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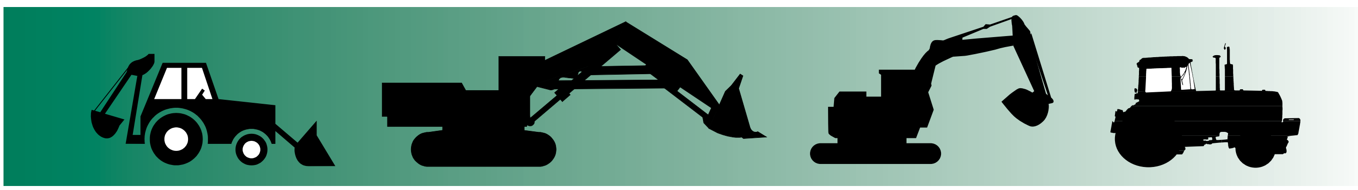
OFF-HIGHWAY VEHICLE TECHNOLOGY ROADMAP



A Joint Venture of Industry and Government

December 2001

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This document will be updated periodically to reflect editorial changes, technological developments, and regulatory developments.

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CONTENTS (Cont.)

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Frank Stodolsky
Argonne National Laboratory
December 2001

[*] From http://www.cordis.lu/scienceweek/inspiration01.htm

NOTATION

ANL	Argonne National Laboratory
bsfc	brake-specific fuel consumption
CFD	computational fluid dynamics
CLP	clean low pressure
CO	carbon monoxide
CVT	continuously variable transmission
DOE	U.S. Department of Energy
DPF	diesel particle filter
EGR	exhaust gas recirculation
EPA	U.S. Environmental Protection Agency
FEA	finite element analysis
HC	hydrocarbon
kW	kilowatts
LHR	low heat rejection
NADS	National Advanced Driving Simulator
NO_x	nitrogen oxides
NTP	non-thermal plasma
OHVT	Office of Heavy Vehicle Technologies
OTT	Office of Transportation Technologies
PM	particulate matter
PNGV	Partnership for a New Generation of Vehicles
R&D	research and development
SCR	selective catalytic reduction
SO_x	oxides of sulfur

EXECUTIVE SUMMARY[1]

The off-highway sector[2] is under increasing pressure to reduce operating costs (including fuel costs) and to reduce emissions. These challenges could affect the broader, non-highway sector, which includes such sources as air (aircraft), water (e.g., inland marine), and rail (e.g., locomotives).[3] In total, non-highway sources (excluding fuel transmission by pipeline) consumed 20.2% of the 26.8 Quads (quadrillion Btu) of energy used by the transportation sector (EIA 2001) in 1999. Distillate fuel (including diesel fuel) is the primary fuel used by the non-road market. Non-road markets consume about 33% of the distillate fuel (excluding home heating oil) (EIA 2000). Improved fuel quality needed for next-generation off-highway vehicles could impact the fuels supplied to the broader non-highway sector.

Emissions from large off-highway diesel engines are significant. Large off-highway diesel equipment includes agricultural equipment (such as tractors), construction equipment (such as backhoes and bulldozers), material handling equipment (such as forklifts), and utility equipment (such as engine-driven generators and engine-driven pumps). According to 2000 estimates, large off-highway diesel engines contribute about 20% of NO_X emissions and 36% of particulate matter (PM) emissions from all mobile sources (including cars, light trucks, and heavy trucks) (USEPA 2000). Within the off-highway sector, large diesels (excluding locomotive diesels) contribute 66% of NO_X emissions and 70% of PM emissions.

Recognizing the importance of fuel costs and emissions compliance to the off-highway sector, the Society of Automotive Engineers (SAE) and the U.S. Department of Energy (DOE) convened a workshop in April 2001 (ANL 2001) to (1) determine the interest of the off-highway industry (consisting of agriculture, construction, surface mining, and inland marine) in crafting a shared vision of off-highway, heavy machines of the future and (2) identify critical research and development (R&D) needs for minimizing off-highway vehicle emissions while cost-effectively maintaining or enhancing system performance. The workshop also enabled government and industry participants to exchange information.

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1 This document will be updated periodically to reflect editorial changes, technological developments, and regulatory developments.

2 The off-highway sector is broad. According to the U.S. Environmental Protection Agency's (EPA's) definition, the off-highway, or non-road category, includes outdoor power equipment, recreational vehicles, farm and construction machinery, lawn and garden equipment, marine vessels, locomotives, aircraft, and other applications. DOE's Office of Heavy Vehicle Technologies (OHVT) currently funds R&D on improving on-road heavy-duty diesel (compression-ignition) engines. To maximize synergy between current R&D programs and off-highway applications, the scope of this Roadmap is limited to surface off-highway applications powered by heavy-duty diesel engines (at least 100 hp [75 kW]). Because of their unique emissions standards applicable upon remanufacturing, locomotive engines are covered separately. While in-land marine sources are not specifically covered, in-land marine engines are common to many of the engines included in this Roadmap.

3 Excludes fuel transmission by pipeline.

During the workshop, it became clear that the challenges facing the heavy, surface-based off-highway sector[4] can be addressed in three major machine categories: (1) engine/aftertreatment and fuels/lubes, (2) machine systems, and (3) thermal management. Working groups convened to address these topical areas. The status of off-highway technologies was determined, critical technical barriers to achieving future emission standards were identified, and strategies and technologies for reducing fuel consumption were discussed. Priority areas for R&D were identified. A joint industry/government team was then established to craft a roadmap, and a goal for the initiative was proposed and established. Workshop participants felt that a joint industry/government research program that addresses the unique needs of the off-highway sector would complement the DOE's Office of Heavy Vehicle Technologies research program for highway vehicles.

This document outlines potential technology R&D pathways to greatly reduce emissions from the off-highway sector and yet greatly reduce fuel costs cost-effectively and safely. The status of technology, technical targets, barriers, and technical approaches toward R&D are presented. Program schedule and milestones are included.

The goal for this industry/government off-highway initiative is:

- By 2006, meet Tier 3 emission standards while maintaining Tier 2 fuel economy;
- By 2010, meet Tier 4 emission standards while improving engine fuel economy by 5% (compared with Tier 2 fuel economy);
- Reduce fuel required by the machine by 21%, through load reduction, resulting in a combined engine/machine fuel reduction of 25%; and
- Maintain and enhance product safety, while reducing overall initial and operating costs.[5]

Subgoals were proposed for each of the three major machine categories consistent with the overall goal. Targets for component efficiency improvement are based on preliminary analysis and judgment. These preliminary estimates were necessary as a starting point for discussion. Estimates and goals for the efficiency of components will be refined during a structured analytical process. A summary of the energy savings goals, totaling 25%, is presented in Table S.1. Because machine uses and configurations vary widely, more detailed assessments of potential energy efficiency improvements warrant future study.

The program schedule and milestones are given in Table S.2. The milestones are general; more specific milestones will be developed after a more detailed assessment of technology options early in the program.

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[4] From now on referred to simply as "off-highway sector."

[5] Relative to 2001 model year products.

TABLE S.1 Engine and System Energy Savings Goals[6]

Parameter	Energy Savings Goal (%)
Engine System[7]	4.8
Powertrain	5.8
Hydraulics	5.3
Traction, mobility, steering	1.6
Implement loadability/controllability	2.6
Operator performance enhancements	2.0
Adaptive machine system performance	3.9
Subtotal, System	21.2
Combined engine/system energy reduction goal[8]	25

TABLE S.2 Off-Highway Program Schedule and Milestones

Program Element	2006	2010
Engine/Aftertreatment and Fuels/Lubes	Maintain Tier 2 fuel efficiency while meeting Tier 3 emission standards	Improve fuel economy by 5% compared with Tier 2 products; meet Tier 4 emission standards, non-petroleum fuel-capable where appropriate
Machine System	Not applicable	Reduce system loads by 21%
Thermal Management	Not applicable	Provide a 65% increase in cooling capacity

[6] Energy reduction goals based on fuel input.

[7] The effects of system components are based on the averages of assumed values for engine thermal efficiency, component energy use, and component efficiency improvement. Comprehensive systems analysis is needed to further refine these estimates.

[8] From combined (not additive) effects of engine and systems efficiency improvements.

On the basis of input from the industrial participants, initial estimates of resource needs for FY 2003 are listed in Table S.3. For industry to meet the goals described in this roadmap, it is likely that this level of funding needs to be sustained for at least for five years (FY 2003–2007).

TABLE S.3 Initial Resource Needs, Off-Highway Research and Development

Category[a]	Recommended Government funding, FY 2003[9] (in $ millions)
Engine	
Systems analysis/performance measures	0.5
Emissions controls	5.0
Systems	
Systems analysis	0.5
All-electric accessories/replace hydraulics	1.5
Noise, vibration, harshness/thermal cycles	3.5
Thermal management	3.0
Auxiliary systems optimization	0.5
Sensors/diagnostics	0.5
Hybrid systems	0.75
Fuels	
Improved fuels and lubes	0.5
Propulsion materials	1.5
High-strength weight-reduction materials	0.5
Total	18.25

[a] Categories were developed before this roadmap was written and correspond to U.S. DOE R&D categories. A multi-year program plan (MYPP) is planned based on this roadmap and will identify resources needed in more detail.

REFERENCES

ANL: Argonne National Laboratory

ANL, 2001, "Leveraging R&D Resources to Meet Industry Needs," Proceedings of the Society of Automotive Engineers-U.S. Department of Energy Off-Highway Emissions and System Efficiency Workshop for Heavy Vehicles, held at Argonne National Laboratory, April 18–19, 2001, Argonne, Ill. (CD proceedings).

EIA: Energy Information Administration

EIA, 2001, "Transportation Energy Data Book, Edition 21," ORNL-6966, Oak Ridge National Laboratory, Sept.

[9] Assumes 50% cost-share by industry.

EIA, 2000, *Petroleum Supply Annual 1999,* U.S. Department of Energy/EIA, Washington, D.C., June.

USEPA: U.S. Environmental Protection Agency

USEPA, 2000, *Program Update: Reducing Air Pollution from Nonroad Engines*, EPA420-F-00-048, U.S. Environmental Protection Agency, Air and Radiation, Office of Transportation and Air Quality, Nov.

1 INTRODUCTION

The off-highway sector[10] is under increasing pressure to reduce operating costs (including fuel costs) and to reduce emissions. Recognizing this, the Society of Automotive Engineers and the U.S. Department of Energy (DOE) convened a workshop in April 2001 (ANL 2001) to (1) determine the interest of the off-highway sector (consisting of agriculture, construction, surface mining, inland marine) in crafting a shared vision of off-highway, heavy machines of the future and (2) identify critical research and development (R&D) needs for minimizing off-highway vehicle emissions while cost-effectively maintaining or enhancing system performance. The workshop also enabled government and industry participants to exchange information.

During the workshop, it became clear that the challenges facing the heavy, surface-based off-highway sector[11] can be addressed in three major machine categories: (1) engine/aftertreatment and fuels/lubes, (2) machine systems, and (3) thermal management. Working groups convened to address these topical areas. The status of off-highway technologies was determined, critical technical barriers to achieving future emission standards were identified, and strategies and technologies for reducing fuel consumption were discussed. Priority areas for R&D were identified. Given the apparent success of the discussions at the workshop, several participants from industry agreed to help in the formation of a joint industry/government "roadmap" team. The U.S. Department of Energy's Office of Heavy Vehicle Technologies has an extensive role in researching ways to make heavy-duty trucks and trains more efficient, with respect to both fuel usage and air emissions. The workshop participants felt that a joint industry/government research program that addresses the unique needs of the off-highway sector would complement the current research program for highway vehicles. With industry expertise, in-kind contributions, and federal government funding (coupled with the resources at the DOE's national laboratories), an effective program can be planned and executed.

This document outlines potential technology R&D pathways to greatly reduce emissions from the off-highway sector and yet greatly reduce fuel costs cost-effectively and safely. The status of technology, technical targets, barriers, and technical approaches toward R&D are presented. Program schedule and milestones are included.

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[10] The off-highway sector is broad. According to the U.S. Environmental Protection Agency's (EPA's) definition, the off-highway, or non-road category, includes outdoor power equipment, recreational vehicles, farm and construction machinery, lawn and garden equipment, marine vessels, locomotives, aircraft, and other applications. DOE's Office of Heavy Vehicle Technologies (OHVT) currently funds R&D on improving on-road heavy-duty diesel (compression-ignition) engines. To maximize synergy between current R&D programs and off-highway applications, the scope of this Roadmap is limited to surface off-highway applications powered by heavy-duty diesel engines (at least 100 hp [75 kW]). Because of their unique emissions standards applicable upon remanufacturing, locomotive engines are covered separately.

[11] From now on referred to simply as "off-highway sector."

1.1 CHARACTERISTICS OF THE OFF-HIGHWAY SECTOR

The off-highway sector is diverse. This category is different from other mobile source categories because of (1) the diverse functions of the equipment in which the engines are used and (2) the wide range of engine sizes and power ratings, including a wide range of power applications within each equipment type. A single engine design is often used in diverse applications, from high-volume machines — such as utility farm tractors, crawler dozers, backhoe loaders and front-end loaders — to low-volume machines — such as log skidders (Block 1998). The engine can be used to propel the vehicle in addition to performing an another function (such as lifting a load of concrete block). Also, the engine can be stationary but portable (as in a generator or a compressor).

The off-highway industry produces significantly lower volumes of off-highway vehicles, as well as equipment, when compared with other industry sectors, such as the on-highway sector. A small number of equipment manufacturers sell about one-half of the off-highway machines, while a large number of other manufacturers share in the sale of the remaining half (Block 1998). Thus, costs of product changes (including emissions-driven modifications) must be amortized over longer periods. Also, the off-highway industry is characterized by a small number of engine manufacturers that must coordinate product offerings among a large number of equipment manufacturers.

About 68,000 diesel engines rated between 75 and 130 kW were sold in 1995 (USEPA 1998). Most of these engines were equipped with direct injection. The top three manufacturers are Cummins (36%),[12] John Deere (25%), and Caterpillar (17%). Other manufacturers include Perkins, Deutz, CNH, Detroit Diesel, Hino, Mazda, Volvo, Komatsu, Hercules, Isuzu, and Mitsubishi. These engines are used mostly in construction equipment, such as backhoes. About 107,000 engines rated between 130 and 4,509 kW were sold in 1995. Most of the engines in this category are used in agricultural equipment. The manufacturers of the smaller engines in this category (130–225 kW) are Cummins (38%) and John Deere (31%). Other manufacturers include Caterpillar (14%), Navistar (6%), CNH (4%), and Detroit Diesel (4%). The largest manufacturers in the 225–450-kW range are Caterpillar (34%), Cummins (33%), and Detroit Diesel (25%). In the engines rated above 450 kW, Caterpillar is the largest manufacturer (46%), followed by Detroit Diesel (27%) and Cummins (26%).

1.2 OFF-HIGHWAY SECTOR ENERGY USE AND FUEL QUALITY

In 1999, the transportation sector consumed 26.8 Quads (quadrillion Btu) of energy (USDOE 2001a). Of this, 20.2% is attributable to the non-highway sector (excluding fuel transmission by pipeline), which includes off-highway, as well as air (aircraft), water (e.g., inland marine), and rail (e.g., locomotives).

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[12] Percent of sales.

Fuel quality needed for next-generation off-highway engines could impact the fuels supplied to the other, broader non-highway sector. As shown in Figure 1.1, non-road markets consume about 33% of the distillate fuel (excluding home heating oil) (EIA 2001).

The distillate market generally includes on-highway diesel (500 ppm max S), off-highway diesel (5,000 ppm max S), and home heating oil (5,000 ppm max S). Approximately 66% of U.S. distillate production is ≤500 ppm S, which is required for on-highway diesel use. Since refining production capacity of ≤500 ppm S distillate exceeds on-highway distillate fuel sales (56%, seen in Figure 1.1), this implies that some of this material is sold into markets with higher sulfur specifications. Therefore, fuel supply and demand issues emerge as fuel quality issues are addressed.

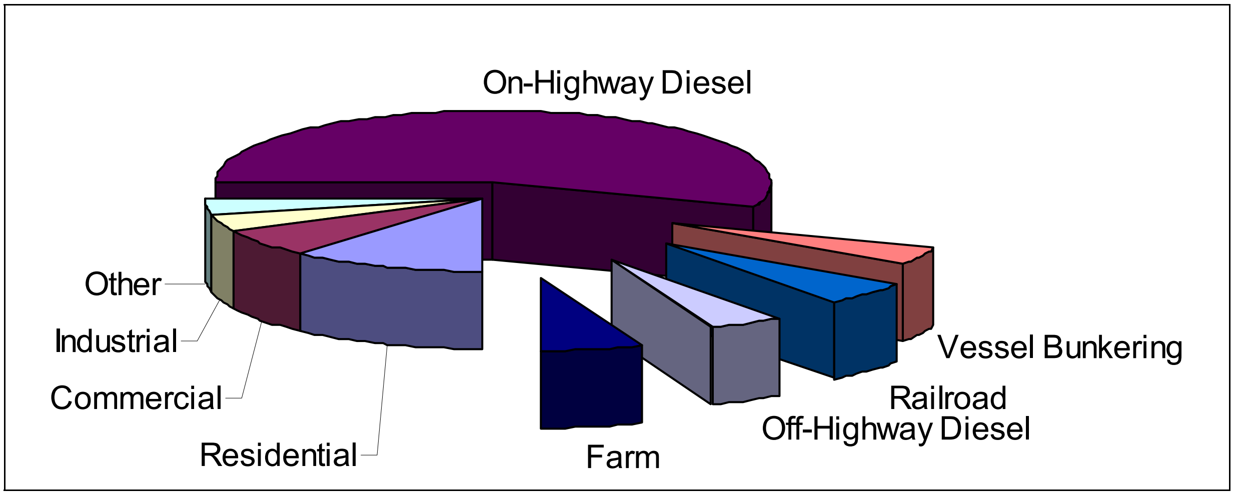

FIGURE 1.1 U.S. Distillate Fuel Sales by End Use

1.3 OFF-HIGHWAY SECTOR EMISSIONS AND THEIR REGULATION

According to 2000 estimates, large off-highway diesel engines contribute about 20% of NO_X emissions and 36% of particulate matter (PM) emissions from all mobile sources (USEPA 2000). Hydrocarbon (HC) and carbon monoxide (CO) emissions from off-highway diesels are relatively minor. Large off-highway diesel equipment includes agricultural equipment (such as tractors), construction equipment (such as backhoes and bulldozers), and material handling equipment (such as forklifts), and utility equipment (such as engine-driven generators and engine-driven pumps). Within the off-highway sector, large diesels contribute significantly to NO_X and PM emissions. Excluding trains, large diesels contribute 66% of NO_X emissions and 70% of PM emissions (see Figures 1.2 and 1.3).

Recognizing the significance of off-highway emissions, and recognizing the unique characteristics of the off-highway sector, the EPA issued in 1994 Tier I emission standards for all off-highway engines greater than 50 horsepower (hp) (37 kilowatts [kW]), except locomotive engines, marine engines, and engines used in underground mining equipment (USEPA 2000). Additional standards were implemented later for off-highway diesel engines less than 50 hp.

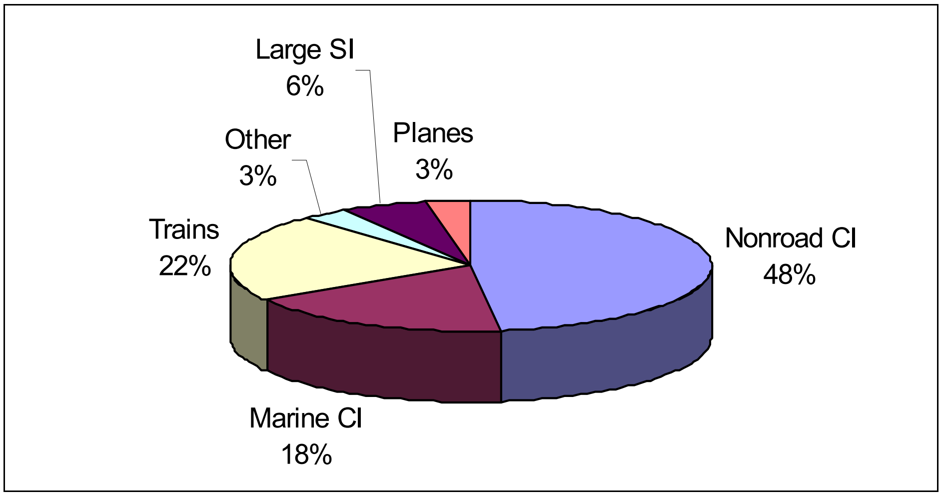

FIGURE 1.2 Non-road NO_x Emissions, Year 2000 Estimates (USEPA 2000)

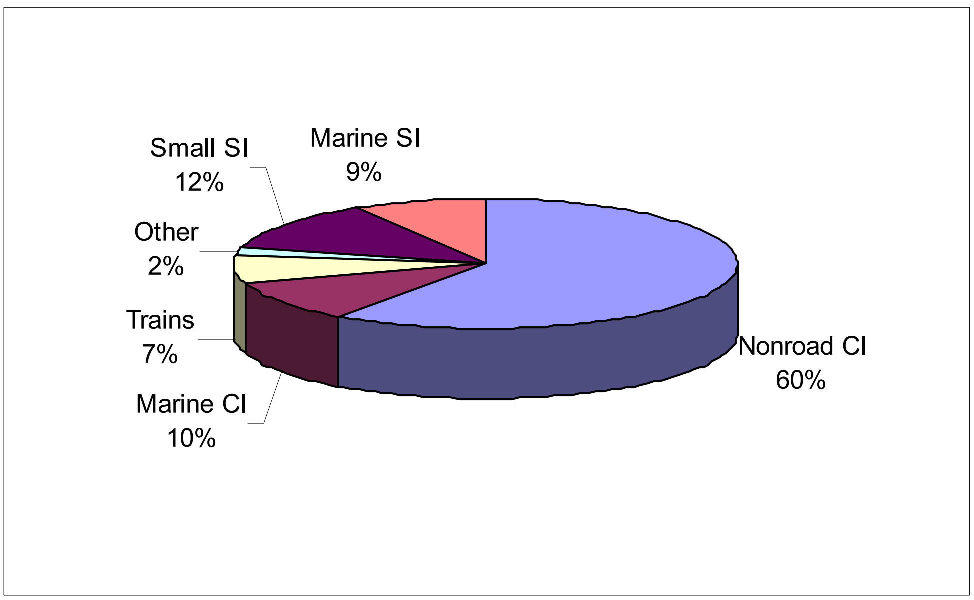

FIGURE 1.3 Non-road PM Emissions, Year 2000 Estimates (USEPA 2000)

Tier 2 emission standards are being phased in from 2001 to 2006, and Tier 3 standards for engines between 50 and 750 hp will be phased in from 2006 to 2008.[13] According to EPA, the Tier 3 standards will reduce off-highway diesel engine emissions by 60% for NO_X and 40% for PM, compared with Tier 1 emission levels. For EPA, a major challenge in regulating non-road engines is the field's lack of vertical integration (USEPA 1998).

