Partnership History, Vision, Mission, and Organization

James Eberhardt, U.S. Department of Energy: Review of Findings from Previous Heavy Vehicle Review

Gurpreet Singh, U.S. Department of Energy, FreedomCAR and Vehicle Technologies Program: Overview of DOE/FCVT Heavy-Duty Engine R&D

Vinod K. Duggal, Cummins Inc.: Diesel Engine R & D and Integration

Jerry Gibbs, U.S. Department of Energy: Heavy Vehicle Propulsion Materials

Kevin Stork, U.S. Department of Energy: Fuel Technologies R&D for Heavy Trucks

Dennis L. Siebers, U.S. Department of Energy: Advanced Engine Combustion Research

Dr. James J. Eberhardt, Chief Scientist, U.S. Department of Energy: FreedomCAR and Vehicle Technologies Program: Overview of the FCVT Health Impacts Activity

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Paul F. Skalny, TARDEC-National Automotive Center: 21st Century Truck Initiative: Briefing to the National Academies' Committee to Review the 21st Century Truck Partnership

Mitchell Greenberg, U.S. Environmental Protection Agency: EPA SmartWay Transport Program: Overcoming Technology Deployment Challenges

Charles L. Gray, Jr., U.S. Environmental Protection Agency: EPA's Transportation R&D

Ken Howden, U.S. Department of Energy: Review of the 21st Century Truck Partnership

Tim Johnson, Corning: Diesel Emission Control Technology Review

K. Thirumalai, Department of Transportation: DOT Response

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Brent Bailey, Coordinating Research Council: "Diesel Emissions Research at CRC" (the ACES Diesel Project)

Joe Mauderly, National Environmental Respiratory Center: Health Impacts Of Diesel Emissions: An Update

Edgar Lara-Curzio, The High Temperature Materials Laboratory: The High Temperature Materials Laboratory Program Overview

Vinod K. Duggal, Cummins Inc.: Diesel Engine Role Toward Energy Security

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U.S. Department of Energy: Review of the 21st Century Truck Partnership

U.S. Department of Energy: Final Answers to DOT Questions August 2007

K. Thirumalai, Department of Transportation: Supplement to DOT Responses

Appendix C

R&D Funding Trends of the FreedomCAR and Vehicle Technologies Program

FUNDING DETAILS

The research and development programs of the FreedomCAR and Vehicle Technologies (FCVT) Program (the U.S. Department of Energy [DOE] parent program of the 21st Century Truck Partnership) have been funded as shown in Table C-1. Note that the table includes some funding that explicitly support the 21CTP as well as the FreedomCAR and Fuel Partnership. (The left-hand column of the table includes such notations where applicable.)

21CTP SUBPROGRAMS

The subprogram descriptions are as follows:

- *Vehicle Systems.* The Vehicle Systems subprogram funds research and development (R&D) on advanced vehicle technologies and auxiliary equipment that could achieve significant improvements in fuel economy for light- and heavy-duty vehicles without sacrificing safety, the environment, performance, and affordability. This subprogram's funding contributes to both the FreedomCAR Partnership and the 21st Century Truck Partnership.
- *Innovative Concepts.* The Innovative Concepts subprogram funds the Graduate Automotive Technology Education (GATE) activity, which aids in the development of interdisciplinary curricula to train the future workforce of automotive engineers. This is accomplished by setting up GATE Centers of Excellence at universities that have been competitively selected, establishing focused curriculum, and providing funds for research fellowships.
- *Hybrid and Electric Propulsion.* From the Hybrid and Electric Propulsion subprogram funds R&D for passenger vehicles. Research and development efforts include research in energy storage systems, advanced power electronics and electric machines. There are three activities: Energy Storage, Advanced Power Electronics, and Subsystem Integration and Development.
- *Advanced Combustion Engine R&D.* The Advanced Combustion Engine R&D subprogram focuses on removing critical technical barriers to commercialization of more efficient advanced internal combustion engines in light-, medium-, and heavy-duty vehicles. The goals are to improve the efficiency of internal combustion engines to 45 percent by 2010 for light-duty applications and to 55 percent for heavy-duty applications by 2013, while meeting cost, durability, and emissions constraints. Research is conducted in collaboration with industry, national laboratories, and universities, and in conjunction with the FreedomCAR and Fuel Partnership and 21st Century Truck Partnership. The Advanced Combustion Engine R&D subprogram includes Combustion and Emission Control, Heavy Truck Engine, Waste Heat Recovery, and Health Impacts Research.
- *Materials Technologies.* The Materials Technologies subprogram supports the development of cost-effective materials and materials manufacturing processes that can contribute to fuel-efficient cars and trucks. This subprogram is a critical enabler for concepts developed in the FreedomCAR and 21st Century Truck Partnerships. The activity consists of three activities: Propulsion Materials Technology, Lightweight Materials Technology, and the High-Temperature Materials Laboratory (HTML).
- *Fuels Technologies.* The Fuels Technology subprogram supports R&D that will provide vehicle users with fuel options that are cost competitive, enable high fuel economy, deliver low emissions, and contribute to petroleum displacement. It consists of two activities: Advanced Petroleum-Based Fuels (APBF) and Non-Petroleum-Based Fuels and Lubricants (NPBFL).

