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OHVT
TECHNOLOGY ROADMAP

U.S. Department of Energy
Office of Heavy Vehicle Technologies (OHVT)
Office of Transportation Technologies

February 2000

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Date published—February 2000

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ACRONYMS AND ABBREVIATIONS

AAMA	American Automobile Manufacturers Association
ABS	antilock braking system
AC	alternating current
ANL	Argonne National Laboratory
ANPRM	Advanced Notice of Proposed Rule Making
APB	Advanced Petroleum-Based
ATA	American Trucking Association
Bmep	brake mean effective pressure
Bsfc	brake specific fuel consumption
C_d	drag coefficient
CAPS	Clean Air Partners
CARB	California Air Resource Board
CFD	computational fluid dynamics
CIDI	compression ignition, direct injection
CNG	compressed natural gas
CO	carbon monoxide
CRT	continuously regenerating trap
CVT	continuously variable transmission
DC	direct current
DDC	Detroit Diesel Corporation
DECSE	diesel emission controls and sulfur effects
DEE	diethyl ether
DFNG	dual-fuel natural gas
DI	direct injection
DING	direct injection natural gas
DME	Dimethyl ether
DMM	dimethoxy methane
DOE	U.S. Department of Energy
DOE-SC	U.S DOE Office of Science
EGR	exhaust gas recirculation
EMA	Engine Manufacturers Association
EPA	U.S. Environmental Protection Agency
ES&HE	Environmental Science and Health Effects
F-T	Fischer-Tropsch
FIE	fuel-injection equipment
FTP	Federal Test Procedure
GDP	gross domestic product
GM	General Motors
GPRA	Government Performance and Results Act
GVW	gross vehicle weight
GVWR	gross vehicle weight rating
HAP	hazardous air pollutant
HTML	High Temperature Materials Laboratory
IC	internal combustion
IDI	indirect injection

LDT	light-duty truck
LDV	light-duty vehicle
LES	large-eddy simulation
LNG	liquified natural gas
LPG	liquified petroleum gas
MDV	medium-duty vehicle
MECA	Manufacturers of Emission Controls Association
MEMS	micro electro-mechanical system
MPG	miles per gallon
MYPP	multi-year program plan
NAAQS	National Ambient Air Quality Standards
NG	natural gas
NMHC	non-methane hydrocarbons
NO_x	nitrogen oxide
NREL	National Renewable Energy Laboratory
NVH	noise, vibration, and harshness
OAAT	Office of Advanced Automotive Technologies
OHVT	Office of Heavy Vehicle Technologies
ORNL	Oak Ridge National Laboratory
OTT	Office of Transportation Technologies
PC	passenger cars
PING	pilot ignition natural gas
PM	particulate matter
$PM_{2.5}$	particulate matter with aerodynamic diameter $< 2.5\mu m$
PNGV	Partnership for a New Generation of Vehicles
PNNL	Pacific Northwest National Laboratory
R&D	research and development
SAE	Society of Automotive Engineers
SCR	selective catalyst reduction
SFAA	Solicitation for Financial Assistance Applications
SI	spark ignition
SING	spark-ignited natural gas
SNL	Sandia National Laboratories
SOP	statement of principles
SULEV	super-ultra-low-emission vehicle
SUV	sport utility vehicle
SwRI	Southwest Research Institute
TBC	thermal barrier coating
TCS	traction control system
ULEV	ultra-low-emission vehicle
VDC	vehicle dynamic control
ZEV	zero-emission vehicle

FOREWORD

The first *OHVT Technology Roadmap* was prepared by the U.S. Department of Energy (DOE) Office of Heavy Vehicle Technologies (OHVT) as a result of recommendations obtained from industry representatives at a workshop convened in April 1996 to elicit input from DOE's heavy vehicle industry customers, including truck and bus manufacturers, diesel engine manufacturers, fuel producers, suppliers to these industries, and the trucking industry. The *Technology Roadmap* was reviewed by industry stakeholders, who provided comments at a workshop in October 1996, held in conjunction with the Society of Automotive Engineers (SAE) International Truck and Bus Meeting and Exposition. The document was published in October 1997. That *Roadmap* was a first step in crafting a common vision for a government research and development (R&D) partnership in this increasingly important transportation sector.

Since the preparation of the first *Technology Roadmap*, changes in emissions regulations and advances in technology have presented new challenges and created new opportunities for the heavy vehicle industry. The current revision of the *Technology Roadmap* reflects these changes. This document, reviewed by selected industry stakeholders and by those who attended a workshop held in conjunction with the November 1999 SAE International Truck and Bus Meeting and Exposition, continues to serve as the foundation for the multiyear program plans which guide the activities of the Office of Heavy Vehicle Technologies.

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Dr. James J. Eberhardt
Director, Office of Heavy Vehicle Technologies

EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) Office of Heavy Vehicle Technologies (OHVT) was created in March 1996 to address the public-interest transportation-energy aspects of a set of customers who at that time had been largely unrecognized, namely, the manufacturers, suppliers, and users of heavy transport vehicles (trucks, buses, rail, and inland marine). Previously, the DOE had focused its attention on meeting the needs of the personal-transport-vehicle customer (automobile manufacturers, suppliers, and users). Those of us who were of driving age at the time of the 1973 oil embargo and the 1979 oil price escalation vividly recall the inconvenience and irritation of having to wait in long lines for gasoline to fuel our cars. However, most of us, other than professional truck owners or drivers, were unaware of the impacts that these disruptions in the fuel supply had on those whose livelihoods depend upon the transport of goods.

Recognizing the importance of heavy vehicles to the national economic health, the DOE created OHVT with a mission to conduct, in collaboration with its industry partners and their suppliers, a customer-focused national program to research and develop technologies that will enable trucks and other heavy vehicles to be more energy-efficient and able to use alternative fuels while reducing emissions.

The Office of Heavy Vehicle Technologies convened a workshop in April 1996 to elicit input from DOE's heavy vehicle industry customers, including truck and bus manufacturers, diesel-engine manufacturers, fuel producers, suppliers to these industries, and the trucking industry. The preparation of a "technology roadmap" was one of the key recommendations by this customer group. Therefore, the *OHVT Technology Roadmap*[*] was developed in 1996 as a first step in crafting a common vision for a government research and development (R&D) partnership in this increasingly important transportation sector. The approach used in developing the *OHVT Technology Roadmap* was to

- formulate goals consistent with the *U.S. Department of Energy Strategic Plan*[†] required by the Government Performance and Results Act (GPRA),
- assess the status of the technology,
- identify technical targets,
- identify barriers to achieving the technical targets,
- develop an approach to overcoming the barriers, and
- develop schedules and milestones.

This structure was followed for three groups of truck classification:

- Class 7 & 8: large, on-highway trucks;
- Class 3–6: medium-duty trucks such as delivery vans; and
- Class 1& 2: pickups, vans, and sport utility vehicles (SUVs).

The foundation of the *OHVT Technology Roadmap* is the *Office of Transportation Technologies Strategic Plan*[‡] and the *DOE Strategic Plan*. The *Office of Transportation Technologies Strategic Plan* addresses the energy, economic, and environmental challenges in meeting the future demand for transportation goods and services. Energy use by heavy vehicles (trucks and other commercial transport) is growing at a faster rate than that of automobiles. Indeed, because of the explosive growth in popularity of pickup trucks, vans, and SUVs, trucks of all classes already exceed passenger cars in annual fuel consumed.

The first *OHVT Technology Roadmap* was reviewed by industry stakeholders, who provided comments in a workshop held in October 1996 in conjunction with the Society of Automotive Engineers (SAE) International Truck and Bus Meeting and Exposition. Additional targeted workshops and one-on-one meetings with industry stakeholders provided feedback and comments. The version incorporating industry input was finalized in October 1997; it is available on the web at http://www.osti.gov/roadmap.pdf.

Since the preparation of the first *Technology Roadmap* in 1996, changes in regulations have occurred (e.g., the U.S. Department of Justice/U.S. Environmental Protection Agency (EPA) "Consent Decree" on heavy-duty engine emissions). Furthermore, advances in technology have presented new challenges and created new opportunities for the heavy vehicle industry. The current revision of the *Technology Roadmap* reflects these changes that have occurred in the past 3 years. This document was reviewed by selected industry stakeholders and was commented on by those who attended the workshop held in November 1999 in conjunction with the SAE International Truck and Bus Meeting and Exposition in Detroit, Michigan.

The OHVT envisions the development of an energy-efficient, near-zero-emissions diesel-engine technology for all truck classes as a real and viable strategy for reducing energy requirements for commercial transport services and the rapidly growing multipurpose vehicle market (pickups, vans, and SUVs). The strategy includes the capability to use alternative fuels as appropriate. The goals of the Heavy Vehicle Technologies Program are as follows:

- Develop by 2004 the enabling technologies for a Class 7 & 8 truck with a fuel efficiency of 10 mpg (at 65 mph) that will meet prevailing emission standards.

- For Class 3–6 trucks operating on an urban driving cycle, develop by 2004 commercially viable vehicles that achieve at least double the fuel economy of comparable current vehicles (1999), and as a research goal, reduce criteria pollutants to 30% below EPA standards.

- Develop by 2004 the diesel engine enabling technologies to support large-scale industry dieselization of Class 1 & 2 trucks, achieving a 35% fuel efficiency improvement over comparable gasoline-fueled trucks, while meeting applicable emissions standards.

The approach of the Heavy Vehicle Technologies Program is to (1) develop partnerships with the domestic transportation industry, energy-supply industry, other federal agencies, and R&D organizations to develop high-efficiency engine technologies and alternative-fuel-utilization technologies for trucks and promote their acceptance and (2) continue development of the following key enabling technologies:

- emission controls (including exhaust aftertreatment),
- combustion technology,
- materials,
- environmental science and health effects,

- truck safety, and
- engineering simulations and modeling.

Among these enabling technologies, combustion, and emissions control are being coordinated through the Diesel Cross-Cut Team, which has linked diesel R&D in the OHVT to analogous activities being conducted under the Partnership for a New Generation of Vehicles. Research and development of fuels and lubricants is conducted jointly by the Offices of Advanced Automotive Technologies and Heavy Vehicle Technologies.

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[*] *OHVT Technology Roadmap*, DOE/OSTI-11690, U.S. Department of Energy Office of Heavy Vehicle Technologies, Office of Transportation Technology, October 1997.

[†] *DOE Strategic Plan*, DOE/PO-0533, U.S. Department of Energy, September 1997.

[‡] *Office of Transportation Technologies Strategic Plan*, U.S. Department of Energy Office of Transportation Technologies, August 8, 1996.

1. INTRODUCTION

The transportation sector is the largest user of petroleum in the United States. The impact of the increased use of petroleum by the transportation sector, primarily cars and trucks, on the nation's economy and on air quality is described in the following excerpt from the U.S. Department of Energy (DOE) *Office of Transportation Technologies Strategic Plan*.[1]

> *The United States faces major challenges in meeting the ever-growing demand for transportation goods and services while minimizing adverse energy, environmental, and economic impacts. The total transportation sector of the U.S. remains over 97% dependent on petroleum fuels and consumes approximately two-thirds of the nation's oil demand. Highway transportation alone uses over half of the nation's oil demand, while the number of vehicles on our roads and miles driven continue to steadily increase. As a result, U.S. oil import demands continue to rise concurrently with an increase in the global demand for oil. Meanwhile, worldwide oil reserves are becoming more concentrated in a smaller number of countries, many of which are often politically unstable and opposed to U.S. interests.*
>
> *This situation leaves us increasingly vulnerable to the potentially serious adverse economic impacts of disruptions in oil supply. The large and growing levels of oil imports also represent a major transfer of wealth from the United States to oil exporting countries; in 1995, this was about $49 billion.*
>
> *There is also continuing concern on the part of many U.S. citizens about the poor air quality in our cities and increasing levels of greenhouse gases. Fifty-four million Americans live in counties (mostly urban) that regularly do not meet air quality standards. Polluting emissions from transportation sources remain a major contributor to this problem.*
>
> *Another national concern is the global market competition in the transportation sector. There is a critical need for the United States to further develop and nurture an advanced transportation technologies base that will enable domestic producers to meet the strong competitive threat from imports and take advantage of the opportunities offered by the rapidly growing overseas market for motor vehicles.*
>
> *To effectively address the above challenges, it is essential that all of our available resources be integrated and focused on a common vision, a supporting mission, and time-related, clearly defined program goals. Our vision means that the use*

of petroleum for transportation, which has maintained a generally upward trend for the last several decades, would start decreasing during the first decade of the next century, as a result of the development of advanced transportation technologies and increased use of alternative fuels. Our realization of this vision, through the effective use of domestic resources and products, will immediately reduce our nation's major concerns relative to the transportation sector.

Within the transportation sector, the petroleum used by heavy vehicles, especially highway trucks, is increasing at a faster rate than that of automobiles. Trucks of all classes use more energy than automobiles do (see Fig. 1). [1, 2]

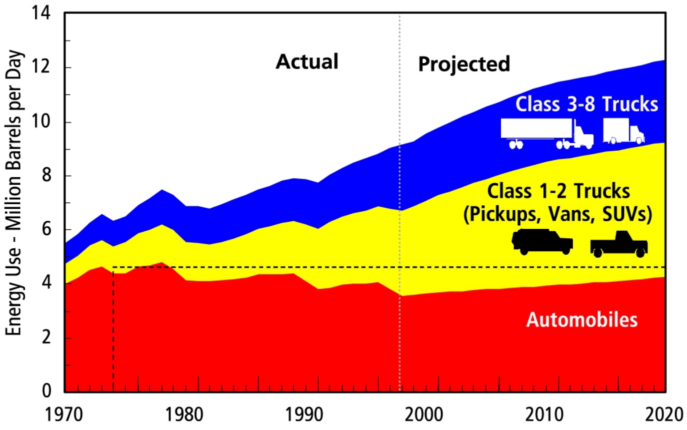


Fig. 1. Trucks account for an increasing amount of highway transportation energy use.

Within the DOE Office of Transportation Technologies (OTT), the Office of Heavy Vehicle Technologies (OHVT) conducts, in collaboration with its heavy vehicle industry partners and their suppliers, a customer-focused national program for research and development (R&D) on critical technologies that will enable the U.S. heavy vehicle transport industry to fully exploit the energy efficiency and alternative fuels capability of the diesel engine while simultaneously reducing highway vehicle emissions. The OHVT heavy vehicle industry customers include truck and bus manufacturers, diesel engine manufacturers, fuel producers, suppliers to these industries, the trucking industry, and other truck users (who must purchase and use advanced heavy vehicles before energy savings can be realized). The scope of the OHVT is not limited to on-highway transport. Other modes of transportation are also recognized to be extremely important. Rail, inland marine, and off-road applications rely primarily on diesel engines for power, and all are either facing or expecting to face new exhaust emissions regulations in the very near future. Each mode of transport plays a crucial role in meeting the overall needs of the nation, and there are still ample opportunities to increase energy efficiency, improve social acceptance, and fine-tune the performance of all such systems.

The OHVT collaborated with its industry customers to craft a common industry/government vision of the Heavy Vehicle Industry of the Future (see Appendix A for a list of workshops and meetings at which OHVT representatives met with their colleagues in industry).

The goal of the Heavy Vehicle Technologies Program is to develop by 2004 the enabling technologies needed to achieve an ultra-low emissions, 10 mile-per-gallon Class 7 & 8 truck and to devolve these technologies down through mid-range trucks (Class 3–6) to Class 1 & 2 trucks, achieving at least 35% fuel economy improvement over current gasoline-fueled Class 1-6 trucks.

The *OHVT Technology Roadmap*, prepared in 1996 and published in 1997,[2] described an industry-government R&D partnership in heavy vehicle technologies of common interest, where expertise could be shared to achieve the vision for a heavy vehicle industry of the future. This revision to the *OHVT Technology Roadmap* updates the status of technology, technical targets, barriers, and technical approach to reflect technical progress and changes in regulatory drivers made since the first *Roadmap* was prepared 3 years ago.

2. STRATEGIC IMPORTANCE OF THE HEAVY VEHICLE TECHNOLOGY PROGRAM

The *Office of Transportation Technologies Strategic Plan* [1] addresses the energy, economic, and environmental challenges in meeting the future demand for transportation goods and services. The Heavy Vehicle Technologies Program is an important component of OTT's strategy for achieving its vision because virtually all of the growth in petroleum highway use is due to heavy vehicles. Heavy vehicles represent a target of opportunity of about 14.3 quads of highway transportation energy use by the year 2010 if all trucks and buses are considered (16.0 quads if rail, marine, and off-highway uses are included), assuming that there are no changes in the current trend in transportation energy use (see Table 1)[3,4]. Increase in energy use by trucks is due to the growth in demand for transport of goods and products (provided by Class 3–8 trucks) as well as the growth in demand for multipurpose vehicles [Class 1 & 2 trucks, which include pickups, vans, and sport-utility vehicles (SUVs)]. Sales of multipurpose vehicles (which predominantly use less-efficient gasoline engines) have increased dramatically in the past 15 years, from approximately 3 million vehicles in 1983 to 6.8 million in 1997 (from 25% to 45%) of the foreign and domestic sales in the United States.[5]

The health and continued growth of the U.S. economy depends on maintaining the energy security and profitability of the trucking industry, now and into the foreseeable future. Trucks are the mainstay for trade, commerce, and economic growth. The gross domestic product (GDP), and hence, economic activity is directly related to freight transport (see Fig. 2). Therefore, the energy demand for movement of goods is critical to the economy. In addition, the U.S. truck manufacturing industry represents approximately 1.8 % of the nation's $8.08 trillion GDP (1997). In 1996, trucks accounted for almost $149 billion of the total $284 billion motor vehicle sales. The heavy vehicle industry as a whole (which includes the trucking industry and other truck users, truck manufacturers, engine manufacturers, fuel producers, and component suppliers) will need to maintain a dominant role in ensuring that the U.S. economy remains healthy.

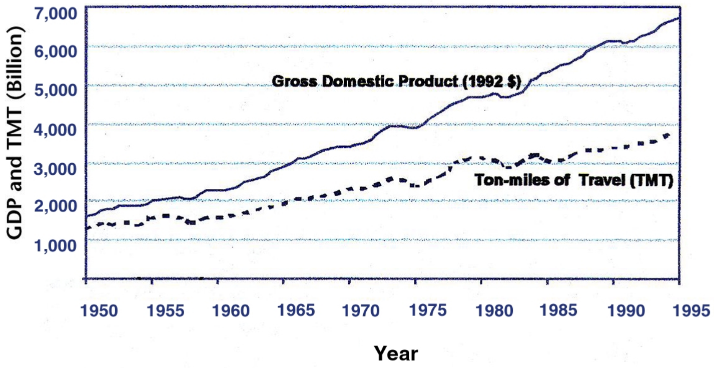


Fig. 2. The nation's economy is linked to efficient heavy vehicle transportation.

Table 1. Targets of opportunity

Vehicle Category	Oil-derived energy (quads)			
	1995[a]	2000[b]	2010[b]	2020[b]
Automobiles	8.5	7.7	8.4	9.0
Heavy vehicles (trucks and others)	11.4	13.3	16.0	17.1
Cl. 1–2 trucks (GVW <= 10,000 lb)	5.7	7.2	9.1	9.8
Cl. 3–6 trucks (10,000 < GVW < 26,500 lb)	0.9	0.9	0.8	0.8
Cl. 7–8 trucks (GVW > 26,500 lb)	3.1	3.5	4.2	4.5
Buses	0.2	0.2	0.2	0.2
Rail	0.5	0.5	0.5	0.6
Domestic marine	0.3	0.3	0.4	0.4
Off-highway	0.7	0.7	0.8	0.8

[a] The 1995 values are from S. C. Davis, *Transportation Energy Data Book*, 17th Ed., ORNL 6919, Oak Ridge National Laboratory, August 1997.

[b] Projections are from Tables 45 and 46 in U.S. DOE Energy Information Administration, *Annual Energy Outlook, 1999*, DOE EIA-0383 (98), July 1998.

2.1 THE OHVT STRATEGY

The OHVT envisions the development of an energy-efficient, near-zero emissions technology, along with safe, energy-efficient, truck-systems technologies as a real and viable strategy for reducing energy requirements of commercial transport services and the rapidly growing multipurpose vehicle market (pickups, vans, and SUVs). The strategy is two-pronged: (1) to improve the efficiency of Class 7 & 8 trucks by developing energy efficient diesel engines and systems technologies that improve the capability to use alternative fuels while reducing emissions to ultra-low or near-zero levels and (2) to utilize the expertise of the world-class U.S. diesel engine manufacturers in developing highly efficient, ultra-low to near-zero emissions diesel engines that will be commercially competitive with gasoline engines in the multipurpose Class 1 & 2 truck markets, achieving at least a 35% fuel economy improvement over gasoline-fueled vehicles. The program strategy involves the development of advanced petroleum-based fuels as well as alternative, nonpetroleum fuels, and includes R&D on in-cylinder processes and exhaust aftertreatment technologies to enable industry to provide clean, efficient, diesel-powered trucks (see Fig. 3).