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[13] For a summary of emission standards, see Emission Standards Reference Guide for Heavy-Duty and Non-Road Engines at http://www.epa.gov/OMS/cert/hd-cert/stds-eng.pdf.

Recognizing the importance of fuel sulfur effects on aftertreatment, EPA issued in 2001 a final rule for on-highway diesel fuel sulfur requirements to coincide with more stringent heavy-duty engine exhaust emission standards (e.g., 0.20 g NO_X/bhp-h, 0.01 g PM/bhp-h). Refiners and importers must begin producing or importing 15 ppm sulfur maximum diesel beginning June 1, 2006. A Temporary Compliance Option allows a refinery to produce 80% of its highway diesel fuel as 15 ppm S and 20% as 500 ppm S. Beginning January 1, 2010, all highway diesel must meet the 15-ppm S standard. The EPA did not change diesel fuel standards for Tier 3 (up to 5,000-ppm sulfur), but it is expected to propose ultra-low sulfur diesel for Tier 4. Note that any regulation that affects one distillate product will have an impact on the other two.

Emissions from the combustion of all petroleum-based fuels have the potential to adversely impact human health and the global climate. Further study is clearly necessary to determine any potential health effects associated with (1) current and future fuels and (2) engine and aftertreatment technologies. R&D efforts are also needed in these areas to minimize the potential for climate change.

1.4 DEPARTMENT OF ENERGY VISION, MISSION, AND GOALS

The U.S. Department of Energy's Office of Transportation Technologies (OTT) vision is within the first decade of the twenty-first century, the United States will turn the corner in the growth of petroleum use for highway transportation (USDOE 2001b).

Consistent with this vision, OTT developed the following goals:

- Develop and work in partnerships with the domestic transportation industry, energy supply industry, and research and development organizations;
- Develop advanced transportation vehicles and alternative fuel vehicles that will reduce oil import requirements, reduce criteria pollutant emissions, and greenhouse gases;
- Promote the commercialization, user acceptance, and achievement of the vision of advanced transportation technologies and alternative fuels; and
- Develop a technology base to enable the transportation industry to sustain a strong competitive position in domestic and world markets.

The Heavy Vehicle Technology Program (OHVT), within OTT, conducts R&D to reduce energy consumption of heavy vehicles while meeting emission standards in a cost-effective way, thereby improving energy security, and enhancing economic growth (USDOE 2000). While the historical focus of OHVT has been on R&D for heavy trucks, a need to address the off-highway sector was recognized during the Thermal Management of Heavy Vehicles Workshop in 1999 (Stodolsky 1999). Current OHVT programs focus on heavy vehicle engines and vehicle systems and do not include off-highway equipment because of their unique operating conditions and industry structure. OHVT R&D on heavy-duty diesel engines (at or above 75 kW), vehicle systems, and fuels could be leveraged to address the needs of this sector.

1.5 REFERENCES

ANL: Argonne National Laboratory

ANL, 2001, "Leveraging R&D Resources to Meet Industry Needs," Proceedings of the Society of Automotive Engineers-U.S. Department of Energy Off-Highway Emissions and System Efficiency Workshop for Heavy Vehicles, held at Argonne National Laboratory, April 18–19, 2001, Argonne, Ill. (CD proceedings).

Burdette, S., 2001, personal communication with Steven Burdette, Manager, Product Safety and Regulation, Case New Holland, at the Society of Automotive Engineers-U.S. Department of Energy Off-Highway Emissions and System Efficiency Workshop for Heavy Vehicles: Leveraging R&D Resources to Meet Industry Needs, held at Argonne National Laboratory, April 18–19, 2001, Argonne, Ill.

Block, M.C., 1998, "The Future of the Diesel Engine in the 21st Century," presented at the 50th Anniversary Ceremony of Land Engine Manufacturers Association (LEMA), Tokyo, Japan, http://www.engine-manufacturers.org/press/21st-21.cfm, October 15.

EIA: Energy Information Administration

EIA, 2001, "Fuel Oil and Kerosene Sales 2000," DOE/EIA-0535(00) [URL http://www.eia.doe.gov/oil_gas/petroleum/data_publications/fuel_oil_and_kerosene_sales/foks.html (as of December 1, 2001)], Sept.

Saricks, C., et al., 1999, *Future Restrictions on Diesel Fuel Combustion in California: Energy and Emissions Implications of Four Scenarios,* ANL/ESD/TM-157, Argonne National Laboratory, Argonne, Ill., Sept.

Stodolsky, F., 1999, *Energy and Emissions Impacts of Heavy Vehicles*, invited presentation at the Thermal Management of Heavy Vehicles Workshop, Argonne, Ill., Oct.

USDOE: U.S. Department of Energy

USDOE, 2001a, "Transportation Energy Data Book, Edition 21," ORNL-6966, Oak Ridge National Laboratory, Sept.

USDOE, 2001b, "Strategic Plan" [URL http://www.ott.doe.gov/strategic.shtml (as of December 1, 2001)].

USDOE, 2000, OHVT *Technology Roadmap*, DOE/OSTI-11690/R1, U.S. Department of Energy, Washington, D.C., Feb.

USEPA: U.S. Environmental Protection Agency

USEPA, 2000, *Program Update: Reducing Air Pollution from Nonroad Engines*, EPA420-F-00-048, U.S. Environmental Protection Agency, Air and Radiation, Office of Transportation and Air Quality, Nov.

USEPA, 1998, *Final Regulatory Impact Analysis: Control of Emissions from Nonroad Diesel Engines,* EPA420-R-98-016, U.S. Environmental Protection Agency, Air and Radiation, Office of Transportation and Air Quality, Aug.

2 TECHNICAL PLAN

2.1 OVERVIEW

2.1.1 Roadmap Organization

The organization of the technical plan is based on consensus among participants of the Off-Highway Emissions and System Efficiency Workshop for Heavy Vehicles, which was held at Argonne National Laboratory in April 2001 (ANL 2001). The roadmap is divided into three major categories: (1) engines, aftertreatment, fuels, and lubricants; (2) machine systems; and (3) thermal management. Although these categories were selected for ease of discussion, they are interrelated. So, the impacts from technological advances in any one area cannot be considered in isolation. Therefore, it is important that the total system be considered when assessing the impact of technology, as described below.

2.1.2 Technology Planning Process

A structured analytical process is necessary to properly plan and implement a complex R&D undertaking. The Partnership of a New Generation of Vehicles (PNGV) program for passenger cars recognizes the importance of planning. On the basis of recommendations by the National Research Council, PNGV has implemented a comprehensive analytical process to help guide its R&D program (National Research Council 1999).

A comprehensive analytical process contains five major steps:

1. Identify goals, objectives, milestones, and responsibilities;

2. Analyze scope, technical measures, and necessary resources;

3. Plan tasks, schedule, and available resources;

4. Implement program, focusing on milestones; and

5. Evaluate progress in peer-review process (Hardy 2001).

Systems analysis (in the second step of the planning process) is the comprehensive, integrated modeling and assessment of the vehicle platform and its components with respect to program objectives and performance requirements to help guide the R&D agenda.[14] Systems analysis helps technology decision-makers focus on the best technology options by enabling an objective evaluation of cost, benefit, and risk. Systems analysis is critical to the successful and

[14] See discussion of machine system simulation in Section 2.5.7.

orderly implementation of the Off-Highway R&D program. Using vehicle and component models, competing technologies and vehicle concepts are compared against vehicle performance requirements and the goals of the program. System analysis also provides focus and guidance to ensure that the different component technologies developed will be designed in a common vehicle system perspective and not only in a single component perspective. To ensure the maximum technology advancement payoff, the system analysis activities will include coordination and cooperation with industry, other federal agencies, and national laboratories. While models have been developed to assess on-highway engine and equipment performance,[15] they need to be modified to address specific off-highway needs.

2.1.3 Summary of Goals and Subgoals

The combined goal of the initiative is:[16]

- By 2006, meet Tier 3 emission standards while maintaining Tier 2 fuel economy; [17]
- By 2010, meet Tier 4 emission standards while improving engine fuel economy by 5% compared to Tier 2 fuel economy;
- Reduce fuel required by the machine by 21%, through load reduction, resulting in a combined engine/machine fuel reduction of 25%; and
- Maintain performance and enhance product safety, while reducing overall initial and operating costs.[18]

Each section in the following technical plan contains targets for component efficiency improvement that are based on preliminary analysis and judgment. These preliminary estimates were necessary as a starting point for discussion. Estimates and goals for the efficiency of components will be refined during the structured analytical process described above. In particular, off-highway equipment performance will be assessed under the wide range of duty cycles to identify relevant R&D trajectories. Table 2.1 summarizes the efficiencies and goals of

TABLE 2.1 Component Efficiencies and Goals[a]

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[15] Examples include ADVISOR, developed by the National Renewable Energy Laboratory (NREL 2001), and PSAT and PSAT-PRO, developed by Argonne National Laboratory (ANL 2001).

[16] Subgoals were proposed for each of the three areas: (1) engine/aftertreatment/fuels/lubes, (2) machine systems, and (3) thermal management.

[17] For a summary of emission standards, see Emission Standards Reference Guide for Heavy-Duty and Non-Road Engines at http://www.epa.gov/OMS/cert/hd-cert/stds-eng.pdf.

[18] Relative to 2001 model year products.

Component	Baseline (Tier 2)	2006	2010
	Efficiency[b]/Emissions		
Engine/Aftertreatment And Fuels/Lubes	Fuel efficiency at Tier 2 emission standards[a]	Maintain Tier 2 fuel efficiency, while meeting Tier 3 emission standards	Improve fuel economy by 5% compared with Tier 2 products; meet Tier 4 emission standards; non-petroleum fuel-capable where appropriate.
Machine System			
Powertrain efficiency	--		10–30% reduction in parasitic load
Hydraulic system efficiency	--		20–30% reduction in parasitic load 25% reduction in heat load
Traction, Mobility, and Steering Efficiency	--		20–40% reduction in parasitic load
Implement Loadability and Controllability	--		10–30% reduction in parasitic load
Operator Performance Enhancements	--		5–20% reduction in parasitic load
Adaptive Machine System Performance	--		10–40% reduction in parasitic load
Thermal Management	--		65% increase in cooling capacity[c]

[a] Cycle average will be specified by engine size and application.
[b] Relative to 2001 baseline.
[c] Includes reduction in heat load listed under Machine Systems.

components, and these targets are described in more detail in the following sections. Because machine uses and configurations vary widely, more detailed assessments of potential energy efficiency improvements warrant future study.

Table 2.2 summarizes approximate energy distribution for a moderate-sized articulated wheel-loader machine (Wehage 2001) and forms the basis for the following discussion.

The nature of the energy related to each component listed in Table 2.2 is briefly described below.

Implement: The hydraulic energy expended maneuvering the implements; in this case, the bucket and supporting mechanisms.

Steering: The hydraulic energy expended articulating the front and rear machine units while negotiating a loading cycle.

TABLE 2.2 Energy Distribution, Articulated Wheel-Loader Machine

Component	Units or Percent	Component	Units or Percent
Implement	6	Wheel Slip	1
Steering	1	Alternator, Air	1
		Cleaner, Muffler, A/C	
Fan Heat	2	Engine Cooling	24
Pilot Heat	2	Engine Stack	38
Transmission Pump	2	Physical Work	10
Powertrain	11	Total	100
Brake	2		

Fan Heat: Hydraulic, electric, direct-drive energy expended driving cooling fans.

Pilot Heat: Energy expended continuously driving dedicated pumps.

Transmission Pump: Energy expended supplying hydraulic power to the transmission.

Powertrain: Energy lost in the torque converter, gearing, transmission, and final drive.

Brake: Energy lost due to braking the machine.

Wheel Slip: Energy lost to wheel slippage while engaging work site and maneuvering.

Alternator, Air Cleaner, Muffler, A/C: Energy expended operating other peripheral units.

Engine Cooling: Energy expended/lost cooling the engine.

Engine Stack: Additional engine heat energy radiated by the physical machine.

Physical Work: Energy expended securing and conveying the actual load. This includes the work of engaging and cutting, as well as payload acceleration and lifting.

A range of potential savings — assuming the goals in Table 2.1 are met — was calculated on the basis of this typical machine. The average savings are summarized in Table 2.3. On the basis of a fuel input of 100 units, gross engine output (excluding auxiliaries like pumps, alternator, and fans) ranges from 30 to 46%. Total energy savings from improvements in the machine system are determined by multiplying each value for efficiency improvement by a factor of 2.2, which accounts for a 46% efficient engine, and by 3.3, which accounts for a 30% efficient engine.

TABLE 2.3 Engine and System Energy Savings Goals[19]

Engine System[20]	4.8%
Powertrain	5.8%
Hydraulics	5.3%
Traction, mobility, steering	1.6%
Implement loadability/controllability	2.6%
Operator performance enhancements	2.0%
Adaptive machine system performance	3.9%
Subtotal, System	21.2%
Combined engine/system energy reduction goal[21]	25%

Powertrain efficiency: In the above example, the powertrain consumes 11% of the total energy. We assume this value ranges from 7 to 15% for various machines. A 10–30% reduction would save about 0.7–1.5% on the low end to 2–4.5 % on the high end.

Hydraulic system efficiency: In the above example, implement and braking consumed 8% of the total energy. Assume this value may range from 5 to 11% for various machines. A 20–30% reduction would save about 1–2.2% at the low end to 1.5–3.3% at the high end.

Traction, mobility, and steering efficiency: In the above example, steering and wheel slip consumed 2% of the total energy. Assume this value may range from 1 to 5% of the total energy. The higher percentages are for tracked and skid-steered machines with considerably more slippage loses. A 20–40% reduction would save about 0.2–1% at the low end to 0.4–2% at the high end.

Implement loadability and controllability: In the above example, physical work consumed 10% of the total energy. Assume that this number could range from 6 to 14% for various machines. Of this value, assume one-half is spent in the Implement loadability and controllability aspect, yielding 3–7%. A 10–30% reduction would save about 0.3–0.7% at the low end and 0.9–2.1% at the high end.

Operator performance enhancements: Improvements in this area will most likely impact implement, steering, braking, wheel slip, and physical work. Those five components together constitute 20 units of energy expenditure. Assume that operator performance will impact 20–40% of this, or 4–8 units. On the basis of these estimates, a 5–20% reduction would save about 0.2–0.4% at the low end and 0.8–1.6% at the high end.

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[19] Energy reduction goals based on fuel input.

[20] The effects of system components are based on the averages of assumed values for engine thermal efficiency, component energy use, and component efficiency improvement. Comprehensive systems analysis is needed to further refine these estimates.

[21] From combined (not additive) effects of engine and systems efficiency improvements.

Adaptive machine system performance: Improvements in this area will again most likely impact implement, steering, braking, wheel slip, and physical work, amounting to twenty units of energy expenditure. As in the operator enhancements, assume adaptive machine system enhancement will impact 20–40% of this, or 4–8 units. On the basis of these estimates, a 10–40% reduction would save about 0.4–0.8% at the low end and 1.6–3.2% at the high end.

A summary of the energy savings goals, totaling 25%, is presented in Table 2.3. Note the combined effects of engine and system efficiency improvements are not additive.

2.1.4 References

ANL: Argonne National Laboratory

ANL, 2001a, "Leveraging R&D Resources to Meet Industry Needs," Proceedings of the Society of Automotive Engineers-U.S. Department of Energy Off-Highway Emissions and System Efficiency Workshop for Heavy Vehicles, held at Argonne National Laboratory, April 18–19, 2001, Argonne, Ill. (CD proceedings).

ANL, 2001b, "Hybrid Vehicles" [URL: www.ipd.anl.gov/ttrdc/hydrids/ct3-PSAT.html], Transportation and Technology Center, Argonne National Laboratory.

Hardy, K., 2001, *I-A-PIE Structured Analytical Process*, oral presentation to James J. Eberhardt, U.S. Department of Energy, by Keith Hardy, Argonne National Laboratory, Argonne, Ill., Sept.

NRC: National Research Council

NRC, 1999, *Review of the Research Program of the Partnership for a New Generation of Vehicles: Fifth Report,* National Academy Press, Washington, D.C.

NREL: National Renewable Energy Laboratory

NREL, 2001, "Vehicle Systems Analysis" [www.ctts.nrel.gov/analysis/], Center for Transportation Technologies and Systems, National Renewable Energy Laboratory.

Wehage, R., 2001, personal communication between Roger Wehage, Caterpillar, Inc., and Frank Stodolsky, Argonne National Laboratory, Dec.

2.2 ENGINE TECHNOLOGY

2.2.1 Status of Technology

In terms of fuel efficiency and durability, there is no currently viable substitute for the diesel engine in off-highway vehicles. However, the diesel engine has come under increased scrutiny in terms of emissions of nitrogen oxides (NO_X) and particulate matter (PM). Significant strides have been made in the last decade to clean up emissions from diesel engines used in on-highway vehicles. PM and NO_X emissions from on-highway engines have been reduced by about 90%, compared to pre-control levels.

In anticipation of more stringent Tier 3 off-highway emissions regulations and the probable convergence of off-highway with on-highway emissions levels when Tier 4 standards are enacted, significant technical and cost challenges are expected. One expectation is that a further 90% reduction in emissions will be required to meet the 2007 on-highway and Tier 4 non-road standards. To meet these difficult future regulations, many technical options, which were dismissed in the past because of excessive initial cost, will have to be reconsidered. As a result, the **cost threshold for new technology consideration will rise dramatically.** Without a major collaborative effort, the impact on future fuel economy will be significant.

In addition to a higher cost threshold for technology inclusion, there will be:

- More **flexibility in combustion control** because of further advances in electronic control, fuel injection equipment, and air handling systems;
- Much greater **sensitivity to heat rejection requirements**;
- **Higher-sulfur fuel** for off-highway vehicles than for on-highway;
- A much **harsher operating environment, overall**;
- Duty cycles that are **more transient** than is typical in on-highway operation; and
- Near-, mid-, and longer-term needs for better **combustion simulation** capability with stronger emphasis on off-highway specific characteristics.

As result of the reasons stated above and other factors, the on-highway technology developed thus far (such as high-pressure multi-stage injection, electronic control, combustion chamber improvements, exhaust gas recirculation [EGR], and turbocharging) will only transfer partially to off-highway vehicles.

2.2.2 Goals

Off-highway vehicles must meet all applicable emissions standards. Tier 3 standards will be phased in beginning in 2006. Tier 4 standards are expected to be implemented in the 2010–2012 timeframe. The challenge for off-highway vehicle and engine manufacturers will be to maintain or improve fuel efficiency and yet meet these stringent emissions standards.

2.2.3 Technical Targets and Barriers

Emissions Targets

Engines designed and developed for off-highway applications must meet all future emissions standards.

Fuel Economy Targets

The targets for fuel economy will be set in two phases. In the first phase, as engines are developed to meet the 2006 Tier 3 emissions standards, the objective will be to maintain current fuel economy levels with no losses allowed. In the second phase, engines will be developed to meet 2010 Tier 4 emissions standards, while improving fuel economy by an aggressive 5%.

Barriers

- To meet visibility and functional objectives in the unique applications for off-highway vehicles (agriculture, mining, construction, etc.), engine and engine compartment packaging are extremely important. These size constraints will make it difficult to add new underhood components like EGR plumbing, EGR coolers, and aftertreatment devices.

- Unlike on-highway trucks, most off-highway vehicles run at very low vehicle speeds. As a result, off-highway vehicles must operate without the benefit of ram air. This lack of ram air will make the incorporation of cooled EGR or other systems that lead to increased heat rejection in these applications even more of a challenge.

- Off-highway vehicles must function in an extremely harsh operating environment. These vehicles are exposed to high levels of dust and debris, which are difficult for filtration and cooling systems to handle. Because of the absence of ram air, poor cooling, and extreme ambient conditions, off-highway engines run at very high temperatures. Off-highway vehicles also endure very high vibration and shock levels. Combined, these environmental factors make the reliable implementation of new technology very difficult.

- Off-highway vehicles come in all shapes and sizes. They also perform a myriad of functions in a broad range of applications. As result, off-highway engines operate under numerous and varied duty cycles. Developing engines and engine emission-control technologies to function satisfactorily and with high fuel efficiency will be extremely difficult across such an extensive variety of applications.

- System cost constraints are a barrier. If new vehicles are too expensive, operators will keep their older machines longer, thereby adversely affecting the environment.

- Off-highway vehicles perform a whole host of functions, operate under many varied duty cycles, and are equipped with a large number of tools and implements. As a result, off-highway machines are subject to significant parasitic losses. These losses are a major obstacle to improving overall vehicle fuel efficiency.

- Off-highway fuels contain a much higher concentration of sulfur than on-highway fuels (see Section 2.4 for details). When EGR is applied, this sulfur can lead to acidic condensates in the engine's intake tract and exhaust system. Intake air chemistry (NaCl aerosols, OH radicals associated with marine applications, dust, particulate matter associated with mining, farming, and similar applications) also affect engine durability. A better understanding of the corrosion and wear mechanisms related to these issues is required. Use of non-EGR-based technology, internal EGR, or changes in materials of construction may provide solutions, but probably with increased cost in some cases.

2.2.4 General R&D Approach

Engine technology R&D focuses on five major subsystems: Combustion System, EGR System, Fuel System, Air Handling System, and Parasitics/Accessory Loading. Research on these subsystems must focus on the specific needs of the off-highway engine. Each area is detailed below.

Combustion System R&D

Some research approaches that appear to be very attractive for off-highway applications and that are suitable for collaboration are described below.

Off-Highway Applicable Combustion Simulation and Modeling. Research should address the greater degree of transient operation and the wider variance of ambient air chemistry (as in mining, agriculture, and construction). There also is a need to link steady-state and transient engine behavior and simulate cycle details. A better understanding of the impact of combustion transients on in-cylinder chemistry and aftertreatment is critical, as is defining options to control or manage those transients.

Transient Response. From a combustion perspective, the capability to optimize the controllable combustion parameters, such as the air composition (oxygen/nitrogen mix) on a cycle-by-cycle basis, should be developed. One way to vary air composition is through the use of membranes. Additional research to make more efficient and durable membranes is required. Advanced turbocharging technology (such as electrical assistance) also could be studied as a method of reducing in-cylinder emissions during transients.