TABLE C-1 Budget Appropriations, Vehicle Technology Program, Office of FreedomCAR and Vehicle Technologies, Parent Agency of 21st Century Truck Partnership in U.S. Department of Energy, FY 2003 through FY 2008

	Funding (thousands of U.S. dollars) by fiscal year (FY)					
Subprogram	FY 2003	FY 2004	FY 2005	FY 2006	FY 2007 Request[a]	FY 2008 Request
Vehicle Systems[b]	13,485	1,4335	13,004	13,056	1,3315	0
Innovative Concepts	1,590	494	500	495	500	0
Hybrid and Electric Propulsion	41,996	45,002	44,066	43,977	50,841[c]	80,664
Advanced Combustion Engine R&D[d]	55,267	54,405	48,480	42,746	46,706	34,550
Materials Technologies[e]	36,094	39,744	35,922	35,269	29,786	33,382
Fuels Technologies	19,164	16,494	12,419	13,709	13,845	13,845
Technology Introduction	4,570	4,939	4,944	6,250	11,031	0
Technical/ Program Management Support	2,005	2,095	1,877	2,475	0[f]	0
Biennial Peer Reviews[g]	0	494	0	990	0	0
Congressionally Directed Activities[h]	0	0	120	24,255	0	0
Vehicle Technology Total	174,171	178,002	161,236	182,104	166,024	176,138

[a]The FY 2007 request includes funding ($4,393,000) for the Clean Cities activity previously funded in the Energy Efficiency and Renewable Energy, U.S. Department of Energy. Weatherization and Intergovernmental Activities Program, U.S. Department of Energy.

[b]Contributes both to the FreedomCAR and Fuel Partnership and to the 21st Century Truck Partnership.

[c]Funding requested in FY 2007 is funding for research and development on those technologies needed for plug-in hybrid-electric vehicles.

[d]Research is conducted in collaboration with industry, national laboratories, and universities, and in conjunction with the FreedomCAR and Fuel Partnership and the 21st Century Truck Partnership.

[e]This subprogram is a critical enabler for concepts developed in the FreedomCAR Fuel Partnership and the 21st Century Truck Partnerships.

[f]Beginning with the FY 2007 request, these activities will be funded from the R&D activities that they support.

[g]Biennial reviews of the FreedomCAR and Fuel Partnership and 21st Century Truck Partnership will be conducted by an independent party such as the National Research Council, to evaluate progress and program direction.

[h]These are activities not requested by the FreedomCAR and Vehicle Technology Program, but conducted at the direction of congressional appropriations legislation.

SOURCE: DOE, FreedomCAR and Vehicle Technologies Program. Available at http://www1.eere.energy.gov/vehiclesandfuels/about/printable_versions/fcvt_budget.html. Accessed June 3, 2008. FY 2005-2008 figures from DOE, Feb. 2007, Congressional Budget Request. Vol. 3, Office of Chief Financial Officer. Doc No. DOE/CF-016.

- *Technology Introduction.* The Technology Introduction subprogram accelerates the adoption and use of alternative fuel and advanced technology vehicles to help meet national energy and environmental goals. This subprogram's efforts logically follow and complement successful research and by industry and government. The primary functions of Technology Introduction include legislative and rulemaking supporting the Energy Policy Act of 1992 (EPAct) alternative fuel and fleet activities; testing and evaluation of advanced technology vehicles; and advanced vehicle competitions. As identified in the National Energy Policy, consumer education and demonstration activities are critical to accelerating the use of advanced energy technologies.
- *Technical/Program Management Support.* Consistent with other U.S. Department of Energy programs under the jurisdiction of the Interior and Related Agencies Appropriations Committees, the Energy Conservation programs provide funding for technical/program management support. This includes activities such as R&D feasibility studies; R&D option development and trade-off analyses; and technical, economic, and market evaluations of research. These activities provide important benefits directly to the Vehicle Technologies Program and are therefore an integral part of the R&D program.
- *Biennial Peer Reviews.* Biennial reviews of the FreedomCAR and Fuel Partnership and 21st Century Truck Partnership will be conducted by an independent party such as the National Academy of Sciences/National Academy of Engineering, to evaluate progress and program direction. This continuous (biennial) activity supports the President's Management Agenda (PMA), Program Assessment Rating Tool (PART), and Research and Development Investment Criteria (R&DIC). The reviews will include evaluation of progress toward achieving the technical goals and program direction of each partnership. Based on the evaluation, resource availability, and other factors, the Partners will consider new opportunities, make adjustments to program targets, and set goals appropriately.

Appendix D

Vehicle Emission Regulations

BACKGROUND

Air pollution from the combustion of coal became a serious problem in the 18th century with the Industrial Revolution in Europe. Concerns about air pollution in the United States arose in Los Angeles in the early 1940s. By 1952, the city's smog had been identified as arising from the exhaust products of the internal combustion engine. (The irritant, ozone, one of the constituents of smog, is formed through complex chemical reactions between precursor emissions of volatile organic compounds (VOCs) and oxides of nitrogen (NO_x) in the presence of sunlight.) Subsequently, air pollution from all potential sources, both vehicular and stationary, was recognized as a national concern.