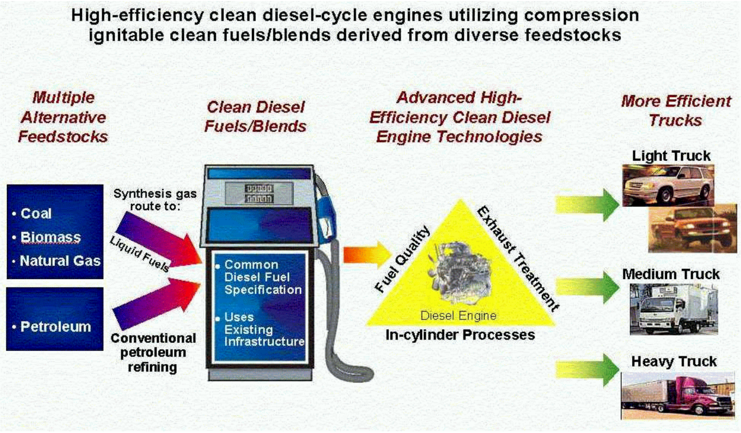


Fig. 3. OHVT Program strategy.

Market penetration of energy efficient technologies will depend on the intended use of the truck. Commercial truck operators will pay a reasonable price for improvements in the fuel economy of their Class 7 & 8 trucks to improve profitability, whereas fuel economy is less important to buyers of multipurpose Class 1 & 2 trucks (especially those predominantly used for personal transportation).

Emissions-control technologies are the key enablers for greater utilization of diesel engines in medium light-duty vehicles. The inherently higher efficiency diesel engines will require advanced emissions control devices if future heavy vehicles are to meet increasingly more stringent U.S. Environmental Protection Agency (EPA) standards. This is the critical requirement for market entry of more-energy-efficient heavy vehicles before potential energy savings can be realized. Although progress has been made in reducing heavy-duty diesel emissions in the last 20 years, the predominantly diesel-powered heavy-duty transport sector is a major contributor to criteria pollutant emissions (see Fig. 4). Critical technological breakthroughs are necessary to cost-effectively meet EPA standards proposed for the year 2006 and beyond.

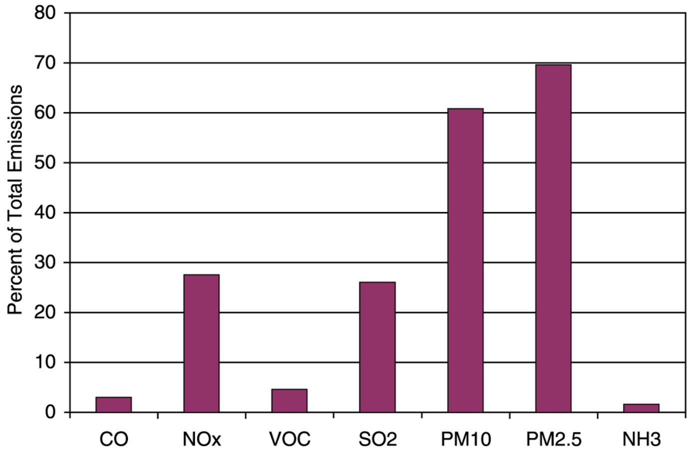


Fig. 4. Heavy-duty diesel truck emissions relative to total on-road emissions. Source: EPA Annual Emissions Trend Report for 1997.

2.2 BENEFITS OF A SUCCESSFUL PROGRAM

Successful implementation of the OHVT technologies outlined in this document is the key to reducing highway fuel consumption. It will reduce Class 1–8 truck fuel consumption by 1.4 million barrels per day oil equivalent (mmb/d oil equivalent) by 2020 and 2.1 million mmb/d by 2030, amounting to a reduction of total highway petroleum consumption (including that of passenger cars) of 12.6% and 18%, respectively (Fig. 5). The decrease in petroleum consumption is a result of improvements in truck efficiency as well as increased use of nonpetroleum fuels. Additional benefits would accrue in the non-road sectors (rail, pipeline, marine, and off-highway vehicle), because these markets use engine technology common to the highway truck market.

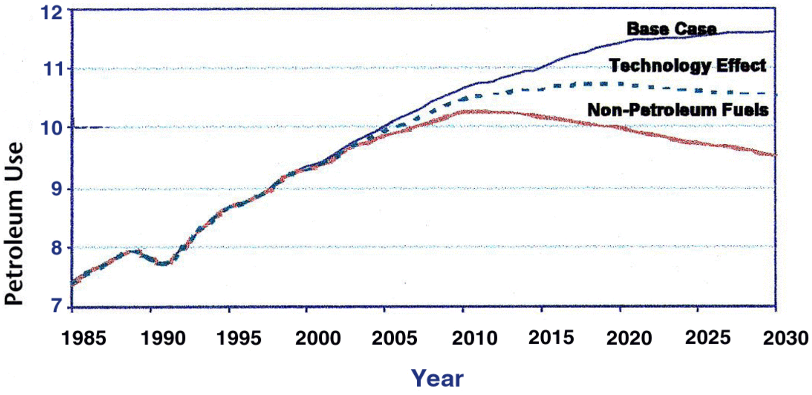


Fig. 5. Highway petroleum-use reductions from OHVT-supported technologies. (Petroleum use is given in units of 10^6 barrels/d oil equivalents.)

3. TECHNICAL PLAN

3.1 CLASS 7 & 8 TRUCKS

The following sections describe the goals for Class 7 & 8 trucks, the status of technology for these trucks, the technical targets to be achieved in order to meet these goals, the technical barriers that must be overcome to achieve the technical targets, and the technical approach to overcoming those barriers.

3.1.1 Goals

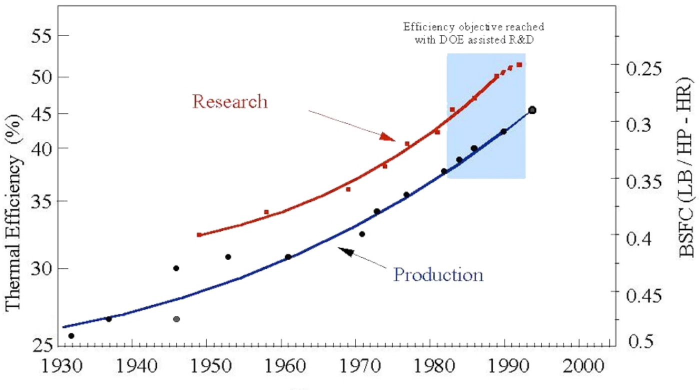
The program goal, with respect to Class 7 & 8 trucks, is to develop by 2004 the enabling technology for a truck that will have a fuel efficiency of 10 mpg (at 65 mph), will meet prevailing emission standards, and will use petroleum-based diesel fuel. A separate task will focus on developing a highly efficient gaseous fuel engine.

The program will achieve this goal by performing the R&D research and development required to achieve higher engine efficiency, reduced power requirements, reduced emissions, and alternative-fuel capability.

3.1.2 Engine Efficiency for 10-mpg Truck

3.1.2.1 Status of Technology

Compression-ignition (diesel) engines derive their high efficiency from being designed to emulate high-efficiency thermodynamic cycles and to minimize mechanical losses. The base thermal efficiency of diesels comes about from utilizing a relatively high compression:expansion ratio, combusting fuel at a high rate. Diesel engines use air-fuel rationing instead of throttling for load control, thus avoiding the part-load pumping losses characteristic of conventional spark-ignition engines. Most modern diesels utilize turbocharging, which increases power density and utilizes exhaust heat to a limited extent. They are designed to operate at relatively low speeds, thereby managing mechanical friction losses. Other design features, like strategic cooling serve to minimize thermal energy losses. Due to their high efficiency, reliability, and availability, diesel engines are the dominant power source for heavy-duty trucks and for city and intercity buses in the United States and are the preferred power source for commercial surface transportation worldwide. Diesel engines are the most efficient energy-conversion devices available; very large units (e.g., land-based and marine engines) exceed 50% thermal efficiency.[6] Turbocharged diesels for highway trucks are now offered that approach 45% efficiency (compared with about 30% for production gasoline engines), an improvement of about 40% relative to diesel engines of the late 1970s (see Fig. 6). The diesel-engine industry believes that this number can be increased to 50% in the next few years in research designs (but not in production markets), even with accelerated implementation of stricter EPA emissions regulations, which will cause a 5 to 10% reduction in efficiency (see Sect. 3.1.4). For example, turbocompounding, essentially an additional turbocharger shaft coupled to the engine output shaft, is a proven technology for exhaust heat recovery, but it is not widely because it is not cost effective.

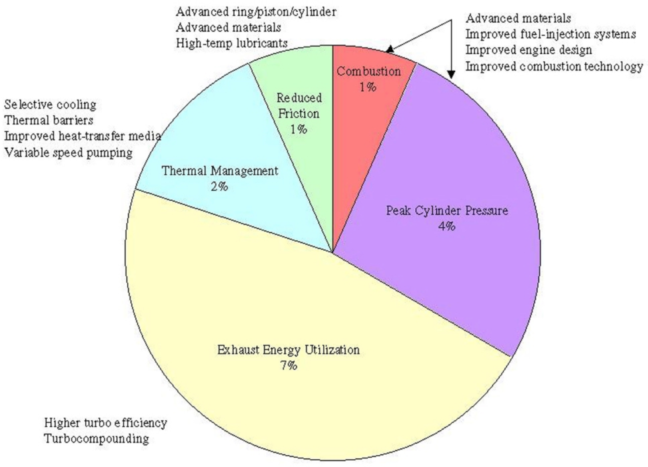


Source: Caterpillar, modified by DOE

Fig. 6. Increasing diesel-cycle engine efficiency.

3.1.2.2 Technical Targets

A brake thermal efficiency of 50% for the engine has been set as an aggressive but achievable objective. Major diesel engine companies have considered this target and have concurred. This target is less ambitious than that in the previous *Roadmap* because of recent events that require further emissions reductions in the near term. The “Consent Decree” between the engine manufacturers, U.S. Department of Justice, and the EPA essentially requires that 2004 emissions standards be implemented in October 2002; it also established new caps on emissions over a wider range of engine operation. To recover the 5–10% loss in efficiency and to meet the emission standards, new exhaust aftertreatment devices will have to be developed.



Adapted from: Don Krull, Caterpillar, Inc., Energy Efficient Heavy Vehicles Technologies, "The Engine Manufacturers Perspective" DOE/SAE Workshop on Energy Efficient Heavy Vehicle Technologies for Reducing Fuel Costs: Leveraging DOE's R&D Capabilities," Romulus, Michigan, April 17–18, 1996

Fig. 7. Projected contributions of advanced technologies to diesel engine efficiency improvement to achieve an increase of 15%.

Further advances in efficiency will be achieved with improvements in components and operating characteristics of engines similar in overall architecture to those now widely used. Contributions of the individual technical targets to the overall engine-efficiency goal of 50% are depicted in Fig. 7. A more detailed presentation of the characteristics of modern diesels and the targets and barriers for advanced technology are shown in Table 2. In addition to improvement to the reciprocator assembly, an effective exhaust heat recovery system is critical to meeting the 50% efficiency target.

3.1.2.3 Barriers

The barriers that must be overcome to achieve the component technical targets for the 50% efficient engine are summarized in Table 2. Additionally, emissions standards must be met while achieving the 50% efficiency goal.

Table 2. Summary of engine-efficiency parameters, technical targets, and barriers critical to 50% efficient engine

Engine parameter	Current practice	Technical target for 2004	Barrier
Peak cylinder pressure, psi	2000–2200	2800–3500	Structural integrity, thermomechanical fatigue, friction control, piston/ring lubrication, NO_x emissions. Advanced fuel-injection systems and electronic control could help decouple NO_x and efficiency
Turbocharger efficiency, %	50–58	72–76% with variable geometry or similar enhancement	Small turbomachinery aerodynamics; rotor inertia; materials for low-mass, aerodynamic rotors
Exhaust heat recovery	Essentially none except turbocharger	Recover additional 12% of exhaust energy cost effectively	Cost and complexity of turbo-compounding; efficiency/cost of direct conversion; materials for low-mass, cost-effective rotors; insulation of exhaust system
Brake mean effective pressure, psi	200–240	340–400	Structural integrity and thermomechanical fatigue (see first-row, "peak cylinder pressure"); limitations of single-stage turbochargers; need for adequate boosting. Fuel-injection rate and quantity need better control
Thermal management	Water and oil cooling, radiator	Selective insulation on piston, ports, head plate. Advanced systems to reduce parasitic thermal losses	Durable cost-effective coatings and other thermal barriers; TBC sealing, variable speed pumps, advanced heat transfer media; hybrid forced-convection/nucleate-boiling systems and fans would reduce losses
Engine mechanical friction		Provide 1% or more efficiency increase	Piston-ring-liner designs and materials are high-friction sources

3.1.2.4 Technical Approach

Specific tasks to improve the efficiency of Class 7 & 8 trucks include the following:

- Define one or more baseline engine designs in sufficient detail to delineate the areas where technology advancement is required. This would serve as a guide for enabling technology projects. Conduct, on a continuing basis, analysis and supporting validation tests to assess progress toward goals.

- Develop advanced combustion-chamber components for high peak pressures and high brake mean effective pressures, utilizing, as needed, new architectures for components, advanced materials, thermal barriers, and novel cooling strategies. Perform materials evaluation to support engine design targets, precomponent tests, performance and durability tests of new components, characterization of enabling materials, and finally, tests of complete engine systems. Identify needs for improved materials as required.

- Develop fuel-injection and combustion technologies that will provide higher peak cylinder pressure for better efficiency without causing higher NO_x. Support technology development with modeling and simulation as an integral component of the systems design strategy. Develop and integrate sensors, controls, diagnostics and enabling experimental tools. Emissions aftertreatment may be an approach to allow peak cylinder pressure to be raised without increasing NO_x (Sect. 3.1.4 and 3.4.3).

- Develop improved turbocharger and air-handling systems that include variable geometry technology, improved rotor aerodynamics, and systems controls. Continue systems analysis to reexamine tradeoffs between turbocharger efficiency and transient response. Review new low-inertia materials and response-enhancing technologies that may emerge.

- Continue analysis and evaluation of new exhaust heat-recovery technologies as they emerge, including direct energy conversion. Develop materials and designs for improved insulation of exhaust systems. Fabricate and test heat-recovery prototypes that are based on promising new technologies.

- Continue development of thermal-barrier designs and enabling materials. Refine analysis of benefits of cooling and thermal-barrier strategies and support with experiments. Develop effective thermal-management systems, including novel coolants and circulation systems, to reduce losses.

- Continue refinement of piston/cylinder designs, valve trains, and other mechanical components for reduced friction losses. Carry out R&D of low-friction materials and lubricants.

3.1.3 Power Requirements for 10-mpg Truck

The realization of 10-mpg trucks will require not only improvements in engine efficiency, but also substantial reductions in the power required to propel the vehicle. This can be achieved by a combination of reduced aerodynamic drag, reduced rolling resistance, and reduced parasitic losses. A previous analysis was reviewed and updated to identify the key contributors to truck power requirements. [7,8] A steady highway speed of 65 mph on level roads was taken as the base case. The present situation for a typical truck is depicted in Fig. 8. The steady-state case illustrates the priority power-consumers, although the

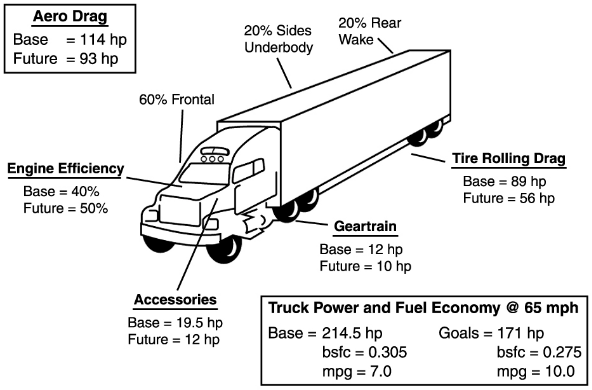


Fig. 8. Distribution of power requirements for a typical Class 8 truck.

value of a lower-weight chassis is less apparent than would be in a variable speed driving cycle. The analysis also highlights just how much fuel economy gain can be attributed to engine developments.

3.1.3.1 Status of Technology

Truck power requirements are dominated by aerodynamic drag, comprising mainly form drag, surface drag (skin friction), and internal drag (engine compartment and passenger ventilation). The combination of these gave large highway trucks a drag coefficient (C_d) of near 1.0 for designs of the mid-1970s. Truck cabs with rounded exteriors, plus a combination of air dams, gap seals, and other fairings can reduce the C_d for the tractor-trailer rig to about 0.55. Estimates of fuel economy improvements are 14–19% for combined aerodynamic treatments to the tractor and trailer. [9]

Reduced aerodynamic drag will put increased pressure on an already extended braking system. An improved braking system is therefore an enabling technology.

Rolling resistance is the second-highest factor in truck power requirements. A major shift toward use of radial tires instead of bias-ply tires has already been made; a low-profile radial tire is in widespread use. The newest generation of tire, the "super single," offers less rolling resistance. It is an available technology offering fuel savings of a few percent, but there is user resistance for a variety of reasons. Among the concerns is the lack of redundancy in the event of a failure and the perceptions that road damage is higher. The super singles are also taller than other radials and thus reduce the freight volume of a closed van trailer. Further, an additional cost is required to switch from the older systems to the new style. Super single tires are used primarily in the niche application of tanker trucks.

3.1.3.2 Targets

The distribution of power requirement comparing a typical Class 8 truck to one with advanced technology is also shown in Fig. 8. Clearly the greatest gains are achievable by attacking losses due to aerodynamic and rolling resistance. Mechanical losses in gears, bearings, and auxiliaries become more important as the major power drains are reduced. The technical targets established to achieve reduced truck power requirements for a 10-mpg truck are given in Table 3. [8–12]

3.1.3.3 Barriers

The barriers to achieving the technical targets for reduced truck power requirements are given in Table 3. [8-12]

3.1.3.4 Technical Approach

Specific tasks to address the power requirements of the 10-mpg truck include the following:

- Update vehicle systems analysis to define fuel-savings benefits of specific technical strategies such as aerodynamic designs, weight reduction, tire substitutions, and auxiliaries improvements.

- Conduct an assessment of the maintenance interferences of aerodynamic aids on vehicles and conduct competition for operator-friendly designs.

- Apply modern computational fluid-dynamics codes to "internal" flows in the radiators/engine compartment and identify new configurations to reduce this element of aerodynamic drag. Follow analysis with design and experimental verification.

- Develop pneumatic aerodynamic devices to control aerodynamic drag and to increase stability. Design and experimentally verify sensors for actuation of devices.

- Conduct design and tests of lightweight vehicle structures that the systems analysis indicate to be promising.

- Work with the U.S. Department of Transportation and the American Trucking Association (ATA) to conduct further assessments of the issues surrounding use of super single tires. Conduct a defining set of tests on the relative road damage of dual and single tires.

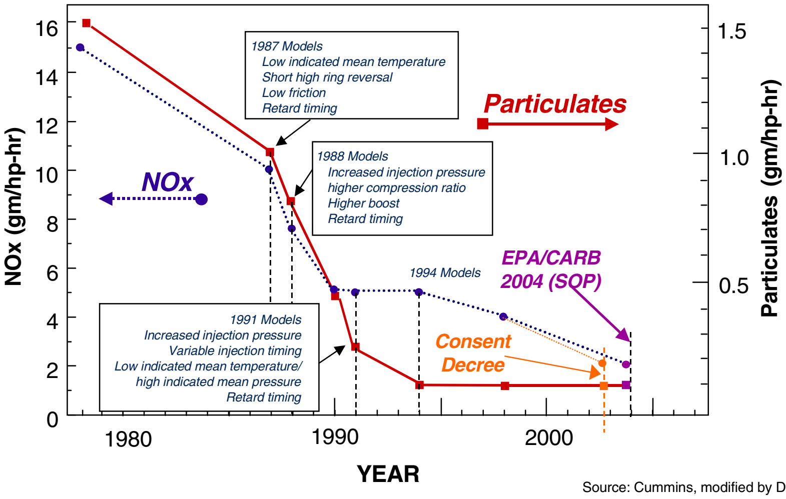
Table 3. Summary of 10-mpg truck parameters, technical targets, and barriers

Vehicle parameter	Current technology	Target	Barrier
Aerodynamic drag	$C_d = 0.55$ with best available designs and added fairings	$C_d = 0.47$ (or 15% reduction in widely used packages)	Maintenance nuisance, cost of aero designs. Nonoptimal underhood designs, large radiator
Rolling (tire) friction losses	Low-profile radials	Reduce rolling resistance by 8% (assume use of super singles)	Road-damage, stability (safety), and cost concerns for super single tires; availability at truck stops
Mechanical losses	Transmission and axles account for up to 7% of power requirements	Reduce by 25%	Cost-effective alternative materials and designs
Auxiliaries, parasitics	Shaft-driven auxiliaries account for up to 12% of truck power requirement	Reduce by 25%	Cost-effective alternative materials and designs

3.1.4 Emissions

3.1.4.1 Status of Technology

Reduction in emissions from Class 7 & 8 diesel engines must also be achieved in addition to improvements in thermal efficiency. When the EPA first began regulating diesel emissions in the mid- to late 1970s, trucks typically had emission values of 10–15 g/bhp-h of NO_x and 1 g/bhp-h of particulate matter (PM). Over the past 20 years diesel-engine manufacturers have achieved remarkable reductions in NO_x and PM emissions by modifying their engines (see Fig. 9). Emissions reductions have been achieved by retarding fuel-injection timing, increasing injection pressures, improving air-handling systems, using oxidation catalysts, and implementing EPA's mandate for low-sulfur diesel fuel (no greater than 0.05% sulfur content) for on-highway vehicles in the early 1990s. Today's heavy-duty diesel engines are regulated to 4.0 g/bhp-h of



Source: Cummins, modified by DOE

Fig. 9. Evolution of heavy-duty diesel engine emissions control.