NO_X and PM Reduction through Better Combustion. New combustion systems — like Homogeneous Charge Compression Ignition (HCCI) — have shown the ability to drastically reduce emissions. Off-highway specific investigation into HCCI and part-mode HCCI, which are also approaches for on-highway vehicles, is important because the NO_X, PM, and brake-specific fuel consumption (bsfc) trade-offs are much different for off-highway engines than for on-highway engines. Other new engine concepts with the potential to provide a better fundamental platform for improved combustion in off-highway applications — like the free piston engine for HCCI used with a hydraulic hybrid drivetrain — also should be studied.

Fuel Efficiency and Sensitivity to Heat Rejection. Low heat rejection (LHR) engine and materials technology should be studied. This work can build directly on leveraged work with the DOE that was conducted in the 1980s and 1990s. Turbocompounding, especially electric turbocompounding, is very effective with lower heat rejection (to the water jacket) engines and is described in more detail below. Research should concentrate on optimization of valving and porting for lower heat rejection (i.e., more quiescent for lower in-cylinder heat-transfer coefficient) and better compatibility with turbocompounding.

Intake System Improvements. Nitrogen enrichment of intake air has been investigated as a “clean” EGR. It provides the diluent effect of EGR without the acid attack on engine internals. This topic deserves additional study because it might prove to be a critical enabler for off-highway engine emissions reduction. Charge air temperature has an important effect on cylinder temperature and in-cylinder NO_X formation. Research into providing more energy-efficient intake air-cooling would be beneficial.

General Approach. The technologies listed above should be studied to develop a fundamental understanding of their advantages and disadvantages. This effort would involve analysis, design, bench development, and engine tests. With a better understanding, accurate models can be developed to evaluate and exploit their interactions with the rest of the system. After the efforts in modeling, the most favorable combustion system can be down-selected. This optimum engine combustion system should then be built, tested, developed, and demonstrated. Additionally, the current OHVT-industry collaborative work involving the study of combustion chemical kinetics and experimental validation could be directed to include off-highway specific needs.

Exhaust Gas Recirculation System

The addition of EGR to on-highway heavy-duty engines is one of the major enablers for meeting the 2002/2004 emissions standards. Likewise, EGR systems will play a vital role in allowing off-highway engines to meet future standards without an excessive penalty in fuel consumption. However, off-highway applications pose some unique challenges for the implementation of EGR.

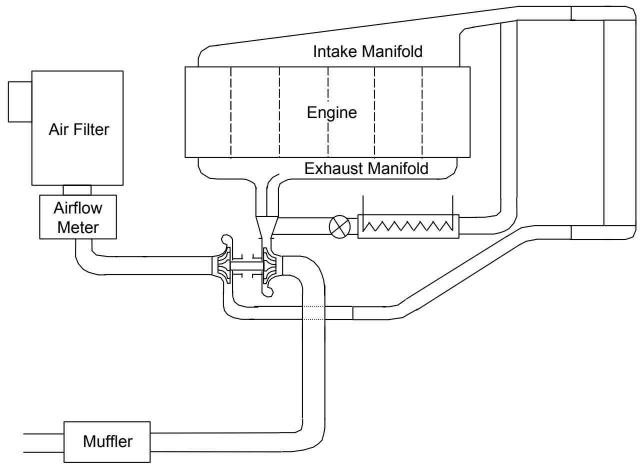
As mentioned above, off-highway vehicles operate without ram air for cooling. The lack of ram air places a very large burden on the cooling system, and the addition of another heat-rejecting system — like EGR — may be impossible. Off-highway vehicles are extremely packaging constrained. The addition of EGR system components, even ignoring the need for another heat exchanger, challenges the vehicle designer's ability to find space. Finally, the use of EGR with current high-sulfur fuels increases the risk of corrosion of engine components. Despite these challenges, the benefits of EGR justify its use and indicate the need for research to enable its expanded application. EGR also increases the amount of soot and combustion by-products that become entrained in the engine lubricant, thereby degrading its ability to protect the engine.

Clean Low-Pressure-Loop EGR. Cooled EGR is one of the prime technologies that is being applied to meet the 2002/2004 heavy- duty on-highway emission standards. The recirculated residual (or inert) gas can be provided from either a high-pressure loop or a low-pressure loop (see Figure 2.2-1). Clean low pressure Loop (CLP) EGR is a version of the low-pressure system, where the EGR source is taken from the "clean" exhaust downstream of a diesel particle filter (DPF). Initial studies have shown that CLP EGR may provide lower fuel consumption than high-pressure systems and yet still meet the NO_X standard. There also may be a greater ability to tailor EGR rates to meet different engine operating conditions with CLP compared with high-pressure systems.

Clean low-pressure-loop EGR should be investigated to determine the fuel consumption potential of this technology compared with high-pressure-loop systems. Additional research should concentrate on minimizing and quantifying the heat rejection of these EGR systems to determine the impact on vehicle cooling systems.

Advanced Internal EGR Systems. External EGR systems require significant packaging space in the tightly constrained engine compartment of off-highway vehicles. Besides consuming valuable space, the addition of an EGR Cooler increases heat rejection and places an extra demand on the vehicle cooling system. In contrast, internal EGR systems can avoid the need for an EGR cooler. There is no external plumbing to occupy space, and EGR system control can be simpler. Some studies have shown that internal EGR is more efficient than external EGR, allowing a greater reduction in NO_X before adversely affecting fuel consumption and PM emissions. Internal EGR also may reduce the sensitivity of the engine to the corrosiveness of acidic exhaust condensate arising from high concentrations of sulfur in the fuel.

High Pressure Loop



Clean Low Pressure Loop

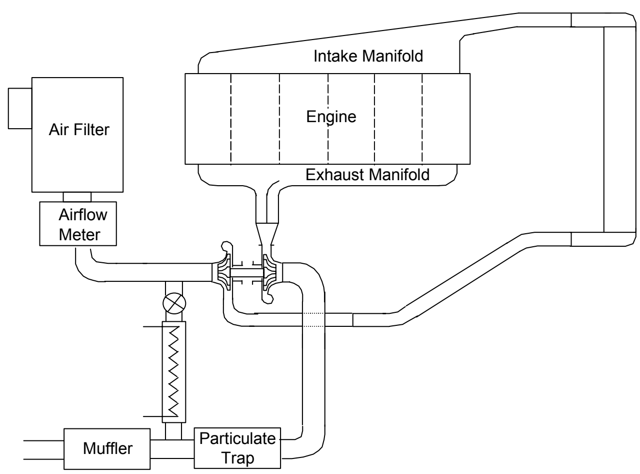


FIGURE 2.2-1 EGR System Configurations

Internal EGR systems range from simple to complex. In the simplest embodiment, residual gas in the cylinder is increased through the addition of a smaller fixed cam lobe to the camshaft. For example, an extra lobe on the exhaust cam allows exhaust “rebreathing” during the intake stroke (Figure 2.2-2).

More complex variable systems may use cam phasers or variable lift systems in conjunction with the additional cam lobe described above to tailor the amount of EGR for different engine operating conditions. In the most complex and flexible internal EGR system, full variable control of valve lift, timing, and duration can be provided through the use of special electromagnetic, hydraulic, or pneumatic valve actuators in place of camshafts.

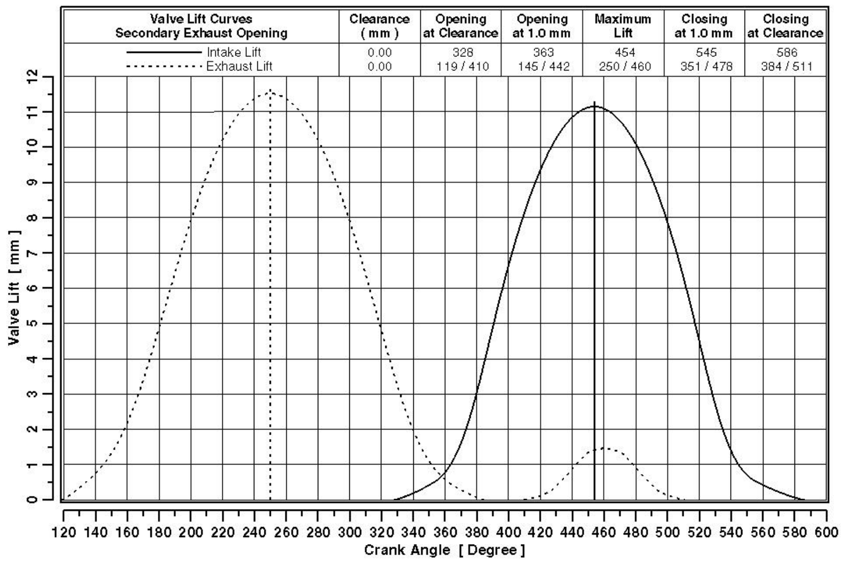


FIGURE 2.2-2 Simple Internal EGR (Additional Exhaust Lobe)

EGR system performance, cost, and calibration effort increase with the complexity of the internal EGR system employed. Research should be undertaken to understand and document the cost vs. benefit trade-offs for these systems. The objective would be to minimize the incremental cost of the system and fuel consumed by the engine and yet meet the applicable emissions standards.

Potential Alternatives to EGR. The use of alternative diluents to EGR should be investigated. Water injection has been shown to significantly lower engine-out NO_X emissions. Many past studies have demonstrated that it is feasible to reduce engine-out NO_X by up to 50% with water injection. Recent work at Argonne National Laboratory (ANL) with an oxygenated diesel fuel/ethanol blend (10–15% ethanol) has shown the potential to reduce engine-out PM emissions by up to 60%. However, a recent AAM/AIAM/API letter to RFA highlighted several issues with ethanol-diesel blends, including safety concerns in meeting minimum flashpoint, fuel stability/storage/handling, and engine/vehicle/materials compatibility concerns.[22] Nitrogen enrichment of the intake air by membrane, as mentioned above, also reduces NO_X emissions. The EPA's Nonroad Diesel Emission Standards paper highlighted Caterpillar's Advanced Combustion Emissions Reduction Technology (ACERT) to meet Tier 3 emission standards using existing diesel engine technology. ACERT is described as a combination of proven hardware, including open-loop electronic engine controls, the HEUI fuel injection system, a variable geometry turbocharger, valve event control, and a diesel oxidation catalyst.[23] The evaluation and comparison of these alternatives would be of great value to engine manufacturers.

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[22] *Hart's World Fuels Today*, Nov. 14, 2001.

[23] EPA 420-R-01-052, October 2001.

Fuel System R&D

To meet future requirements, a systems approach must be adopted. It will be necessary to consider the fuel, the combustion system, the aftertreatment system, and the fuel system together as a larger system. For example, aftertreatment devices may require special fuels that may have lower lubricity, which, in turn, will affect the design of the fuel system. Although the fuel system for any vehicle must be designed with the combustion system, the aftertreatment system, and the fuel in mind, fuel systems could be improved in a number of ways that are applicable to almost any fuel or aftertreatment technology.

Spray and Combustion Fundamentals. Because the current design of fuel systems relies heavily on empirical approaches, research should be conducted into the effects of injection rate control, higher injection pressure, and other factors that influence spray and combustion. A systematic investigation of advanced fuel injection systems using multiple injections, variable injection rates (see Figure 2.2-3), smaller orifice size, and higher pressures to optimize the NO_X vs. PM trade-off would contribute a great deal to a fundamental understanding of diesel combustion. This effort should include measurement of effects during transients and steady-state.

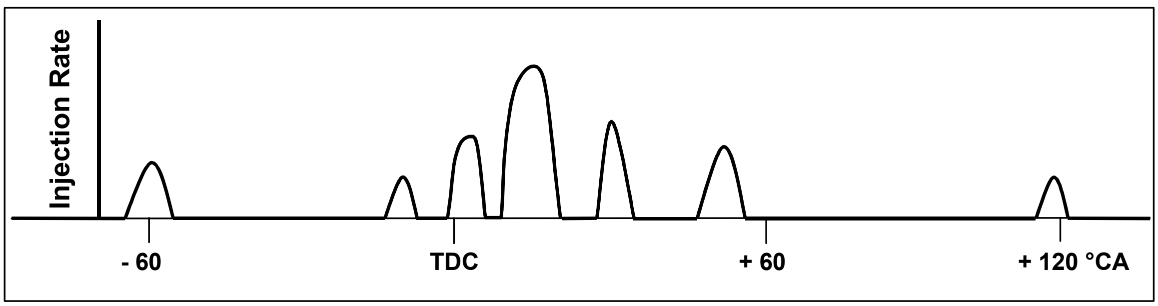

FIGURE 2.2-3 Variable Rate and Multiple Injection Capability

Control Strategies. Besides developing an improved understanding of fuel injection strategies to control in-cylinder emissions, the influence of fuel injection strategies on exhaust gas aftertreatment should be studied as well.

Modeling and Simulation. Currently available models do not provide enough information about the relationships between spray characteristics and combustion characteristics. There also is a general lack of understanding of internal nozzle behavior. Research should be performed to develop improved models of spray, including spray formation in noncircular orifices and multiphase spray. Emphasis should be placed on improved models for fuel atomization, flow inside the injector, and the interaction of fuel spray with combustion. Current methods for incorporation of chemical kinetics into transport codes need significant improvement if PM and NO_X emissions are to be modeled.

Advanced Diagnostics and Instrumentation. The quantities of fuel in pilot, multi-pulse, and post-injections will become smaller and smaller. Along with these reduced fuel quantities will come a demand for closer tolerances on variability. Current measurement techniques are not accurate enough for effective quality control. Techniques for measuring very small quantities of fuel in a single stroke must be developed to measure the performance of new fuel injection systems in support of manufacturing, development, and modeling tasks.

Manufacturing. As fuel injection pressures move higher and the demand for increased uniformity between cylinders grows, machining tolerances of 0.5–5 μm will be required. Current manufacturing technology is not adequate to produce such close tolerances repeatably. A dedicated effort should be undertaken to develop low-cost, very high precision manufacturing processes for producing ultra-small holes. This is an ideal task to be conducted at the national laboratories with their expertise.

Materials. Higher pressures and smaller sizes will place increased demands on the fatigue strength of fuel system materials. There is a trade-off between fatigue strength and machineability of current materials. While fatigue resistance can be improved by generating compressive residual stresses at critical locations, it is currently difficult to predict the level of residual stresses that will be generated by various heat treatments and secondary operations. The use of high-strength materials should be explored in conjunction with the advanced manufacturing techniques mentioned above to miniaturize nozzles. Some of the desired properties include higher fatigue strength; higher stiffness; lower density; and improved resistance to corrosion, particle erosion, and cavitation.

Multiple injections with rate shaping will require extremely rapid actuators. At the same time, actuator movement must be less abrupt to minimize pressure waves and reduce noise. It is clear that solenoid actuators will have to be replaced by piezoelectric actuators, but even the best current piezoelectric actuators are not entirely satisfactory for this application. Additional research into improved piezoelectric performance would be extremely beneficial. Also needed for this initiative are materials that are resistant to fuels with varying levels of lubricity.

Fuels and Tribology. Low-sulfur fuels, which will enable increasingly stringent emissions standards to be met, may have lower lubricity. This reduction in lubricity, in conjunction with higher pressures and temperatures, will place increasing demands on moving surfaces. In addition, smaller and more precise actuators will require minimal wear to maintain performance and accuracy. An effort to study the effects of fuel properties on the durability of injection systems, including wear, corrosion, injector plugging, and deposit formation, should be undertaken.

Alternative Injection Methods and Advanced Design Concepts. Research into lower-pressure injection systems, which achieve satisfactory fuel atomization, based on other technologies (such as electrothermal, electrostatics, or ultrasonics) could result in higher fuel efficiency. Variable orifice geometries and full rate shape control also could be investigated.

Sensors. To operate future engines with closed-loop control systems, low-cost and reliable sensors need to be developed to measure cylinder pressure, injection pressure, needle position, and fuel quality. These sensors also must be robust enough to survive in the harsh operating environment of off-highway vehicles.

Air Handling System R&D

Turbocompounding. As emissions standards have become more stringent, off-highway vehicle manufacturers have resorted predominantly to the turbocharging of diesel engines. Turbocharging not only increases power density, but it provides an improved NO_x vs. PM trade-off. Once turbochargers are included as standard equipment, other opportunities for improvement become possible. One option is turbocompounding.

A conventional turbocharger uses an exhaust-driven turbine to recover waste energy from the exhaust. The turbine drives an inlet air compressor that allows the engine to operate at higher pressure and efficiency. While turbochargers are very effective at recovering waste exhaust energy, there is still a significant amount of exhaust energy that escapes. This problem has led many engine manufacturers to pursue turbocompounding, with some notable examples already in production (Scania Truck). Turbocompounding attempts to recover as much of the remaining waste energy as possible by driving another turbine, which is “compounded” or connected to the engine’s output shaft. There are several options for compounding the second turbine to the output shaft. The most typical method of compounding is mechanical (e.g., reduction gear, clutch, or coupling, etc.). However, other methods are possible — turbine-driven electric generator or hydraulic pump, for example. It is even possible to “stretch” the concept to include only one turbine.

Research should be conducted to investigate the potential of turbocompounding to reduce fuel consumption. Turbocompounding can be accomplished by mechanically linking the secondary power turbine to the crankshaft. The power turbine also could be coupled electrically through a generator to a storage medium (i.e., battery, ultracapacitor, etc.) or hydraulically through a pump to an accumulator to recover waste energy for later use. Each compounding type should be optimized and then evaluated and compared against the objective of minimizing fuel consumption at the lowest possible cost.

Alternatively, the primary power turbine of the turbocharger could be assisted electrically or hydraulically. This option is quite attractive because it offers the additional benefits of improved transient response, torque curve shaping, and elimination of other control elements (such as a waste gate or variable turbine nozzle geometry). The generator can be used as a motor to accelerate the compressor at low engine speeds to improve transient response and torque while reducing emissions. This same feature can be used to shape the torque curve by driving the compressor electrically when there is insufficient exhaust energy. At high engine speeds, when exhaust energy exceeds the amount necessary to drive the compressor, the generator can absorb energy to control turbine speed, thereby eliminating the need for a waste gate or variable geometry turbine. This electrical energy recovered can be stored for later reuse in the vehicle. Research efforts should concentrate on optimizing this concept so that it can be compared with the other compounding methods described above. This should allow engine and vehicle manufacturers to make decisions about the most effective technology for their off-highway applications.

Finally, low-heat-rejection concepts should be reevaluated. Low-heat-rejection engines, which were studied extensively during the 1980s and 1990s, could play a key role in maximizing the benefits to be obtained by turbocompounding. Recent advances in materials and manufacturing technology could allow the realization of the benefits of low-heat-rejection, turbocompounded engines.

Energy-Efficient Intake Air Cooling. Charge air temperature significantly impacts cylinder temperature and in-cylinder NO_x formation. Because of the limited packaging space in off-highway engine compartments and lack of ram air, effective charge air-cooling is extremely difficult. Advanced computational fluid dynamics (CFD) analysis could point the way toward more efficient heat exchanger designs and air handling systems. Development of more energy-efficient intake air-cooling would be beneficial for reducing emissions and fuel consumption in off-highway vehicles.

Parasitics and Accessory Loading

In this section, engine mechanical friction and accessory load reduction are discussed.

Mechanical Friction. In a typical modern diesel engine, the mechanical friction breaks down as follows:

- Camshaft and Fuel Injectors 10%
- Connecting Rod and Cranktrain 35%
- Pistons and Rings 55%

In each of these three areas, improved fundamental understanding of tribology, better simulation tools, new coating materials, and advancements in lubricants are the means to reduce friction and improve wear life. Progress to improve these complex tribological systems has been slow because it requires a broad-based and capital-intensive effort. With future fuels and lubricants expected to have much lower lubricity because of much lower sulfur content, these systems will need significant improvement just to maintain their current share of engine losses. Collaborative efforts could be especially effective in developing key enabling technologies, particularly in the areas of advanced materials and lubricant chemistry.

Accessory Loading. Accessory loading includes, for example, all of the engine-driven pumps, the alternator, fans, and the air conditioning compressor. These accessories currently are driven by belts or gears and are mounted on the engine. Cooling system fans for off-highway machines consume significant fractions of the engine power. Parasitic loads range from 10 to 20% of the total power output. Projections for off-highway vehicles meeting Tier 3 emissions standards place the share of cooling fan power at even higher levels. Electrically driving these accessories with motors combined with a starter motor/generator, energy storage system (batteries, ultracapacitor, etc.), and a sophisticated control system can save significant energy. Each accessory can be managed with a power-on-demand strategy instead of having to be designed for the worst condition and allowed to waste energy at most operating conditions. This approach also enables other opportunities, such as the relocation of the air conditioning compressor outside of the hot engine compartment, which provides additional savings and packaging flexibility.

2.3 AFTERTREATMENT TECHNOLOGY

2.3.1 Status of Technology

Off-highway engine-out emission levels will require effective and durable aftertreatment technology in order to meet future emission standards. Of most concern are the emissions of particulate matter (PM) and oxides of nitrogen (NO_x).

Particulate Matter Emission Controls. Diesel PM control technologies have advanced significantly in recent years — to the point of limited commercial application. Catalyst-based diesel particulate filters (DPFs), used on engines operated on low-sulfur diesel fuel, can achieve PM reductions of over 90%. When ultra-low-sulfur fuel (<10 ppm) is used, the PM collection efficiencies of the DPF often exceed 95%. Two types of DPF technologies have undergone limited field trials for both on and off-highway vehicles: continuously regenerating diesel particulate filters (CR-DPF) and catalytic diesel particulate filters (CDPFs). In each of these systems, PM is removed from the exhaust stream by collecting it on a ceramic wall-flow filter element followed by oxidation of the collected PM.

The CR-DPF technology, often referred to as Continuously Regenerating Technology (CRT™), regenerates by converting exhaust nitric oxide (NO) to nitrogen dioxide (NO_2) using an oxidation catalyst placed upstream of a DPF. If the exhaust temperature is greater than 300°C, the NO_2 oxidizes the trapped PM to complete the regeneration. Sulfur present in the exhaust as sulfur dioxide (SO_2), however, can be oxidized to sulfite (SO_3) over the CR-DPF. During dilution and cooling, the SO_3 converts to sulfuric acid (H_2SO_4), which is measured as PM emissions. Sulfur oxides also interfere with the formation of NO_2 by competing for active catalyst sites, making it more difficult to regenerate the device.