The Clean Air Act of 1963 was the beginning of federal influence over mobile-source emissions. Subsequent amendments established the U.S. Environmental Protection Agency (EPA), gave EPA broad responsibility for regulating motor vehicle pollution, and directed the agency to set health-based National Ambient Air Quality Standards (EPA, 1994). EPA established maximum concentrations for six "criteria pollutants" as indicators of air quality, above which adverse effects on human health may occur. The six criteria pollutants are ozone, carbon monoxide (CO), nitrogen dioxide, sulfur dioxide, particulate matter (PM) and lead (EPA, 2007b). To curtail exceedance of the maximum concentrations of the criteria pollutants, EPA currently regulates emissions from a variety of mobile and stationary sources. The currently regulated emissions from motor vehicles, which are predominately passenger cars, light-duty trucks, and heavy-duty trucks, include the following: total hydrocarbons (HCs) and nonmethane hydrocarbons (NMHCs) or nonmethane organic gases (NMOGs), that includes oxygenated and nonoxygenated HC emissions, CO, NO_x, and PM. Lead in gasoline is also regulated to near-zero levels, which also facilitates long life for the catalytic converter in gasoline-fueled vehicles.

EVOLUTION OF EMISSION STANDARDS

The control of emissions from motor vehicles began with model year 1963 when California implemented the requirement for positive crankcase ventilation that recycles the discharged blowby that had previously been vented to the atmosphere by the road draft tube.

Attention subsequently was focused on the control of exhaust emissions of motor vehicles. The first exhaust emission standards were introduced in California effective with 1966 model year passenger vehicles and in the United States as a whole with model year 1968 vehicles. The progressively more stringent federal emission standards for light-duty vehicles are shown in Figure D-1.

Since the early 1960s when exhaust emissions were unregulated, the subsequent exhaust emission regulations by model year 2004 have resulted in the reduction of exhaust emissions from light-duty vehicles by the following amounts:

Hydrocarbons	99 percent reduction
Carbon Monoxide	96 percent reduction
Oxides of Nitrogen	99 percent reduction

Emission standards for light-duty trucks with a gross vehicle weight rating (GVWR) under 8,500 lb have been somewhat higher than passenger car standards because of differences in weight. However, in the near future, light-duty truck standards will be the same as passenger car standards, as shown in Table D-1.

Control of emissions from the engines of heavy-duty trucks with GVWRs over 8,500 lb began in 1969 in California and in the United States as a whole in 1974 (Johnson, 1988). The progressively more stringent emission standards for heavy-duty diesel engines are shown in Figure D-2 (DOE, 2006).

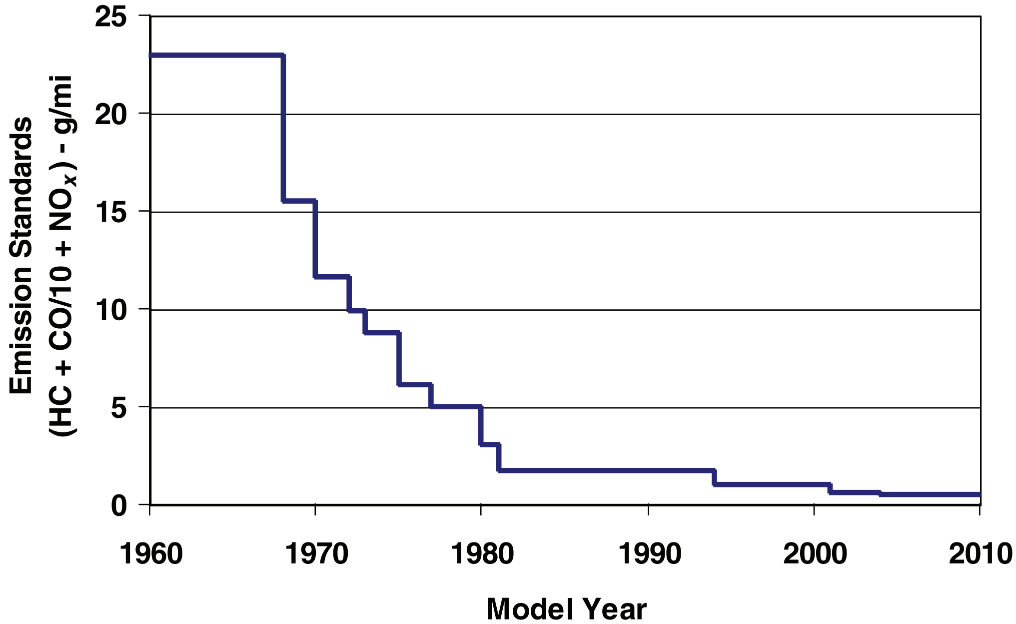

FIGURE D-1 Historical trend in emission standards for light-duty vehicles. Individual emission standards for HC, CO, and, NO_x are combined for illustration only. SOURCE: Data from Ehlmann and Wolff (2005).