NO_x and 0.10 g/bhp-h of PM (<0.05 g/bhp-h for transit buses), and substantially lower emissions have been achieved in research engines.

In spite of these reductions, there continues to be concern about the environmental and health effects of diesel-engine emissions. The California Air Resource Board (CARB) has declared diesel particulate matter to be a "toxic air contaminant," and there is widespread uncertainty about the health effects of diesel and gasoline emissions within the health-effects community itself. In 1996, the EPA, the state of California, and major engine manufacturers prepared a Statement of Principles[13] (SOP) that required further reduction to 2.4 g/bhp-h of NO_x plus non-methane hydrocarbons (NMHC) or 2.5 g/bhp-h of NO_x plus NMHC with a maximum of 0.5 g/bhp-h of NMHC by 2004.[14] Recently, an action by the EPA and the U.S. Department of Justice resulted in a consent decree with the diesel-engine manufacturers that moves the SOP requirements to October 2002 and places caps on emissions at all operating conditions. The requirement for the diesel-engine manufacturers to meet these lower emissions standards will result in reduced engine efficiency until new engine and emissions technologies are developed.

Meeting the stringent emission standards set forth in the consent decree while improving engine efficiency constitutes a major challenge for diesel-engine manufacturers. To address these challenges one can consider three approaches: (1) minimizing the pollutants coming out of the engine (engine-out emissions), (2) cleaning the engine emissions to an acceptable level before exhausting to the environment (exhaust aftertreatment), and (3) fuel reformulation with or without additives.

3.1.4.1.1 Engine-out emissions

Optimizing fuel combustion. Significant reductions in emissions have been made through combustion modifications (e.g., retarded injection timing, increased injection pressure, and lower temperatures); however, further reductions are needed. The key is an improved understanding of the diesel combustion and emissions formation processes and the development of design tools (i.e., models) that incorporate the improved understanding and allow engine designers to rapidly explore alternative combustion system designs. Much progress has been made in understanding and modeling diesel combustion. However, the level of detailed understanding of the mechanisms controlling combustion and emissions that is needed by engine designers to make further improvements is not available. Recent work has led to the development of new diagnostics that are providing this detailed understanding.

As new diagnostics advance the understanding of in-cylinder processes in diesel engines, more advanced concepts are being evaluated. A homogeneous-charge, compression ignition diesel engine offers the possibility of diesel-like efficiencies with very low engine-out emissions; the challenge is control of the process.

Fuel-injection equipment (FIE) plays a pivotal role in the combustion process. Improved understanding of FIE through modeling and testing and evaluation of performance and durability are important in the overall development of reduced engine-out emissions.

Lubricant control. Particle emissions from diesel engines originate from the combustion of lube oil as well as from combustion of fuel. Although this effect is markedly less, it is nonetheless important if the new, more stringent regulations are to be met. Recent studies illustrate the magnitude of the PM contribution from lube oil. A recent study of fuel effects in a light-duty engine showed that about 5% of the total particle emissions originated from the lube oil, while the number was about 10% for a heavy-duty engine.[15] However, this value is very engine-specific, and the particle contribution from lube oil can range from a few percent to as much as 30% of the total particulate emissions.[16] Efforts continue to quantify the effect and to develop the means to minimize the lube-oil contribution to particulate emissions while maintaining adequate engine lubrication.

3.1.4.1.2 Exhaust aftertreatment

Several concepts are being pursued that could potentially affect both NO_x and particles but most still require significant development before they could be considered ready for commercial use.

Lean-burn catalysts. Catalytic systems in today's automobiles operate with air:fuel ratios at or close to stoichiometric. In such systems, both reduction of NO_x and oxidation of carbon monoxide (CO) and hydrocarbon (particles) can be accomplished in a single catalyst bed; sufficient reducing gases are present to reduce NO_x, and enough oxygen is available to oxidize the CO and hydrocarbons. However, because diesel engines operate under lean-fuel conditions (i.e., excess oxygen), conventional catalysts are not effective; therefore, new catalysts are required. This is an active area of R&D in which many promising ideas are being pursued by engine manufacturers around the world. NO_x conversion efficiency with these systems is presently inadequate for most emissions targets.

Plasma systems. In plasma systems, short electrical discharges are used to create a plasma that contains electrons, ions, and radicals that are used to reduce NO_x and oxidize hydrocarbons. However, such systems working alone have been found to be energy intensive and primarily oxidative and, therefore, not attractive for NO_x reduction. Plasma-assisted catalysis offers the potential of enhanced performance over unassisted lean-NO_x catalysis. Potential benefits include more efficient (80%) NO_x reduction, a much broader operating temperature range, and less need for noble metals.

Particle traps. For commercial use a particle filter must (1) filter carbon particles from a high-temperature diesel exhaust gas at an acceptable backpressure; (2) survive thousands of thermal transients due to regeneration or cleaning of the filter by oxidizing the collected carbon; (3) be durable and reliable over the life of the filter which is in excess of 300,000 miles (10,000 h); and (4) provide a low overall operating cost that is competitive with other filtering techniques. State-of-the-art systems for filtering carbon particles and regenerating the trap have a few remaining shortcomings. Particle filters are costly and result in modest fuel-consumption penalties. Their regeneration requires catalytic systems that are sensitive to sulfur in some designs. Other catalytic soot filters still require regeneration temperatures that may be too high for some applications.

An alternative aftertreatment for particles is the use of plasma devices (see previous section), which have shown great potential for particle destruction in preliminary tests.

NO_x absorbers. Absorber materials are being developed to reduce NO_x under lean exhaust conditions. These materials would be regenerated (i.e., they would reduce the NO_x) by a pulse of hydrocarbons introduced into the exhaust system. While effective with ultra-low-sulfur fuels, the current fuel sulfur levels significantly reduce the absorption capacity of current materials. R&D is required to develop materials that are less sensitive to sulfur, exhibit high NO_x absorption capacity and regenerative capacity over the expected exhaust-temperature range and life of the truck. The regeneration requires a near-oxygen-free environment in the exhaust for short periods, which is a major engineering and control-system challenge.

Selective Catalyst Reduction (SCR). Selective catalyst reduction materials effectively reduce NO_x over a catalyst bed in the presence of a reducing agent that is added to the exhaust system in controlled amounts. R&D is needed to reduce the sensitivity of the catalyst materials to sulfur and to evaluate their performance at expected operating conditions over the life of the truck. Because of the lean diesel-exhaust environment, both NO_x absorbers and SCR materials require the addition of a reducing agent. Further research is needed to define the addition and control of reducing agents added to the exhaust system. The infrastructure needed to distribute the SCR reagent (e.g., urea) is a major impediment.

3.1.4.1.3 Fuel reformulations and additives

To reach the goal of lower emissions while maintaining efficiency, fuel quality standards must remain high. Fuel reformulations and additives can lead to lower exhaust emissions, better fuel economy, and improved cold start performance. Additives can also be used to improve lubricity in low-sulfur fuels. Efforts are under way to understand the effectiveness of different additives and to determine how their use can be optimized (see Sect. 3.1.5 for more detailed discussion of fuels and lubricants).

3.1.4.2 Technical Targets

The emissions targets are as follows: 0.01 g/bhp-h PM and 2.4 g/bhp-h of NO_x plus NMHC or 2.5 g/bhp-h of NO_x plus NMHC with a maximum of 0.5 g/bhp-h of NMHC or less by October 2002, while achieving the efficiency goals. The program has developed strict emissions targets of 1.0 g/bhp/h NO_x and 0.05 g/bhp/h PM for 2006 (see Table 4).

3.1.4.3 Barriers

The barriers to achieving the technical targets for emissions from diesel engines for Class 7 & 8 trucks are given in Table 4.

Table 4. Summary of goals, technical targets, and barriers for Class 7 & 8 emissions

Goals	Technical targets	Barriers
Minimize engine-out emissions	By 2002: 0.1 g/bhp-h PM 2.4 g/bhp-h NO_x + NMHC *or* 0.1 g/bhp-h PM 2.5 g/bhp-h NO_x + NMHC with maximum of 0.5 g/bhp-h NMHC	NO_x/PM trade-off; that is, maintaining efficiency and keeping PM down. Meeting the target across the load and speed map. Reliability. Limitations on cost-effective fuel additives and reformulation
Develop effective aftertreatment	By 2006: 1.0 g/bhp-h NO_x and 0.05 g/bhp-h PM	Development of lean combustion catalyst. Cost effectiveness. Durability/reliability

3.1.4.4 Technical Approach

Meeting the technical targets for emissions will require the three-pronged diesel-engine emission-control strategy described in Fig. 10: (1) understanding and optimizing in-cylinder combustion processes, (2) optimizing fuel formulation, and (3) developing exhaust aftertreatment technologies such as improved catalysts. The following are specific R&D tasks.

- Apply advanced diagnostics to describe and quantify (when possible) the in-cylinder formation of NO_x and PM.

- Develop advanced fuel-injection systems, including high-strength, non-galling, wear-resistant materials for increased injection pressure and reduced particle emissions.

- Reduce or eliminate particulate contributions from lube oil by development of advanced solid lubrication materials for use in valve guides. Investigate operation of valve guides without liquid lubrication.

- Develop advanced materials, designs, and regeneration technologies for particle traps.

- Evaluate effectiveness of varying amounts of exhaust gas recirculation to control emissions, and determine its effect on engine life.

- Determine effectiveness of fuel-injection rate shaping. This will be fuel-injector-specific and will require integration with sensors and controls.

- Develop fuel additives and compare the effectiveness of fuel additives and reformulated diesel fuel to baseline fuel. (See Sect. 3.1.5 for a more detailed description)

- Characterize fuel injector sprays that provide optimal combustion parameters.

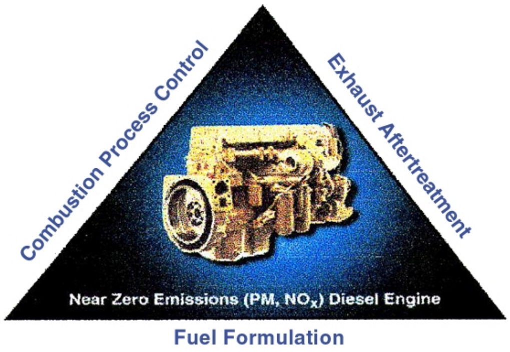


Fig. 10. Multifaceted emission-control approach necessary to ensure that fuel-economy, cost, and durability goals are in harmony with ambitious emission targets.

- Formulate new, cost-effective catalysts and systems that reduce NO_x in lean combustion environments. This task includes investigation of SCR catalysts and NO_x adsorbers.

- Evaluate effective catalyst formulations for longevity and stability to meet 300,000-mile requirement.

- Evaluate plasma-assisted catalysis at high flow rates of diesel-engine exhaust.

- Conduct experimental and modeling program to form a better understanding of the chemical and physical mechanisms of plasma-assisted catalysis.

3.1.5 Fuels Utilization—Advanced Petroleum-Based Fuel Program

The OHVT program strategy focuses on improving the performance of diesel engines and reducing their emissions by using either advanced petroleum-based (APB) fuels or liquid or gaseous alternative fuels. Therefore, fuels and lubricants R&D activities are divided into two programs: the Advanced Petroleum-Based Fuels Program and the Alternative Fuels Program.

To enable the development of ultra-low-emission vehicles, the Advanced Petroleum-Based Fuels Program includes reformulation of diesel fuels and lubricants derived from crude oil. The program aims to develop pragmatic, near-term solutions for improving thermal efficiency of diesel engines and reducing their emissions. It includes research on blendstocks and additives used to upgrade or extend diesel-base fuels. A multiyear program plan[16] has been developed jointly by the DOE Office of Advanced Automotive Technologies, DOE-OHVT, industry representatives, research partners, and other stakeholders.

The Alternative Fuels Program is focused primarily on natural gas and Fischer-Tropsch (F-T) synthetic diesel produced from natural gas and biomass feedstocks, but also includes research on fuels of the future. To successfully achieve DOE-OTT goals to reduce the nation’s reliance on imported oil and promote energy diversity, it is important for alternative fuels to be used in heavy vehicles. This section discusses the possibility of using these alternative fuels in heavy trucks and buses and some of the barriers that must be overcome. Each of the medium- and heavy-duty engine manufacturers offers production engines designed to operate on alternative fuels. Cooperative industry and government projects will be established to optimize fuel formulations and engine system technologies concurrently.

3.1.5.1 Status of Technology

Since 1990, the EPA has required that all diesel fuel sold for use in on-road vehicles have no greater than 500-ppm sulfur content (the resulting average is about 340 ppm). In addition, it must meet the limits of either a maximum aromatic content of 35% or a minimum cetane number of 40. Since 1993, CARB has required that in addition to limiting sulfur content to 500 ppm, diesel fuel sold in California for both on-road and off-road diesel vehicles must have a maximum of 10% aromatic content (20% for small refiners; alternative formulations with higher aromatic content are allowable if they are proven to produce the same or lower emissions). These limits on diesel fuel properties are intended to reduce emissions of NO_x and PM.

Much of the diesel fuel research to date has focused on higher cetane number, lower sulfur content, and lower aromatic content to reduce engine exhaust emissions. However, the blending of other fuel components, such as oxygenates or paraffins, in diesel fuel can also dramatically reduce engine emissions. Biodiesel, methylal, and F-T synthetics are all effective blendstocks for diesel-based fuels; 20 to 60% reductions in engine-out PM are possible based on laboratory testing in a variety of unmodified engines. Researchers have concluded that significant engine-out emission reductions are possible through modifications of diesel fuel properties beyond those mandated to date by EPA and CARB.

Further reducing the sulfur content of diesel fuel to 30 ppm or lower has the potential to enable several emission-control/aftertreatment devices that could significantly lower NO_x and particulate emissions. Additional fuel modifications have the potential to further lower engine-out emissions and make these emission control devices more effective, less costly, or both. The Diesel Emission Controls and Sulfur Effects (DECSE) project, a cooperative research effort between the OHVT, Engine Manufacturers Association (EMA), and Manufacturers of Emission Controls Association (MECA), is underway to study the effect of sulfur content on aftertreatment system performance.

3.1.5.2 Technical Targets

Technical targets are outlined in Table 5 and are more extensively defined in the DOE-OAAT/OHVT *Advanced Petroleum-Based Fuels (APB) R&D Multiyear Program Plan*.[17]

Technical targets for the APB Fuels Program have been established to enable achievement of the overall emissions and efficiency goals set by the OHVT engine development program areas. Research on this program will (1) assist in achieving emission reductions to meet near-term emission standards, (2) determine relationships between fuel properties and emissions for future mid-term enhancements of fuels, and (3) provide a foundation for longer-term development of new fuels. Advanced petroleum-based fuels not only will enable this engine class to meet future emissions standards, but also will provide opportunities for substantial improvements in energy efficiency and reductions in greenhouse-gas emissions.

Separate technical targets are listed for engines without aftertreatment (engine-out emissions) and for engines equipped with aftertreatment/emission controls (post-aftertreatment or “tailpipe-out” emissions). Several technical approaches are possible to meet future emissions regulations, depending on the stringency of the engine application, the stringency of the emissions standard, the incremental fuel cost, the incremental vehicle cost, and the service life expectation.

3.1.5.3 Barriers

Technical barriers to the development and implementation of advanced petroleum-based fuels for next generation of diesel engines and emission control systems are described in the following paragraphs. These barriers are listed without regard to their relative severity or program emphasis.

- Fuel property effects on emissions and efficiency: Data and models correlating fuel properties to engine-out emissions and efficiency are limited in scope and have unexplained differences among various engine types. Emissions and efficiency tradeoffs may be substantially different for new fuels, especially if engines are equipped with emission-control devices.

Table 5. Summary of technical targets and barriers for advanced petroleum-based fuels for medium & heavy-duty applications

Attribute	Current practice	Target	Barrier
Fuel cost	Retail price of conventional on-road diesel is about $1.00/gal	Incremental price of reformulated diesel <$0.05/gal or <5%	Production economics, retooling refineries, infrastructure costs, health, safety, and regulatory costs especially for nonpetroleum blendstocks and additives
Engine efficiency	46% peak thermal efficiency in truck engines	50% peak thermal efficiency by 2004	NO_x-efficiency trade-off, fuel reformulation to enable durable, active NO_x emissions controls and advanced injection timing
Engine emissions	EPA 2004 on-highway truck, standards required to be met by October 2002 (only required for 95% of diesel engines) NO_x+ NMHC=2.5 g/bhp-h PM=0.1 g/bhp-h (trucks) PM=0.05 g/bhp-h (buses)	**Engine-out:** NO_x+NMHC<2.4 g/bhp-h PM < 0.1 g/bhp-h by 2002	**Engine out:** NO_x-efficiency tradeoff, lube oil contributions, toxic emissions for non-petroleum blendstocks and additives
		With aftertreatment: By 2006, 50% NO_x reduction compared to Diesel No. 2 without after-treatment and 75% PM reduction. Research targets: 1.0 g/bhp-h NO_x 0.0125 g/bhp-h PM	**With aftertreatment:** fuel sulfur content, fuel reformulation to enable durable NO_x and PM emissions controls, fuel additives for catalyst/filter regeneration, toxic emissions for non-petroleum blendstocks and additives, optimization for emissions controls, emission-control system deterioration and service life. Also: EGR, lack of standard test procedures for emissions controls, ultrafine particle emissions
Engine reliability	Emissions certified to 435,000 miles equivalent, plus customer expectation for million-mile truck engine (before first major overhaul)	Engine durability equivalent to that of engines using diesel No. 2	Concerns about service life of emission controls and effect of lube oil reformulation, fuel lubricity, and EGR on engine durability

- Emission system degradation: Knowledge is limited of how fuel properties affect engine-out emissions, the deterioration rates of emission aftertreatment devices, and the durability of emission control components.

- Effect of sulfur: Sulfur from the fuel and consumed lubricating oil poisons and rapidly renders ineffective many aftertreatment devices and reduces the durability of other systems such as cooled exhaust gas recirculation (EGR) systems. Data are lacking on the magnitude of the impacts and on reversibility following exposure to fuels with high sulfur levels.

- Ultrafine particles: Diesel engines may be significant contributors to the existing ambient inventory of ultrafine particles in the atmosphere, and the study of the measurement of ultrafine particles (i.e., particles of diameter $< 0.1\ \mu$m) is just beginning. The formation mechanism of ultrafine particles is related, among other things, to how exhaust gases are diluted with the air. Likewise, the role of aftertreatment devices on formation of ultrafine particles is not well defined, but oxidation catalysts have been shown to cause increases in the number of ultrafine particles while reducing the mass of particulate emissions. The lack of knowledge in these areas may inhibit the development of advanced petroleum-based fuels that could significantly reduce ultrafine particulate emissions from diesel engines.

- Toxic emissions: Data are limited on the emissions and human-health impacts of petroleum based-fuel and nonpetroleum components on emission of toxics as defined by the Clean Air Act amendments of 1990. Emissions of additional compounds that could be considered toxic are coming under increasing scrutiny by regulators. The lack of data about toxic emissions from existing fuels and engines is a barrier to determining desirable characteristics of advanced petroleum-based fuels and any nonpetroleum fuel components. Thus the benefits of various fuel formulation and engine/emission system control options cannot be determined at this time.

- Engine durability: Use of alternative fuels or advanced/reformulated petroleum-based fuels may necessitate the use of new fuel additives to enhance lubricity and elastomer compatibility.

- Advanced fuel production and costs: Data on refinery economics and processing strategies are insufficient to compare options for advanced petroleum-based fuels. Nonpetroleum fuel components typically have preliminary or proprietary production economic data. Insufficient advanced-fuel production and cost data are barriers to making informed decisions about the commercial viability of advanced petroleum-based diesel fuels.

- Health, safety, and regulatory issues: Data pertaining to health, safety, and regulatory issues for most nonpetroleum fuel components are sparse or incomplete. Without knowledge of these issues, it is difficult to screen out those components with undesirable characteristics. This lack of information raises a barrier to investigation of potential nonpetroleum fuel components that could have substantial emissions and energy efficiency benefits. Should desirable advanced fuels have health, safety, or regulatory issues, the issues will need to be resolved to the extent required by regulatory bodies to allow their sale and use in motor vehicles (see Sect. 3.4.4 for description of research related to this issue).

- Infrastructure impacts: Little is known about the technical and economic impacts of nonpetroleum fuel components of advanced petroleum-based fuels on the distribution, storage, and retailing infrastructure. If the characteristics of nonpetroleum fuel components were to cause compatibility or fungibility problems with the diesel-based fuel, barriers would be raised to their widespread use. Advanced petroleum-based fuels will not be successful commercially unless they can be distributed, stored, and sold in a manner that meets regulations and is acceptable to consumers.