The second DPF technology, CDPFs, has a catalyst coating on the DPF washcoat and uses the available oxygen to promote oxidation of the trapped PM. As with the CR-DPF, sulfur in the exhaust is oxidized to form sulfate PM, which contributes to the overall PM emissions. Different catalyst formulations can be used to minimize the amount of sulfate formed, but these formulations have higher regeneration temperatures.

The performance of these technologies depends on the exhaust-gas temperature and the fuel-sulfur level. Poor or no regeneration can occur at low exhaust temperatures, leaving the filter susceptible to plugging if the fuel quality is poor or if there are long periods of low exhaust temperatures.

Both CR-DPFs and CDPFs are presently undergoing field trials for on-highway applications. These systems have demonstrated acceptable durability: they achieve excellent PM removal rates over 600,000 km of engine operation, while using fuel containing up to 50 ppm sulfur.

NO_X Emissions Control. The NO_X control aftertreatment technologies most often considered are lean-NO_X catalysts, NO_X adsorber catalysts, non-thermal plasma (NTP) systems, and selective catalytic reduction (SCR) systems. All four are at a less-mature stage of development than the PM filters. The NO_X adsorbers, NTP, and urea SCR systems appear to have the greatest potential to reduce NO_X emissions to the regulated levels, although all face development challenges. NO_X adsorber catalyst technologies are highly susceptible to sulfur poisoning, even at very low levels of sulfur in the exhaust. Also, because NO_X adsorber catalysts depend on periodic rich operation to purge and reduce stored NO_X, new engine control systems also need to be developed. Urea SCR systems are more sulfur tolerant, but the implementation of a urea SCR system will require a urea supply and delivery infrastructure that currently does not exist. The NTP system is also sulfur-tolerant, but the power requirements are substantial.

The performance of all NO_X control systems depends on exhaust temperature. Their effectiveness declines dramatically at temperatures below approximately 250°C. This presents a problem at low load and during idling, when exhaust temperatures could drop to 150°C or lower. A major development focus is to design effective aftertreatment for the exhaust conditions of non-road engines because of the wide range of load conditions for non-road equipment, which offers cycles that vary between full load and low load/idle conditions.

The performance of integrated PM/NO_X systems is not well documented over a wide range of operating conditions. This lack of knowledge is currently being addressed by a number of U.S. Department of Energy (DOE) -sponsored investigations, and additional modeling efforts are underway to further elucidate the behavior and effectiveness of PM/NO_X systems. These models may be useful in guiding the development and integration of PM/NO_X combined aftertreatment systems.

2.3.2 Goals

The overall goal of our efforts is to develop an aftertreatment system for off-highway use that will enable the vehicle to meet future emissions standards (in particular, for PM and NO_X) with minimal fuel economy penalties. Because the off-highway applications are varied (and often unique), the system must be durable against impact and vibrational forces, operate over a wide range of fuel properties, and be small in size (i.e., meet visibility requirements) for each specific off-highway application. The system must also be practical and cost effective.

2.3.3 Technical Targets and Barriers

Targets. Many of the targets are yet to be specified, but they generally include the following:

- Meet U.S. Environmental Protection Agency (EPA) certification standards for tailpipe- out emissions,
- Provide durability of over 8,000 operating hours, and
- Allow no compromise of overall fuel economy targets.

Barriers. Many of the barriers associated with the implementation of aftertreatment technologies for off-highway applications have already been identified for on-highway applications. They include the following:

- Intolerance of NO_X adsorber catalysts to fuel sulfur, even at ultra-low sulfur levels (3 ppm to 15 ppm),
- Emissions trade-off between NO_X and PM,
- Unproven durability of aftertreatment systems, especially those related to NO_X control,
- Poor performance of NO_X aftertreatment systems during transient operation,
- Lack of existing infrastructure for urea SCR, and
- Incomplete systems integration and optimization for NO_X and PM control technologies.

In addition to the these barriers, off-highway applications also face the following unique barriers:

- A wider range of fuel types are used for off-highway applications. At present, off-highway fuel sulfur levels are as high as 5,000 ppm.
- Off-highway vehicles have packaging constraints that must be met. Agricultural vehicles and those used in construction must allow the operators to have a wide field of view.
- Off-highway applications employ a wide range of engine sizes, as well as highly varied engine load conditions. With such a wide range of applications, a "one system fits all" approach may not be workable.

- Off-highway engines have a long lifetime and tend to travel relatively short distances. Retrofit programs that target geographic areas with the most severe air quality problems could be a cost-effective approach to improving control of off-highway emissions.

2.3.4 General R&D Approach

Aftertreatment systems are currently being investigated for on-highway platforms. Some of the issues related to off-highway emission controls are already being addressed by the on-highway R&D activities. Meeting the technical targets for off-highway emissions will require a comprehensive R&D plan that complements, but does not duplicate, the efforts already undertaken for on-highway vehicles. Consequently, the aftertreatment R&D approach should focus on those parameters that differ significantly from parameters for on-highway usage. Some of these differences that have already been discussed include the wide variety of duty cycles, increased shock and vibration, and differences in operating temperatures.

Research and development activities involving aftertreatment systems such as oxidation catalysts, NO_X adsorber catalysts, plasma-assisted catalysis, PM traps, and SCR systems are already being addressed for on-highway usage. However, these systems will need to be sized and integrated (and modeled) for off-highway applications and operating environments. The influence of exhaust gas recirculation (EGR) on exhaust emissions will also need to be considered. To aid in efforts to adapt aftertreatment systems to off-highway vehicles, researchers need to accurately assess emissions from off-highway engines. It is reasonable to assume that the levels of PM and NO_X produced by off-highway engines are higher than those from on-highway engines because of the higher sulfur content of the fuels used, the high load operation, and the lack of engine controls to minimize PM.

From an aftertreatment perspective, the research areas should target the following primary parameters affecting off-highway applications:

- High concentrations of sulfur in fuel,
- Emissions characterization associated with engine and load cycle,
- Conditions required for NO_X adsorber catalyst and DPF regeneration and the exhaust temperature management strategies needed to achieve these conditions, and
- Mechanical durability studies that consider temperature, duty cycles (including seasonal), shock, and vibrational forces.
- Development of robust retrofit packages for existing off-road engine applications to reduce emissions.

High-Sulfur Fuel. Currently, the sulfur level in off-highway diesel fuels may approach 5,000 ppm. This concentration is considerably higher than concentrations for highway fuel, which are currently below 500 ppm and will be regulated to a 15-ppm cap with phase-in beginning in 2006. The phase-in schedule requires 80% that all fuel used in highway vehicles meet the 15-ppm sulfur specification by September 2006; 100% availability will be required by 2010. The diesel fuel standards for Tier 3 will be the same as those for Tier 2 (up to 5,000 ppm sulfur), but the fuel standards for Tier 4 are expected to be similar to the 2007 on-highway fuel standards (15 ppm sulfur). The Tier 4 standards will be proposed in 2003. However, some off-highway vehicles currently use on-road fuel and that once the 15-ppm fuel is available for on-road vehicles, it would also be available for off-highway engines fitted with aftertreatment equipment. It is important that the fuel sulfur content be properly matched to engine emission control system requirements. Because off-highway engines typically operate in a more limited geographical area than on-road engines, matching of potentially higher levels of fuel sulfur associated with off-highway applications could increase the complexity of using sulfur-sensitive aftertreatment technologies.

Researchers have shown that several aftertreatment technologies — including diesel oxidation catalysts, DPFs, and NO_x adsorber catalysts — are sensitive to sulfur (DESCE 2000). Their performance over time is degraded by sulfur compounds and/or the hydrothermal stability of the catalyst support during regeneration.

Fuel Sulfur and NO_x Adsorbers. In NO_x adsorbers, sulfur oxide (SO) competes with NO_x for the adsorber sites on the catalyst coating. This process is shown in Figure 2.3-1. First, SO_2 gas is converted to SO_3 by reacting with oxygen on the platinum sites. The SO_3 then reacts with the barium oxide (BaO) sites to form the stable compound barium sulfate ($BaSO_4$). Because these metal sulfates are more stable than metal nitrates, the barium sites gradually become saturated with sulfur, which results in a loss of activity toward the adsorption of NO_2. The higher stability of metal sulfates necessitates higher temperatures (and also more time) to regenerate (Bailey 2000). The requirement for more time and higher temperatures is considered to be the major problem in the development of NO_x adsorber systems. Typically, desulfurization requires

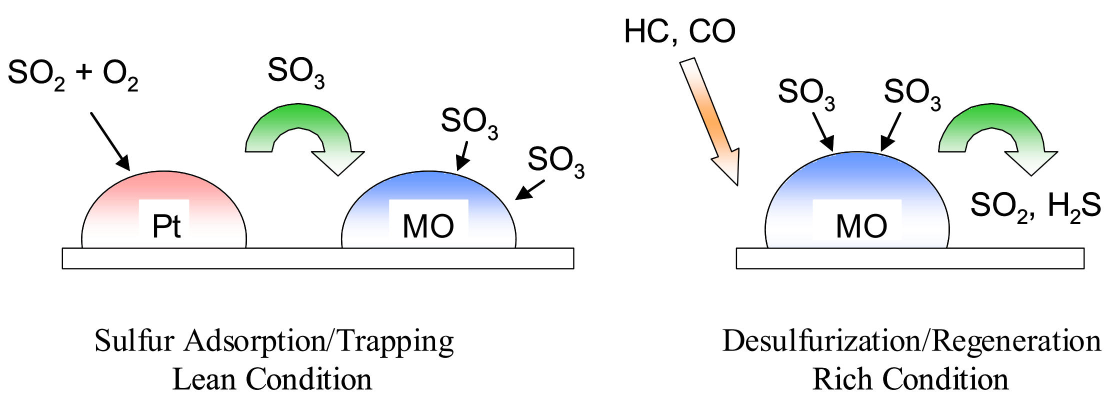

FIGURE 2.3-1 Schematic representation of sulfur poisoning mechanism of NO_x adsorbers

exhaust mixture enrichment, high inlet temperatures (approximately 700°C), and long regeneration times (up to 7 minutes) (DECSE 2000; Bailey 2000). During desulfurization, undesirable species of carbonyl sulfide (COS) and hydrogen sulfide (H_2S) may also be emitted as reductant products. Fuel sulfur levels approaching 1,000 ppm would likely poison an adsorber so quickly that it would not be practical to regenerate effectively. Therefore, this technology should only be considered for moderate-to-low fuel sulfur levels.

High Fuel Sulfur and Particulate Filters. Sulfate particulates exist primarily as H_2SO_4, which is formed by the reaction of water vapor with gaseous SO_3. Because the nucleation of H_2SO_4 (as a liquid aerosol) takes place at relatively low temperatures (<170°C), the sulfate trapping efficiency of a noncatalytic DPF will decrease with increasing temperature (McKinley 1997). Catalytic DPFs will oxidize SO_2 to SO_3, which passes through the filter and is subsequently converted to H_2SO_4 after leaving the DPF. This process may actually increase PM emissions. Therefore, high fuel sulfur would likely increase the formation of sulfate particles downstream of the trap and, subsequently, the overall PM emissions as well. Although several studies have investigated PM emissions from SCR-DPF systems, the emissions chemistry for high-sulfur fuel has not been assessed. This issue should be a priority when examining aftertreatment systems for high-sulfur fuel in off-highway applications.

High Fuel Sulfur and Sulfate-Induced Corrosion. Another potential concern with the high sulfur levels in fuels (if appropriate materials of construction are not employed) for off-highway vehicles is the increased risk of corrosion caused by higher H_2SO_4 concentrations in the exhaust (and the intake tract on cooled EGR-equipped engines). Studies have shown that SO_3 in the exhaust reacts with moisture to form H_2SO_4 at temperatures below 170°C (McKinley 1997; Kreso 1998). The formation of H_2SO_4 is represented graphically in Figure 2.3-2. A small fraction of the SO_2 in the exhaust is rapidly oxidized into SO_3. The SO_3 in turn reacts with the exhaust water vapor to form H_2SO_4, which condenses at temperatures below 170°C. Therefore, during idle operation and immediately following engine shutoff, the aftertreatment systems may

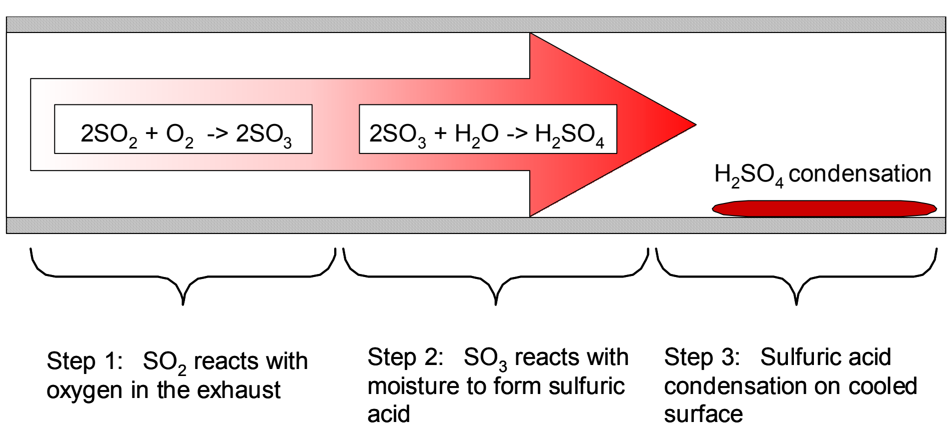

FIGURE 2.3-2 Mechanism for sulfuric acid formation in diesel exhaust

be subjected to sulfuric acid attack. The corrosion risk for aftertreatment devices (especially SCR and DPF systems) associated with H_2SO_4 attack is unknown and would need to be determined for off-highway applications employing high-sulfur fuel.

In the longer term, it is reasonable to expect that 15-ppm sulfur fuels may eventually be mandated or widely available for off-highway usage. In the short term, however, we need to consider the possibility of higher fuel sulfur levels and the technologies that are applicable for use with the high sulfur levels. High near-term sulfur levels will also mean an emphasis on SCR systems. In the longer term, it is reasonable to expect that 15-ppm sulfur fuels will be mandated for off-highway usage. A research program should be undertaken to develop compact, durable, and efficient urea SCR catalysts for off-highway applications. These catalysts should be packaged for use in tightly constrained off-highway machines and should function effectively over all possible operating conditions. If off-highway fuel sulfur levels eventually converge with on-highway levels, NO^x adsorber catalyst technology will need to be included in the research plan.Several research approaches address the high fuel sulfur usage for off-highway applications; those that are suitable for collaboration include, but are not limited to, the following.

Continued Improvement of Sulfur Traps. Sulfur trap systems have shown effectiveness in reducing sulfate (SO_2 and SO_3) emissions. Development of highly effective sulfur traps is needed to enable the use of such aftertreatment technologies as NO_x adsorbers and DPFs. However, the integration of a physically separate sulfur trap upstream of an adsorber will necessitate a bypass or counter flow system to prevent additional poisoning of the NO_x adsorber during regeneration of the sulfur trap. For fuel sulfur levels approaching 5,000 ppm, the concentrations of sulfur oxides in the exhaust will likely be too great for a trap to handle effectively; therefore, this technology should only be pursued for vehicles that employ moderate- to low- (below 500 ppm) sulfur fuels. Further research should be directed toward development of integrated sulfur trap/NO_x adsorber systems, including new materials and materials systems.

Desulfation Strategies for NO_x Adsorbers. A NO_x adsorber desulfation strategy was developed and demonstrated as part of the DECSE program. Because the sulfates of NO_x adsorber compounds are more stable than their nitrates, much higher temperatures (around 650°C), long regeneration times, and mixture enrichment are required to desulfurize a NO_x adsorber. Current desulfation strategies involve increasing the exhaust temperature via post injection and close-coupled catalysts. These strategies need to be further developed in order to operate effectively (maintain desulfation temperature) throughout the operating regime of the engine while minimizing the fuel penalty. Other new concepts with the potential to improve desulfation — such as microwave-induced desulfation — also need to be explored. For applications in which the concentration of fuel sulfur is high, it is important to develop systems that are sulfur intolerant or allow continuous regeneration.

Influence of Sulfur Emissions on SCR Systems. The performance of SCR systems exposed to high sulfur emissions needs to be elucidated. Although SCR systems are somewhat intolerant to sulfur for current on-highway fuel levels (approximately 350 ppm), their performance under high fuel sulfur loadings needs to be determined.

Non-Thermal-Plasma System for NO_x Control. The current research on NTP systems has been with less than 500-ppm S fuel. The effect of high-sulfur fuel on NTP systems needs to be determined, as do the performance and durability requirements.

Desulfation/Trap Simulation and Modeling. The performance of sulfur traps, desulfation, and SCR devices needs to be accurately assessed and modeled to understand how these systems influence the performance of other aftertreatment devices, especially DPFs. A better understanding of sulfur-related transients on aftertreatment is important, especially when considering emission management over the load cycle.

Sulfuric Acid-Induced Degradation. When the engine is idling or turned off following a load cycle, there is a potential for H_2SO_4 to form in the aftertreatment devices if the temperature is allowed to drop below 170°C. (This effect is similar to what is expected to happen with cooled EGR.) Sulfuric acid is highly corrosive and has the potential to rapidly degrade these systems. Studies need to be undertaken to assess the potential for H_2SO_4 to form and to degrade the aftertreatment device. Of particular interest is the corrosion risk of SCR systems and DPFs because these devices are more likely to be used for high fuel sulfur applications.

Sulfur (SO_x) Sensors. The development of sulfur traps may necessitate the development of SO_x sensors to determine when sulfur loading of the traps is optimized. A highly sensitive and fast SO_x sensor would be needed to determine the optimum point for trap regeneration.

Regeneration and Exhaust Thermal Management. The major challenge for exhaust aftertreatment systems is that they must be operated in a narrow temperature window in order to be effective. The DPFs need to be operated above a certain temperature to ensure regeneration, and the NO_x aftertreatment technology has both a low and a high temperature requirement. A typical regeneration strategy for a NO_x adsorber is described in West et al. for a transient FTP. The extent and period of regeneration are highly dependent on the engine operating conditions.

Another problem with off-highway equipment is that there are thousands of different applications for the engines and, consequently, the exhaust temperatures vary widely depending on how the engine is used. It is necessary to investigate ways to control or manage the exhaust temperature so that the exhaust aftertreatment is always operated in the optimum temperature range. The thermal management methods developed must apply to small, as well as large, engines. Research efforts should concentrate on the following areas.

Mapping of Conditions to Regenerate NO_x Adsorbers and Particulate Traps. The thermal profile of the engine-out exhaust needs to be determined in order to assess the thermal requirements for regeneration under a particular operating condition for both adsorbers and particulate traps. New engine control strategies should be developed to provide the conditions needed for trap regeneration at every operating point. For those engine operating conditions under which regeneration is not possible, researchers need to investigate and develop robust, active regeneration systems (burners, electric heaters, exhaust coolers, etc.) to ensure regeneration under any condition that is likely to be experienced by off-highway vehicles. The development of coupled sensor/control systems capable of monitoring engine history, as well as instantaneous exhaust gas concentrations, could be used to optimize real-time aftertreatment response.

Durability. The off-highway durability requirement for the emission control technology is 8,000 hours. Off-highway equipment is typically operated seasonally, placing additional demands on the aftertreatment system. Test methods must be developed to evaluate the emission control technology to meet these severe requirements. Finally, the shock and vibrational forces that are associated with off-highway operation are considerably higher than those for on-highway applications, and these forces need to be identified and quantified. A research program should be conducted to develop aftertreatment system aging protocols. The test procedures developed should then be used to develop and validate aftertreatment systems with sufficient durability for off-highway use.

2.4 FUEL AND LUBRICANT TECHNOLOGY

2.4.1 Status of Technology

Distillate Market Production and End Use. The continued growth of the on- and off-highway vehicle industry has led to steady increases in diesel fuel usage in the United States. The Energy Information Administration (EIA) projects that the demand for distillate will increase from 3.5 million barrels per day (MMBD) (in 1999) to 3.8 MMBD by 2007. The distillate market generally includes on-highway diesel (maximum of 500 ppm sulfur [S]), off-highway diesel (maximum of 5,000 ppm S), and home heating oil (maximum of 5,000 ppm S). Approximately two-thirds of the U.S. distillate produced contains ≤500 ppm S, which is required for on-highway diesel use (Figure 2.4-1). In 1999, slightly more than half of distillate fuel sales were for on-highway use (56%), with the balance used in home heating oil, commercial, farm, railroad, off-highway, marine, and industrial applications (Figure 2.4-2) (EIA 2001a). The refining production capacity of ≤500-ppm-S distillate exceeds on-highway distillate fuel sales, so some of this material is sold into markets with higher sulfur specifications.