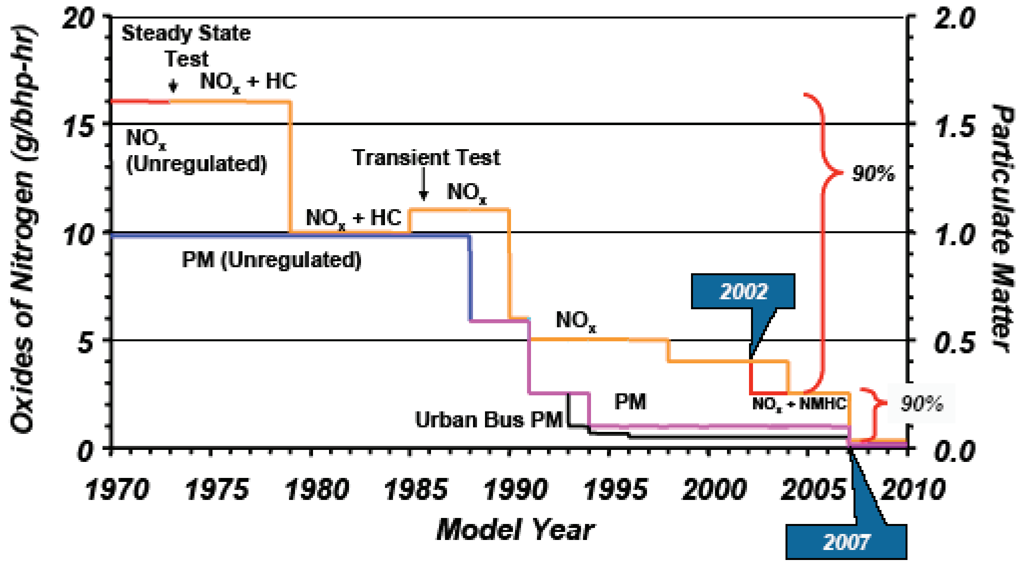

FIGURE D-2 Historical trend in emission standards for heavy-duty diesel engines.

CURRENT AND FUTURE EXHAUST EMISSION STANDARDS

The emission standards currently in effect in the United States are promulgated by the U.S. Environmental Protection Agency (EPA) for the 49 states and by the California Air Resources Board (CARB) for the state of California. California is the only state that has been granted authority, within the original Clean Air Act, to establish separate, stricter standards for vehicle emissions, independent of the federal government. All other states are required to comply with the federal vehicle emission standards or adopt the stricter California standards. Numerous states have adopted the latest CARB emission standards.

Passenger Car and Light-Duty Truck

Federal Emission Standards

The Tier 2 federal passenger car emission standards, phased in beginning with the 2004 model year, are listed in Table D-1. For the first time since the enactment of emission standards in the United States, the same standards are to be applied to both passenger cars and light-duty trucks. EPA created a "bin" system, with eight emission standard bins, that allows manufacturers to average emissions across their fleets each year. The passenger car (PC), LDT1, LDT2, LDT3, and LDT4 fleet average NO_x requirement is 0.07 (g/mi) at 120,000 miles for model year 2009 and beyond. The standards listed are the emission limits at "full useful life" of 120,000 miles.

California Emission Standards

California's Low Emission Vehicle II (LEV II) standards were introduced for 2004 and subsequent model years. These standards for all passenger cars and light-duty trucks under 8,500 lb are listed in Table D-2. California categorizes the standards as LEV, Ultra Low Emission Vehicle (ULEV), and Super Ultra Low Emission Vehicle (SULEV) standards. The manufacturer selects the appropriate category for each vehicle line so that the fleet average NMOG meets the CARB mandated fleet average, which deceases with each model year through 2010.

Heavy-Duty Engine Emission Standards

The federal emissions standards for highway trucks were harmonized with California standards beginning in the model year 2004. The emission standards that apply to model year

TABLE D-1 Federal Tier 2 Light-Duty Vehicle Emission Standards: Emission Limits at Full Useful Life of 120,000 Miles

		Mandatory for Model Year 2009 and Beyond				
Bin	Vehicle Class	NMOG (g/mi)	CO (g/mi)	NO_x (g/mi)	PM (g/mi)	Mileage Requirement
8	PC/LDT1/2	0.125	4.2	0.2	0.02	120,000
	LDT3/4/MDPV	0.156	4.2	0.2	0.02	120,000
7	All	0.09	4.2	0.15	0.02	120,000
6	All	0.09	4.2	0.1	0.01	120,000
5	All	0.09	4.2	0.07	0.01	120,000
4	All	0.07	2.1	0.04	0.01	120,000
3	All	0.055	2.1	0.03	0.01	120,000
2	All	0.01	2.1	0.02	0.01	120,000
1	All	0	0	0	0	120,000

NOTE: ALVW, adjusted load vehicle weight, average of curb (empty) weight and the GVWR; GVWR, gross vehicle weight rating, maximum fully loaded vehicle weight; LVW, loaded vehicle weight, nominal empty vehicle weight + 300 lb; LDT1, light-duty truck 1, up to 6,000 lb GVWR and 3,750 lb LVW; LDT2, light-duty truck 2, up to 6,000 lb GVWR and between 3,751 and 5,750 lb LVW; LDT3, light-duty truck 3, between 6,001 and 8,500 lb GVWR and between 3,751 and 5,750 lb ALVW; LDT4, light-duty truck 4, between 6,001 and 8,500 lb GVWR and over 5,750 lb ALVW; MDPV, medium-duty passenger vehicle, trucks between 8,501 and 10,000 lb GVWR; PC, passenger car.