3.1.5.4 Technical Approach

An integrated technical approach has been developed to address the barriers and to meet the technical targets in the 2000–2004 time period. The technical approach summarized in this section is comprehensively presented in the *DOE OAAT/OHVT Advanced Petroleum-Based Fuels R&D Multiyear Program Plan*.[17]

The technical approach comprises the following integrated work elements:

- Fuels screening. Potential constituents of an advanced petroleum-based fuel for diesel engines will be screened and assessed according to three principal factors prior to extensive engine testing under the program: (1) general combustion characteristics, (2) safety and health properties, and (3) production and distribution issues.

- Fuel and lubricant property testing for reduced engine-out emissions. Engine laboratory tests will be performed to study efficiency and emissions tradeoffs. In addition, the effect of lube oil as an emission-control containment will be evaluated.

- Fuel and lubricant property testing to enable emission controls. Engine laboratory tests will be performed to evaluate fuel and aftertreatment device combinations and to study efficiency and emissions tradeoffs.

- Potential for higher efficiency and reduced emissions. Empirical models will be generated from test data collected during the fuel and lubricant testing to reduce engine-out emissions and to enable emission controls. The models will be validated by comparison with test data and will be used to identify promising fuel formulations and emission control-options from a technical perspective.

- Refinery and fuel processing economics. The potential economic viability of advanced petroleum-based fuels and fuel components will be studied.

- Infrastructure. The compatibility of advanced petroleum-based fuels and nonpetroleum fuel components with the current infrastructure for producing, transporting, and storing fuels will be studied.

- Vehicle performance. The compatibility and durability of the vehicle fuel system, engine, and emission-control system will be investigated for promising fuels. Fleet tests will be used to evaluate the “real-world” performance of advanced petroleum-based fuels.

- Safety, health, and consumer acceptance aspects of advanced fuels. Health risks, safety risks, environmental risks, and perceived odor issues will be assessed.

- Assessment of fuel options. The results from the work elements will be used to evaluate fuel options. Limited program resources will be expended to provide guidance to DOE and its industry collaborators on the relative merits of advanced diesel fuel options.

3.1.6 Fuels Utilization—Alternative Fuels Program

3.1.6.1 Status of Technology

Alternative fuels can displace diesel fuel in Class 7 & 8 truck and bus applications. Biodiesel and synthetic diesel fuel may be used in unmodified or slightly modified engines and vehicles. However, most other alternative fuels cannot be used directly in unmodified vehicles, but rather require substantial engine and vehicle modifications. Technical and infrastructure barriers are associated with alcohol and gaseous fuels, and these barriers lessen the widespread deployment and utilization of alternative-fuel vehicles.

To maximize performance and reduce emissions from alternative-fuel vehicles, engine and vehicle systems must be optimized for each type of fuel. Alternative fuels for use in unmodified or fuel-flexible engines may be desirable for certain applications and markets but may result in compromised performance and emissions, thereby not fully exploiting the attributes of cleaner alternative fuels.

Substantial progress has been made for the following alternative fuels:

- Fischer-Tropsch (F-T) Diesel Fuel
  - — Commercial-scale production plants are producing synthetic gasoline and diesel fuel in South Africa. Neat synthetic diesel fuels have been used to fuel unmodified heavy commercial vehicles.
  - — In the United States, F-T diesel was tested in unmodified Class 8 trucks and transit buses with no detectable performance difference compared with conventional diesel fuel. Substitution of F-T diesel resulted in a 10 to 15% NO_x reduction and about a 25% PM reduction.
  - — F-T diesel has been used as a commercial-scale blendstock to upgrade diesel fuel to meet California diesel fuel standards.

- Gaseous Fuels (natural gas and propane)
  - — Vehicle emissions tests indicate that NO_x emissions are typically 50% lower and PM emissions are typically 90% lower than with diesel fuel. Overall efficiency for these engines is approximately 10 to 15% lower than with diesel fuel.
  - — Cummins, DDC, Deere, and Mack offer dedicated homogenous-charge, spark-ignited, natural gas engines for Class 7 & 8 vehicles. Cummins is discontinuing the L10G natural gas engine product due to disappointing sales.
  - — Compressed natural gas (CNG) transit buses are proven in service, now accounting for about 25% of new bus orders in the United States.
  - — Customers have requested higher-power natural gas (NG) engines for Class 8 applications. Mack is developing a 400-hp dedicated NG engine for the Class 7 & 8 truck market. Caterpillar, in collaboration with Clean Air Partners (CAPS), offers C12 dual-fuel engines rated at 400 hp.
  - — Cummins offers a propane engine (the B5.9-LPG), but commercial sales have been below expectations.

  - — Stratified-charge, direct-injection natural gas (DING) and micro-pilot fuel systems are being developed in the engine laboratory to overcome part-load efficiency barriers.

- Alcohols
  - — In the United States, highly modified direct-injection (DI) diesel engines with high-compression ratios and glow-plugs were developed to combust low-cetane alcohols. Near-diesel efficiency was achieved. DDC 6V-92 alcohol engines were tested in trucks and buses and were sold commercially with mixed results.
  - — European manufacturers are actively introducing alcohol-powered vehicles equipped with diesel-like engines. These engines require a fuel additive to improve the cetane number and enable autoignition of the fuel.

- Future Fuels (Toxicity data will be collected and evaluated prior to any recommended introduction of future fuels.)
  - — Biodiesel. Essentially no major engine changes are required; normal diesel-cycle engine operation has been demonstrated. Diesel-like efficiency and substantial PM reductions have been measured on a variety of engines.
  - — Dimethyl Ether (DME). Direct injection of DME requires extensive changes to the fuel delivery and injection systems. Nearly soot-free combustion and efficiency near or equal to diesel fuel has been demonstrated in the laboratory.
  - — Dimethoxy Methane (DMM, Methylal). DMM is less volatile than DME but more volatile than diesel fuel. DMM has been successfully tested in unmodified engines in the laboratory; very low particulate emissions have been demonstrated.
  - — Diethyl Ether (DEE). DEE is a renewable pathway for oxygenating diesel from the biomass ethanol process. Based on preliminary engine testing, DEE is not as effective as DME and DMM for reducing PM emissions when blended with diesel.

The Alternative Fuels Program R&D efforts continue to focus mostly on F-T synthetic diesel fuel and natural gas. These priorities are in agreement with findings from the OAAT/OHVT Fuels Plan, and research pathways are consistent with the DOE-OHVT Government Performance and Results Act (GPRA) Performance-Based Management process.

Over the past two years, the DOE has been actively evaluating F-T fuel for use in diesel engines. Laboratory research and vehicle tests indicate that F-T diesel can be safely substituted for diesel fuel without significant performance loss. Substantial NO_x and PM reductions have also been measured in a variety of emissions laboratories. Still further emissions reductions may be realized if engine systems are optimized for use with F-T diesel. F-T diesel may also enable the use of sulfur-intolerant aftertreatment and emission-control devices. Additive packages to improve cold-flow and lubricity properties are under development.

Most alternative-fuel heavy-duty engines being offered today run on natural gas. These engines are primarily used in city buses, school and shuttle buses, refuse haulers, and centrally fueled truck fleets. The following two approaches are being used in production engines today.

- Spark-ignited natural gas (SING) engines. These engines are usually based on a diesel engine block but are converted to spark ignition. Cummins, Detroit Diesel, Deere, and Mack have homogeneous charge, throttle-body injection engines in production. All of these production engines use a lean-burn strategy for better fuel economy. At full load, the lean-burn spark-ignition engines reach near-diesel efficiency; however, at idle and part-load conditions, their efficiency is significantly less than that of a diesel engine. Very low vehicle emissions have been demonstrated in the laboratory and in service. The Deere 8.1-liter natural gas engine developed for the Ultra-Safe Ultra-Low Emission Blue Bird School Bus has demonstrated 1.0 g/bhp-h NO_x, less than 0.03 g/bhp-h PM, and 40% peak thermal efficiency, perhaps the best available benchmark for future technology comparisons.

- Dual-fuel natural gas (DFNG) engines. These engines can be run on diesel only but cannot be run on natural gas only because the autoignition characteristics of natural gas are poor. At idle and low load conditions they burn mostly diesel fuel. At full load, a small pilot injection of diesel fuel is used to ignite the main charge of natural gas; over the full cycle, the engines burn up to 95% natural gas. Caterpillar, in collaboration with CAPS, has developed a full line of heavy-duty DFNG engines that are finding applications in California. Westport Innovations is collaborating with Cummins and DDC to develop dual-fuel DI fuel systems for the Signature 600 and 6V-92 engines, respectively. The manufacturers claim that these engines overcome part-load thermal-efficiency penalties associated with dedicated natural gas engines, while maintaining diesel-like rated power. Preliminary chassis dynamometer tests indicate that the Caterpillar/CAPS dual-fuel vehicle emissions are lower than diesel vehicles but are substantially higher than dedicated SING-powered vehicles.

DI natural gas fuel-injection systems and diesel micropilot fuel-injection systems are being developed in the research laboratories to overcome part-load inefficiencies associated with the SING engines and to further reduce engine-out emissions.

Natural gas is currently stored either as a CNG at pressures up to 3600 psi or as liquefied natural gas (LNG), a cryogenic liquid, on board heavy vehicles. Development of high-pressure tanks has resulted in lighter tanks in the past few years, and efforts are under way to lower the cost of these tanks. DOE sponsors work on developing effective adsorption media to store natural gas at low pressures. LNG is the preferred fuel storage technology for Class 7 & 8 applications because these vehicle applications require greater range. The availability and reliability of refueling stations must be improved to facilitate more widespread deployment of natural gas vehicles.

3.1.6.2 Technical Targets

The technical targets for the Alternative Fuels Program are outlined in Tables 6 and 7. The following are the primary targets:

- For a liquid alternative fuel such as F-T synthetic diesel, less than 2.2 g/bhp-h engine-out NO_x emissions and less than 0.05 g/bhp-h PM by 2004, and peak thermal efficiency over 50% by 2006.

- For dedicated gaseous-fuel engines, less than 1.0 g/bhp-h NO_x emissions, improved part-load thermal efficiency and peak thermal efficiency over 45% by 2004.

Table 6. Summary of technical targets and barriers for Class 7 & 8 Fischer-Tropsch-fueled diesel engine

Parameters	Current practice	Target	Barrier
Cost	F-T has been used as a blendstock to meet California diesel fuel standards and is used as a neat-fuel in South Africa	Same as engine optimized for ultra-low sulfur diesel fuel	Fuel supply and distribution infrastructure issues. Acceptance by market place of any cost penalty
Efficiency	Same as diesel on an energy-equivalent basis	50% peak thermal efficiency by 2006	Same barriers as for a high efficiency diesel engine, plus optimum compression ratio, injection timing, and EGR rate are different for F-T fuels
Emissions	EPA 2004 on-highway truck standards: NO_x + NMHC = 2.5 g/bhp-h NO_x = 2.4 g/bhp-h PM = 0.1 g/bhp-h	Engine-out: NO_x < 2.2 g/bhp-h PM < 0.05 g/bhp-h by 2004	NO_x-efficiency tradeoff and possible adaptation of NO_x-reduction aftertreatment devices. Optimum EGR rate may be different for F-T fuels
Reliability	Similar to or same as diesel	Same as diesel	Possible concerns about cold-flow properties, seal compatibility, and lubricity

Table 7. Summary of technical targets and barriers for Classes 7 & 8 dedicated gaseous-fuel engine

Parameters	Current practice	Target	Barrier
Cost	15 to 100% more than a diesel engine	Same as diesel engine	Current production volumes are low. Fuel storage system costs are high. Added components and complexity add cost
Efficiency	Maximum of 40% with lean-burn SING, 15% less efficient than diesel in the field with SING engines, 4% less than diesel with pilot ignition natural gas	>45% peak thermal efficiency by 2004	Same barriers as for a high-efficiency diesel engine, plus low cetane rating of fuel makes diesel cycle difficult. May need low-cost sensors for knock detection and ignition system improvements
Emissions	Dedicated lean-burn NG spark ignited engine: NO_x = 1/4 g/bhp-h NMHC = 0.5 g/bhp-h CO = 6.0 g/bhp-h PM < 0.05 g/bhp-h	NO_x < 1.0 g/bhp-h PM < 0.03 g/bhp-h	Maintaining low emissions while increasing efficiency
Reliability	Similar to diesel	Same as diesel	Spark plug life (if SI), fuel delivery system reliability, valve/valve seat wear

Both emissions targets are for the U.S. EPA federal test procedure (FTP) transient test cycle and are significantly lower than the 2004 on-highway emissions standards that engine manufacturers must now meet by October 2002 as a result of the Consent Decree with the EPA.

Recent laboratory tests show that F-T diesel fuels have the potential to reduce NO_x emissions by 10 to 15% in unmodified engines without significant changes in fuel energy consumption. Since F-T diesel is also sulfur-free, it enables the use of sulfur-intolerant NO_x aftertreatment devices, such as NO_x adsorbers and lean NO_x catalysts.

Laboratory research has shown that direct injection of natural gas is feasible and can lead to low NO_x emissions with diesel-like thermal efficiency. The Caterpillar DING system has achieved 2.5 g/bhp-h NO_x and 40% peak thermal efficiency, but requires the use of EGR. More advancements are needed to meet this target, and two laboratory research projects are under way. The direct-injection stratified charge fuel system developed by Deere and the Southwest Research Institute (SwRI) allows very lean engine fueling overall.

Micro-pilot injection, which uses a pilot charge of diesel fuel to ignite the main charge of natural gas, is also being tested on a single-cylinder engine in the research laboratory. Both of these technologies show promise for meeting this target.

3.1.6.3 Barriers

Barriers to deploying F-T-fueled and gaseous-fueled engines are given in Tables 6 and 7, respectively. The primary barrier is probably a market barrier and not a technical one. Because of their additional cost and complexity, an incentive such as lower alternative-fuel cost or perceived threat of a fuel shortage will be required to create a market for alternative-fuel engines.

The primary barriers for F-T diesel are economic. Fuel production facilities would need to be constructed and would be most attractive where large quantities of inexpensive natural gas are available. In such locations, which are usually remote, capital costs for production facility construction would be high because of a lack of general infrastructure (e.g., roads). Additionally, if F-T diesel (or a blend) were marketed at the same time as other grades of diesel, it would presumably be necessary to segregate types of diesel fuel to some extent. Minimally, additional tankage would be required at fueling stations. Also, fungibility of the F-T diesel for pipeline transport has not been verified.

For natural gas vehicles, technical barriers pertain more to vehicle fuel storage and refueling stations rather than with the engine. The weight of the vehicle resulting from the extra components required on the engine as well as additional fuel tanks can be a barrier. Any increase in weight reduces load-carrying capacity. If extra fuel tanks are required, the space availability on the vehicle for the extra tanks can also be a barrier. Insufficient fueling infrastructure and unreliable fueling stations are also barriers to gaseous fuel use.

3.1.6.4 Technical Approach

Technical Approach for the Fischer-Tropsch diesel engine. Unmodified diesel engines can be operated on F-T diesel; however, there are no commercially available engines optimized for use with F-T or other liquid alternative fuels. This program will support the research needed to develop an engine optimized for F-T diesel and will address the technical barriers to developing a commercially viable liquid alternative fuel truck. The following are specific elements of the technical approach to overcoming the barriers outlined in Table 6.

- Conduct basic research on F-T diesel fuel to better understand the combustion process.
- Support R&D targeted at creating a high-efficiency engine optimized for use with F-T diesel fuel. Examine emissions and efficiency tradeoffs.
- Reduce exhaust emissions by optimizing injection-timing events, lowering combustion temperature, using EGR, and developing lean NO_x aftertreatment devices.
- Investigate low-cost additive packages for F-T fuels.
- Make low cost a priority on all development projects. Identify technologies that overcome the other barriers at the lowest cost.

Technical Approach for the gaseous-fuel engine. Gaseous-fuel truck and bus engines are now available and proven; however, most of these engines are more costly and have significantly lower part-load efficiency than comparable diesel engines. The Alternative Fuels Program will focus on improving the efficiency of these engines, thereby reducing the operating cost. The program will aim to develop Class 7 & 8 LNG trucks and Class 7 & 8 CNG/LNG buses that are fully comparable in cost and performance with their diesel counterparts. The following are specific elements of the technical approach to overcoming the barriers outlined in Table 7.

- R&D targeted at improving the efficiency of dedicated gaseous-fuel engines. Work may include extending the lean limit, developing advanced control systems, and developing direct injection, micro-pilot injection, variable valve timing, skip firing, Miller cycle,[18] or other strategies.
- Development of sensors or other technology to detect fuel-quality variations and to adapt the engine controls to extend the lean limit.
- Development of durable, low-cost ignition systems, addressing emissions impacts with each development step.
- Development of durable, wear- and corrosion-resistant intake valves, valve seats, and valve guides to increase durability of natural gas engines.
- Development of safe, lightweight, fuel tanks and fuel-storage media.
- Research aimed at expanding fueling infrastructure and improving performance of existing LNG and CNG refueling stations. Pursue research on such technologies as leakless, freeze-resistant nozzles, odorization of LNG, improved cryogenic pumps and safe breakaway hoses. Also, continue work on broadening LNG supply by supporting R&D on innovative, small-scale liquefaction technologies.

3.2 CLASS 3–6 TRUCKS

The following sections describe the goals for Class 3–6 trucks, the status of technology for these trucks, the technical targets to be achieved in order to meet these goals, the technical barriers that must be overcome to achieve the targets, and the technical approach to overcoming those barriers. The original Roadmap[2] included only a cursory treatment of the Class 3–6 medium-duty urban vans and trucks. Important initiatives regarding the development and implementation of hybrid propulsion systems for this class range are discussed here. The technical plan is structured around Class 3–6 vehicles, which may be characterized by the commercial subgroup of urban trucks, delivery vans, and buses. Some of the urban vehicles (e.g., transit buses and refuse trucks) are actually in Class 7 & 8; they are included here because their urban driving cycles are similar. Also, several types of off-road, earth-moving and construction vehicles have similar duty cycles and are included in this activity.

3.2.1 Goals

The program goal with respect to Class 3–6 trucks on an urban driving cycle is to develop and demonstrate, by 2004, commercially viable vehicles that achieve at least double the fuel economy of comparable current vehicles (2000), and as a research goal, to reduce criteria pollutant emissions to 30% below 2004 EPA standards.

3.2.2 Emissions Reductions and Improved Fuel Economy

The technology status, targets, barriers, and development plans for advanced diesel engines are adequately described in other parts of this Roadmap; the advancements would be applied to Class 3–6 engines to reduce emissions and improve fuel economy. A separate, key technology applicable to Class 3–6 urban heavy vehicles is the hybrid electric propulsion system, which could be a viable means of reducing emissions and improving fuel economy. The emphasis of this section is to consider the technical barriers, targets, and actions associated with hybrid electric propulsion.

3.2.2.1 Status of Technology

Growing numbers of urban trucks, vans, and buses generally are powered by diesel engines. With the frequent starts and stops associated with urban driving cycles, and with the visible and foul-smelling emissions from older diesel engines, many urban-cycle heavy vehicles have developed a bad reputation for their emissions. Concurrently, pollution in cities has become an acute problem; many major cities frequently issue warnings about poor air quality. The need for cleaner urban heavy vehicles has become a significant issue. Vehicles powered by natural gas are becoming increasingly popular for urban truck and bus fleets.

3.2.2.2 Technical Targets

The technical target for fuel economy is to double that of today's comparable urban heavy vehicles. The absolute numbers vary greatly for different types of vehicles and different driving cycles.

The technical target for emissions is to achieve a level of 30% below the heavy-duty diesel emissions regulations for 2004 and beyond as indicated in Sect. 3.1.4.

The research goal is 30% below regulation (see Table 8).

Table 8. Technical targets and research goals for emissions from Class 3–6 trucks

Emission component	Technical target, g/bhp-h[a]	Research goal, g/bhp-h
Non-methane hydrocarbons	0.5	0.35
NO_x	2.5	1.75
Particulate matter	0.05	0.07

[a] An option in the proposed regulation would limit combined hydrocarbons plus NO_x to 2.4 g/bhp-h.

3.2.2.3 Barriers

Heavy hybrid electric vehicle propulsion systems present technical challenges that are related to the individual components and to their system integration. As with other mobile systems, improved performance, improved reliability and maintainability, reduced weight, reduced volume, and lower costs are all inherent needs in realizing commercial success for heavy hybrid vehicles.

The following sections describe technical barriers to the development of various key components and system integration.

Engine and generator. Prime movers for heavy hybrid vehicles that are under development involve an integrated internal combustion engine and an electrical generator. This document considers natural gas-fueled spark-ignition (SI) engines and use of clean diesel in compression-ignition engines. The peak thermal efficiency of the engine is a critical parameter. In a hybrid configuration, the engine will operate much of the time at conditions of peak efficiency and minimized emissions.

Natural gas as an SI engine fuel is knock-resistant and thus tolerant of operation at a higher compression ratio. In fact, operation at a higher compression ratio is required to compensate for the lower energy content of the CNG fuel. Engines optimized for natural gas are sensitive to the correct air:fuel ratio. Precision combustion control and improvements in oxygen sensing and fuel injection (e.g., multiport, sequential) will be required.

Several types of electrical generators are available. There are several barriers involved in the development of a generator with the desired characteristics. The generator should be compact, lightweight, highly efficient, and have low production cost.

The engine/generator package serves as the prime power source, and high overall thermal efficiency is crucial for achieving high fuel economy for the vehicle. Peak thermal efficiency needs to be improved to the 45–50% range.