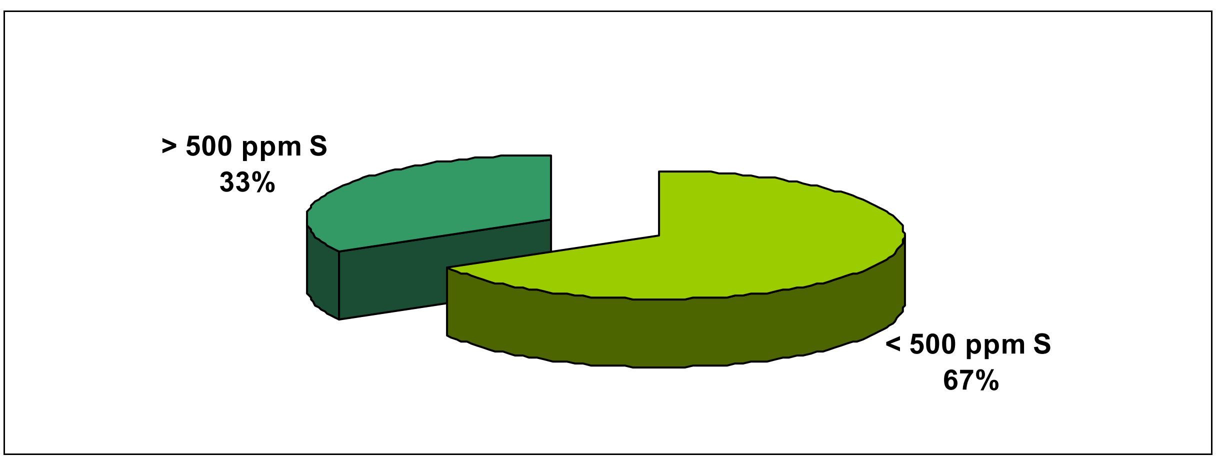

FIGURE 2.4-1 U.S. Distillate Fuel Production by Sulfur Level

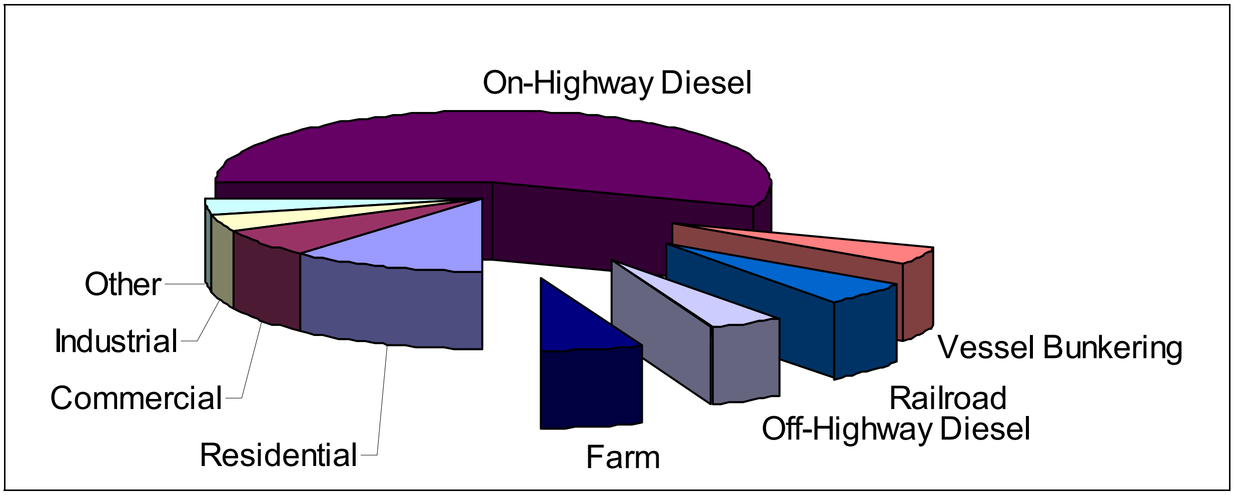

FIGURE 2.4-2 U.S. Distillate Fuel Sales by End Use

Low-Sulfur Diesel Regulatory Scenarios. On January 18, 2001, the U.S. Environmental Protection Agency (EPA) issued a final rule for on-highway diesel fuel sulfur requirements to coincide with more stringent heavy-duty engine exhaust emission standards (e.g., 0.20 g oxides of nitrogen [NO_x]/bhp-h, 0.01 g particulate matter [PM]/bhp-h). Refiners and importers must begin producing or importing 15-ppm S (maximum) diesel beginning June 1, 2006. A Temporary Compliance Option allows a refinery to produce 80% of its highway diesel fuel as 15 ppm S and 20% as 500 ppm S. Beginning January 1, 2010, all highway diesel must meet the 15-ppm S standard. The EPA indicates that there would be no change in the diesel fuel properties for Tier 3 (EPA 2001). The diesel fuel standards will be the same as those for Tier 2 (up to 5,000 ppm sulfur), but the fuel standards for Tier 4 are expected to be similar to the 2007 on-highway fuel standards (15 ppm sulfur). It is possible that in the 2010–2012 timeframe, all distillate markets (except home heating oil) will be 15 ppm sulfur.

Distillate Fuel Impacts on Emissions. Experts expect that advanced aftertreatment systems will be required to meet the exhaust emission standards for 2007 model year on-highway heavy-duty engines. Although many technical hurdles remain, a well-tuned, robust aftertreatment system using ultra-low sulfur diesel (ULSD) offers the potential for dramatic reductions in NO_x and PM.[24] On the other hand, NO_x and PM benefits from other fuel quality changes are small when compared with the potential impact of aftertreatment with ULSD. Changing non-sulfur fuel properties will also increase energy consumption and emissions and may reduce diesel fuel energy content. It is mandatory that advanced heavy-duty vehicles equipped with aftertreatment devices have access to low-sulfur fuels to ensure that the full potential of these technologies is met. However, manufacture of ULSD will increase refinery energy consumption and emissions. Because the initial volume of advanced heavy-duty vehicles will be small, it is important to

[24] "Catalyst-Based Diesel Particulate Filters and NO_x Adsorbers: A Summary of the Technologies and Fuel Sulfur Effects," Manufacturers of Emission Controls Association, Aug. 14, 2000 (available for download at www.meca.org).

consider alternate fuel introduction strategies that match the needed supply of ULSD to the demand so that total emissions are minimized.

Distillate Hydrotreating Technology. Untreated refinery distillate streams typically contain sulfur at concentrations of several thousand ppm. Lighter-boiling distillate streams are generally in the range of 1,500 ppm S; heavier fractions are in excess of 2,000 ppm S. Hydrotreating is the technology of choice to produce low-sulfur distillate fuels. This technology combines hydrogen with the sulfur-containing distillate stream over a hydrotreating catalyst to produce gaseous hydrogen sulfide and a lower-sulfur distillate product. A range of sulfur species is present in distillate. As the overall percent of sulfur removal increases, the hydrotreating process must handle species that are increasingly more difficult to remove. Sulfur species that are bound in aromatic ring structures (e.g., dibenzothiophenes) are the most difficult to remove. These hard-to-remove sulfur species are particularly prevalent in previously converted streams, for example, from coking and fluid catalytic cracking (FCC) process units (approximately 35% of the U.S. distillate pool is from coker and FCC units) (National Petroleum Council 2000). Because even 500 ppm sulfur distillate requires greater than 97% desulfurization to produce a 15-ppm S fuel, more rigorous hydrotreating is needed. As hydrotreating becomes more rigorous, additional non-desirable reactions can occur; for example, the hydrogenation of aromatic molecules. This leads to increased hydrogen consumption and higher refinery-based emissions (National Petroleum Council 2000).

Distillate Supply/Demand and Alternate Introduction Strategy. Each refinery investment decision to produce on- and/or off-highway ULSD will depend on a number of factors, such as feed sulfur content, refinery size, current refinery configuration, and percentage of cracked distillate stocks. Some refineries may opt to install new grass-roots units, revamp existing units, reduce throughput, or exit the on-/off-highway distillate business. Recently, EIA completed a supply/demand assessment of the diesel fuel market driven by the new ULSD requirement. Diesel fuel cost increases were projected to range from 6.5 to 7.8 cents per gallon (cpg) (includes 1.1 cpg distribution costs) based on EPA's assumption of a 5.2% return on investment, after tax (EIA 2001b). This return is generally lower than refining industry or economic community expectations. The EIA report points out that fuel costs could be higher if supply falls short of demand as a result of fewer-than-expected refiners opting not to make the necessary investments to produce lower-sulfur fuels.

Because only a small fraction of the heavy-duty diesel fleet will be able to take advantage of ULSD during the first several years after introduction, alternate approaches that minimize cost and supply impacts should be considered. For example, taking a market-based approach — in which the supply of 15-ppm S diesel is matched with the introduction of advanced highway and off-highway vehicles — would minimize diesel production requirements, alleviate potential supply shortages, decrease refinery-based emissions, and provide additional time for new technologies to lower production costs. Establishing a minimum phase-in volume in the 20–30% range should ensure adequate availability for on- and off-highway vehicles that require ULSD. Once the heavy-duty diesel vehicle demand reaches this level, the market would be allowed to match supply with demand.

Alternative Fuels. The refining, distribution, and retail segments of the industry are part of a highly integrated and efficient chain that is driven by cost, safety, environmental, and quality considerations. The chain is very capital intensive and has a mature asset base. With the enormous drive to reduce costs at each step, fuels have become interchangeable commodities. For various reasons, alternative fuels such as Fischer-Tropsch (F-T) diesel, biodiesel, oxygenates, and water-based distillate emulsions have generally not gone beyond niche applications and, therefore, have never gained the benefits of scale. Any non-interchangeable fuel that cannot take advantage of this system is at a huge disadvantage and its use will lead to inefficiencies and higher costs. However, because of the diversity of off-highway vehicle fueling stations (e.g., remote fuel dispensing, bulk distribution facilities), there may be some justification for use of alternate fuels in unique circumstances.

While various researchers have made claims that some of these alternative distillate fuels reduce engine-out emissions, a careful well-to-wheel and cost/benefit analysis needs to be conducted to substantiate these claims. For example, a conventional compression-ignition direct-injection (CIDI) engine or hybrid CIDI vehicle fueled by F-T diesel was found to have lower energy efficiency and higher greenhouse gas (GHG) emissions than a low-sulfur, crude-based diesel (Argonne National Laboratory et al. 2001). Lower-density directionally improves emissions performance, but adversely impacts peak engine power and fuel economy. Renewable fuels, such as biodiesel or rape seed methyl ester (RSME), have lower energy content relative to conventional diesel. The emissions impact of biodiesel is mixed (Rickeard and Thompson 1993). Depending on the drive cycle, PM emissions can be reduced; however, the high boiling point of the fuel means that PM soluble organic fraction (SOF) can be high under cold driving-cycle conditions. RSME has been shown to increase NO_X emissions relative to conventional diesel. Biodiesel fuels have the potential to lower GHG emissions, but a complete fuel-cycle analysis is needed because approximately 50% of the potential benefit is lost due to energy consumed in growing, collecting, and processing the biomaterial. Beyond niche applications, issues such as land use requirements and production efficiencies will need to be addressed. Finally, the cost of alternative fuels tends to be higher when compared to conventional fuels because of one or more of the following factors: feedstock costs, production efficiencies, and distribution and/or retail upgrades.

Lubricants. Lubrication of components for off-highway engines and vehicles is an important business, with just under 50% of the total volume of lubricants directed at heavy-duty applications. Off-highway lubricants are used in four main areas: agriculture, construction and quarrying, mining, and railroad applications. In recent years, changes in diesel engine design configuration and operating conditions to improve emissions control have been the main driving force that defined lubricant requirements.

The recent Tier 2 emission requirements, which took effect in 2001 and continue into 2006, can be met using existing lubricant technologies. These lubricants are based on partial or sole use of Group II and/or Group III base stocks, which have superior thermal stability and improved antioxidants for operation under high temperatures and with extended drain intervals. They also provide powerful dispersants for improved soot handling capability.

Future emissions standards (e.g., Tier 4) will coincide with the use of low-sulfur diesel fuels and aftertreatment technologies. Both of these factors will impact lubricant composition and performance capability. The use of low-sulfur fuel will decrease the contribution from fuel sulfur but increase the pressure to reduce the sulfur contribution from the lubricant to manage SO_2 emissions. This pressure will force the use of only Group II and Group III base stocks that offer minimal sulfur contribution and require sulfur restriction in the additives. These developments will represent a major challenge for lubricant formulation, because sulfur compounds are key to antioxidant and antiwear properties and are used as extreme-pressure additives. The implementation of advanced aftertreatment systems will also restrict lubricant phosphorus and ash, which are known to compromise aftertreatment efficiency and durability. Lubricant detergency and wear control ability, however, are strongly dependent on phosphorus and ash.

Given these challenges, there has been an increasing emphasis on the formulation of lubricants that are compatible with aftertreatment devices. Additive companies, major original equipment manufacturers (OEMs), and oil companies have begun a concerted effort to develop these next-generation lubricants.

2.4.2 Goals

The following goals are critical to the fuel and lubricant technology areas:

- Ensure availability of cost-effective hydrocarbon fuels for advanced heavy-duty diesel engine systems,

- Develop an improved understanding of fuel and lubricant impacts on advanced engine combustion processes to optimize fuel economy and/or reduce emissions,

- Develop a database of emissions levels and fuel economy as a function of fuel quality to aid in establishing realistic emissions standards, and

- Include a life-cycle cost analysis (total system efficiency/carbon dioxide [CO_2] emissions) for alternative fuel options

2.4.3 Technical Targets and Barriers

A primary target is the wide availability of low-cost fuels and lubricants that enable development of low-emissions diesel engine systems. As a secondary target, it may be necessary to develop lubricants formulated specifically for the high loads and intermittent duty cycles of off-highway engines.

The primary barriers are the fuel- and lubricant-derived poisons that degrade emission control system performance and durability. Sulfur in diesel fuel and, to a lesser extent, in lubricating oil, is known to directly impact the effectiveness of NO_x adsorber catalysts. Certain ash-containing additives in diesel lubricating oils may adversely affect the performance of diesel particle filters and traps. Cost-effective replacements for the antiwear agent zinc dialkyl dithiophosphate (ZDDP) may not be available. ZDDP is critical because it is both an antiwear and antioxidant additive, but it contributes significantly to the sulfur and ash content of finished lubricants.

2.4.4 General R&D Approach

The following are recommended R&D paths for off-highway fuel and lubricant technology.

- Document the impact of non-sulfur fuel properties on engine-out emissions based on published information.
- Determine the fuel sulfur level that is required for non-road fuels to enable:
  - Cooled and internal EGR
  - High-efficiency aftertreatment
- Assess the impact of expected market variations in fuel sulfur on emissions, fuel economy, and durability of advanced engines and aftertreatment systems.
- Assess the impacts of non-sulfur fuel properties on advanced engines and aftertreatment systems.
- Develop a life-cycle cost analysis of fuel impacts (both petroleum-based and alternative fuels).
- Evaluate lubricant formulation (sulfur, ash, phosphorus, etc.) impacts on engine-out emissions and on advanced aftertreatment systems.
- Investigate the performance of advanced low-sulfur, low-ash lubricants on engine and aftertreatment performance.
- Explore opportunities to reduce lubricant consumption and characterize the subsequent impacts on aftertreatment.
- Investigate on-board sulfur management technologies.
- Establish strategies to develop low-emission engine lubricants from a systems perspective, in which new base stocks and additives, along with biodegradable lubricants, are evaluated in terms of their effect on aftertreatment systems and engine component materials and surface treatments.

2.4.5 References

Argonne National Laboratory, General Motors Corporation, BP, ExxonMobil and Shell, 2001, *Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel Vehicle Systems — North American Analysis: Volumes 1 & 2,* June.

Bailey, O.H., D. Dou, and M. Molinier, 2000, *Sulfur Traps for NO_X Adsorbers: Materials Development and Maintenance Strategies for their Application,* SAE 2000-01-1205.

DECSE, 2000, "Diesel Emission Control Sulfur Effects Program, Phase II Summary Report: NO_X Adsorber Catalysts" [URL: http://www.ott.doe.gov/decse/], U.S. Department of Energy, Oct.

EIA: Energy Information Administration

EIA, 2001a, "Fuel Oil and Kerosene Sales 2000," DOE/EIA-0535(00) [URL http://www.eia.doe.gov/oil_gas/petroleum/data_publications/fuel_oil_and_kerosene_sales/foks.html (as of December 1, 2001)], Sept.

EIA, 2001b, *The Transition to Ultra-Low Sulfur Diesel Fuel: Effects on Prices and Supply*, May.

EPA, 2001, "EPA Nonroad Diesel Emission Standards-Staff Technical Paper," EPA 420-R-01-052, Oct.

Haug, E.J., et al., 1998, "Virtual Proving Ground Simulation for Vehicle Design," Proceedings of DETC '98, 1998 ASME Design Engineering Technical Conference, Atlanta, Ga., Sept. 13–16.

Kreso, A.M., J.H. Johnson, L.D. Gratz, S.T. Bagley, and D.G. Leddy, 1998, *A Study of the Vapor- and Particle-Phase Sulfur Species in the Heavy-Duty Diesel Engine EGR Cooler*, SAE 981423.

McKinley, T.L., 1997, *Modeling Sulfuric Acid Condensation in Diesel Engine EGR Coolers*, SAE 970636.

National Petroleum Council, 2000, *U.S. Petroleum Refining*, June.

Rickeard, D.J., and N.D. Thompson, 1993, *A Review of the Potential for Bio-Fuels as Transportation Fuels*, SAE 932778.

West, B.H. and C.S. Sluder, 2000, "NO_X Adsorber Performance in a Light-Duty Diesel Vehicle," Society of Automotive Engineers, technical paper 2000-01-2912, Society of Automotive Engineers, Warrendale, Pa.

2.5 MACHINE SYSTEMS EFFICIENCY TECHNOLOGIES

Many off-highway machines operate in diverse environments. Convenience, safety, cost, and reliability are often emphasized, and energy efficiency is mostly neglected. This discussion summarizes system-energy efficiency needs in three areas: inside the chassis, outside the chassis, and between the machine and its environment. Research possibilities include, but are not limited to, efficient, continuously variable transmissions (CVTs); drivetrain and implement energy storage/transfer; smart machine control and adaptation; high-strength materials/weight reduction; operator performance enhancement methods; and rejected heat recovery.

In concert with these efficiency topics, this section summarizes potential research in seven related areas:

- Powertrain efficiency;
- Hydraulic system efficiency;
- Traction, mobility, and steering efficiency;
- Implement loadability and controllability;
- Operator performance enhancements;
- Adaptive machine system performance; and
- Machine system simulation.

The last subsection, machine system simulation, is a critical supplement to the others. A comprehensive summary of the status of technology, technical targets, barriers, and technical approaches is beyond the scope of this brief outline. Singling out a minor subset of issues to emphasize would certainly stifle innovation and reduce the potential for major breakthroughs. Therefore, we have emphasized performance areas in which machine energy efficiency and technology are lacking and could benefit from further research and development.

2.5.1 Powertrain Efficiency

Off-highway machines primarily use pneumatic tires and steel and rubber tracks. Significant amounts of energy are lost at the interfaces between the various moving elements. The initially attained efficiency may be reduced by excessive wear and contamination caused by diverse operating environments. Many of these machines require substantial speed reduction, which is another source of energy loss. Automatic transmissions, torque converters, and CVTs (such as hydrostatic transmissions) consume additional energy. Wide variations in engine load and speed increase energy losses, heat rejection, and emissions. Load balancing using flywheels, accumulators, or regeneration methods could substantially improve performance.

Status of Technology. The powertrain may be divided between those components located inside the chassis and those outside. On the outside, the undercarriage is subject to the vagaries of the environment. A major emphasis has been on designing for increased component wear life, which indirectly reduces friction and improves energy efficiency. Inside the chassis, the focus has been on simplicity, reliability, and operator convenience. There is room for innovative improvements in both areas.

Technical Targets. Undercarriage energy loss occurs primarily in tracked machines. Sprockets, friction drives, rollers, and idlers propel and support the tracks and generally perform best when new. Friction losses increase when parts become contaminated and wear modifies their profiles. Improved design for reduced and controlled wear progression could help efficiency. Some of the advances made in on-highway vehicles could be exploited to enhance efficiency inside the chassis. Improvement of speed reduction and CVT systems, more prevalent in off-highway machines, may have the greatest impact. A 10–30% reduction in energy could be expected.

Barriers. Cost and reliability are major factors. Advanced materials and design processes are required. Better sensor and control devices, along with semi-intelligent neural-fuzzy systems, should be developed and tested. The lack of highly efficient CVT technology is a limiting factor.

Technical Approach. Full-scale machine modeling in realistic operating environments will provide the most cost-effective tool to investigate innovative concepts. The machine, drivetrain, undercarriage, hydraulics, and controls, operating in realistic work environments, can be emulated on today's computers at a fraction of the time and cost of prototypes. Component wear and life can be predicted and optimized, indirectly affecting long-term energy efficiency.

2.5.2 Hydraulic System Efficiency

Hydraulic performance is more easily quantified than the performance of other parts of a powertrain. Most off-highway construction or mining machines use hydraulic implement power to move, dig, or lift materials, including earth and ore, as well as scrap, raw, or finished materials of any type. Hydraulic systems, which are generally complex, consist of pumps, motors, valves, cylinders, reservoirs, filters, coolers, and lines to control the hydraulic fluid. Systems are designed to provide the maximum power required during the operating cycle, and excess energy at other times is primarily converted to heat. Multiple machine subsystems often oppose each other, consuming nonproductive energy. Various types of force and pressure sensors and corresponding control devices could be exploited to reduce or eliminate such losses.

Status of Technology. Improvements in electrohydraulic actuators, computational power, sensors, and component designs have enabled more precise control of fluid flow; however, the potential improvements in system energy efficiency have barely been touched. Current emphasis has been on adding features and providing power boost rather than conserving energy.

Technical Targets. Technical targets include:

- 20–30% reduction in fuel energy requirements (based on hydraulic-intensive machines, such as excavators, backhoe loaders, wheel loaders)[25] and
- 25% reduction in heat load (see Section 2.6).

Barriers. The following technologies are needed:

- Efficient energy-storage devices;
- Controls to capture and reuse energy at the right time; and
- Accurate, responsive sensors.

Technical Approach. The technical approach involves the following tasks:

- Eliminate direct drive of pumps; drive pumps only when hydraulic power is needed;
- Improve efficiency of pumps and motors;
- Enable adaptive learning to increase productivity of operators;
- Capture gravity and inertia-based potential energy for reuse and to shave peak power requirements; and
- Identify and optimize hydraulic energy storage devices.

2.5.3 Traction, Mobility, and Steering Efficiency

Efficiently maneuvering material and earthmoving equipment over a broad range of terrain profiles and physical conditions poses greater technical challenges for off-highway machines than for on-highway vehicles. However, many of the energy-efficiency problems are similar — and so may be the solutions. Traction problems arise most often when terrain profiles and properties fail to match those assumed for the undercarriage design. Slipping and plowing wheels and tracks consume energy whatever the cause. In its simplest form, mobility is the opposite of getting stuck. Maintaining optimal traction is an integral part of mobility, but not all. Exploiting a machine's momentum and maintaining optimal ground pressure distribution is often crucial. Steering efficiency relates to effectively maneuvering multi-axle and articulated, wheeled machines, and tracked vehicles having large rectangular footprints. The added cost of

[25] See Table 2.3 for a summary of energy-savings goals.

employing multi-wheel steering in skid-steered loaders and other machines could be recovered rapidly as a result of reduced energy consumption.

Status of Technology. Advanced sensing and control capabilities have grown exponentially. Onboard computers are used in nearly all on- and off-highway applications. The technology has been applied extensively in on-highway traction and braking control and less so in steering applications. Military traction and mobility likely represent the largest off-highway uses. Sensing and control of wheel slippage has been implemented on a number of large-wheel loaders.

Technical Targets. Undercarriage/terrain interface energy losses come primarily from surface slippage, sinkage, and plowing. The three effects are closely related, and so improving any one will usually help the others. Maintaining optimal pressure distributions may provide the largest gain to all three factors. Adapting terrain-engaging subsystems to conform to irregular profiles and working conditions will reduce losses. Quantifying possible energy reduction is difficult because of the broad spectrum of terrain conditions and operating scenarios. Twenty to forty percent energy reduction may be possible.