TABLE D-2 Current California LEV II Light-Duty Vehicle Emission Standards

GVWR (lb)	Emission Category	NMOG (g/mi)	CO (g/mi)	NO_x (g/mi)	PM (g/mi)	Mileage (Durability) Requirement
All PCs and	LEV	0.09	4.2	0.07	0.01	120,000[a]
LDTs 8,500 lb	ULEV	0.055	2.1	0.07	0.01	120,000[a]
and less	SULEV	0.01	1.0	0.02	0.01	120,000[a]
MDV	LEV	0.195	6.4	0.2	0.12	120,000[a]
8,501-10,000 lb	ULEV	0.143	6.4	0.2	0.06	120,000[a]
Test at ALVW	SULEV	0.1	3.2	0.1	0.06	120,000[a]
MDV	LEV	0.23	7.3	0.4	0.12	120,000[a]
10,000-14,000 lbs	ULEV	0.167	7.3	0.4	0.06	120,000[a]
Test at ALVW	SULEV	0.117	3.7	0.2	0.06	120,000[a]

NOTE: ALVW, adjusted load vehicle weight, average of curb (empty) weight and GVWR; GVWR, gross vehicle weight rating, maximum fully loaded vehicle weight; LDT, light-duty truck; MDV, medium-duty vehicle; PC, passenger car. Other acronyms in the table are defined in Appendix E.

[a]Optional 150,000 mileage durability requirement for partial zero emission vehicle.

TABLE D-3 Heavy-Duty Emission Standards: Model Year 2007 and Beyond

Non-Methane Hydrocarbons (NMHC) (g/bhp-hr)	Carbon Monoxide (CO) (g/bhp-h)	Nitrogen Oxides (NO_x) (g/bhp-h)	Particulate Matter (PM) (g/bhp-h)
0.14[a]	15.5	0.20[a]	0.01

TABLE D-4 Service Classes Used by EPA

Service Class	Required Useful Lives of Engines
Light heavy-duty diesel engine (LHDDE):	8 yr or 110,000 mi
Under federal regulations, between 8,500 and 19,500 lb gross vehicle weight rating (GVWR); in California, between 14,000 and 19,500 lb GVWR[a]	
Medium heavy-duty diesel engine (MHDDE): 19,500 lb to 33,000 lb GVWR	8 yr or 185,000 mi
Heavy heavy-duty diesel engine (HHDDE) (including those for diesel buses): heavier than 33,000 lb GVWR	10 yr or 435,000 mi or 23,000 hr

[a]Under federal light-duty Tier 2 regulations, vehicles of GVWR up to 10,000 lb used for personal transportation are reclassified as medium-duty passenger vehicles (MDPV—primarily SUVs and passenger vans) and are subject to light-duty vehicle legislation.

TABLE D-5 Additional Emission Requirements

Test	Limits
Supplemental Emission Test (SET)	Federal Test Procedure (FTP) Standards
Not-to-exceed (NTE) Limits	1.5 × FTP Standards

2007 and later heavy-duty highway engines are listed in Table D-3. Federal regulations do not require that complete heavy-duty diesel vehicles be chassis-certified; instead requiring the certification of their engines. Consequently, the emissions standards are expressed in grams per brake horsepower hours (g/bhp-hr) and require emission testing over the transient Federal Test Procedure (FTP) engine dynamometer cycle. Table D-4 lists the useful lives of the engines in various service classes; the required useful life of Class 8 engines as required by the emission standards is 435,000 miles, or 10 years, or 22,000 hours.

Additional emission testing requirements, first introduced in 1998, are shown in Table D-5 and include the Supplemental Emission Test (SET) and Not-to-Exceed (NTE) limits.

The SET is a 13-mode steady-state test that was introduced to help ensure that heavy-duty engine emissions are controlled during steady-state type driving, such as a line-haul truck operating on a freeway.

The NTE limits have been introduced as an additional instrument to ensure that heavy-duty engine emissions are controlled over the full range of speed and load combinations commonly experienced in use. The NTE requirement establishes an area (the "NTE zone") under the torque curve of an engine where emissions must not exceed a specified value for any of the regulated pollutants.

For Further Information

The preceding review of current and future emission standards is intended to provide an overview of the key aspects of current and future emission standards that either are applicable to the 21CTP or provide background information to aid in evaluating the Partnership. For a complete understanding of past and present emission standards highlighted in this section, the reader is directed to the actual regulations promulgated by the U.S. Environmental Protection Agency and the California Air Resources Board.