Hybrid configuration/transmission. Existing systems typically involve a parallel or a series arrangement of the internal combustion (IC) engine/generator tandem and the drive motors, transmission, and differential. In the series design, the IC engine directly and exclusively drives a generator that provides electrical power for the wheel-traction motors and auxiliary systems. There is no mechanical transmission of power. In the parallel design, clutches and transmission gears can be selected to exercise either mechanical or electromotive power at the wheels. In the parallel configuration, it is possible to combine the generator and traction motor into one unit.

The parallel configuration allows the flexibility for electric “power-assist” of the normal IC engine powertrain when warranted. Mechanical friction losses are higher in the parallel configuration, and synchronization of one driveline to the other is critical. Use of a continuously variable transmission (CVT) can allow greater operational flexibility as well as improved fuel economy and performance. The series configuration requires the electrical system to handle higher power and energy (making it more expensive). Different vehicle use profiles dictate the torque and speed requirements at the wheels. Many factors determine the choice of hybrid configuration (series or parallel), and different driving cycles may lead to the use of different configurations. Another important variable is the relative power levels of the engine/generator and the energy storage/traction motor. In either configuration, the overall system benefits from operation of the engine at optimal conditions, resulting in higher efficiency and reduced emissions.

Energy storage/regenerative braking. Existing systems almost exclusively involve batteries for storage of electrical energy. Flywheels and ultracapacitors are also considered as possible options in parallel hybrid configurations where the energy-storage requirement is small. The batteries typically are used for surge or acceleration capacity over and above the baseline IC engine drive. The batteries are also usually of sufficient capacity to permit short-term 100% electric drive of the vehicle with the engine off. This “zero-emission vehicle” (ZEV) operation can be an attractive option in certain situations.

An important aspect of a hybrid vehicle is the use of regenerative braking. Regenerative braking converts the kinetic energy of the vehicle into electrical energy during deceleration. The electrical energy is stored in the battery for future use. With conventional friction brakes, the kinetic energy is dissipated as heat and is lost.

The vehicle use profile dictates the type of desirable battery characteristics (e.g., high specific power vs high specific energy). Battery technology is tailorable to high-energy or high-power applications, with the latter generally being the more important parameter for hybrid electric vehicles. Specific battery targets are as follows:

Specific energy	>120 Wh/kg
Energy density	>275 Wh/l
Specific power	>750 W/kg
Price	<$200/kWh

Power electronics. The power electronics package handles the conversion between AC and DC and provides frequency control for the AC power. The power electronics must be efficient, compact, lightweight, and highly reliable. The cost of the power electronics package is one of the significant cost issues associated with hybrid technology.

Traction motor. Electric and hybrid electric vehicles typically employ electric motors (e.g., AC induction, brushless DC, or switched reluctance) at or near the drive wheels. Areas targeted for motor improvement include reduced weight, size, and cost with increased efficiency. The traction motor and the generator share similar technology, and they face the same technical barriers.

Auxiliary systems. Various systems that provide power-assisted functions in conventional trucks and buses (e.g., braking, steering, air-conditioning, etc.) may need to be re-engineered from exclusively belt-drive or direct shaft-drive to electric-motor drive. Improvements in the efficiency of auxiliary devices are needed to minimize losses.

High integrity, lightweight, CNG storage on-board. Successful deployment of natural-gas-powered vehicles requires ample on-board storage of the gaseous fuel. Because natural gas has an approximate energy equivalence of 122 std ft^3 to 1 gal of gasoline, significant compression of the gas must occur to fit the necessary volume into a reasonably sized on-board tank. Pressures of 3000 psi are in current use, and an increase to 3600 psi is foreseen for 2004 vehicles. It is obvious that robust, high-strength and low weight tanks must be used. Composite materials such as filament-wound wraps over thin-section steel bladders are viable candidates for the application. With its high methane content, natural gas rises in air and dissipates in open space. Thus, a fuel break (i.e., tank rupture) would provide a different set of safety issues from those associated with a gasoline spill (gasoline pools on the ground and readily ignites). To avoid ignition of fuels, the electrical system must be designed to prevent electrical arcs in accident scenarios.

System integration. Integration of the various components into a complete system is a challenging task. The various components must be able to handle the appropriate power levels. All components must be balanced so that the vehicle operates as a unit and operation of the power train is transparent to the driver. Other integration issues include thermal management, radio frequency interference, shock and vibration, safety, driver information, and operation of the control system.

3.2.2.4 Technical Approach

Dramatic reductions in emissions and dramatic (2X) improvements in fuel economy can be achieved by a combination of (1) implementing hybrid electric propulsion technology and (2) improving the vehicle system by reducing vehicle weight and rolling resistance, and improving the efficiency of auxiliaries.

Initially, the primary technical approach will be to support industry commercialization of heavy hybrid vehicles. A Solicitation for Financial Assistance Applications (SFAA) is being prepared on the topic of natural-gas-fueled hybrid propulsion technologies for urban heavy vehicles. The strategy is to establish cost-shared programs with industry teams in support of the introduction of heavy hybrid electric vehicles in various niche markets. A major emphasis of the program will be on reducing the cost of the hybrid propulsion system. The program is expected to include component-level improvements, system level integration improvements, and development of lower-cost manufacturing designs and techniques. The program will be initiated in FY 2000 if funding is provided.

Computer simulations will be performed to predict the operation of various configurations. Complete vehicles will be built and tested to confirm the predictions.

Some of the other necessary technologies will be leveraged from other programs. For example, the DOE Light Duty Truck Clean Diesel Program may result in a new engine that would be ideally suited for use in a medium-duty hybrid vehicle. Other vehicle system improvements (e.g., aerodynamics, reductions in drag and rolling resistance) may devolve from work in progress on Class 7 & 8 trucks.

3.2.3 Fuels and Lubricants

Urban trucks, delivery vans, and buses may use advanced petroleum-based fuel as defined in Sect. 3.1.5 or an alternative fuel such as natural gas or F-T synthetic diesel, which is produced from natural gas and biomass feedstocks. For those using advanced petroleum-based fuels, the issues discussed in Sect. 3.1.5 for Class 7 & 8 trucks are also relevant in Class 3–6 vehicles. It is highly probable that a single diesel-fuel formulation would be required for Class 3–8 vehicles. Likewise for those using natural gas or another alternative fuel, the status of technology, technical targets, and barriers would be the same as those defined in Sect. 3.1.5 for Class 7 & 8 vehicles. This similarity exists because the original equipment manufacturers, engine manufacturers, and component suppliers are essentially the same for Class 3–6 medium-duty and Class 7 & 8 heavy-duty vehicle platforms. Moreover, the alternative-fuel utilization issues, design technologies, and emissions standards under consideration are very similar to both vehicle platforms.

The technical approach for Class 3–6 alternative fuel vehicles is also very similar to the approach for developing Class 7 & 8 vehicles, with the following exceptions.

- The program will aim to develop a Class 3–6 CNG vehicle platform that is fully compatible in cost and performance with its diesel counterpart. The program will not consider LNG for Class 3–6 alternative-fuel vehicles.
- The program will develop a natural gas engine and fueling system design for use with a Class 3–6 hybrid electric vehicle.

3.3 CLASS 1 & 2 TRUCKS

The following sections describe the goals for Class 1 & 2 trucks, the status of technology for these trucks, the technical targets to be achieved in order to meet these goals, the technical barriers which must be overcome to achieve the targets, and the technical approach to overcoming those barriers.

3.3.1 Goals

The program goal with respect to Class 1 & 2 trucks is to develop by 2004 the enabling technology to encourage significant dieselization of Class 1 & 2 trucks, thereby achieving at least a 35% improvement in fuel efficiency improvement over gasoline-fueled engines for these vehicles, while at the same time meeting required federal and state emission requirements.

3.3.2 35% Fuel-Efficiency Improvement—45% Efficient Diesel Engine

3.3.2.1 Status of Technology

The market share of diesel passenger cars in Europe continues to rise, reaching about 28% recently. There has been a trend toward phasing out indirect-injection (IDI) systems in favor of the more efficient direct-injection (DI) engines; DI has captured nearly half of the current passenger car diesel sales. Furthermore, most engines very recently introduced or planned for introduction in the next 2 years employ high-pressure, common-rail fuel injection with electronic injection control for rate shaping. Volkswagen, which has an advanced-unit injector-type system on some models, is a notable exception to this trend. All the fueling systems rely heavily on electronic control. Significant attention is being given to the fuel-injection, fuel-spray, fluid-mechanics and rate-shaping issues that control combustion. A sampling of data for DI diesels of approximate size and power for light trucks gives a range of efficiencies at peak power of 38 to 42% (see Table 9). The sample includes high-speed diesels from Europe as well as heavy-duty diesels used in large pickups. Of course, over the FTP fuel-economy and emissions-test cycle, these engines operate most of the time at lower efficiency, but still much better than SI engines. Preliminary simulations in 1997 showed that diesels in this range could improve vehicle fuel economy by 35% (or more), which led to the selection of the program goal.

Table 9. Key efficiency-related characteristics of engines of approximate size and power for Class 1 & 2 trucks

Engine characteristic	Present automotive diesel	Present automotive SI engine	Present heavy-duty diesel
Best full-load thermal efficiency, %	41	26	43.3
Best thermal efficiency, %	42.8	34	46.5
Peak mean effective pressure (max), kPa	Up to 1400	800–1100 (non-turbo)	Up to 1900
Power-specific weight, kg/kW	2.0	1.1	3.6
Mean piston speed, rated power (typical), m/s	12.0–13.0	12.0–15.0	8.0
Compression ratio	19.0–21.0	9.5–10.0	15.0–17.5

The minimum standard engine power in a full-size pickup is 108 kW (145 hp), with optional engines capable of about 215 kW (288 hp). The trend is toward higher-powered engine offerings. For most operators, the engine torque characteristics are more significant than the power rating. The diesel has an advantage in this attribute, especially at low speeds.

In the United States, there are only two light-duty DI diesel light-duty vehicles that are emissions certified, even with the presently relaxed emissions standards for diesels. The large pickup trucks, with engines certified to the heavy-duty diesel standards, are a major market success; sales of these diesels now number in hundreds of thousands, essentially taxing production capacity. Several U.S. manufacturers now have intense development programs on new diesel engines for light trucks, partially in response to the DOE Light Truck Clean Diesel Program. Prototypes are undergoing tests and refinement in SUVs. The engines are typically V-6 designs, with EGR and electronic controls. With nominally 220 to 250 hp, and abundant torque, they represent completely new designs as opposed to refinements of existing models. Preliminary tests have yielded fuel-economy values that exceed the program goals. For cars and light trucks, the shortcomings of the diesel engine that slow its market acceptance are its lower power density and higher cost (which negates the fuel cost savings). Significant progress has been made on the once-objectionable diesel noise and exhaust odor. The key here has been the development of electronic controls and related improvements for fuel injection. Emissions certification is still problematic for the year 2004 and beyond.

The greatest challenge in diesel-engine technology is emission control for NO_x and PM, as described in Sect. 3.3.3.

3.3.2.2 Technical Targets

Fuel conservation will occur by the dieselization strategy only if (1) an efficient diesel engine suitable for Class 1 & 2 trucks is made emissions-compliant to offer for sale and (2) the diesel option provides advantages in performance or other parameters for consumers so they will select it over less-efficient SI engines.

Technical targets and barriers for a high-efficiency diesel engine that would be rapidly implemented in pickups and SUVs are summarized in Table 10. The principal efficiency target is operation at more than 40% efficiency through a wide range of loads and speeds. Although efficiency in diesel engines does not drop as markedly at light loads as it does in SI engines, the low-power duty cycle of pickups and SUVs calls for more emphasis on light-load efficiency than that of Class 7 & 8 trucks. In the light-duty-vehicle FTP emissions/fuel economy driving cycle, a typical SUV will consume nearly 90% of its fuel with the engine operating at less than 30 hp. Most improvements to the engine that boost peak power efficiency will also help part-load efficiency. The power-specific weight of the engine should be reduced to maintain vehicle power requirements at present levels.

3.3.2.3 Barriers

The principal barriers (other than emissions, which are covered in Sect. 3.3.3) to be overcome for dieselizing Class 1 & 2 vehicles are the engine’s cost and some nontechnical barriers, such as market perceptions. Although pricing practice does not always reflect cost, the diesel option, for the few vehicles for which it is available, costs at least $1,000 more (in some cases much more) than the base gasoline engine. The fuel-injection system for diesels, necessarily complex to achieve fine control of injection spray at high pressure, is one of the key cost drivers. The fuel injection system is critical to engine performance, efficiency, and emissions. Further adding to the cost is the air-handling system, including the turbocharger, aftercooler, and related hardware that diesels need to have competitive power density and responsiveness.

Generally, due to its constraints on engine speed and necessarily more robust construction, the power-specific weight of diesel engines is greater than that for SI engines. Therefore, unless the power-specific weight is reduced, some of its fuel-economy advantage will be negated when applied to a Class 1 & 2 vehicle.

There are some fundamental barriers to improving engine efficiency at part load, given that the engine must be designed for a peak power roughly five times that at which it most often operates. Heat losses and losses from friction and pumping, for example, represent a larger fraction of the net engine output at light loads. Fortunately, with no need of a throttle for power control, the diesel engine has an inherent efficiency advantage even at light loads.

3.3.2.4 Technical Approach

Many aspects of the technical approach called for in the 1997 *OHVT Technology Roadmap* are incorporated in the ongoing Light Truck Clean Diesel Program. The key elements of the approach are stated here to amplify where continued improvements in components or enabling

Table 10. Summary of pickup/SUV diesel engine targets and barrier technical approach

Engine parameter	Current practice	Target	Barrier
Efficiency, %	38–42% DI diesels, 80–150 kW, maximum	Up to 45% peak, with adequate part load efficiency to achieve a 35% fuel efficiency improvement	Need high Bmep and low friction losses at part loads
Power-specific weight, kg/kW	Gasoline: 1.2 Auto diesel: 2.0 Heavy diesel: 2.5 and up	<2.0	Current designs using lightweight materials have inadequate strength for diesel cylinder conditions. Diesel requires turbocharger and extra fuel system components. Inherent limitations on speed
Cost, $/kW	Often $1000 + price premium for diesel	Overall cost competitive with SI engines	Cost of fuel-injection system and air-handling system. Relatively limited volume of production
Durability, miles		Greater than SI engines of similar application	
Emissions (g/mi)			See emissions section
NO_x	SI: 0.15–0.20 Diesel pickup: ≥ 1.0	0.05	
HC	0.20, SI or CI	0.055	
CO	1.5, SI; 0.2, CI	2.1	
PM	0.08, CI auto	0.01	
Noise	DI diesel powered vehicles achieving similar noise levels to SI engines, yet retain certain NVH issues	Comparable to today's gasoline-powered vehicles	Need more control of fuel-injection and combustion process, such as by advanced fuel-injection systems. Need engine system materials and structures to improve noise control

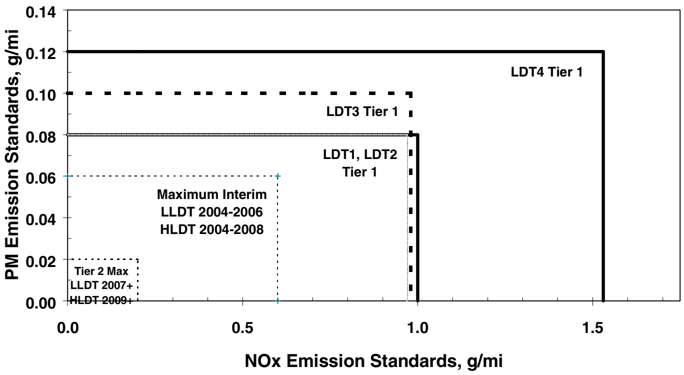
technology are required. For FY 2000 and beyond, certain parts of diesel-engine R&D will be integrated across the DOE OHVT and OAAT.

- Develop cost-effective fuel injection systems with the precise control of injection characteristics necessary for optimized combustion, low noise, and low emissions. Analyze possible simplification and cost-savings of the fuel system if an effective exhaust aftertreatment is developed.
- Develop and apply cost-effective manufacturing methods and materials for overall cost reduction of injectors, fuel pumps, and fuel-injection control systems as well as other key engine components.
- Evaluate and assess new engine/component architectures that would have inherently lower cost and/or reduced noise compared with that of current practice. Take designs to fabrication and test phase as warranted. Finalize development with the vehicle team.
- Increase brake mean effective pressure for better power density and efficiency through improved air-handling and fuel-injection systems. Develop turbochargers with higher efficiency and more flexibility.
- Through improved engine architecture and application of low-density materials, further increase the engine’s power-specific weight to a level competitive with SI engines.

3.3.3 Emissions

3.3.3.1 Status of Technology

Emission certification of diesel engines for pickups and SUVs up to 8500 lb gross vehicle weight rating (GVWR) is more challenging than is certification for heavy trucks because of the tiered structure of emissions standards and because of the different test procedures for heavy- and light-duty vehicles. Pickups and SUVs up to 8500 lb GVWR must be certified as light-duty trucks. The FTP, conducted on a chassis dynamometer, is the same as that used for passenger cars. The regulations for NO_x and PM for light-duty trucks are more stringent than those for heavy-duty diesel engines that are certified according to the Federal Transient Test Procedure, which is conducted on an engine dynamometer. The prevailing Tier 1 and proposed Tier 2 PM and NO_x standards are shown in Fig. 11.



Tier 1 emissions standards apply through 2003.
LLDT, Light Light-Duty Trucks, includes LDT1 and LDT2, Gross-Vehicle-Weight Rating (GVWR) up to 6000 lb.
HLDT, Heavy Light-Duty Trucks, includes LDT3 and LDT4, Gross-Vehicle-Weight Rating 6001-8500 lb.
Proposed Tier 2 standards phase-in during the interim period 2004-2008.
Under Tier 2, all vehicles up to 8500 lb GVWR must meet the same emissions standards starting in 2009.
Tier 2 imposes fleet average NO_x emissions of 0.07 g/mi in 2007 for LLDT, in 2009 for all vehicles.

Fig. 11. Light-duty diesel Tier-1 and Tier-2 PM and NO_x emissions standards.

In December 1998, California adopted the LEV II Program, to be phased in between 2004 and 2010. The LEV II Program will require diesel vehicles to meet the same emissions standards as those for gasoline vehicles (a change from current practice). In general, LEV II contains lower emission standards for all light-duty vehicles. Another significant change is that the same standard is being applied to all vehicles under 8500 lb GVWR.[18]

In May 1999, the EPA released a proposal for Tier 2 (year 2004) emission standards for light-duty vehicles, including cars, vans, SUVs and light-duty trucks.[19] Current standards have five emission classes, based on gross vehicle weight, with different standards for gasoline and diesel. The Tier 2 proposal provides the same standards for gasoline and diesel vehicles by 2004. Between 2004 and 2008 two weight classes will be established (light-duty vehicles <6000 lb GVWR and heavy light-duty trucks ranging from 6001 to 8500 lb GVWR). The Tier 2 phase-in would culminate with the establishment of a single light-duty class up to 8500 lb beginning in 2009. When emission-reduction standards are phased in, emission bins for averaging fleet emissions will be used. A fleet average of 0.07 g/mile NO_x will be required for light-duty vehicles by 2007 and heavy light-duty trucks by 2009. The proposed Tier 2 rule will also apply the FTP (US06 and SCO3) to both gasoline and diesel vehicles. The application of "US06" is potentially critical for diesel-powered vehicles because it would further exacerbate NO_x and particles over the FTP. The maximum allowable emissions under the proposed Tier 2 rule are shown in Fig. 11. Table 11 shows the ranges of emissions standards, current vehicle emissions, and the DOE research goals.

Sulfur present in diesel fuel is thought to dramatically reduce the effectiveness of many new emission-control technologies. The current maximum sulfur level in U.S. highway diesel fuel is 500 ppm. Recently, the EPA announced an Advanced Notice of Proposed Rulemaking (ANPRM) on the quality of diesel fuel. The ANPRM solicits comments on what sulfur levels are needed and on what time schedule. The reduction of sulfur levels to levels below 30 ppm could have a dramatic influence on the ability of new emission-control technologies to reduce diesel emissions to regulated values.

The ability to meet emissions regulations up to 2003 with DI diesel-powered pickups and SUVs up to 8500 lb appears to be feasible based on scaling from DI passenger cars and from early data from the DOE Light Truck Clean Diesel Program. (The highly popular DI diesels available in full-size Ford and Dodge pickups are certified as heavy-duty diesel engines. Preliminary analysis suggests that these engines, packaged for a smaller vehicle, would exceed light-duty NO_x standards by a factor of three.)

The Mercedes E Class and the Volkswagen TDI, both being turbocharged DI diesels, are the only two DI diesel engines available in passenger cars in the United States to study as points of departure. They meet the present standards for NO_x and PM with use of minimal aftertreatment but do not have sufficient power for most pickups and SUVs. Larger, heavier SUVs and pickups will require even better emission technology because of test protocol for light-duty vehicles and because of regulations based on mass emissions per mile. As mentioned in the previous section, diesel-engine manufacturers in the U.S. have opted to develop completely new engines for the SUV market.

European firms have led the light-duty diesel emission refinements for the last 15 years or so due to the higher demand for diesel engines in Europe. Emission-control strategies are similar to that described for heavy-duty diesels with the exception that EGR is used on many light-duty diesels. In general, based on the emission index (mass pollutant per mass of fuel consumed), modern small diesels for passenger cars emit less NO_x but more PM than do new highway truck diesels. EGR, especially cooled EGR, is one of the most effective technologies for NO_x control.