Barriers. Cost, simplicity, and reliability are issues. Many off-highway machines are manufactured in limited quantities, and excessive R&D costs and system complexity could make otherwise desirable systems impractical. Owners expect long life and relatively trouble-free machine operation, and complexity increases failure rates, as well as owning and operating expenses.

Technical Approach. Practicality must be the driving force behind any implementation. The emphasis should be on minimizing the number of hardened sensors and controls. Sophistication should reside in inexpensive and reliable intelligent and adaptive control software.

2.5.4 Implement Loadability and Controllability

Many off-highway machines use ground-engaging tools of various shapes and sizes to process and manipulate materials with widely varying properties. Tool reaction forces and displacements are an integral part of machine energy efficiency. Loadability involves maneuvering tools to reduce resistance and increase machine effectiveness. Controllability is the process of sensing and reacting to perceived states to improve machine and tool performance. Tool geometry, coupled with linkage design and control strategies, contributes to machine loadability and controllability performance, thus affecting energy efficiency. Carry back, where part of a load adheres to a tool, can reduce production efficiency and increase ground engagement energy requirements.

Status of Technology. The design and optimization of ground-engaging tools is an art that has progressed slowly. The inability to model tool/material dynamic interaction to any degree of accuracy has been one limiting factor. The inability to model machine/terrain interaction is another limiting factor because this significantly affects tool performance.

Expensive scale model and field tests are the primary methods employed. These empirically based methods make sensitivity analysis more difficult. The introduction of computer-based dynamic tool/undercarriage/ground models, coupled with shape optimal design algorithms, will speed up the ground-engaging tool performance design and optimization process.

Technical Targets. A significant amount of energy loss associated with ground-engaging tools comes from forcing blunt edges through highly resistive and irregular material. Carry back also reduces productivity and increases tool drag. An improvement in energy efficiency of 10–30% could be expected.

Barriers. Cost and reliability are the primary barriers. Maintaining adequate payload-to-tool mass ratio is another because this could degrade performance and efficiency. Many machines are designed to operate with a range of tools that may require adaptive mechanisms and control strategies.

Technical Approach. Full-scale computer-based machine models should be used to demonstrate potential gains of innovative concepts. Various geometric designs and control strategies could be studied and optimized. Only the most promising candidates would have to be fabricated. Incorporating lateral/vertical shearing mechanisms on the leading edge of tools could substantially reduce forward resistance. Current control strategies use fixed teeth and oscillate the tool vertically or tilt it to dislodge or circumvent large or tough obstacles. New methods for reducing carry back and tool drag may prove most beneficial.

2.5.5 Operator Performance Enhancements

Mishandling off-highway machines as a result of operator inexperience or fatigue reduces energy efficiency. A number of semi-automated and autonomous processes have been tested, and some have been implemented. Highly trained, rested operators may outperform the best automatic processes over short intervals, but they soon fall behind because of fatigue or boredom. Operator overload is another problem. Ergonomics research, as related to obtaining and sustaining optimal efficiency in diverse environments, is a rich area for research.

Status of Technology. Sensor- and control-based methods that maximize mass per unit time transfer rates are in production. This does not equate to maximizing mass per unit fuel rates. The trained and rested operator performs many conscious and subconscious sensory and response operations to complete tasks. Through repetition and monitoring actual production rates, the operator learns to maximize mass per unit time. Maximizing mass per unit fuel is less intuitive. The operator would require a mass-per-unit-fuel indicator to gauge his/her progress. Similar processes indicating distance per unit fuel when maneuvering generally do not exist.

Technical Targets. The first target is to reduce fuel consumption by providing autonomous or semi-autonomous processes to replace or augment complex operator tasks. The second is to provide visual or audio feedback to indicate correct operator input. Depending on the applications and operator skill levels, a 5–20% reduction in energy could be achieved.

Barriers. Diverse off-highway operating scenarios require rapid changes in control strategies. Adaptive neural-fuzzy systems have potential but are still experimental. The traditional undercarriage, drivetrain, and implement configuration mindset must be modified to enhance operator performance.

Technical Approach. The technical approach involves the following tasks:

- The National Advanced Driving Simulator (NADS) in Iowa City (Haug 1998) is a state-of-the-art device for conducting operator-in-the-loop studies of man-machine interactions. Currently, the NADS is optimally configured for on-highway applications. With suitable modifications to enhance the visual system for off-highway applications, the NADS could provide an ideal platform to evaluate the effects of proposed operator performance enhancements on off-highway machine energy consumption.

- An extensive computer-based search of optimal off-highway machine configurations should be conducted to enhance operator performance. Dynamic models would include composite machine and implement, drivetrain and undercarriage, terrain and operating environment, human/autonomous/ semi-autonomous sensor and control, and adaptive neural-fuzzy systems. Design sensitivity analysis and optimization could be performed, and the acquired knowledge could be transferred to practical implementations.

2.5.6 Adaptive Machine System Performance

Off-highway machines have an operational disadvantage compared with their on-highway counterparts. On-highway vehicles, for the most part, have well-defined, consistent operational environments, and their performance can be more easily optimized to those conditions. Off-highway machines are required to interact more tightly with their environments over a broader range of physical conditions. The performance of most non-adapting off-highway machines cannot be optimized over their operational envelopes. It is beneficial to study intelligent systems capable of assessing a machine's reaction to its differing environments and adapt or reconfigure itself, as necessary, to improve its performance. Sensing and controls, information processing, and telecommunications could be major players in successful systems.

Status of Technology. Substantial advances have been made in autonomous machine operation and intelligent, adaptive control. For example, adaptive suspensions have increased maximum speeds and stability of off-highway military tanks and trucks. Intelligently controlled redundant actuators have improved robot and earthmoving machine performance.

Technical Targets. One target is to reduce fuel consumption by providing autonomous (or semi-autonomous) processes to sense machine and implement production efficiency and automatically adjust configurations and power inputs to reduce energy losses. Machines can be optimized for a narrow range of operating and load conditions. Adaptive machines will greatly widen the range of optimal conditions. One might expect to see a 10–40% percent increase in energy efficiency.

Barriers. Cost, simplicity, and reliability are issues. Many off-highway machines are manufactured in limited quantities, and excessive R&D costs and system complexity could make otherwise desirable systems impractical. Owners expect long life and relatively trouble-free machine operation, and complexity increases failure rates, as well as owning and operating expenses.

Technical Approach. To enhance overall machine system performance, an extensive computer-based search of optimal off-highway machine configurations should be conducted. Dynamic models would include composite machine and implement, drivetrain and undercarriage, terrain and operating environment, human/autonomous/semi-autonomous sensor and control, and adaptive neural-fuzzy systems. Design sensitivity analysis and optimization could be performed, and acquired knowledge could be transferred to practical implementations.

2.5.7 Machine System Simulation

Most areas of machine system design and performance evaluation will benefit from large-scale, synergistic, computer-based models, including design sensitivity and optimization. Realizing these models requires a coordinated effort of data acquisition, system characterization, model definition, algorithm development, model validation, and results analysis. Increased competition and costs, as well as accelerated development and implementation schedules, leave less room for expensive and time-consuming build-test-fix cycles.

Status of Technology. The analysis and simulation technology may be broken down into commercial and in-house software. The advent of gigahertz processors with gigabytes of memory and adequate disk storage allows most programs to run on desktop computers. General-purpose software often suffers from computational overhead. Special-purpose software is often less accessible and not as easily integrated.

Technical Targets. Replacing physical development and tests requires computer-based models with sufficient resolution and accuracy. Test-measurement accuracy for validation (however that may be defined) is the ultimate goal for computer-based machine system models. Synergistic system models will be applicable to most areas covered by the roadmap.

Barriers. The primary barriers are nonexistence of critical subsystem models and the inability to integrate others. Synergistic performance analysis implies that all subsystems communicate causally. This capability exists sporadically, at best.

Technical Approach. Computer-based synergistic machine-system models are being applied to a number of off-highway problems. The least developed and most critical components are dynamic undercarriage/terrain and implement/terrain interaction models. The second area requiring further development is dynamic operator cognizance and response modeling. Current models are far too complex for real-time human and hardware-in-the-loop simulations. This task requires investigation of semi-empirical modeling methods for both of the above areas as a compromise between computational speed and accuracy.

2.6 THERMAL MANAGEMENT

Thermal management is a crosscutting technology that impacts machine efficiency, emissions, durability, safety, packaging, cost, productivity, noise control, and operator visibility. Thermal management includes the generation, dissipation, rejection, and control of machine heat transfer and temperatures. Machine systems technologies that improve productivity and secondarily decrease heat rejection per unit productivity are described in Section 2.5.

There is some overlap between the thermal management of off-highway vehicles and that of heavy trucks, for which a Technology Roadmap has already been developed (USDOE 2000). However, off-highway machines have specific constraints on thermal management that will require technological solutions that are likely to be different from those for trucks. Key technical differences include the lack of ram air, high heat load factors, dust/dirt/debris-laden environments, high shock/vibration loads, a wide range of ambient temperatures (deserts to arctic), omni-directional operator visibility requirements (e.g., leads to underhood exhaust systems), and sound regulations that limit fan speeds. A key commercial difference is the enormous variety of machines and small production volumes.

A partial overview of the status of thermal management technology may be gleaned from the Proceedings of the Vehicle Thermal Management Systems Conference (SAE 2000).

2.6.1 Goals

The program goal is to develop thermal management and cooling system technologies and innovations to meet the demands of emissions compliance, according to future governmental regulations (e.g., EPA Tier 3 or prevailing EPA standards) expected to come into effect in the next 10 years. This is likely to require:

1. An increase of present cooling capacity by up to 65%. The increase will accrue because of increased heat rejection, a potential need for EGR cooling, decreased fan noise, increased exchanger restriction, and lower temperatures while:

    - using existing machine architectures,

    - maintaining or reducing cooling system input power, and

  - maintaining commercial viability (performance, durability, operator visibility, and cost).

2. Improved design, analysis, simulation, and test methods to enable development of complex machine cooling and thermal management systems in a short time frame to comply with rapidly changing emissions and sound requirements.

3. Identification of new technologies and inventions to enable additional thermal management and cooling system improvements beyond EPA Tier 3 to minimize additional machine design changes and costs (of Tier 3 machines) to meet Tier 4 requirements.

Up to 65% increased cooling capacity may come from a combination of innovations and technologies, such as:

- 20% lower component heat loads,
- 25% higher fluid temperatures,
- 25% higher effective heat rejection from fluid/thermal system improvements,
- 30% increased heat rejection from air system improvements, and
- 20% lower effective heat loads via thermal management and control.

2.6.2 Machine Thermal Sources

Reduced component heat rejection enables reduced cooling air mass flow through the heat exchangers and correspondingly lower cooling fan pressure, fan speed, fan input power, and fan noise. Alternatively, decreased component heat rejection enables smaller, lower-weight, lower-cost exchangers and machine package volumes to achieve similar ambient temperature capabilities and fan input power or noise levels. The primary heat sources are the diesel engine, powertrain, and implement (hydraulic) systems.

Off-highway diesel engine heat loads have evolved from and are strongly interrelated to requirements for performance, emissions, fuel economy, and other commercial needs. The status of these technologies, impact on engine heat rejection, and technology needs are further described in Section 2.2.

The heat loads of powertrain and hydraulic systems have evolved from similar requirements related to performance, efficiency, and commercial needs related to component size, weight, and cost. Improvements in powertrain and hydraulic system efficiencies and regeneration (that generally lead to less heat rejection and required cooling) are described in Section 2.5.

In addition to fundamental improvements in performance and efficiency, the heat load to the cooling system may also be reduced by increasing direct heat rejection from the component to the environment via increased conduction, convection, or radiation. This "direct cooling" is briefly discussed in this section.

Status of Technology. Direct cooling of the diesel engine is typically fixed by the airflow of the primary cooling system. Suction mode air systems provide only marginal direct cooling because of the relatively low temperature differential of the heated air (by the exchangers) and the engine surface temperatures. Blower mode air systems provide increased direct cooling, but increase the air temperature to the exchangers, offsetting the direct cooling effects. New cooling/engine compartment configurations that separate the cooling system and engine compartment have not had extensive investigation relative to direct engine cooling effects or potential for improvements.

Direct cooling of powertrain or hydraulic components has not been fully studied. For small off-highway machines, cooling fins or larger fluid system tanks (to increase surface area) are occasionally used to increase heat transfer area for direct convection to avoid the need for a heat exchanger.

Technical Targets. Technical targets include reducing engine, powertrain, and implement heat loads by 20% via efficiency improvements (Sections 2.2 and 2.5) and direct cooling.

Direct Cooling

Barriers. Extensive work has not been carried out to increase direct component heat transfer due to the perceived cost/benefit. In general, the costs (product development time, product development costs, component costs) may be substantial based on the large number of engine installation, powertrain, and hydraulic system designs and variants and relatively small production volumes to justify tooling and engineering costs. The cooling system performance benefits may also be small for typical changes in direct cooling.

Technical Approach. First, direct cooling concepts and the theoretical potential to increase direct cooling via increased surface temperatures, surface areas, and convection (secondary airflows) requires quantification. The impact on required cooling loads, exchanger size, fan input power, and fan noise can then be quantified.

Some of the technologies to evaluate could include:

- Heat sinks – conduction (attach component to machine structure with significant thermal inertia and surface area).

- Heat sinks – mass transfer (increase surface area of pipes, tanks, and other components for component fluids systems – e.g., lubricants, hydraulic fluids).

- Increased component surface area (fins).

- Active surface (vibration, micro-fans).

- Ventilation means (openings, flows, locations).

- Active ventilation (exhaust entrainment, separate fans, convection inducement, suction from main cooling system).

- Precision cooling (cooling only critical thermal elements in the component; other areas run hotter with an increase in direct cooling).

- Heat pipes (connect critical, high-temperature, internal component areas to external thermal inertias, convective exchangers).

Development of direct cooling will likely require improved definition of internal thermal sources, internal heat transfer, and direct heat rejection mechanisms (conduction, convection, radiation). Because of the wide variety of machine designs, variants, and applications, cost-effective methods are required to evaluate and develop direct cooling. In general, development of models and modeling techniques is required for internal heat transfer models (heat generation and finite-element thermal models) and external cooling models (convective heat transfer, CFD thermal models). The effects of direct cooling on engines due to engine enclosures are further complicated by the enclosure and other high-temperature underhood components, such as exhaust systems (see Underhood Thermal Management under Section 2.6.6 on Thermal Management and Control).

2.6.3 High-Temperature Machine Cooling

Higher fluid temperatures in the machine heat exchangers provide a higher temperature differential with the ambient air (heat sink); allow the exchangers to reject the required heat load with less airflow; and therefore reduce air system pressure, air power, fan input power, fan speed, and fan noise. Alternatively, smaller, lower-weight, lower-cost exchangers and machine packaging can be used.

Status of Technology. Off-highway diesel engine cooling systems have evolved around the use of water as the primary coolant and temperatures near the boiling point of water. Modern engine cooling systems are pressurized (7–14 psi range) and use a 50/50 mix of ethylene glycol and water to achieve a maximum operating temperature range of 100–110°C.

The maximum temperatures for the powertrain lube oil have evolved with the engine cooling system because of frequent use of engine coolant to cool the powertrain oil. Lube oil in the transmission is usually required to be below 105°C. The maximum hydraulic fluid temperatures are based on properties of available oils and on component manufacturing capabilities related to surface finishes and bearings. The hydraulic oils must have acceptable viscosity at low ambient temperatures to allow proper controllability and function, and at high ambient temperatures, they must provide adequate viscosity to ensure proper durability and life. Powertrain and hydraulic systems are trending toward operation with lower maximum temperatures to enable lower cost fluids, lower cost components, and extended fluid service life.

Because of these constraints, several decades of experience have developed reliable engine, powertrain, and hydraulic components (e.g., seals, hoses, clutch materials, lubricating fluids, and gear designs) for these temperatures. Increased machine cooling system temperatures will require significantly new technology related to material performance and durability at higher temperatures, improved materials, improved knowledge of engine and component structures and performance at higher temperatures, and development in many areas.

Technical Targets. Technical targets include increasing the temperature differential between the machine cooling fluids and the ambient air by 25% or 25°F; maintaining similar fluid temperatures for engine cooling, powertrain cooling, and hydraulic cooling to simplify exchanger configurations; improving average exchanger performance, and improving design robustness.

Barrier: High-Temperature Engines

Without redesigning the engine, elevating maximum engine coolant temperatures by 25°C is likely to increase engine metal temperatures by a similar amount. Engine durability is already limited by the temperature of critical engine regions and thermal stresses in items like piston rings, cylinder heads, and liners. The wear life of bearings and oil pumps could also be a concern if lubricating oil viscosity and oxidation life is not controlled. Higher temperatures may affect fuel properties and the performance and life of fuel injectors. Hence, there is a concern that elevated temperatures might shorten engine life. Increased air temperatures within the engine compartment may require changing the materials for other components within the compartment to withstand the higher temperatures.

Also, engine coolant temperatures are strongly linked to other components, especially where engine coolant is used to cool powertrain or hydraulics via oil-to-water exchangers. Engine jacket water heat may be used to heat other components for cold temperature operation in extremely cold and harsh environments.

There is also a risk that elevated coolant temperatures might lead to higher combustion gas temperatures and lead to higher NO_X emissions. However, it is unlikely that any increase in NO_X would be significant.

Barrier: High-Temperature Powertrain

Temperatures of such components as powertrain clutches, hydraulic hose, various and non-metallic seals are limited by current materials. The use of new materials for seals and non-metallic components is hampered by lack of accurate data regarding high temperature life. Other areas (like friction materials for clutches) are constrained by the current availability of higher-temperature materials. The wear life of bearings and oil pumps is another concern, unless oil viscosity and oxidation rates can be modified without affecting low-temperature operations and clutch friction values.

Barrier: High-Temperature Implement Systems

The wear life and durability of the hydraulic components must be maintained with the higher temperatures. If improved oils are used to maintain the viscosity at higher temperatures, they must also allow proper functioning of controls and flows at low ambient temperatures. Improved oxidation rates at the higher temperatures would also be required.

Barrier: High-Temperature Fluids

The current engine coolant (50/50 ethylene glycol – water) will not provide sufficient boiling protection without increasing the coolant system pressure. An increase of system pressure is undesirable because of the need for more expensive components, and existing codes would require pressure testing of each component manufactured. Alternative coolants may be required that at least compare favorably with 50/50 ethylene glycol – water from a functional standpoint but, in addition, permit a higher operational temperature without increasing the operating pressure. Alternative coolants with higher boiling points (e.g., nonaqueous propylene glycol) have inadequate convective heat transfer performance.

Improved lubricating fluids with global availability are also required. The number of different fluids per machine should be limited to reduce risks of using inadequate fluids.

Technical Approach. The technical approach involves the following tasks:

- Review the design of the engine coolant jacket to permit operation at higher coolant temperatures (which may involve locally increased coolant velocities to improve cooling and reduced heat paths in the cylinder head and liner). Consider the use of higher-thermal-conductivity materials for head and liner. Identify required design changes to the engine and its fluids to obtain acceptable engine life and performance.

- Identify new coolant(s) that offer good heat-transfer properties and acceptable operating life and boiling point while maintaining acceptable freeze protection.

- Demonstrate that acceptable engine life can be obtained at higher coolant temperatures.

- Identify, evaluate, and demonstrate new materials for seals, hoses, clutches, and other temperature-critical components.

- Identify and develop alternative lubricants, hydraulic fluids, and transmission fluids for high temperatures.

- Demonstrate that acceptable machine, engine, transmission, hydraulic, and cooling system life can be obtained with higher operating temperatures.

- Demonstrate a unified approach to increased machine coolant temperatures to use a single, efficient, coolant-to-air heat exchanger (higher performance per unit air-side pressure drop). Additionally, a single exchanger can be designed for a lower peak heat load since the peak engine, powertrain, and hydraulic heat loads likely occur at different point in the machine work cycle. With individual exchangers, each exchanger must be designed for the peak heat load of that fluid.

Boiling/Condensing in Cooling Systems

Status. Cooling systems currently operate below the boiling point of the fluid. Local nucleate boiling occurs in high-heat-flux regions of the engine, but the intent is for any vapor formed to quickly condense. Work has been done by several companies on boiling cooling systems. However, these have not made it to mass production because of system complexity and cost.

Target. A cooling system that allows boiling in the engine could allow for less water pump power, a smaller condensing radiator, higher temperature difference between the coolant and air, and more even engine metal temperatures. This allows higher operating temperatures.

Barriers. Barriers include the following:

- Potential for excessive pressure build-up in the cooling system.

- Possibly reduced heat exchanger life as a result of higher temperature cycles and increased pressure.

- Complex control strategy may be needed.

- Cost.

- Commercial coolants (50/50 ethylene glycol-water) have large, undesirable differences in boiling and condensing temperatures.

- Boiling increases the potential for formation of deposits and requires improved coolant maintenance by the customer.

- Potential need to redesign engine cylinder heads to prevent steam vapor pockets and development of models to guide redesigns.

Approach. Off-highway machines should be analyzed to determine if there is a significant benefit to a two-phase cooling system. The study should identify the potential reduction in heat exchanger size and likely improvements to engine efficiency and reduced emissions. Heat exchanger and engine manufacturers should be engaged to assess the effects on durability of components and cost. If this study indicates there is a clear benefit, vehicle performance and durability should be demonstrated. Many of the correlations for boiling heat transfer have been developed for large channels. A better understanding of boiling phenomena in small passages with coolant mixtures could lead to improved design rules for engine cooling.

Advanced Fluids

Status. Present engine cooling systems primarily use a 50/50 mixture of ethylene glycol-water as a coolant. This mixture offers a good compromise in terms of boiling/freeze points and heat transfer capacity. To this, about 5% by volume of inhibitor chemicals are added, and these chemicals protect the engine against corrosion and liner cavitation. Engine structural life is currently limited by the thermal stresses in the engine. Hence, a coolant with improved heat-transfer capability would help reduce metal temperatures relative to the surrounding coolant temperatures. If the goal is to increase coolant temperature by 25°C, then a new fluid is likely to be required. Nanofluids, which consist of a base fluid in which special nanometer-sized solids have been dispersed, may offer the potential for a higher-performance coolant, and nanofluid technology is likely to enhance the performance of any fluid chosen. However, the development of nanofluids is still in its infancy, and the enhancement of a base fluid with nanoparticles is unlikely to change its boiling point.

Target. The target is to:

- Identify a coolant that allows safe operation at 125°C and less than 150 kPa absolute pressure and

- Develop the use of nanofluids or other coolants with conductive heat transfer equal to or greater than that of water.