EMISSION STANDARDS NOT ADDRESSED BY THE 21CTP

Evaporative Emissions

Evaporative emissions, produced from the evaporation of fuel, have been a large contributor to urban smog, because the heavier molecules of unburned fuel stay closer to ground level. Fuel evaporates from a vehicle in the following ways: by gas tank venting, from running losses, and from refueling losses. Evaporative emission standards were first promulgated for 1971 model year vehicles when charcoal canisters were introduced to trap gasoline vapors. These

TABLE D-6 Timetable for Implementation of On-Board Diagnostic (OBD) II Systems for Heavy-Duty Vehicles (more than 14,000 lb GVWR)

Regulatory Body	Model Year	Comments
California Air Resources Board (CARB)	2007	Basic Engine Manufacturer Diagnostic (EMD) system
CARB	2010 Proposed	Comprehensive OBD II system
U.S. Environmental Protection Agency	2010 Proposed	Notice of Proposed Rule

standards become more stringent in recent years. The most stringent evaporative emission standards have recently been introduced for gasoline-fueled vehicles. California currently has an optional zero evaporative emission standard, which is one of the requirements for certifying a vehicle with SULEV exhaust emissions as a partial zero emission vehicle.

In recognition of the high temperatures that diesel fuel can reach in modern common rail fuel systems, evaporative emission standards for diesel fuel vehicles have also been adopted. Because technology to control diesel evaporative emissions are not considered to be a significant issue, these emissions are not included in the scope of 21CTP and will not be discussed in this report.

On-Board Diagnostic II (OBD II) System

The On-Board Diagnostic II (OBD II) system was phased in on light-duty vehicles beginning with the 1994 model year vehicles. The purpose of the on-board diagnostic system on vehicles is to ensure the emission control system and other engine-related components are operating properly. When the OBD II system detects a problem, a corresponding "Diagnostic Trouble Code" (DTC) is stored in the computer's memory and a special light on the instrument cluster called a Malfunction Indicator Lamp (MIL) is illuminated.

The OBD II system is intended to ensure proper emission system operation for every vehicle throughout its lifetime, and notifies the driver of a problem before the vehicle's emissions have increased significantly.

Heavy-duty engine OBD II, also referred to as the engine manufacturer diagnostic system, is similar to the light duty OBD II system, except that the monitors are not required to be tied to the emission standards (Dieselnet, 2005; EPA, 2006).

The timetable for implementation of OBD II for heavy-duty vehicles as shown in Table D-6.

Although OBD II is a key element in maintaining the stringent emission levels that are the focus of the 21CTP, the development and application of OBD II are not included in the scope of this partnership and are not discussed further in this report.

Defeat Devices

Manufacturers must ensure that vehicle emission control systems operate in use as they do on the prescribed test cycles. If, without properly informing EPA, an emission control system operates differently when in use, the emission control system is considered "defeated" and a "defeat device" is present. EPA may seek judicial penalties for each vehicle sold containing a defeat device (EPA, 2007a).

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Appendix E

Acronyms and Abbreviations

21CTP	21st Century Truck Partnership
ACES	advanced collaborative emissions study
AH	ampere-hour
AHHPS	Advanced Heavy Hybrid Propulsion System
ALVW	adjusted loaded vehicle weight
APBF	Advanced Petroleum Based Fuels
APU	auxiliary power unit
AVTA	Advanced Vehicle Testing Activity
bhp-h	brake horsepower-hour
BTL	biomass-to-liquids
CARB	California Air Resources Board
CERDEC	Communications-Electronics Research, Development and Engineering Center
CFD	computational fluid dynamics
CH_4	methane
CMV	commercial motor vehicle
CLEERS	Cross-cut Lean Exhaust Emissions Reductions Simulations
CO	carbon monoxide
CO_2	carbon dioxide
CRADA	Cooperative Research and Development Agreement
CRC	Coordinating Research Council
DCT	Diesel Crosscut Team
DEC	Diesel Emission Control
DEER	Diesel Engine-Efficiency and Emissions Research
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DPF	Diesel Particulate Filter
DPIM	Dual Power Inverter Model
EERE	Energy Efficiency and Renewable Energy (Office of)
EGR	exhaust gas recirculation
EPA	Environmental Protection Agency
EMD	engine manufacturer diagnostic
EPA	U.S. Environmental Protection Agency
FCFP	FreedomCAR and Fuel Partnership
FCVT	FreedomCAR and Vehicle Technologies
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FMVSS	Federal Motor Vehicle Safety Standards
FOT	field operational test
FTP	Federal Test Procedure
FY	fiscal year
gal	gallon
g/bhp-h	grams per brake horsepower-hour
GCW	gross combination weight
GFIC	ground-fault interrupter circuit
g/mi	grams per mile
gpm	gallons per mile
GREET	Greenhouse Gas Regulated Emissions, and Transportation
GTL	gas-to-liquid
GVW	gross vehicle weight
GVWR	gross vehicle weight rating
HC	hydrocarbon
HCCI	homogeneous-charge compression ignition
HEI	Health Effects Institute
HEV	hybrid electric vehicle
HFC	halogenated fluorocarbon
HFRR	high frequency reciprocating rig
HHDDE	heavy heavy-duty diesel engine
HHV	hybrid heavy-duty electric vehicle
HP	high pressure
hp	horsepower
HTML	High Temperature Materials Laboratory
HVAC	heating, ventilation, and air conditioning
ICE	internal combustion engine
ITS	Intelligent Transportation Systems
JCAP	Japanese Clean Air Program
KOH	potassium hydroxide
kWh	kilowatt-hour
lb	pound
LCFS	Low Carbon Fuel Standard