It has had minimal application in heavy-duty engines to date, even though it is used on almost all SI-engine-powered passenger cars. For heavy-duty engines, EGR brings some concerns for durability and reduced efficiency, and there is an observed trend of EGR causing PM to increase.

Significant reductions in emissions have been made through combustion modifications involving optimization of fuel- and air-handling systems. Fuel-injection developments, including electronic injection timing control, increased injection pressure, and recently, injection-rate shaping or two-stage injection, have contributed to emissions reductions. Similarly effective have been developments in air handling and aftercooling. Variable geometry turbocharging or waste-gate controls also appear to have the potential to further reduce emissions.

It is evident that existing and proposed regulations for 2004 to 2010 cannot be met without significant advances in in-cylinder controls, aftertreatment for NO_x, PM reduction, and reformulation of the fuel.

Table 11. Range of full useful life light-duty FTP emissions standards and DOE research goals

	Emissions range for automobiles through LDT4, g/mile			
	THC	**CO**	**NOx**	**PM**
Tier 1 gasoline standard	0.31–0.56[a]	4.2–7.3	0.6–1.53	-
Tier 1 diesel standard	0.8	4.2–7.3	1.25–1.53	0.10–0.12
1999 diesel production vehicles	0.02–0.10	0.2–0.4	0.6–0.9	0.04–0.08
Prototype diesel vehicles (engine-out)	-	-	0.4+	0.06+
Tier 2 standard (gasoline and diesel)	0–0.125[b]	0–4.2	0–0.2[c] 0.07[d]	0–0.02[c]
DOE automotive/light-duty truck research goals	-	-	0.05	0.01

[a] Measured as NMHC.
[b] Measured as NMOG.
[c] Tier II requires that a portion of regulated vehicles have zero emissions.
[d] Fleet average NO_x by 2009.

3.3.3.2 Technical Targets

Concerns about the effects of particulate matter on human health, plus perceptions about smoky diesels, suggest that aggressive emissions targets be established for a pickup/SUV engine.

Federal and California regulations for light-duty-truck emissions were reviewed in depth. The choice of a technical target for emissions could range from Tier 2 fleet average for passenger cars to accepting at face value the present regulations for 1999+. Given a clean diesel philosophy, the following emissions targets have been selected.

NO_x	0.05 g/mile
NMHC	0.055 g/mile
CO	2.1 g/mile
PM	0.01 g/mile

These targets are approximately the same as those in California LEV II, ULEV for light-duty vehicles and those in the proposed Federal Tier 2 emission standards, which would capture most of the SUVs and full-size pickups. Phase-in of the Tier 2 standard is to be completed by 2009.

3.3.3.3 Barriers

Meeting NO_x and PM emission regulations with engines of high efficiency and low cost is a significant barrier, particularly in the higher power range necessary for heavy light-duty trucks. For in-cylinder controls, further development of EGR is necessary. Cooled EGR has not been adequately developed for full commercialization. Present fuel-injection systems do not have the characteristics needed for emission control. Aspects of the fuel-air mixing process are still insufficiently understood or modeled to optimize engine design. Additionally, NO_x and PM aftertreatment systems are not sufficiently developed for commercial application. Perhaps the most prominent barrier to reduction of diesel emissions is the sulfur content of today's diesel fuel, which is high enough to deactivate the better aftertreatment devices. EGR-equipped engines are further adversely affected by fuel sulfur. This is more thoroughly discussed in Sect. 3.1.5. In high-power versions of light-duty diesels, the challenges will be in achieving a significant efficiency advantage over gasoline engines and matching the longevity expected from heavy-duty diesel engines.

3.3.3.4 Technical Approach

The technical approach to reduce emissions in Class 1 & 2 trucks will include the following steps.

- Through experiments and simulations, develop an improved understanding of fuel-air mixing, including wall effects.

- Develop and apply cooled EGR systems to diesel engines.

- Develop fuel-injection components, controls, and systems for improved control of fuel-injection rate and timing based on improved understanding of phenomena.

- Develop more-effective NO_x aftertreatment systems with overall conversion of >90% NO_x and durability for 120,000 miles [per EPA Tier 2 Emission Regulations for HLDT and LDT (64 FR 58505–58506)].

- Develop cost-effective aftertreatment systems for PM controls.

- Evaluate and demonstrate the integration of proposed aftertreatment technologies (i.e., reduction and oxidation technologies with particulate removal technologies) and required sensors to meet emission targets.

- Improve air-handling systems, including turbocharger systems, for reduced emissions, including during transients.

- Develop catalyst formulations that enable low light-off temperatures.

3.3.4 Noise, Vibration, and Harshness; Smoke and Odor; Cold Starts

The diesel engine has a recognized advantage over the gasoline engine in fuel efficiency. However, it is also perceived to suffer from shortcomings in the areas of noise, vibration, and harshness (NVH); visible smoke and odor; and limitations in very low ambient temperatures. Some of these shortcomings can be ameliorated through improved design and component development, as described in the next section.

3.3.4.1 Status of Technology

Differences between gasoline and diesel engines in regard to NVH, smoke, and odor are related to their respective combustion process. Gasoline engines use relatively smooth, PM-free, premixed combustion; diesels employ a rougher, heterogeneous type of combustion. Engines emit noise through three paths: the exhaust, the intake, and the external walls of the engine proper. Because the diesel needs more air for a given power output, its intake and exhaust are slightly noisier. This problem can be solved by conventional muffler design, but with a slight cost penalty. The largest difference between the two types of engines, however, is the much higher noise level radiated from the walls of diesels. Diesel engines require a high compression ratio, which results in much higher cylinder pressures. Higher pressures cause bigger deformation of the block and head, which translates into higher noise radiation from the external walls. In addition, the heterogeneous combustion of diesel engines cause a much higher rate of pressure rise inside the cylinder during firing. The faster rising cylinder pressure increases noise and causes stronger torsional vibrations usually perceived as “roughness.” Secondary reasons for higher noise and roughness are found in the heavier reciprocating masses typical of diesels, which usually result in stronger unbalanced forces that cause additional noise and vibrations. The noise-generation phenomena in diesel engines has been well understood for some time. Matters were aggravated by the relatively crude mechanical or hydraulic fuel-injection equipment (FIE) of the past because engines were always mistimed at some part of the speed/power range, such as idle or early acceleration. Consequently, noise was often very high during certain operating conditions. However, the advent of electronically controlled FIE has allowed nearly optimal timing throughout most of the operating range, resulting in very significant reductions in noise.

Imperfect heterogeneous combustion often results in the generation of PM and odor; however, this is a rare phenomenon in homogeneous (i.e., premixed) combustion, as in the gasoline engine. For the diesel to minimize these problems, it will be necessary to achieve nearly perfect (complete) combustion most of the time, including during load and speed transients. The key to achieving nearly complete combustion resides in the ability to retain control of air and fuel mixing, even during transients. Steady-state combustion is seldom a problem, but during quick transients (acceleration from stop, gear shifting) control of air and/or fuel is often briefly lost, and a short plume of smoke and/or partially burned hydrocarbons (a source of odor) is released. Modern electronically controlled FIE has already vastly improved the situation, but complete resolution of these problems will require significant improvements in air-handling systems (e.g., turbochargers), in addition to further refinements in FIE.

Cold start of engines always presents a challenge, but especially for diesels, because self-ignition occurs less readily at low air temperatures. As a result, diesel engines normally include “starting aids” (e.g., heaters, glow plugs, or ether dispensers) to make them easier to start in cold weather. Additionally, the heavier fuels used by diesels are more difficult to handle at low temperatures. When the temperature is low enough to reach the “cloud point” of the fuel, paraffin waxes begin to separate and drop out, clogging filters and lines and often stopping flow of fuel altogether. For extended operation in cold climates, fuel-system heaters are also often added as options, increasing cost. The improved flexibility of electronic FIE controls has resulted in superior low-temperature starting capabilities, but the time delays and complexities associated with the use of starting aids still remain somewhat vexing. The problem of separation of wax in the fuel at very low temperatures, however, is more fundamental and very difficult to resolve other than by developing special low-wax winter fuels, additives, and/or heating the fuel tanks and lines.

In summary, progress made with modern FIE in the last several years and the use of electronic control have provided new means to reduce noise and vibration. Engine manufacturers have learned how to control the transmission of noise from the inner walls of the cylinder to the external surface by clever structural design and have thus managed to reduce airborne noise. These approaches give hope to the task of making a modern diesel engine reasonably competitive in the NVH area with the gasoline engine. More sophisticated control of fuel and air also results in reduced smoke and odor emissions and even improved low temperature starting. Therefore, NVH, cold starting, smoke, and odor are expected to achieve significant improvement from related hardware development (i.e., more sophisticated electronic controls, better charge-air-handling systems, and improved structural engine design).

3.3.4.2 Technical Targets

In an engine near-field noise test, noise is to be reduced by 3 dB(A) and by 6 dB(A) with noise shields. In a vehicle drive-by noise test, noise is to be reduced by 6 dB(A) without heavy encapsulation. These targets appear to be realistic based on actual improvements recently achieved by Mercedes-Benz.

Also, there should be very significant reduction in noise at idle and during acceleration, the two most objectionable modes that differentiate the noise made by diesel engines from that made by gasoline engines. However, specific noise and vibration targets should be set up by industry based on the actual needs to achieve competitiveness with gasoline engines.

The target for cold-start performance is to achieve perceived parity with the gasoline engine, preferably with fully automatic starting aids that do not add appreciable delay to the cranking process. Similarly, the targets for PM and odor emissions are based on total or nearly total elimination, so that the current perception of diesels being smoky and smelly would disappear.

3.3.4.3 Barriers

The key to the solution of most of these problems lies in developing a fuel-injection system and an air-induction system that allow accurate control of injection events and air-to-fuel ratio throughout the operating range, including transients. Therefore, the main barriers are in the form of development of sensors and components for these systems that are effective and low cost. Control of vibrations will require development of lightweight reciprocating components, which will be a difficult challenge given the higher cylinder pressures expected. Effective noise reduction will also require careful structural design of the main engine components (the block and head, primarily) as well as selection of a favorable basic engine architecture. This approach will involve several compromises among competing goals and therefore will further increase already difficult design challenges.

3.3.4.4 Technical Approach

The technical approach to reduce the NVH of the advanced light truck diesel engine will include the following steps.

- Selection of an FIE system that is inherently low in mechanical noise.
- Selection of an FIE system that provides adequate control of timing events throughout the entire operating speed and load ranges.
- Selection of an FIE system that provides control over injection rate, at least during the time delay period and preferably over the entire operating range,
- Careful design of reciprocating engine components and possible use of lightweight materials to minimize mechanically induced loads and thus reduce vibration and noise.
- Use of advanced structural design of the engine components (e.g., block, head, oil pan) to minimize the transmission of noise to the external surfaces.
- Design a basic engine architecture that results in an inherently balanced engine and use of as many cylinders as is economically feasible (i.e., V-8 would be better than an in-line 4).

Reduction of smoke and odor will require some of the same treatment as well as the following steps.

- Improved control of air:fuel ratio throughout speed/load transient.
- A fast-reacting intake-air-pressure charger to minimize acceleration response delays.
- Fuel-injection nozzles with minimum dead volume (near zero) to reduce uncontrolled fuel evaporation after the end of injection.
- Aftertreatment devices.

3.3.5 Fuels and Lubricants

Fuel and lubricant R&D activities for Class 1 & 2 vehicles are being conducted by OAAT. Only a very brief summary is provided here; more details can be found in the *Multiyear Program Plan for Advanced Petroleum-Based Fuels R&D*,[17] which has been developed jointly by OAAT, OHVT, industry representatives, research partners, and other stakeholders.

For Class 1 & 2 vehicles using advanced petroleum-based fuels, as defined in Sect. 3.1.5., the status of technology, technical targets, barriers, and technical approach are defined in the *Multiyear Program Plan for Advanced Petroleum-Based Fuels R&D*.[17]

No formal activity on alternative fuels is planned for Class 1 & 2 trucks; however, some of the F-T diesel fuel R&D effort for Class 3–8 vehicles (discussed in Sect. 3.1.5) could help enable Class 1 & 2 light trucks and SUVs to meet California LEV II or EPA Federal Tier 2 emissions standards. Also, OAAT is planning to continue laboratory research on a DME fuel and engine system for passenger car applications.

3.4 ENABLING AND SUPPORTING TECHNOLOGIES

The OHVT goals and technical plans are directed specifically toward R&D to increase efficiency and to reduce emissions of Class 1–8 trucks. The cross-cutting, enabling technologies in the following list are critically important to meeting the roadmap goals:

- emission control (including exhaust aftertreatment),
- combustion technology,
- materials,
- environmental science and health effects,
- truck safety, and
- engineering simulation and modeling.

Multi-year program plans (MYPPs) are being developed for each of these enabling and supporting technologies. The MYPPs will describe in detail the R&D requirements of each technology and will be published separately. The following sections contain brief descriptions of each enabling and supporting technology.

3.4.1 Emission Controls (Exhaust Aftertreatment)

Emission-control technologies (i.e., exhaust aftertreatment technologies) are critically important for enabling diesel-powered vehicles to meet future emission standards. The most important are the technologies needed for reducing tailpipe NO_x and PM. Although changes to the fuel and further improvements in engine technology are expected to contribute to reductions in tailpipe emissions, they cannot by themselves provide the reductions demanded by the standards expected from Tier 2 or beyond. Current expectations are that future NO_x reductions of greater than 80% and PM reductions of greater than 70% will be needed for light duty trucks. The eventual demands for emissions reductions for heavy-duty vehicles may approach those of light-duty vehicles. Thus, only through the effective utilization of advanced emission-control technologies will these future emissions requirements be met.

3.4.1.1 Barriers and Concerns

Before the promise of advanced emission-control technologies can be realized, a number of technical barriers must be overcome. In addition, a number of concerns should also be addressed in anticipation of future requirements or because of their potential for limiting the effectiveness of the possible approaches to the problems. The following list contains barriers to realizing the needed reductions through the application of EC technologies.

- Greater reductions are needed than are currently possible with existing EC technology.
- Current EC technologies can be too sensitive to contaminants present in the exhaust (e.g., sulfur); the contaminants can reduce their performance to well below the needed levels.
- Light-off temperatures for some catalyst technologies are too high, allowing substantial emissions to occur during the first few minutes of engine operation.
- The temperature range for which the catalyst performance is acceptable is either too high for practical use or is too narrow to perform effectively during all operating conditions.
- The understanding and tools needed for predicting catalyst behavior are insufficient, limiting the ability to address EC technology shortfalls.
- EC technologies that eliminate or neutralize contaminants such as sulfur have not been demonstrated.
- Rapid-aging test methodologies are insufficient for research screening of new technologies.

The following concerns are foremost among those that should be addressed in further R&D of emission control technologies:

- device cost;
- device degradation from aging;
- the effect of changes in fuel or lubricant formulation on device performance (e.g., activity and durability);
- the effect of device activity on unregulated toxic emissions; and
- preventing or limiting the reduction in fuel economy
  —from increased back pressure in the exhaust stream,
  —from power requirements to operate a device, or
  —the effects of off-optimal engine operating parameters required by a device.

In addition, questions about other topics also need to be addressed in an R&D program because of their potential impact on future results or needs. One is the determination of the influence of EC technologies on the size, size distribution, and shape of PM emitted from the tailpipe. This issue rises from the concern that an important contribution to the undesirable health effects of diesel exhaust may be from the ultrafine and nano-sized particles present and that the number of these particles could be adversely affected by some EC technologies. Although this is conjecture, the issue still merits attention because of its uncertainty and potential consequence. In addition, there are numerous needs to improve sensors, reductant injection systems, and other technologies needed to construct effective EC systems.

3.4.1.2 Technologies

A broad spectrum of emission control technologies are either already in use or undergoing R&D that might contribute to solving the emissions problem, both for the control of NO_x and PM.

- NO_x control technologies:
  —lean NO_x catalyst,
  —NO_x adsorber catalyst,
  —nonthermal plasma-assisted catalyst, and
  —selective catalytic reduction (SCR).

- PM control technologies:
  —oxidation catalyst,
  —catalyzed trap,
  —continuously regenerating trap (CRT), and
  —microwave regenerated trap.

As can be seen in Table 12, the effectiveness of each technology varies in its ability to provide the reductions needed. In those cases where the reductions are sufficient, or nearly so, there is a compromising "down side" to the technology. For example, in the case of the NO_x adsorber catalyst, the superior levels of performance are met only when very low levels of sulfur are present in the exhaust stream; otherwise, the catalyst is deactivated by the presence of sulfur and a satisfactory means to regenerate it has not been found.

3.4.1.3 Approach

Continuing efforts to improve catalyst performance, to further develop non-thermal plasma-assisted catalysts, and to develop emerging but promising catalytic materials is warranted based on results to date. Likewise, reduction of catalyst sensitivity to deactivating materials such as sulfur or to finding another means to eliminate this key challenge is needed. The R&D process must include experiments to better define the fundamental mechanisms by which EC technologies work (including efforts in advanced microcharacterization of materials) so as to improve the R&D process for synthesizing new and improved catalytic materials. This process requires development and/or improvements in analytical measurements for insitu evaluation of catalysts in real and simulated exhaust streams. There must also be research to define the optimal reductant, to develop a process for on-board reductant production, and the optimal means for reductant introduction. Ensuring that the levels of catalyst performance seen in the laboratory are maintained in production remains a key challenge.

The nonthermal plasma approach needs further development to reduce power consumption, to improve plasma generation, and to reduce package size. Because PM trap technology will be needed, continuing effort is warranted to reduce fuel-economy penalties, and sulfur sensitivity and to improve trap performance. Likewise, additional development of control systems and sensors is required to ensure a complete and functional system, including any legislatively mandated diagnostics. A cost-effective sensor for NO_x has been identified as a high-priority requirement.

Table 12. Diesel emission-control technologies

Technology	Approximate reductions		
	PM (%)	NO_x (%)	Downside
Lean NO_x	30	30–50	Sulfates, activity too low, fuel-economy penalty
NO_x adsorbers	30	>90	Severe deactivation by sulfur
Selective catalyst reduction	>30	>80	Possible production of other toxics, control of reductant, infrastructure
Plasma-assisted	50	70	Cost, fuel-economy penalty, unproven
Oxidation catalyst	30	<10	Makes sulfate, only reduces soluble organic fraction of particulate
Catalyzed trap	>90	0	Makes sulfates, fuel-economy penalty
Continuously regenerating trap	>90	0–5	Sulfur deactivation, fuel-economy penalty
Microwave trap	>90	0	Cost, fuel-economy penalty

Catalyst technology will benefit from work performed in the DOE 2000 Materials Microcharacterization Collaboratory. This effort, jointly sponsored by the OHVT and DOE's Office of Science (DOE-SC), brings together instrumentation and expertise from DOE laboratories, universities, and industry for real-time, collaborative remote experiments. Development of catalyst technology is also expected to benefit from the catalyst modeling that is part of the Engineering Simulation and Modeling activities described in Sect. 3.4.6. These efforts will take advantage of the progress in simulation and large scale computing (e.g., massively parallel computing) to produce tools for addressing many of the catalyst issues. Complementary experiments on catalyst behavior supported by OHVT will help accelerate the progress toward achieving accurate and accessible simulation tools.

3.4.2 Combustion Technology

Enabling technologies within Combustion Technology can be divided into four areas: (1) diesel combustion research, (2) model and submodel development, (3) utilization of alternative fuels and fuel additives, and (4) advanced concepts to reduce engine-out emissions. In the area of diesel-combustion research, the application of advanced laser diagnostics has improved considerably the understanding of in-cylinder combustion and emission formation. However, most previous studies have generally focused on the early and middle stages of diesel combustion; there has been little detailed understanding of the late stages and the mechanism(s) whereby carbonaceous PM escapes oxidation to become a tailpipe emission. Future studies will focus on late combustion and the PM/NO_x trade-off.

Improvements in spray and PM submodels are still inadequate for accurately describing the diesel combustion process. Research is required to develop new techniques (such as improved flamelet models) that will better describe the combustion process within a flame zone yet be computationally efficient. Work is also required in developing or improving codes so that they can be run efficiently on parallel machines or in a distributed computing environment (see Sect. 3.4.6 for a more detailed discussion of modeling and simulation).

The investigation of alternative fuels and fuel additives will build on the information generated from utilizing conventional fuels. Water is known to be an effective additive in reducing NO_x by decreasing the in-cylinder combustion temperature. However, the most effective means of introducing water while maintaining efficiency is in need of research. Vegetable oil esters are considered to be potential blending agents with diesel fuel; the formation of NO_x is an issue at high blending levels. Chemical additives (e.g., oxygenates) could also play an important role in reducing emissions while maintaining efficiency. Advanced petroleum-based fuels, as well as alternative fuels and fuel additives, offer potential for emissions reduction, but a fundamental understanding of the combustion process is required to achieve their full potential (see Sect. 3.1.5).

Future research on conventional approaches may reveal other ideas to further reduce diesel NO_x emissions, but it appears unlikely that they will provide sufficient NO_x reduction to meet the standards for super-ultra-low-emission vehicles (SULEVs). Advanced concepts that provide improved engine-out emissions while maintaining efficiency offer much promise but require substantial R&D. Areas of investigation include homogeneous-charge compression ignition, a selective membrane to separate oxygen and nitrogen in the intake, and new fuel-injection equipment.