Barriers. Barriers include the following:

- Identifying a suitable coolant (performance, flammability).

- Ensuring freeze protection is met.

- Ensuring that engine and heat exchanger life is not overly compromised.
- Worldwide availability (including least developed nations).
- Overcoming customer maintenance issues.

Approach. The approach involves the following:

- Agree on the requirements for a new engine coolant.
- Identify candidate coolants and analyze their impact on cooling system performance and engine life.
- Carry out a vehicle demonstration of improved function and durability with new coolant.
- Continue fundamental studies of nanofluids.

2.6.4 Liquid Thermal Subsystem

Technical Target. The technical target is to increase effective heat rejection by 25% while maintaining similar fan input power, required temperatures, similar packaging volumes, and required cooling-system sound levels.

Variable-Speed Electric Pumps

Status. Conventional coolant pumps are mechanically driven and circulate coolant through the engine to remove excess heat. The mechanical drive links the pump rpm, and thus the coolant flow rate, to the engine rpm. As a result, these pumps are producing — up to 95% of the time — much more (and sometimes less) flow rate than that required to maintain an optimal engine temperature. Conventional pumps also tend to be high- warranty components because of the mechanical seal and highly loaded bearings.

Tests have been conducted with electric coolant pumps, demonstrating benefits across most of the operating range. With electronic control, the engine would receive the correct amount of flow in all conditions, thus saving a considerable amount of energy.

Electric oil pumps are also an important part of the thermal management system. They are not only used to lubricate bearings, but to cool the pistons. Like water pumps, oil pumps are designed to operate under the most extreme conditions, leading to a tremendous amount of parasitic loss and decreased oil life at all other operating points. Controlled electric pumps are currently under development for main engine cooling and secondary system cooling. Pumps are being developed that have long life, low weight, and high efficiency. Electric pumps will be the enablers for many of the thermal management techniques discussed in this report.

Barriers. Barriers include the following:

- Current low-voltage-motor efficiency is inadequate.
- Current low-voltage alternators are inefficient (less than 70%).
- Engine flow requirements (other than maximum flow rates) are ill-defined; hence, acceptability of lower flow rates is unknown.
- High-voltage pumps are required for larger engines; efficient high-voltage power is needed.

Approach. The approach involves the following tasks:

- Use high-efficiency electrical pumps, thus dropping the cost of electronics and maximizing the benefits.
- Use cooled alternators or starter generators in a high-efficiency configuration for the power source.
- Develop computer models to help determine control logic and the optimal system configuration.
- Consider a family of standard water pumps and multiple electric pumps for larger engines.
- Consider using a second water pump for auxiliary applications.
- Determine critical diesel engine issues for reduced water flow and identify required design changes.
- Determine operating conditions that can tolerate reduced flows to guide control strategy.
- Develop computer models to optimize system design and controls.

Electronic Thermostats and Valves

Status. Conventional thermostats are mechanical valves that consist of eutectic wax that changes phase when heated. The valve restricts coolant from flowing to the engine radiator and bypassing back to the engine until a set coolant temperature has been reached. Thermostats respond slowly to the coolant temperature, which can lead to unnecessary temperature fluctuations. Thermostats are usually very restrictive, causing additional parasitic losses. In addition, tests have shown that engine outlet temperature is not always the best indicator of bypass requirements, especially in cold climates. Because of their simple configuration, they are extremely low cost components with relatively good reliability.

Tests have shown that a control valve in place of a thermostat can help improve efficiency during cold operating conditions. During these cold ambient conditions, an electrical valve could be used to raise the coolant temperature higher than with a conventional thermostat and still satisfy the engine's needs during high thermal load situations. In this manner, the engine can run warmer than normal, which can help enhance combustion along the walls, improve heat flow return, and obtain higher combustion temperatures. In addition, creativity in design will allow an electric thermostat to have considerably less pressure drop than a conventional configuration, thus saving pumping power.

Barriers. Problems implementing an electric valve have involved the added cost and lack of understanding of true engine requirements (see variable water pump discussion above). Additionally, the valves may need to maintain certain pressure requirements for the coolant in the engine.

Approach. The approach involves developing a low-pressure-drop electric valve, which will help decrease parasitic loss; developing control logic through testing and modeling of systems; determining the value of reduced engine coolant flows to accelerate engine warm-up and reduce cold temperature over-cooling; and providing manual valve control for system performance diagnosis.

Advanced Heat Exchangers

Status. The industry currently uses a variety of heat exchanger types, configurations, and materials. Heat exchanger types include radiators, oil coolers, charge air coolers, condensers, evaporators, heater cores, and EGR coolers. The primary fluid for these heat exchangers can transfer heat to either an air or a coolant stream. Heat exchanger configurations include plate fin cores, serpentine fin cores, shell-and-tube cores, round-tube plate-fin cores, bar plate cores, modular cores, and parallel flow cores. Materials include copper, brass, aluminum, and stainless steel.

Reduction in emissions from engines — and the reduction of gases that can cause global warming — are the drivers for new technology alternatives. For engine emissions, the use of EGR devices can reduce NO_X emissions. However, durability, corrosion, and fouling issues for these heat exchangers in heavy-duty applications must be examined more thoroughly. Additional heat loads to the charge air and coolant systems are forcing the reexamination of coolant module sizing and materials. Higher temperatures into the charge air cooler may require pre-cooling devices or higher-strength aluminum materials.

On-highway truck and automotive applications have been able to significantly increase radiator performance by using thinner material and more fins per inch, as well as louvered heat transfer surfaces, to increase the heat transfer at the fin/air interface. High impact loading, as well as severe dust and debris in the cooling air, makes these technologies very difficult to transfer to the off-highway machine world.

Barriers. A wide range of technical barriers prohibit the use of some advanced technology for these heat-transfer devices. Some of these technologies are presently unavailable because of cost, durability, corrosion resistance, and fouling. However, environmental regulations, including emissions and noise legislation, are reducing some of these barriers and are opening up some of these advanced technologies for consideration.

- Structural: the heat exchangers in an off-highway machine must live for thousands of hours while operating under impact loads of up to 10 g on a regular basis.

- Air-side fouling: machines operating in some environments must contend with cooling air filled with large, low-density debris, like sawdust, chaff, or cotton seed lint. Other machines must operate in an environment filled with very small debris, like dust. These contaminants clog the airflow passages in a radiator and can significantly reduce heat transfer performance in a very short time.

- The heat exchangers must be capable of being cleaned to remove the air-side fouling. High-pressure air cleaning is forbidden by OSHA, so high-pressure (1,000 psi and above) water washers are often used regularly to clean debris from heat exchanger fins. High-pressure washers can bend thin, soft fins flat, making it impossible for air to pass through the heat exchanger.

- Some off-highway machines use blower fan configurations, where the cooling air is blown from the fan through the heat exchanger. Some materials, like aluminum, have proven to wear away very quickly when used in blower fan configurations operating in sandy environments.

Approach. Several areas and approaches can be taken to implement advanced heat exchangers in the off-highway market. Approaches are discussed in each of these essential areas: materials, performance improvements, emissions, and new technology.

In the materials area, the goal to reduce weight in off-highway vehicles is driving the increased potential for aluminum heat exchangers. However, durability, fouling, and corrosion resistance of these materials need to be examined more thoroughly before wide adoption. Alternative technologies to soldered copper/brass heat exchangers are also being examined. Brazed copper (e.g., CuproBraze) products are being examined as a replacement for traditional soldered copper/brass heat exchangers. Process development must be thoroughly examined, and the cost differences between this process and the more traditional joining techniques must be understood.

Improvements in performance on the tube and fin side of heat exchangers are being examined to give incremental improvements over existing designs. These enhancements can be classified into passive and active techniques. Passive techniques include treated surfaces, rough surfaces, extended surfaces, displaced enhancement devices, swirl flow devices, coiled tubes, surface tension devices, and additives for liquids and gases. Active techniques include mechanical aids, surface vibration, fluid vibration, electric or magnetic fields, injection or suction, and jet impingement. On the tube side, the use of dimpled tubes is being examined to help turbulate liquid flow to increase heat transfer for a minimal pressure drop penalty. Other tube-side enhancement techniques include turbulence promoters in channels, oscillating flows, and electrohydrodynamics (EHD). Serpentine fin styles are being examined to improve performance and reduce cost. Types of serpentine fin styles include corrugated, wavy fins and louvered fins. Other fin-side improvements include perforated fins, vortex- generation devices, wire mesh fins, and carbon and metal foams. However, fouling issues must be addressed to better understand the applications to which these fins can be applied.

New technology items might include the use of totally different materials for the air- side heat-transfer surface, such as the use of graphite foam, which promises high thermal conductivity, but it is currently easily plugged and brittle. Use of nylon materials may enable lower cost, lower weight, and innovative shapes.

The use of primary surface exchangers may be possible for similar fluids. For some applications, lower cost materials could be explored, such as nylon.

The use of improved shapes (circular, cylindrical, or other exchanger shapes) could effectively use available open volumes in the engine compartment or enable more effective shapes for the given flow paths or aerodynamic fan types.

The use of air filtration to remove the debris from the cooling air could immediately open up the possibility of using denser, more aggressive fin designs in all fluid-to-air heat exchangers. To be successful, an air filtration device must be compact, have very low pressure drop, and may have to provide nearly engine combustion air cleanliness levels to the heat exchanger (see section on Filtration under the Air Subsystem).

Fluid/Thermal System Configurations

Status. The industry currently uses module combinations of heat exchangers in front-to-back and side-by-side configuration in the coolant air stream. Radiators, charge air coolers, oil coolers, and condensers are typically located in these modules.

Barriers. Cost, durability, and space requirements of these new configurations are the barriers to introducing this new technology. Engine definitions and technology changes are making the extent of these changes questionable. Some engines may require minor modifications to existing modules to meet emissions requirements while others may require the box-type configurations. Noise requirements may also drive the box-type configuration.

- Cost and efficiency of the fan drive are often significant factors that make the use of multiple fan/heat exchanger modules unacceptable to the machine designer. The typical fan drive in many off-highway machines is a constant drive ratio belt drive. Variable ratio fan drives, seen on all on-highway trucks, are not part of most off-highway machine cooling systems.

- Because of concerns about cross contamination of systems, most off-highway machines have separate sumps (and possibly different oil types) for the engine, transmission, hydraulic system, and other components. This makes combining systems to reduce the number of heat exchangers more difficult.

- The anticipated use of catalytic converters for emissions reduction is expected to reduce the available volume under the hood of the machine for the installation of components. These same catalysts will probably provide an added heat source to the engine compartment.

- Frontal area and system layout are often not dictated by the cooling system designer. Cooling system frontal area is typically dictated by outside factors, such as shipping requirements, and operator visibility. The location of the cooling system and direction of air flow can be dictated by visibility concerns (the fan stirs up too much dust), operator concerns (dust and/or heat is blown toward the operator), or other concerns (oil coolers mounted above the engine could leak oil onto a hot manifold).

Approach. Emissions and noise legislation are pushing the industry to examine new module arrangements, including compartmentalization of heat exchangers in box-type modules to reduce noise and increase heat exchanger surface area and use of alternative fan technology (such as mixed-flow and radial fans). Integration of EGR coolers into the fluid/thermal system may also require different configurations, depending on whether the EGR cooler is mounted to the engine and exchanges heat with the coolant or is included in the coolant module and cooled by air. In the latter case, high-temperature ambient air may need to have special ductwork to prevent melting of non-metallic components within the engine compartment.

Cost and space savings may drive the industry to look at combination heat exchangers. Oil coolers that cool both engine and transmission oils are in use today. Combinations of the radiator and condenser may also be examined. Because of increased charge-air-cooler temperatures from EGR, indirect charge air cooling may be required in more applications. For the indirect charge air cooling, the cooling module consists of a main radiator and a low-temperature radiator. The coolant flow in the low-temperature radiator is adjusted to reach temperatures below the charge-air-cooling target temperature. Although there are two steps in heat transfer, the better heat transfer from air to coolant allows the same heat transfer rate as the direct system.

Other combinations of low- and high-temperature exchangers, low- and high-temperature circuits, and multiple pumps and valves could be explored.

2.6.5 Air Subsystem

Technical Target. The primary technical target is to develop air subsystems that reject 30% more heat with less noise, similar input power, and similar overall package volumes as conventional air subsystems.

The air subsystem involves airflow management to the heat exchangers and may include airflow management for direct component cooling or underhood temperature control. Primary components are the heat exchangers, fan, fan installation, fan drive, air inlet/outlet ducts and grilles, noise-suppression elements, and filtration elements. The machine width, machine length, and machine height limit the size of the air system. These parameters are, in turn, constrained by operator visibility, machine balance/productivity, machine shipping requirements, and other key functional requirements. The fan may consume 5–10% of machine engine power or more and is one of the major — and sometimes dominant — sources of machine noise.

Heat Exchangers

Heat exchangers are discussed as part of the liquid/thermal subsystem. Air-side performance of heat exchangers is a critical element of the air subsystem's performance, playing a primary role in determining the required air and fan input power and fan sound power. Heat exchanger packages with increased heat transfer performance per unit area, acceptable restriction, and acceptable resistance to plugging are required. For a constant "frontal area," the core package should minimize the product of volumetric flow rate and total pressure losses (QP) to minimize air and fan input power and should minimize the pumping task (QP^2) to minimize fan sound power.

Fans and Shrouds

Status. The industry currently uses sheet metal or polymer axial-flow fans operating in fixed shrouds without multiple stages or stators. Typical fan blades are cambered plates or thin airfoils with little or no twist from hub to tip. The fans are typically engine-driven and engine-mounted and may operate in either pusher (blower) or puller (suction) modes. Some advanced applications are using non-axial fan technology and fans with rotating shrouds.

Typical shrouds are "box" transitions between the fan and exchangers, with an orifice or "knife-edge" in the box adjacent to the fan tip to help guide airflow into and out of the fan tip and prevent flow re-circulation. Adequate tip clearances are provided for relative motion of the engine (fan) and shroud (radiator) that is typically fixed to the frame. Some advanced applications use contoured shrouds and hydraulic motors to enable common-mounted fans and shrouds with reduced tip clearances.

Technical Targets. Technical targets include increasing overall air-moving device efficiency from 35–40% for current axial fans to over 65% and reducing sound levels at constant airflow and pressure by 10 dB(A).

Barriers. Barriers include the following:

- Optimization of current axial fans and other aerodynamic fan types is limited by quick and accurate aerodynamic design methods for open-running impellers, test costs of prototypes, cost and definition of standard *in-situ* test methods, and inventive use of materials and manufacturing processes for acceptable production costs in limited volumes.

- Use of blade sweep (bladed inclined in direction of rotation) may reduce noise, but it decreases fan strength and increases manufacturing complexity and costs.

- Optimization of shrouds is difficult because of inadequate models and generally requires *in-situ* testing for specific effects on flow, efficiency, and sound.

- Multiple stages — including inlet stators, outlet stators, series fans, or counter-rotating fans — are not used because of increased noise and added axial depth and cost.

- Inlet/outlet ducting (such as large bell-mouth inlets and vaneless exit diffusers) is similarly limited by space and cost.

- Mixed-flow, radial-flow, or cross-flow air-moving devices can provide performance or packaging advantages, but available components are unsuitable for off-highway machine cooling systems because of inadequate durability, compactness, cost, weight, sensitivity to high sealing or tip clearances, and/or noise.

- Other aerodynamic innovations have not been adequately developed or demonstrated in an off-highway machine air system.

Approach. The approach involves the following activities:

- Develop efficient methodologies for modeling fans with modern one-dimensional rapid CFD methods and detailed multiple-reference-frame three-dimensional CFD models and develop optimization methods to generate improved fan blades. Consider optimization of such features as variable camber, variable twist, variable chord length, thick airfoils, new airfoil thickness distributions, slotted airfoils, and blade sweep.

- Investigate feasibility of vaneless diffusers, inlet stators, outlet stators, bell-mouth inlets, inlet screening, and other devices affecting fan inlet and outlet conditions. Investigate shroud geometry, blade tip treatments, slotted shrouds, new rotating shrouds, forced secondary flows through the shroud, and other aerodynamic fan tip/shroud improvements by using CFD and laboratory tests. Develop improved methods and tools for rapid design of off-highway machine fan-stator systems.

- Use computational aeroacoustics or other time-based CFD approaches to better identify noise mechanisms associated with the fan and identify specific improvements for lower sound. Currently, no method is available to accurately estimate the noise level of a new fan design.

- Evaluate and demonstrate potential for other aerodynamic fan types in off-highway cooling systems, including mixed-flow fans, meridionally accelerated axial-flow fans, radial fans, forward-curved centrifugal fans, and cross-flow fans. Pursue fan optimization methods that are similar to those for axial-flow fans, as described above. Evaluate use of scrolls, volutes, and other flow-enhancement devices with these fan types.

- Develop fan designs for compact integration with the fan installation, shroud, stators, and motor packages and for manufacturing in moderate production volumes. Consider innovative use of non-metallic materials and production processes.

- Use rapid prototyping methods and installed fan tests to validate improvements in flow performance, efficiency, and fan sound power.

- Use new molding and joining processes for nonmetallic materials; consider new materials.

Fan Installation and System Restriction

Status. The fan size is constrained by the heat exchanger or "frontal area" and the fan depth by general machine length constraints and proximity to such components as exchangers, engines, and fan guards. In addition to affecting system restriction, proximate obstructions create distortion and turbulence that reduce fan efficiency and increase noise. Air system inlets and outlets use various restrictive grilles and screens to provide protection from rocks, trees, and other large and small debris. Flow paths are often "tortuous" because of obstructions, such as engines, and limited inlet and outlet locations and areas.

Technical Targets. Technical targets include defining installation requirements and innovative components to minimize fan performance degradation, excessive noise, and excessive air system restriction by 50% (excludes "useful" restriction of heat exchangers).

Barriers. Barriers include the following:

- Adequate methods to efficiently and effectively develop low-noise, efficient fan installations do not exist.

- Current models do not adequately predict effects of inlet distortion and turbulence on fan efficiency and noise.

- Machine tests are expensive and have limited control over experimental variables and control variables to investigate lower noise installations.

- Excessive inlet and outlet restrictions are limited by the cost of complex geometry:

- Current grille, screen, and opening designs are limited to simple geometry with typically abrupt, restrictive flow contractions and expansions. Cost-effective production of complex aerodynamic inlets and outlets, even if defined, are limited by many unique parts in small production volumes.

- Small inlet and outlet openings are used for protection, resulting in low net inlet area and high restriction; larger grille and screen areas reduce the enclosure sound attenuation for both fan and engine noise.

Approach. The approach involves the following activities:

- Investigate computational aeroacoustics and other time-based CFD methods for use in understanding/improving fan installation conditions.

- Consider designed experiments and test rigs to define key parameters and sensitivities of fan noise and efficiency to installation conditions.

- Use CFD methods to define critical inlet/outlet restrictions and devise improved openings and coverings that can be made by using lower-cost methods.

- Consider use of non-metallic materials and high-production "modules" that can be combined in parallel and series into various inlet/outlet sizes and protection grades.

Fan Drives

Status. Methods of fan drive include direct drive, viscous clutch, and on/off clutch technology. Advanced applications use hydraulic drives to provide continuously variable operation, despite low efficiencies from cost-effective pumps and motors. Clutch-based, variable-speed drives have been developed for some applications, but they lack reliability for the high absorbed power. Variable drives with continuously variable operation (as a function of ambient temperatures) provide lower average sound levels and significant advantages for certification relative to current European sound regulations.

Technical Target. The technical target is a highly reliable, continuously variable fan drive with over 90% efficiency.

Barriers. Compact, cost-effective, durable, high-efficiency, continuously variable fan drives are not commercially available. Potential mechanically driven, continuously variable concepts are expensive to develop and may not be cost-effective.

Approach. The approach involves the following activities:

- Define and investigate alternative concepts and drive systems developed for other applications that could be adapted for fan drives.

- Consider various CVTs using belts, cones, and steel bands and various power split CVTs that use efficient mechanical drive, planetary gear(s), and differential inputs controlled via clutches, variable-speed mechanical drives, hydraulic motors, and electric motors.

- Examine experience from automotive, machine tools, and other powertrain systems.

- Consider high-density, high-voltage drives as a direct method to implement variable speed control.

- Examine potential for advanced drives using alternative fan types or hub designs for a highly compact, integrated approach. Integrate drive elements as part of the fan hub for dual functionality.

Air Systems Configurations

The air system configuration includes the airflow mode, arrangement of exchangers (parallel, series, parallel-series, upstream of the fan, downstream of the fan, or both), number of fans, location and general geometry of the air system, use of air systems separate from the engine compartment, and use of multiple or distributed air systems.

Status. Typical air systems use heat exchangers packaged in parallel, series, or parallel-series in one to three core planes that are tightly coupled to a single axial-flow fan. The fan is most often engine-mounted and engine-driven. The flow path is either blower mode (airflow moves into the engine compartment, around the engine, through the fan, through the heat exchangers, and is ejected away from the machine — thus removing heat and dust away from the machine and operator) or suction mode (airflow enters the machine and heat exchangers and then moves through the fan, around the engine, and out of the engine compartment — providing improved fan flow conditions, cooler ambient air temperature to the exchangers, and reduced impingement of high-speed particles on the exchangers, resulting in reduced “sandblasting” wear).

Some installations use hydraulic fan drive motors, enabling the air system to operate in blower mode, but the exchanger and fan positions are reversed to improve flow conditions for the fan, improve fan efficiency, improve fan noise, reduce sand-blasting, and still eject hot air and dust away from the machine and operator.

Other air systems further separate the primary cooling air system from the engine compartment to enable improved engine noise attenuation. Separate air systems require some engine compartment ventilation (such as an exhaust venturi) to draw out engine compartment air, auxiliary fans, or fans with dual inlets (non-axial fans). Remote air systems may be used for cab HVAC condensers or for engine charge air cooling. Use of an air system for EGR cooling is described in the next section.

Technical Target. The technical target is to develop air system configurations that reduce the primary cooling air system volume by 30% or more.

Barriers. Barriers include the following:

- New aerodynamic fan types with different airflow paths can enable new air system configurations (e.g., cores both upstream and downstream, cores radially distributed around a centrifugal fan, fans with dual inlets, etc.), but design tools and installation knowledge for compact arrangements are lacking. These systems could provide improved thermal performance, lower fan input power, or lower fan sound power for a given package volume.

- Use of multiple fans, especially new fan types, can enable reduced package depth and new package shapes. However, costs and methods to drive multiple fans are cost-prohibitive.