LDT	light-duty truck
LDT1	light-duty truck 1
LEV	Low Emission Vehicle
LHDDE	light heavy-duty diesel engine
LP	low pressure
LSD	low sulfur diesel
LTC	low-temperature combustion
LVW	loaded vehicle weight
MBRC	Miles Between Road Call
MDPV	medium-duty passenger vehicle
MDV	medium-duty vehicle
MET	More Electric Truck
MFC	Model Fund Consortium
MHDDE	medium heavy-duty diesel engine
mi	miles
mpg	miles per gallon
mph	miles per hour
MYPP	Multi-Year Program Plan
N_2O	nitrous oxides
NAC NO_x	absorber catalyst
NHTSA	National Highway Traffic Safety Administration
NMHC	nonmethane hydrocarbon
NMOG	nonmethane organic gas
NO_x	oxides of nitrogen
NPBF	Non-Petroleum Based Fuels
NRC	National Research Council
NREL	National Renewable Energy Laboratory
NTE	Not-to-Exceed
NTP	National Toxicology Program
OBD	on-board diagnostic
OECD	Organization for Economic Cooperation and Development
OEM	original equipment manufacturer
OHVT	Office of Heavy Vehicles Technology
ORNL	Oak Ridge National Laboratory
PART	Program Assessment Rating Tool
PC	passenger car
PCCI	premixed charge compression ignition
PHEV	plug-in hybrid electric vehicle
PM	particulate matter
$PM_{2.5}$	particulate matter smaller than 2.5 micrometers in diameter (also PM_{10})
PNGV	Partnership for a New Generation of Vehicles
PSAT	Powertrain Systems Analysis Toolkit
R&D	research and development
RFS	Renewable Fuels Standard
rpm	revolutions per minute
SAE	Society of Automotive Engineers
SCR	Selective Catalytic Reduction
SET	Supplemental Emission Test
SI	spark-ignited
SO_2	sulfur dioxide
SULEV	Super Ultra Low Emission Vehicle
SUV	sport utility vehicle
TACOM	U.S. Army Tank-Automotive Command
TARDEC	Tank-Automotive Research, Development and Engineering Center
ULEV	Ultra Low Emission Vehicle
ULSD	ultra-low sulfur diesel
USCAR	U.S. Council for Automotive Research
UTQGS	Uniform Tire Quality Grading System
VIUS	Vehicle Inventory and Use Survey
Wh/kg	watt hours per kilogram
WHR	waste heat recovery

Appendix F

State of the Art in Light-Duty Electric Vehicles

A wide range of data have been published on light-duty vehicles, such as electric vehicles, with high-capacity electrical storage systems. These data, presented in Table F-1, can be used to show the progress of various technologies over time as well as defining the state of the art today.

TABLE F-1 Technical Specifications for Production and Near-Production Vehicle Batteries

Model Year	Vehicle	Vehicle Type	Battery Technology	Battery Manufacturer	Total Voltage	Nominal Capacity (Ah)	Nominal Power Capacity (kW)	Nominal Energy Capacity (Wh)	Pack Weight (lb)
1995	Solectria Force	Electric vehicle	Nickel-metal Hydride	GM Ovonic	185	85 (1C)	>34.4	<15,725	559
1995	Solectria E-10	Electric vehicle	Sealed Lead Acid	Hawker	144	30 (1C)	>71.6	<4,320	1,261
1996	Rav4	Electric vehicle	Valve Regulated Lead Acid	Matsushita	288	55 (1C)	>58.6	<15,840	1,210
1997	Chevrolet S-10	Electric vehicle	Valve Regulated Lead Acid	Delphi Energy	312	48 (C/2)	>104.3	<14,976	1,265
1997	GM EV1	Electric vehicle	Valve Regulated Lead Acid	Dephi	312	53 (1C)	>116.4	<16,536	1,175
1998	Chevrolet S-10	Electric vehicle	Nickel-metal Hydride	Ovonic Energy Products	343	85 (C/2)	>98.5	<29,155	1,079
1998	RAV4	Electric vehicle	Nickel-metal Hydride	Panasonic	288	95 (C/3)	>57.3	<27,360	1,014
1998	Ford Ranger	Electric vehicle	Valve Regulated Lead Acid	Delphi Energy	312	60 (C/2)	>87.4	<18,720	1,914
1999	Chrysler Epic	Electric vehicle	Nickel-metal Hydride	SAFT	336	82 (C/3)	>91.3	<27,552	1,170
1999	GM EV1	Electric vehicle	Nickel-metal Hydride	Ovonic Energy Products	343	85 (C/2)	>104	<29,155	1,058
1999	Ford Th!nk	"Universal electric vehicle"	Nickel Cadmium (NiCd)	SAFT	114	100 (C/3)	>9.5	<11,400	245
2001	Frazer-Nash City Car	"Neighborhood electric vehicle"	Absorptive Glass Mat	Electrosource	48	136 (C/2)	>4.24	<6,528	462
2001	Frazer-Nash Truck	"Neighborhood electric vehicle"	Absorptive Glass Mat	Electrosource	48	136 (C/2)	>5.23	<6,528	462
2002	Columba ParCar 2 passenger	"Neighborhood electric vehicle"	Flooded Lead Acid	Trojan	48	146 (C/2)	>2.65	<7,008	493