3.4.3 Materials

Materials needs for heavy vehicles are divided into two major categories: propulsion materials, associated with engines and emission-control systems, and high-strength weight-reduction materials, associated with body, chassis, and other systems.

3.4.3.1 Propulsion Materials

The development of cleaner, higher-efficiency diesel engines imposes greater mechanical, thermal, and tribological demands on construction materials. Often the enabling technology for a new engine component is the material from which the part can be made. The Heavy Vehicle Propulsion Materials Program is a partnership among DOE, the U.S. diesel-engine companies, materials suppliers, national laboratories, and universities. A comprehensive R&D program has been developed to meet the enabling-materials requirements for the diesel engines of the future.

Higher-efficiency engines will require higher peak and brake mean effective pressures, higher stresses on components, higher temperatures (resulting in increased thermal fatigue), greater precision, and lighter weight. Requirements include materials for advanced combustion-chamber components, cylinder heads and engine blocks; low-inertia materials for turbochargers; materials for improved insulation of the exhaust system; improved coatings and other thermal barriers; materials for advanced fuel systems to improve combustion and reduce emissions; materials for advanced piston/ring/cylinder components to reduce friction; and low-density materials to increase the engine power-specific weight to a level competitive with SI engines.

Emission control will require improved catalysts, better PM traps, alternative aftertreatment technologies, better lubricant control, and improved fuel-injection systems. Associated materials requirements include more-durable catalyst materials, supports, and wash coats; durable materials for effective, regenerable particulate traps; improved materials for lubricant control to reduce PM emissions; and high-strength, nonscuffing, wear-resistant materials for high-pressure fuel-injection systems to reduce PM emissions.

Engines that run on alternative fuels (such as natural gas) require materials that are chemically compatible with the fuels and are durable in the presence of low-lubricity fuels. Materials requirements include stable, corrosion-resistant materials for glow plugs and durable components such as wear- and corrosion-resistant intake valves, valve seats, and valve guides.

The candidate materials developed in the program are chosen to overcome critical engine-technology barriers identified by the diesel-engine industry in response to the goals of the OHVT. Candidate materials include high-temperature alloys, intermetallic alloys, ceramic-metal composites (cermets), structural ceramics, bulk amorphous alloys, ceramic and metal-matrix composites, thermal-barrier coatings, and wear coatings.

Materials R&D encompasses both the development and application of new materials and the critical work on characterization, from microstructure through physical and mechanical properties. Choosing the appropriate material for an advanced-engine application requires a database of physical and mechanical properties, an understanding of the mechanisms that lead to component failure, and the methodology to estimate the lifetime of a component in service.

A comprehensive program is ongoing, including projects in

- materials for fuel systems,
- materials for exhaust aftertreatment,
- materials for valve-train components,
- structural and insulating materials, and
- materials standards.

Tentative technical plans have been developed for 2001 and beyond. A technology-assessment and program-planning activity is continuing and is expected to lead to a published multiyear program plan in the first quarter of the year 2000.

3.4.3.2 High-Strength Weight-Reduction Materials

One of the most significant actions that can be taken to improve the productivity and fuel efficiency and to reduce emissions of all classes of trucks and buses, including pickup, vans, and SUVs, is to reduce vehicle weight. The objective of the High-Strength Weight-Reduction Program is to identify and develop materials and materials-processing technologies that can contribute to weight reduction without sacrificing strength and functionality. The use of alternative, light-weight materials can reduce weight by 25 to 50% and thus can yield significant benefits in fuel efficiency and emissions reduction. The challenges are to develop lightweight materials that are cost-effective, stronger, more reliable, and safer and to develop efficient manufacturing processes to make the materials available to the market.

Recent emphasis on increased fuel economy, decreased emissions, increased demands from the consumer, and increased competitive pressures in a worldwide market have placed new demands on vehicle manufacturers and fleet operators. Additional demands stem from the increasing emphasis on recyclability and environmentally benign manufacturing. Successful application of lightweight materials in all classes of trucks and buses requires the simultaneous consideration of material, process, design, and manufacturing techniques. An extensive body of knowledge about these alternative materials is needed to give designers the flexibility to design systems utilizing these materials. The High-Strength Weight-Reduction Program, a partnership among DOE, truck manufacturers, fleet operators, suppliers, universities, and national laboratories, is focused on addressing these needs through collaborative R&D.

The principal target for Class 7 & 8 trucks is to reduce chassis weight of tractor-trailer combinations by at least 5000 lb by the year 2005. Such reductions must not compromise the reliability, durability, or the structural integrity of the cab or the ability to carry payloads. The reduction of overall vehicle weight of pickups and SUVs by 40 to 45%, while retaining performance and utility, is a significant challenge that can only be met by systematic weight reductions in all structural components. The technical target for Class 1 & 2 trucks will be to develop and demonstrate by 2003 design, materials, and manufacturing technologies that can reduce the weight of a pickup or SUV frame by a minimum of 35%. Weight reductions of this magnitude will facilitate the use of significantly smaller-displacement diesel or SI engines, resulting in additional reductions in emissions. Other targets include increased energy-absorption capability through the development of advanced materials and/or designs and the development of manufacturing techniques that can reduce the cost of using lightweight materials.

The principal barriers to overcome in reducing the weight of trucks and buses are as follows:

- the inherently higher cost of alternative materials,
- the lack of understanding of high-volume manufacturing methods as applied to new materials,
- insufficient experience in joining,
- the lead time to bring new materials and processes into the manufacturing cycle,
- the lack of appropriate databases for use by design engineers, and
- the lack of experience in repairability and maintenance; and a limited supplier base.

The High-Strength Weight-Reduction Program will focus on developing technologies that are aimed at addressing these barriers and will include predictive modeling capabilities to aid in accelerated development and introduction into the trucking industry.

Materials development focused on weight reduction for heavy-duty trucks and buses will address three key elements:

- development of technologies for enhanced manufacturability of lightweight components for trucks and buses;
- development of design concepts and material databases to provide design engineers the flexibility to consider lightweight materials in vehicle design; and

- development of technology in support of advanced materials, joining, maintenance, and repair.

3.4.3.3 High Temperature Materials Laboratory

The High Temperature Materials Laboratory (HTML), located at ORNL, is a research facility dedicated to materials characterization that provides a unique, enabling capability for meeting the goals of OHVT. The objective of the HTML is to assist American industries, universities, and governmental agencies in developing advanced materials by providing a skilled staff and numerous sophisticated, often one-of-a-kind, materials-characterization instruments. The HTML specializes in the ability to assist in the development of materials that must operate at elevated temperatures and/or stresses, such as are found in internal combustion engines like advanced diesels. The HTML works in collaboration with companies and universities performing materials development for propulsion materials and high-strength weight-reduction materials (see Sects. 3.4.3.1 and 3.4.3.2).

The HTML is a national user facility that houses six “user centers,” containing specialized equipment dedicated to specific types of property measurements. The user centers offer a range of materials-characterization capabilities including electron microscopy and microchemical characterization, crystal-structure analysis by X rays and neutrons, mechanical and thermophysical property measurement, wear testing, and advanced grinding evaluations. Complete tribological characterization is also available, including sliding, rolling, fretting, and impact under conditions of controlled atmosphere and temperature, with or without lubricating fluids present.

The HTML User Program provides researchers from industry and academia state-of-the-art capabilities to solve materials problems. Both nonproprietary and proprietary research can be performed. There were more than 500 user agreements in place at the end of 12 full years of operation (FY 1999). These agreements have resulted in more than 900 approved research proposals, which are in various stages of completion. These proposals have involved several hundred individual users (industry, staff, government-agency staff, university faculty, and students) performing research in the HTML. Industrial user companies range from the very small (fewer than 20 people, such as LoTEC Inc., and several suppliers of components to the heavy vehicle industry) to the very large (e.g., Cummins Engine Company, Caterpillar Inc., and Detroit Diesel Corporation). Projects have included numerous efforts to improve diesel fuel injector components by testing materials such as surface-modified alloys, coatings on metals, and monolithic ceramics. Research at the HTML has included development of machining technologies, performing tribological characterizations and nanohardness measurements on thin film coatings, and performing residual stress analyses for fuel-injection components. Residual stress analysis has also been utilized to solve problems with pistons, piston rings, crankshafts, and other components. In the Materials Analysis User Center, exhaust catalysts, and more recently, exhaust emissions (particles), have been studied, as have failed components, to determine the source of failure.

Through the HTML User Program, the HTML will continue to provide expert materials-characterization assistance to the OHVT’s stakeholders.

3.4.4 Environmental Science and Health Effects Program

The goal of the Environmental Science and Health Effects (ES&HE) Program is to establish a scientific basis that accurately describes the contributions of vehicle and fuel emissions to both air quality and potential health effects.

The activities encompassed in this program are driven by changing and increasing regulatory pressures on mobile-source emissions. The main areas of focus currently are emission precursors of ozone and airborne particles having an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$). The pollutants generally considered important for ozone formation are hydrocarbons and NO_x ; those significant in the formation of $PM_{2.5}$ include exhaust particles and NO_x. New regulations dealing with hazardous air pollutants (HAPs) and regional haze will become increasingly important in the future for mobile-source emissions. For example, the CARB recently declared diesel PM to be a toxic air contaminant.

A particular strength of the ES&HE Program has been collaborative research with other industry and government sponsors. For example, a current program focusing on measurement of diesel particle emissions is sponsored by the OHVT ES&HE Program through NREL, along with the Coordinating Research Council, Engine Manufacturers Association, American Petroleum Institute, Cummins Engine Co., Caterpillar Inc., South Coast Air Quality Management District, and CARB.

To accomplish project goals, the ES&HE Program conducts work in the following areas:

- effects of fuel, in-cylinder processes, and aftertreatment on the size, mass, and composition of PM and vapor-phase emissions;
- environmental and health effects of emissions as related to fuel, engine, and aftertreament parameters,
- sampling and characterization of PM and PM precursor emissions from motor vehicles in both laboratory and real-world situations,
- modeling and emissions inventories for mobile-source emissions, and
- physics and chemistry of atmospheric formation, transport, transformation, and deposition of PM, and representation of these processes in air-quality simulation models.

3.4.4.1 Atmospheric Effects

An overview of the atmospheric-effects portion of the ES&HE program is shown in Fig. 12. The following areas of research have been identified in response to regulatory needs:

- emissions measurement and characterization technology,
- vehicle emissions measurement,
- emissions inventory development/improvement, and
- atmospheric impacts.

The following are current or planned multi-year programs to investigate the influence of mobile source emissions on air quality:

- a collaborative study to understand the causes of high weekend-ozone concentrations in California's South Coast (Los Angeles) Air Basin,
- a cooperative program to understand how to measure and characterize ultrafine and nanoparticle emissions from in-use and dynamometer-tested diesel engines and vehicles, and
- a multiple-sponsor program to understand the contribution of heavy vehicle emissions of PM and NO_x to an airshed.

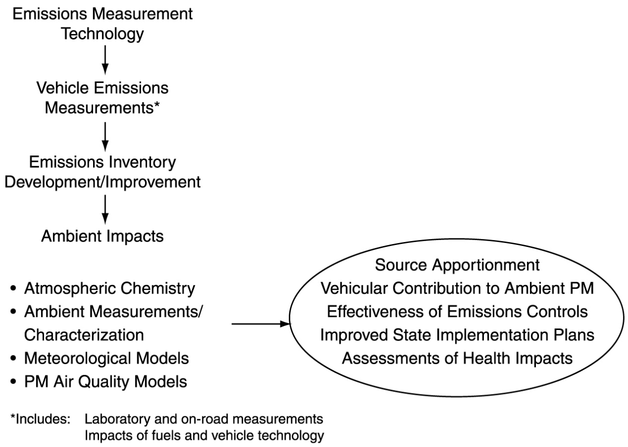


Fig. 12. Environmental Science and Health Effects Program—focus areas for atmospheric-effects research.

3.4.4.2 Health Effects

The goal of the health-effects portion of the ES&HE Program is to facilitate the appropriate future role for compression-ignition engine technology by supporting the identification and mitigation of health risks in parallel with the program's advances in engine emissions reduction, energy efficiency, and utility.

The DOE Office of Biological and Environmental Research and the OHVT have initiated a study of health issues associated with new engine technologies.

Research is being conducted in two areas. First, in FY 1999 a collaborative study was initiated to compare the toxicities of a matrix of particle and semivolatile organic exhaust samples from a range of low-emitting and high-emitting diesel and gasoline engines under different operating conditions. The samples are being collected under a contract administered through the NREL according to a plan that was developed with broad input from industry. It is expected that the toxicity evaluations will begin in late FY 1999 and will continue into FY 2000.

The second research area is the determination of the distribution of ultrafine particles deposited in the respiratory tract by inhalation. Although the biological behavior and potential health implications of inhaled ultrafine particles are unknown, they must be resolved as input to continued engineering developments. Methods for generating suitable solid tracer particles were developed, and the distribution of particles in the lungs and elsewhere in the body was evaluated and compared between rats and monkeys.

The following are current and planned multi-year programs to investigate the influence of mobile-source emissions on health effects.

- Compare exhaust-emissions toxicity from gasoline and diesel-powered vehicles.

- Provide a linkage between relative toxicity as evaluated in cells and toxicity as measured in mammals.

- Determine the health implications of ultrafine particles by examining the behavior of ultrafine organic particles in different regions of the respiratory tract.

- Compare health effects of gasoline and diesel emissions in animals exposed by inhalation.

3.4.5 Truck Safety

As more energy-efficient trucks are developed, care must be taken to ensure that truck safety is not compromised. Truck safety encompasses numerous topics, including driver control, crash-energy management, and vehicle stability. Efforts to reduce total vehicle weight will rely primarily on increased use of lightweight materials and innovative designs. However, the introduction of alternative materials or designs must not sacrifice the ability of the driver to control the vehicle or the vehicle's ability to absorb energy during crashes. Trucks and SUVs made lighter to improve fuel economy must be evaluated for tendencies to roll over or become unstable in crosswinds. Since aerodynamic drag currently provides a significant fraction of the force required to stop a truck, reduction in aerodynamic drag resulting from more streamlined, energy-efficient designs and other drag-reducing technologies described in Sect. 3.4.6 will impose significantly greater requirements on brake systems. The development of improved brake systems, therefore, is a safety-related enabling technology for the development of trucks with reduced aerodynamic drag.

This *Technology Roadmap* covers only the major safety-related issues likely to be influenced by advances in energy-efficient technologies. These include

- improvements of brakes and braking systems to compensate for the decreased drag that results from improved vehicle aerodynamics or other reductions in running resistance;

- evaluation of crash-energy management to take into account increased use of advanced materials and designs that reduce weight;

- evaluation of improved body and frame designs to protect occupants during rollover; and

- evaluation of more energy-absorbing front-end structures, made possible as the development of more efficient thermal-management systems reduces the need for space under vehicle hoods.

3.4.5.1 Status of Technology

Brakes. Heavy-vehicle braking systems are typically air brakes with the pressure to operate the brake mechanisms coming from an engine-driven pumping system. State-of-the-art truck brake systems in the United States are disk brakes on the front wheels and standard drum brakes on the rear of tractors and on trailers and dollies. In Europe, there has been a major switch to disk brake systems; these systems are expected to attain 50% market penetration in 1999 and 80% by 2002.

Advancements in truck brake systems currently being evaluated in the United States include automatic slack adjustment, anti-lock braking systems (ABSs), and improved materials of construction, including the friction materials themselves. Under evaluation for application in the longer term are disk brake systems, traction-control systems (TCSs), and vehicle dynamic control (VDC) systems. Futuristic concepts include "smart" brake systems or self-adaptive systems that are fully integrated with the total vehicle electronic systems.

Efforts to reduce the weight of vehicles for energy efficiency include the consideration of lighter-weight brake system components; this implies a need to dissipate more energy in lighter-weight vehicles. Aluminum and/or aluminum/alumina or aluminum/SiC composite brake rotors are beginning to be used in some cars. Whether similar efforts are under way for heavy vehicles is unknown.

There are many other opportunities for improvements in heavy vehicle brake systems. A recent ATA document discusses the truckers' needs for reliability and durability (a braking system that will work the same way repeatedly and last a long time between overhauls).[20] The long lifetime of some tractors and most trailers has led to an incompatibility problem in which the trailer's braking system is not matched well with that of the tractor because of advancements made in one but not the other. This may lead to a mismatch in the application or release of braking power of as much as several seconds between the tractor and the trailer. Mistimed or unequal application of either the tractor or trailer brakes leads to loss of vehicle control and "jackknifing" or "trailer swing."

Reliable and durable systems do not currently exist to assist the trucker in determining the state of his brake components while on the road. Brake adjustment may vary from wheel to wheel as materials wear differently, and one brake may reach its maximum useful life before another on the same vehicle, causing an unbalanced distribution of brake power and a potential safety problem.

The introduction of hybrid propulsion systems in Class 3–6 trucks will involve the use of regenerative braking. The design and implementation of electrical generators for regenerative braking in concert with existing mechanical braking systems provides an opportunity for overall system improvement. Heavy vehicles typically have space available in which to locate peripheral or safety equipment. It has been proposed that some of this space could best be used for a regenerative braking system, providing a system to recuperate the power of stopping by charging a battery which could then be used to accelerate the vehicle. Used in combination with the hybrid propulsion systems (discussed in Sect. 3.3.2) these devices could save considerably on the amount of fuel utilized in accelerating heavy hybrid vehicles.

It will be desirable to capture as much of the braking energy as possible, but it is unlikely that the electrical generators will be sufficiently large to handle the high power requirements. Also, the batteries may not have sufficient energy-storage capacity to store all of the regenerated energy. It is reasonable to expect that mechanical braking systems will continue to be standard equipment on vehicles with hybrid propulsion systems.

Materials and Designs for Weight Reduction. Currently, most trucks rely on relatively heavy steel frames and components to provide strength and stiffness necessary to achieve desired load-carrying capability and to provide adequate crash-energy management. Lightweight materials, such as aluminum and polymer composites and designs that address the use of high-strength steels are being evaluated in various segments of the ground transportation industry to achieve weight-reduction goals. The ability of these new materials to provide adequate or improved crash-energy management is extremely important and is being addressed for passenger vehicles by the OAAT as well as by the automotive industry. Additional efforts will be required to ensure that these issues are addressed for trucks.

Front-end Structures. The design of Class 7 and 8 tractors is currently controlled, to a large extent, by the need to incorporate larger engines with the necessary peripherals (e.g., turbochargers, cooling systems, and air-handling systems). The size of these components generally precludes the use of advanced aerodynamic designs and does not allow for the consideration of new, more-efficient, crash-energy management systems; rather, safety in crash situations is provided by heavy steel construction. However, innovations in thermal management and air handling may make it possible to significantly downsize many compenents under the hood. The space that is made available would provide room for new crash-energy-management materials and designs to enhance the safety of these vehicles.

3.4.5.2 Technical Targets

For brake systems, the primary technical target is development of a braking system that is effective at stopping a fully loaded vehicle in as short a distance as possible, while exhibiting the attributes of durability, reliability, and maintainability. The system should also be able to constantly present the driver with an indication of its state of readiness and repair. Stopping distances and stability controls should meet or exceed all existing and planned federal regulations, while remaining able to do so for 100,000 miles without repair or replacement. A reliable and durable, simple-to-read, easily maintained system to indicate readiness and repair status should be designed and implemented.

The principal target related to the increased use of alternative lightweight materials is optimization of the materials and/or designs for fuel efficiency as well as for crash-energy management and occupant protection.

3.4.5.3 Barriers

Barriers to the development and implementation of improved truck-braking systems include (1) the current lack of materials for brake components that can either tolerate or dissipate the stress and heat generated during braking without experiencing excessive wear, (2) the current lack of cost-effective, rugged designs for dissipation or utilization of the braking-generated heat, (3) the cost of improved systems, and (4) the lack of awareness of and experience with currently available improved systems.

Barriers to the optimized design for crash-energy management include the lack of understanding of energy-absorption mechanisms for new materials and the lack of a design database.

3.4.5.4 Technical Approach

The technical approach to improving truck safety will include the following steps.

- Develop improved frictional materials. This would involve performance of tests on various procured friction pairs to include friction and wear measurements as well as thorough materials characterization to determine types, quantities, and microstructures of the frictional materials. Testing would also involve preparing and testing new experimental frictional materials in an attempt to develop improved materials based on knowledge generated by testing the procured materials.

- Evaluate potential regenerative braking systems.

- Develop and implement sensors and actuators for brake safety systems, utilizing sensing technologies to measure signals from the brake hydraulic system, and analyze these signals to detect the development of potential problems. For instance, the signal-analysis system could determine the forces applied to each brake and could be used with actuator valves to actively balance these forces and thus control the vehicle's braking dynamics. Signals from brake system hydraulics or other sources could also be used to determine the extent of brake wear and thus the need for repair.

- Assess entirely new designs for braking systems, such as electric or hydraulic systems, or even systems that could act independently of the wheels and tires, such as aerodynamic devices like the flaps or air deflectors currently used on airplanes.

- Develop predictive-modeling capabilities to aid in enhancing crash-energy management performance of new advanced lightweight materials.

- Develop an empirical database on high-strain-rate deformation behavior of new materials.

- Develop and evaluate innovative designs for crash-energy management and for the provision of occupant safety in rollovers.

3.4.6 Engineering Simulations and Modeling

Computational models continue to play an ever-increasing role in the development of all transportation vehicles. This trend is largely fueled by the need to further refine vehicle designs for increased efficiency and performance. It is enabled by the continuing dramatic increases in the computational power of multiprocessor computers. Computational models that directly support the development of efficient heavy vehicles include (1) structural models (static, dynamic, and crash); (2) computational fluid-dynamics (CFD) models (vehicle aerodynamics and fuel handling and mixing); and (3) combustion models (in-cylinder combustion and exhaust aftertreatment). Once validated against controlled experiments, these analytical methods become valuable tools to evaluate and optimize the performance of components or processes. When linked together, these simulations can be performed concurrently and/or in series to predict the interaction of multiple phenomena on system performance. Three areas where computational models can greatly improve heavy vehicle efficiency are (1) materials and structural modeling; (2) fuel injector, combustion, and aftertreatment modeling; and (3) external aerodynamics.

3.4.6.1 Materials and Structural Modeling

Fuel efficiency and lower emission standards have driven the heavy vehicle industry to use lighter-weight structures of steel, aluminum, plastics, and magnesium. These lightweight materials and improved designs have also required improved engineering analysis, including crashworthiness modeling. The following questions must be convincingly answered during the development of a successful vehicle design.

- Can efficient processes be engineered to manufacture the components and assemble the vehicle?

- Will the as-built performance meet the required acceptance standards?
- Will the as-used performance (in normal and accident conditions) satisfy the necessary economic, environmental, and safety standards that are imposed?

Current vehicle development cycles require that many real prototypes be built and tested in full-scale crash experiments. Although final acceptance of vehicle designs should continue to be confirmed in actual tests, the development of larger, more powerful computers provides the opportunity to use modeling and simulation for optimizing design solutions, thus reducing a vehicle's development cost and time to market.

3.4.6.2 Fuel-Injector Modeling

The historical improvement in power and efficiency of diesel engines is due, to some extent, to advances in efficiency and precise fuel delivery through better fuel injectors. Adequate in-cylinder mixing between fuel and air is strongly dependent on the characteristics of the fuel injector, in addition to other conditions, such as chamber pressure and geometry. This is especially true for DI engines, in which the fuel is directly injected into the cylinder without any prior contact with the air.

Because fuel-spray characteristics such as velocity, spray angle, and droplet size are critical factors in fuel-air mixing, it is important to understand the relationship between these characteristics and injector design. Traditionally, injector design has been based on extensive empirical correlations between experimentally measured spray characteristics and specific design parameters. However, because the dimensions of injector flow passages are small (0.1 mm or smaller) and their geometries are complex, it is almost impossible to obtain accurate, nonintrusive experimental measurements of the flow inside injectors. Thus, computational fluid-dynamics modeling of the flow inside and at the exit of injectors could provide important new information about how design parameters actually relate to spray characteristics.

There are still wide gaps in the understanding of the physical processes inside the injector and how they relate to the subsequent formation of liquid sheets and drops beyond the injector exit. One prominent theory is that atomization is caused by aerodynamic interaction of the liquid jet with the gas into which it is injected. Another theory suggests that atomization is caused by the conversion of turbulent energy within the liquid sheet that is initiated within the injector. High-resolution computational fluid dynamics models of a fuel injector could help resolve these theories and could provide both fundamental and specific design information for the next generation of high-efficiency, low-emission, heavy-duty diesel engines.

The flow within the fuel injector is at the extreme limits of the continuum regime and borders on being a nonequilibrium molecular-dynamics regime. In the open literature, there is no validated model to fully capture the physics of the flow inside the injector. Molecular dynamics or lattice Boltzmann calculations have been used with some success in the past for micro electro-mechanical systems (MEMS) and ink injectors of printers. Continuum approaches such as volume-of-fluid, boundary integral method, and the level-set method, and have shown promise in modeling the complex surface interactions in droplet breakup and coalescence. An extensive systematic testing and validation of this approach to injector modeling is needed to ascertain its limits and best methodology to be followed. Because of the high level of detail required to adequately describe the fuel-injector phenomena, it is likely that Teraflop-scale, high-performance computing will be a necessity. Such computing capabilities are not available in industry or at universities but will be available at national laboratories.

Droplet vaporization downstream of the injector can be modeled by solution of the spray equation by means of a Monte Carlo particle method. This mixed Eulerian-Lagrangian approach models the dispersed phase and has the ability to accurately model the dilute (low-liquid-volume-fraction) spray regime. The integration and coupling of this continuum process to the flow within the fuel injector needs to be addressed and studied. The result will be a valuable design tool to model the next generation of fuel-efficient, low-emission engines. The understanding obtained will make it feasible to generate new sub-models that plug into existing codes (e.g., KIVA and CHAD) to model the spray formation processes more accurately.

3.4.6.3 Combustion Models

In-Cylinder Combustion Modeling. Beyond the injector, diesel-combustion performance is determined to a large extent by the efficiency with which the liquid fuel droplets evaporate and mix with the air. Thus, it is also important to have computational models that simulate the impact of droplet characteristics (such as velocity and size distributions) and air flow features (such as swirl and tumble). At a minimum, this type of simulation requires consideration of the three-dimensional continuum turbulence associated with both flows. Further, the heat released during combustion can modify the turbulence in the flow, resulting in a fully coupled evolution of the fluid-flow and chemical processes. All these processes are highly unsteady and occur in most real systems in an environment of major transients (e.g., acceleration) imposed by the driver. Current understanding of this type of flow field is limited and comes primarily from laser-based optical measurements obtained through the use of optically accessible single-cylinder engines and engine simulators. Future advancement in engine design and increases in efficiency (i.e., reduced fuel consumption and pollutant emission) will require significant further improvements in our understanding of how the flow and combustion processes couple together in this transient environment.

Numerical simulation of key aspects of in-cylinder combustion coupled with advanced experimental approaches will begin to play an integral role in developing this enhanced understanding of flow and combustion processes. For example, KIVA and CHAD are existing state-of-the-art computer codes that have already been successfully used by industry and DOE to study certain aspects of diesel combustion. Both of these codes are widely known for their ability to simultaneously address both the computational fluid dynamics and at least low-order descriptions of the combustion chemistry. However, it is also clear that there are many important phenomena that cannot currently be simulated by these codes. For example, a detailed description of how NO_x and PM generation are related to the precise combustion sequence has yet to be achieved, perhaps because the chemical kinetics submodels used by these codes is far too simplified; also the codes cannot address the coupling between engine cycles that influences overall emissions and performance. With the availability of massively parallel systems and the recent development of more detailed reaction kinetics, these limitations can be significantly reduced.

It is also likely that the turbulence models currently used in codes like KIVA and CHAD will not be able to address some issues of importance to the OHVT. Specifically, since fuel-air mixing and combustion produce large density variations and can vary from cycle to cycle, conventional ensemble-averaged turbulence models used in KIVA and CHAD cannot give important field information. More advanced large-eddy-simulation (LES) and variable-density turbulence models are just beginning to be implemented and tested in CHAD. The modeling talk will require full implementation and extensive verification and validation of these advanced models. In LES, scales larger than the grid are computed using a time- and space-accurate scheme, while the unresolved smaller scales are modeled semi-empirically. A modeling process known as "bootstrapping" can be used to define the turbulent scaling relationships in these sub-grid regions, thereby eliminating the need for calibrating various *ad hoc* modeling constants and improving the robustness of the modeling procedures.

Aftertreatment Device Modeling. Often, the simultaneous goals of high fuel efficiency and low emissions are strongly at odds. This is especially true for diesel combustion, which is carried out under extremely lean (oxygen-rich) conditions that do not favor the subsequent reduction of NO_x in the catalytic converter. In fact, current catalytic converters are, in fact, incapable of reducing diesel exhaust NO_x levels to the proposed new federal standards, and there is no clear route to how these standards can be met. Clearly, a new level of converter technology will be needed.

Up to the present, development of new catalytic converter technology has depended almost totally on empirical, incremental developments. Catalysts and converter designs have been initially selected on the basis of educated guesses and long-term testing to scale up from the laboratory to device scale. However, it is expected that models of the dominant physical and chemical processes involved could greatly speed the development of new generations of catalytic converter technology. It may be possible to reach the stage of the so-called "designer catalysts," in which totally new catalyst formulations are proposed on the basis of a detailed model relating catalyst composition and morphology to on-the-road performance. Although the "designer catalyst" idea has much appeal, it is likely that other developments will initially have more near-term implementation.

First, there is a strong need to accurately model the flow, mass transport, and heat transport in the exhaust gases flowing through the converter and the coupling between these macroscopic flow effects and the chemical processes occurring on the catalyst surface. This connection between the macroscopic flow field and chemistry is critical because either of these general regions can dominate the overall converter performance, depending on operating conditions. In many cases, the rate-limiting step can switch from one region to another as transients are imposed by the engine. The effect of transients is likely to be particularly important in diesels for certain operational periods such as cold start and rapid acceleration, which are key parts of the FTP for emissions performance. Transients are also a major factor in the functioning of so-called NO_x traps, where the nitrogen oxides are adsorbed onto special "storage" sites for extended periods and then are released and reduced by the addition of hydrocarbon pulses to the converter.

Secondly, there is a major need to develop better models for the surface chemistry and appropriate kinetics models that will accurately reflect the effects of individual exhaust-gas species and local variations in temperature. The surface kinetics currently available for most of the important reactions are poorly understood and incomplete. The kinetics that are typically available are derived from experimental global conversion measurements at steady-flow conditions where detailed surface temperature and concentration profiles are unknown. Such information cannot be used to make accurate predictions for flow and boundary conditions that are significantly different from the experiments used to derive it, and each new catalyst material must be empirically evaluated before simulations can be run. Because of the considerable computational burden imposed by considering a large number of elementary reaction steps, there is a strong incentive to identify the major reaction pathways that can have a significant impact on global conversion.

The above two modeling components could be combined in both fully detailed and low-order forms. The former term refers specifically to simulations in which the macroscopic flow effects and surface kinetics are considered simultaneously in high detail. Although such simulations should offer the most accurate predictions about the impact of design changes or changes to the catalyst properties, it will require Teraflop levels of computational effort similar to that described for detailed modeling of the in-cylinder combustion. Low-order models offer another approach for situations where computational speed (as opposed to detail) is essential (such as for real-time diagnostics and control). In this second case, it would be advantageous to develop simplified versions of the detailed models that can still produce the correct overall system dynamic response. An example application would be the evaluation of how the combination of certain engines and catalyst aftertreatment systems collectively respond to certain types of driving transients. Such information could be extremely valuable for assessing the effectiveness of various types of on-board emissions sensors.

A third major modeling need for diesel emissions control is to simulate the mechanisms for catalyst poisoning and particle coarsening. Sulfur poisoning is a major issue because of the potential impact it could have on fuel-processing requirements. Specifically, if alternative methods are not found for reducing sulfur's rapid inhibition of lean NO_x catalysts, diesel fuels will have to be processed to extremely low sulfur levels. A detailed model for the physical and chemical processes involved in sulfur poisoning could potentially lead to improvements in catalyst design and/or operation that would significantly increase their sulfur tolerance and would lessen the need for expensive fuel processing.

Catalyst particle coarsening is one of the major causes of catalyst degradation not caused by poisoning. It specifically involves the physical migration and agglomeration of individual catalyst particles in the washcoat so that the effective catalyst surface area is much reduced. As yet, no one has been able to explain the basic physical mechanisms involved or to predict how coarsening relates to the initial washcoat morphology or the time-temperature exposure history. Like sulfur poisoning, the impact of coarsening is so large that the development of options for retarding or eliminating it would be considerable.

3.4.6.4 External Aerodynamics

One of the barriers to achieving a 10-mpg truck is vehicle drag (see Sect. 3.1.3). The target is to reduce the C_d from 0.55 to 0.47, a reduction of 15%. New approaches for the numerical simulation and analysis of aerodynamic flow will play an important role in the R&D to reduce aerodynamic drag. [20]

3.4.6.5 Drag Reduction

CFD calculations of the truck configuration will provide guidance on designs that offer the least drag. These designs are closely coupled to other requirements such as underhood thermal limitations and the geometric constraints imposed by the functional requirements, of the tractor-trailer combination. Manufacturing costs and other parameters also have to be considered in this optimization. Experimental verification and validation of new CFD methods are an important part of this task.[21]

3.9.6.6 Underhood Thermal Management

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

4. PROGRAM SUMMARY

The implementation of this OHVT *Technology Roadmap* is described in the *Multiyear Program Plan of the Office of Heavy Vehicle Technologies and Heavy Vehicle Industry Partners*[22] and in the multiyear program plans listed in Appendix B. The reader should consult the more detailed multiyear program plans for complete information.

4.1 PROGRAM GOALS

- Develop by 2004 the enabling technologies for a Class 7 & 8 truck with a fuel efficiency of 10 mpg (at 65 mph) that will meet prevailing emission standards.

- For Class 3–6 trucks operating on an urban driving cycle, develop by 2004 commercially viable vehicles that achieve at least double the fuel economy of comparable current vehicles (1999), and as a research goal, reduce criteria pollutants to 30% below EPA standards.

- Develop by 2004 the diesel-engine enabling technologies to support large-scale industry dieselization of Class 1 & 2 trucks, achieve a 35% improvement in fuel efficiency over comparable gasoline-fueled trucks, and meet applicable emissions standards.

4.2 PROGRAM APPROACH

- Develop a partnership with the domestic transportation industry, energy-supply industry, other federal agencies, and R&D organizations to develop high-efficiency-engine technologies and alternative fuel-utilization technologies for trucks and to promote their acceptance.

- Continue development of key enabling technologies:
  —Emission control (including exhaust aftertreatment)
  —Combustion technology
  —Materials
  —Environmental science and health effects
  —Truck safety
  —Engineering simulations and modeling

Among these enabling technologies, combustion and emissions control are being coordinated through a diesel cross-cut team that has linked diesel R&D in the OHVT and the Partnership for a New Generation of Vehicles (PNGV).

4.3 SCHEDULE AND MILESTONES

The OHVT program key activities and milestones are shown in Fig. 13.

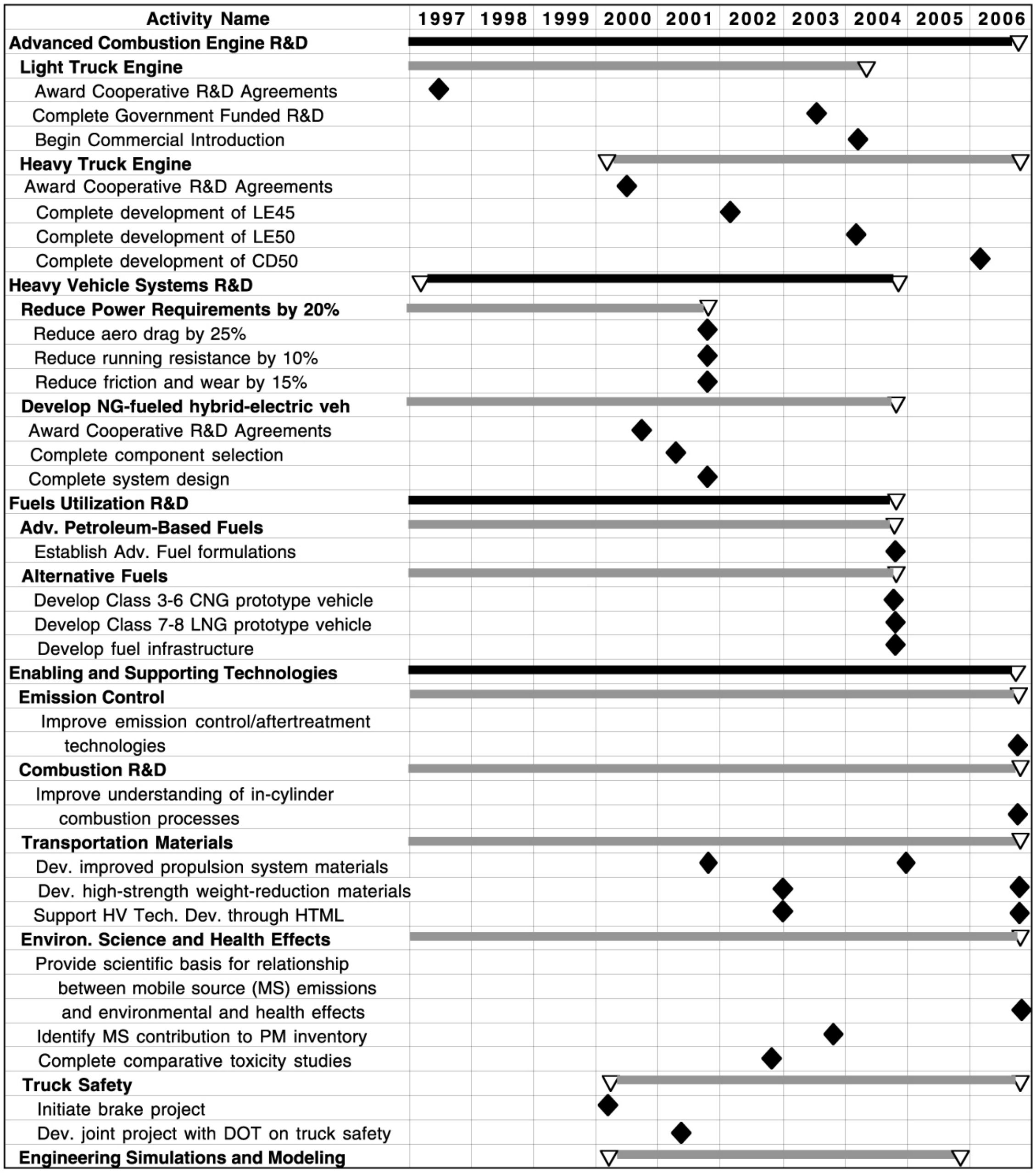


Fig. 13. Key activities and schedule of OHVT.

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APPENDIX A. OHVT WORKSHOPS AND MEETINGS TO SOLICIT CUSTOMER INPUT

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DOE/SAE Workshop on Energy Efficient Heavy Vehicle Technologies for Reducing Fuel Costs: Leveraging DOE's R&D Capabilities, Romulus, Michigan, April 17–18, 1996.

DOE/Office of Heavy Vehicle Technologies Customer Focus Workshop, Golden, Colorado, May 14–15, 1996.

SAE Truck and Bus Council Meeting, Miami, Florida, June 24–25, 1996.

DOE/OHVT Workshop on Applications of Carbon Products for Efficient Operation of Heavy Trucks, Buses, and Other Commercial Vehicles, Chicago, Illinois, September 4–5, 1996.

1996 SAE International Truck and Bus Meeting and Exposition, Detroit, Michigan, October 14–16, 1996.

DOE Automotive Technology Development Customers' Coordination Meeting, Dearborn, Michigan, October 28–November 1, 1996.

Workshop on Alternative Fuels for Heavy Vehicles, Chicago, Illinois, November 1996.

Workshop on Improving Heavy Vehicle Aerodynamics, Phoenix, Arizona, January 1997.

1997 Diesel Engine Emissions Reduction Workshop, La Jolla, California, July 28-31, 1997

DOE-OTT Automotive Technology Development Customers' Coordination Meeting, Dearborn, Michigan, October 1997.

DOE-OHVT/Energy Frontiers International Fuels and Engines Meeting, in San Antonio, Texas, January 14, 1998. (Attended by representatives from the oil industry and engine manufacturers.)

Workshop on Performance and Emissions of New Diesel Cycle Fuels for Heavy Vehicles, San Antonio, Texas, January 15, 1998.

Workshop to Review Multi-Year Program Plan on Heavy Vehicle Aerodynamic Drag, Livermore, California, February 20, 1998.

DOE/Engine Manufacturers Association Meeting on New Motor Fuel Options for Diesel Engines, Washington, D.C., March 16, 1998.

1998 Diesel Engine Emission Reduction (DEER) Workshop, Castine, Maine, July 6–9, 1998.

DOE-OHVT/Energy Frontiers International "Fuels, Lubricants, Engines, and Emissions" Meeting,, San Antonio, Texas, January 18–20, 1999. (Attended by representatives from the oil and lubricants industry, engine manufacturers, emissions-control manufacturers, and health-effects community representatives.)

DOE-OHVT Workshop on Emissions Control Strategies for Internal Combustion Engines, Tucson, Arizona, January 21, 1999.

Workshop on Research Needs for Reducing Friction and Wear in Transportation, Argonne, Illinois, March 22–23, 1999.

1999 SAE Government/Industry Meeting, Washington, D.C., April 26–28, 1999.

1999 Diesel Engine Emission Reduction (DEER) Workshop, Castine, Maine, July 5–9,1999.

HTML User Forum, Knoxville, Tennessee, August 16–17, 1999.

DOE/ORNL Workshop on "Opportunities for Heavy Vehicle Energy Efficiency Gains Through Running Resistance and Braking Systems R&D, Knoxville, Tennessee, August 18–19, 1999.

Heavy Vehicle Propulsion Materials Workshop, Knoxville, Tennessee, August 19–20, 1999.

APPENDIX B. MULTIYEAR PROGRAM PLANS

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