continued

TABLE F-1 Continued

Model Year	Vehicle	Vehicle Type	Battery Technology	Battery Manufacturer	Total Voltage	Nominal Capacity (Ah)	Nominal Power Capacity (kW)	Nominal Energy Capacity (Wh)	Pack Weight (lb)
2002	Columba ParCar 4 passenger	"Neighborhood electric vehicle"	Flooded Lead Acid	Trojan	48	146 (C/2)	>3.06	<7,008	493
2002	GEM E825 2 passenger	"Neighborhood electric vehicle"	Flooded Lead Acid	Trojan	72	79 (C/2)	>2.53	<5,688	396
2002	GEM E825 4 passenger	"Neighborhood electric vehicle"	Flooded Lead Acid	Trojan	72	79 (C/2)	>3.12	<5,688	396
2001	Honda Insight	Hybrid electric vehicle	Nickel-metal Hydride	Panasonic EV Energy	144	6.0 (C/2)	>1.35	<864	48
2001	Toyota Prius	Hybrid electric vehicle	Nickel-metal Hydride		274	N/A	N/A	N/A	N/A
2002	Toyota Prius	Hybrid electric vehicle	Nickel-metal Hydride	Panasonic EV Energy	274	6.5 (C/2)	>2.0	<1,781	86
2003	Honda Civic	Hybrid electric vehicle	Nickel-metal Hydride	Panasonic EV Energy	144	6.0 (C/2)	>1.35	<864	48
2004	Toyota Prius	Hybrid electric vehicle	Nickel-metal Hydride	Panasonic EV Energy	201.6	6.5 (C/2)	<4.435	<1,310.4	65
2004	Chevrolet Silverado	Hybrid electric vehicle	Valve Regulated Lead Acid	Panasonic	36	70 (C/?)	<2.250	<2520	137
2005	Ford Escape	Hybrid electric vehicle	Nickel-metal Hydride	Sanyo Electric	330	5.5 (C/?)	<4.752	<1,815	110
2005	Honda Accord	Hybrid electric vehicle	Nickel-metal Hydride	Sanyo Electric	144	6 (C/?)	<2.045	<864	48
2006	Honda Civic	Hybrid electric vehicle	Nickel-metal Hydride	Panasonic EV Energy	158.4	5.5 (C/?)	<1.072	<871	N/A
2006	Lexus RX400h	Hybrid electric vehicle	Nickel-metal Hydride	Panasonic EV Energy	288	6.5 (C/?)	<3.02	<1,872	N/A
2006	Toyota Highlander	Hybrid electric vehicle	Nickel-metal Hydride	Panasonic EV Energy	288	6.5 (C/?)	<3.07	<1,872	N/A
2007	GM Saturn Vue	Hybrid electric vehicle	Nickel-metal Hydride	Cobasys	36	18.4 (C/?)	<0.514	<662	N/A
2007	Toyota Camry	Hybrid electric vehicle	Nickel-metal Hydride	Panasonic EV Energy	244.8	6.5 (C/?)	<2,247.264	<1,591	160
2008	Toyota Highlander	Hybrid electric vehicle	Nickel-metal Hydride	N/A	288	N/A	45 kW	N/A	N/A
2008	Toyota Prius	Hybrid electric vehicle	Nickel-metal Hydride	N/A	201.6	N/A	21 kW	N/A	N/A
2008	Toyota Camry	Hybrid electric vehicle	Nickel-metal Hydride	N/A	244.8	N/A	30 kW	N/A	N/A
Military	HE-HMMWV	Heavy-duty hybrid electric vehicle	Li-ion	SAFT	300		152	18,000	N/A
Military	RSTV	Heavy-duty hybrid electric vehicle	Lithium ion	SAFT	216		70	17,200	N/A
Military	LANCER	Tank	Lithium ion	SAFT	5,600		150	N/A	N/A
Military	US Army Future Tactical Truck System (FTTS)	Heavy-duty hybrid electric vehicle	Nickel metal hydride	Cobasys	336		280	11,000	N/A
TBD	GMC 2500	Van	Nickel metal hydride	Cobasys	336	8.5 (C/?)	70	2,800	N/A
2006	Toyota Prius	Parallel hybrid electric vehicle	Lithium ion	Valence	230.4	43	N/A	N/A	N/A
2007	Toyota Prius	Parallel hybrid electric vehicle	Lithium ion	A123	184.8	25	N/A	N/A	N/A

Appendix G

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