- Use of separate air systems for larger machines requires more extensive engine compartment ventilation. Ventilation requirements and impact on underhood temperatures, primary cooling system heat loads, and underhood component materials, are largely unknown. Methods to ventilate engine compartments in a reliable, adequate manner have not been demonstrated.

- Use of multiple air systems can reduce the primary cooling air system size or sound power levels and the overall package volume/machine frontal area. Cost-effective fan drives, high-performance fans, and packaging analyses are required to develop these systems.

- Special-purpose multiple air systems can be used, but they require further concept and demonstration. A remote charge air-cooling package could use a small auxiliary, non-axial fan, but suitable and cost-effective components are not available. An air-cooled EGR system could be used to reject heat at higher temperatures, thus dramatically reducing (avoiding) heat rejection requirements of the primary cooling air system. Adequate design methods, suitable compact exchangers, exchanger fouling, and high-pressure fan components are lacking.

Approach. The approach involves the following activities:

- Investigate alternative fan types, potential exchanger configurations, use of multiple fans, potential package sizes and shapes, and machine packaging opportunities for various product types and sizes.

- Develop new fan and component models and lumped parameter methods to quantify various packages for equivalent cooling and sound.

- Apply CFD to refine concepts, improve flow distributions, investigate exchanger heat transfer performance effects of distributions, and define potential re-circulation problems.

- Build demonstration models to validate performance and discover installation trade-offs.

- Create acoustic and thermal models of separate engine compartments and determine trade-offs of engine noise reduction, underhood component temperatures, and adverse heat transfer effects.

- Consider energy-based noise models, use of statistical energy analysis, and numerical acoustical analysis methods to model engine enclosure acoustics.

- Develop models for acoustical boundary conditions (such as impedance).

- Validate the acoustics models.

- Consider lumped parameter models for underhood thermal analysis and CFD models to evaluate localized heat transfer and temperature distributions.

- Obtain engine and exhaust surface temperatures to drive the models.

- Validate the thermal models.

- Develop ventilation requirements and conceive novel means to ventilate the compartment. Demonstrate on a prototype machine.

- Develop air-cooled systems for charge air, EGR, or other auxiliary heat loads. This will require the development of new components.

- Demonstrate new machine air system configurations (further details for cooled EGR are described in the next section).

Cooled Exhaust Gas Recirculation

A potential path for controlling diesel engine emissions is EGR combined with cooling the EGR to maintain acceptable NO_X emissions. Cooled EGR imposes significantly higher heat loads on the primary cooling system that require larger air systems, expensive components, and likely operation at higher fan input power and sound levels. An alternative is to use a secondary air system for cooling the EGR.

Status. An air-cooled EGR system has not been adequately developed.

Barriers. Barriers include the following:

- A compact, gas-to-air heat exchanger is required that does not foul; a primary surface type could be developed for the required unique application.
- A small, high-pressure, cost-effective air-moving device is needed.
- A control system is needed to prevent condensation.

Approach. The approach involves the following activities:

- Develop a concept system, compact heat exchanger, and appropriate aerodynamic fan type.
- Demonstrate practicality, size, cost, and controls to prevent condensation.

Fan and Machine Noise Control

The air system has two major impacts on machine exterior sound power (regulated) and operator sound levels (market-driven): (1) cooling fans generate 10% to over 50% of overall machine noise and (2) the air system results in major airborne paths for engine noise, limiting its control.

Fan noise is aeroacoustic and generated by the rotating blades, non-aerodynamic blade shapes (flow separations), fan stall (overloaded blades), poor inlet environment (excess noise from inlet distortion and turbulence to the blades), and tip noise (high turbulence at tip clearance). Methods to improve blade geometry, fan installation, stators, and shrouding that impact these mechanisms are discussed in the section of Fans and Shrouds and Fan Installation and System Restriction.

The fan noise mechanisms and resulting fan sound power increase with speed. Thus, larger cooling systems or changes to reduce heat loads, increase fluid temperatures, reduce air-to-core temperature, or improve heat exchanger performance enable lower fan speed and lower fan noise. These methods are described in sections on Machine Thermal Sources, Higher

Temperature Machine Cooling, Liquid Thermal Subsystem, System Restriction, and Air System Configurations. Variable drives enable lower average fan speed and lower average fan noise.

This section discusses direct attenuation of the fan and engine noise based on the air system.

Status. For air systems that are integral with the engine compartment, acoustic louvers are used to attenuate both fan noise and engine noise. These are typically parallel baffles with rounded louver ends. Fiberglass or faced-foam absorption materials are located in the engine compartment to absorb both engine and fan noise.

For separated air systems, the engine noise is controlled by using a more complete enclosure with much less open area plus absorption materials.

Technical Target. The technical target is to develop noise-attenuation devices capable of 5 dB(A) net fan sound power reductions.

Barriers. Effective sound attenuation is limited by silencer depth and restriction. Noise attenuation of parallel acoustic louvers significantly increases with depth, but depth is highly limited on machines. Reduced open area also increases attenuation, but it also increases restriction, fan speed, and fan source noise, limiting attenuation. Complex aerodynamic shapes are not cost-effective because they require unique tooling and can be produced in only small volumes for each product type and size.

Blocking the line of sight with an acoustically lined airflow plenum, duct, or baffle increases attenuation, but it significantly increases air system restriction and space requirements.

Approach. The approach involves the following activities:

- Apply three-dimensional analysis methods, such as multi-domain numerical acoustic models and CFD, to define improved louver/baffles geometry considering both noise attenuation and flow restriction.
    - Examine the use of modular baffles that can be combined in parallel for larger air systems and in series for high sound attenuation levels.
    - Consider use of new non-metallic manufacturing processes and plastic welding to create low-cost acoustical silencers.
- Analyze use of three-dimensional silencers that attenuate sound but do not block flow (e.g., a vaneless diffuser). Examine synergy of new fan types and silencer designs to attenuate both fan noise and engine noise.
- Improve separate air systems using acoustical enclosure analysis.

- Consider energy-based noise models, use of statistical energy analysis, and numerical acoustical analysis methods to model engine enclosure acoustics.
- Develop models for acoustical boundary conditions (such as impedance).
- Validate the acoustics models.

Fouling

Status. Fouling is a very complex, time-dependent process that depends on numerous variables. Typical fouling in off-highway equipment is on the gas side of these heat exchangers, either on the air side or in the combustion exhaust gases. Understanding the characteristics of the fouling deposits is important. What are the “sticking” characteristics of these deposits? How do surface material, roughness, and temperature influence this “sticking”? How and where does the fouling start? What is the influence of local gas velocity? Oil? Are the deposits soft and flaky or rigid and adherent?

On the air side of heat exchangers, fouling usually occurs as a result of dust, dirt, and debris infiltrating the inlet area of the heat exchanger. Tests have shown that dust does not usually stick to a dry heat exchanger surface. Oils have been found instrumental in causing the dust to stick. Usually, this fouling is confined to the front core face such that the fouling behaves as if it were a perforated screen fixed to the front face of the core. Therefore, the cores least likely to suffer from the effects of fouling are those with large hydraulic diameter on the front face orifices. Second, having fin surfaces that can pass through the fouling material that does penetrate beyond the inlet is also critical. These include plate fins and square wave serpentine fins.

For combustion exhaust gases, fouling can occur in several ways: particulate fouling (deposit of “soot,” or oily substances); corrosion fouling (involving H_2SO_4 reaction products), and solidification fouling (dew point condensation). Therefore, the exact nature of the fouling deposit can vary with the type of diesel fuel used (may depend on the impurities and additives in the fuel) and the operating conditions of the engine. Fouling parameters include gas, wall, and dew-point temperatures; gas-to-wall temperature gradient; surface material, finish, and roughness; gas velocity, turbulence intensity, and shear stress at the gas-surface interface; particle shape, state, composition, concentration, and size distribution; and thermal, electromagnetic, and gravity forces acting on the particles.

Barriers. Mitigation of fouling can be difficult because (1) the passive techniques to reduce fouling typically are detrimental to thermal performance and (2) the active techniques to reduce fouling are costly.

Approach. The key to proper design is to understand the fouling process and then to try and configure the heat exchanger in such a way that fouling can be reduced and that cleaning can be easily accomplished. Heat exchangers should have large fin spacing and no stagnant, recirculating, low-gas-velocity regions in which fouling deposits may accumulate. Flow velocities should be high and as uniform as possible across the face of the heat exchanger. Also, whenever possible, one must avoid operating characteristics that promote a dirty fuel exhaust and accelerated fouling. The gas may be cleaned by using collectors, filters, precipitators, and other appropriate means.

Various techniques have been proposed to clean the heat exchanger surfaces. These include soot blowing with high-pressure air jets, oscillating the gas flow or vibrating the heat exchanger surface, using high-frequency acoustic waves, using thermal or chemical cleaning, using electrostatic fields, and using swirl devices.

Cleaning/Filtration Systems

Status. The industry currently relies on a variety of screens and louvered grills to prevent fouling of heat exchanger air-side surfaces. In addition, the industry relies on uninterrupted finned surfaces with reduced fin densities to prevent debris from lodging inside the heat exchangers. Systems are designed as much as possible for easy cleaning of the frontal area of the heat exchangers to the outside of the cooling system compartment.

Target. The target is to develop an air filtration system capable of very low maintenance that enables higher cooling system performance (i.e., enables high-density heat exchangers such that gains in heat transfer performance offset system restriction increases of the exchangers and filtration device).

Barriers. Passive filtration systems, such as filters, are not heavily used because of increased air-side pressure drop, maintenance, and cost. Active filtration systems, such as inertial separators, are not used because of high cost. Cleaning systems, such as high-pressure air jets, electrostatic fields, or chemical cleaning, are also not typically used because of cost considerations.

Approach. The approach involves the following activities:

- Examine improved passive swirl-type devices using CFD to optimize flow restriction and separation capability. Examine axial flow, cyclone type inertial separators such as those proven in military applications.

- Determine potential for higher-performance exchangers (higher-performing fin surfaces). Examine potential viability considering alternative aerodynamic fan types with higher-pressure capabilities.

- Consider use of alternative fans for both air-moving devices and inertial separation devices.

- Consider gas and particulate filters.

2.6.6 Thermal Management and Control

This section describes innovations and technologies related to reducing the effective cooling system heat loads by dissipating, averaging, and controlling thermal loads before the coolers.

Technical Target. The technical target is to develop thermal management systems that effectively require 20% less heat rejection from the primary machine cooling system while improving cab comfort at extreme ambient temperatures.

Fluid/Air Subsystem Controls

Status. Current off-highway diesel engine pumps for coolant, engine lube, and auxiliary systems operate proportionally with engine speed. Hydraulic pumps also operate proportional to engine speed, but they may include variable displacement with load feedback to minimize parasitic losses and input power. Fan drives are traditionally engine driven, but new fans may operate with hydraulic motors that allow variable-speed operation.

Technical Target. The technical target is to manage air and fluid flows to reduce parasitic losses and effective heat loads.

Barriers. Barriers are as follows:

- Pumps that are reliable, cost-effective, efficient, variable-speed, and controllable are not fully developed and commercially available.

- Continuously variable speed mechanical fan drives that are reliable, cost-effective, efficient, variable-speed, and controllable are not developed and commercially available.

- Dynamic cooling system (fluid/thermal/air subsystem) models and component models are not adequately developed.

- Methods to optimize overall system controls subject to various sound, emissions, and temperature constraints have not been developed.

- Control strategies are not well defined, especially for optimizing the machine, fluid, and air systems concurrently.

Approach. The approach involves the following activities:

- Use variable-speed electric pumps and variable-speed fan drives described earlier.

- Develop and validate lumped parameter models of the machine fluid/thermal systems, air systems, cooling system thermal inertias, machine thermal convection, machine thermal inertia (heat sink), pump dynamics, fan dynamics, and other thermal factors to enable dynamic thermal analysis and control system development.

- Develop methodologies using commercial codes (e.g., EASY5) and rapid control development tools (e.g., dSPACE) to enable modeling and control development for a large number of product types, work cycles, product sizes, and product variations in a cost-effective and timely manner.

- Use analysis and testing to define required constraints on all fluid temperatures (local peak, local average, system average), required coolant flow rates, required coolant pressures, and other relevant parameters.

- Define and develop control strategies to maintain temperatures (e.g., coolant, lube oil, powertrain, hydraulics, charge air) under various work cycles and due to various system thermal interactions.

- Ensure adequate flow and/or pressure to provide local engine cooling and to avoid boiling.

- Alternatively, define flow/pressure/temperature combinations to adequately control boiling.

- Determine how to control different fluid flow rates and fan drive speeds to optimize overall system efficiency (considering both fan and pump parasitic losses) and/or to reduce effective heat loads and required cooling system (exchanger) size.

- Develop optimum controls by considering trade-offs of various variable-speed pumps, variable airflow rate(s), interactions of various thermal systems, and acceptability of all fluid temperatures.

- Apply optimization methods to ensure overall system is optimized (i.e., separate optimization of air system and fluid system may be sub-optimal).

- Apply stability analysis methods to ensure multiple-input, multiple-output control stability.

Underhood Thermal Management

Status. Most current engine enclosures are integral with the cooling air subsystem (i.e., the significant cooling airflow for the exchangers also provides ventilation of the cooling compartment). Generally, underhood temperatures are less problematic with this arrangement. In blower (pusher) airflow models, flow entering the radiator often moves by the engine and exhaust systems, causing a rise in air-to-core temperature and the need for increased cooling airflow, resulting in increased fan input power and fan sound power. Predicting the air-to-core temperature rise above ambient temperature can be problematic. In suction (puller) models, heated airflow from the exchangers flows around the engine and exhaust. This airflow can result in higher temperatures in the engine compartment that can affect fuel temperature, cab air conditioner performance, and engine compartment temperatures (relative to electronics or non-metallic materials). Finally, sealed engine compartments are being used to meet more stringent sound regulations. These enclosures require forced ventilation.

Technical Target. The technical target is to improve thermal efficiency of the main cooling system by controlling underhood temperatures for blower mode air systems and separate air systems.

Barriers. Barriers include the following:

- Models for underhood thermal analysis of off-highway systems are not adequately developed.
- Ventilation requirements for underhood temperature control have not been defined.
- For separate air systems, ventilation means, use of active ventilation, and control of ventilation are not well defined.
- Detailed models that predict blower mode air-to-core temperature rise due to re-circulation within the fan are not adequate.

Approach. Both lumped parameter and three-dimensional CFD models should be developed for off-highway machine engine compartments that couple to one-dimensional engine, cooling, and exhaust system thermal models. Efficient modeling methods for engine compartments that lack ram air are needed to predict heat transfer, temperatures, distributed temperatures, and flow.

Adequate engine compartment ventilation means for separate air systems are required. A separate fan or use of main cooling fans with multiple inlets are options. Special ducting arrangements may also be used. Controllable fan speeds or ducts and control system strategies should be defined. The primary strategy is the control of underhood temperatures.

Advanced Controls/ Diagnostics

Given variable-speed fluid and air subsystems, additional improvements using advanced controls to optimize input power, sound power, or heat transfer for the entire system could be pursued. Second, various controls could be applied for "peak shaving" or even feed-forward to meet peak demands with a smaller air system. Information used for control could be used for systems diagnosis or operator warnings that enable corrective operation or service before cooling system overheating.

Approach. The approach involves developing more comprehensive control strategies that enable the control of multiple fluid pumps (coolant, engine lube, power train, hydraulic, compressor, etc.), control valves, thermostats, primary fan drive(s), ventilation fan drives, and EGR cooling fan drives that are subject to emissions requirements (e.g., charge air temperature or recirculated EGR temperature), sound requirements (lower average fan sound power), multiple fluid temperatures, multiple component temperatures, fluid system flow rate constraints, and fluid system pressure needs.

In addition, other tasks include:

- Developing optimum controls considering trade-offs of various variable-speed pumps, variable airflow rate(s), interactions of various thermal systems, and acceptability of all fluid temperatures.
- Applying optimization methods to ensure that the overall system is optimized (i.e., separate optimization of air system and fluid system may be sub-optimal).
- Optimizing underhood ventilation (e.g., to reduce fan speed and overall input power and sound power).
- Applying stability analysis methods to ensure multiple-input, multiple-output control stability.
- Enhancing control optimization for thermal dynamics and work cycle dynamics. Investigating the use of feedforward controls and/or adaptive controls to anticipate peak thermal loads and provide fluid and air system performance averaging.
- Investigating information from control sensors or algorithms that could be used to provide operator warnings relative to machine operation, ambient conditions, or service requirements. Diagnostic information could be used to define degradation in cooling component performance for proactive maintenance.

Distributed Cooling

Management of local component cooling is part of overall machine thermal management. This activity includes methods to increase natural convective heat transfer from components requiring cooling, methods to introduce or increase ventilation flows to increase convection, or active use of cooling fans (see Section 2.6.6 on Underhood Thermal Management and Control).

Where distributed cooling uses active localized cooling means or is affected by other elements of machine thermal management (such as fan speeds and underhood thermal management), distributed cooling should be integrated as part of overall underhood thermal management and/or fluid and air system controls. It may be possible to control localized cooling as part of an overall optimization strategy.

Cab Thermal Control

Status. Because of cost considerations and the lack of available technology for off-highway equipment, thermal storage devices are not used in today's equipment.

- Warming up the cab depends on engine waste heat rejection. In very low ambient temperatures, engine heat rejection is often not adequate to heat the cab to a comfortable level. This is especially true for low-power vehicles and in cases when there is little or no engine load. Also, cab temperature make take considerable time to increase. Efforts are made to insulate the cab to reduce the heat loss. Heater core capacity can also be increased to improve amount of heat provided to the cab.

- In high ambient temperatures, it is often found that too much heat is transferred from the engine compartment via engine fan blast and convection from the vehicle transmission system to the cab, especially when the vehicle is under load. This reduces the effectiveness of the cab air conditioning system. The following approaches are currently being considered: keeping the engine fan air flow away from the cab by controlling fan air flow direction, insulating the cab, and increasing refrigerating capacity of the air conditioning system.

Waste Heat Exploitation

Status. Waste energy from mechanical and combustion losses is not currently used. About 30% of engine output energy goes to the thermal system and is sent to heat exchangers or cooled by convection. This relatively low-grade heat energy can be difficult to use. Components that presently take advantage of this waste energy are turbochargers and cab heaters.

Efforts are being made to turn this heat into energy. Thermal storage, thermal generation, and thermal redirecting are the most promising methods. Thermal storage can take excess heat and store it in a container of high-heat-capacity fluid or similar media. This heat is then used during cold periods for cab heat or during cold start. Thermal generation can be accomplished in several ways. First, excess exhaust can be sent to a turbocharger and used to turn on an electric generator. This power can than be used to drive electric accessories or stored in batteries or capacitors. Similarly, heat pump configurations can generate power by creating a thermodynamic cycle of a special fluid, which evaporates and condenses, thereby creating energy. Another mode is direct conversion of heat to electricity by using the thermoelectric effect. Thermal redirecting is done by directing excess heat strategically to the areas of the vehicle that need it. Redirection can involve the better use of coolant and exhaust to warm up the engine quicker or maintain higher engine temperatures in extreme cold. Extra valves and/or heat exchangers are typically used.

Barriers. Cost is the largest barrier to any of the thermal regeneration systems. Such components as valves, pumps, and storage devices need to be added to effectively use this energy, adding cost, complexity, and weight. Efficient storage devices for the excess heat or electricity are also important for maximum use of the energy.

Size and packaging are a second major barrier because of the large amount of mass or volume required for the large amount of energy involved.

Cost, availability, and need have prevented this technology from being used in today’s off-highway equipment.

Approach. The approach involves the following activities:

- Control coolant flow rates, airflow rates, thermal inertia, and other cooling system parameters on the basis of temperatures and machine states to enable smaller cooling systems or maximize cooling system efficiency.

- Develop sensors and actuators to provide such control.

- Exploit peak shaving, higher temperature differentials, feed-forward, or anticipatory control, among other techniques.

- Exploit waste heat recovery, thermal storage, thermal conversions, etc. to recycle thermal energy.

- Use auxiliary ventilation devices and controls to limit engine compartment and related component temperatures. These may be part of the cooling system control.

To address insufficient cab heat and time required heating the cab, the following technologies should be considered: heat generation devices, heat storage systems, waste heat recovery systems, and heat pumps. Controls, auxiliary heat generation devices, heat pumps, and system configurations should be considered to provide the required thermal sources for emissions, engine, component, and operator warm-up under extreme conditions.

To maintain comfortable cab temperature in high ambient temperatures, the following approaches and technology should be investigated: effective methods of deflecting engine fan air discharge from the cab, cost-effective cab insulation materials and methods, and more efficient air conditioning systems.

Two types of thermal storage systems have the potential to be used in off-highway equipment: cold storage devices using gas hydrates and hot storage devices using eutectic salts. Gas hydrates are a class of solids in which small gas molecules occupy the voids in ice-like lattices of hydrogen-bonded water molecules. This increase in the stability of the crystal lattice leads to “ice” formation at elevated temperatures. Eutectic salts are salt compounds that change state between solid and liquid at a constant critical temperature and “store” the energy of transformation. Cool storage devices can be used primarily to improve air conditioning in the operator compartment. Applications include engine-off pre- and post-cooling of the operator compartment, improved air-conditioning transient performance during pull-down conditions, and improved air-conditioning idle performance. Eutectic salts have been used in the automotive field in heat storage batteries. A heat battery is a passive device capable of capturing energy from engine coolant in the form of heat, retaining it during engine-off periods, and releasing the energy back into the coolant immediately upon command. This heat can be used to preheat the operator compartment, improve the performance of windshield defrosting, reduce engine emissions, and reduce fuel consumption. In the latter two cases, heat from the battery is dumped directly to the engine, allowing faster warm-up that reduces emissions and fuel consumption.

Mathematical models should be analyzed to help estimate the savings associated with using thermal regeneration systems, determine optimal configuration, and define cost. Devices that can convert waste energy to electricity could have the most promise since the powertrains of the future will continue to move toward electrically driven components. Advanced storage methods, such as batteries, flywheels, or ultracapacitors, which are reliable, cost-effective, and efficient should also be emphasized.

2.6.7 Engineering Simulation and Models

Using machine and thermal systems simulations and various types of cooling system models is increasingly important to develop a machine with acceptable component temperatures, emissions controls, and sound levels within increasingly shorter product development cycles. Increasingly rapid changes in global competition, global regulations, and global product constraints demand shorter product development cycles. Development of machines with acceptable component temperatures is complicated by more complex air systems and multiple exchanger packages, more complex fluid/thermal systems with multiple cooling fluids and circuits, more stringent constraints (noise, emissions, packaging, costs, etc.), a large number of system interactions (underhood temperatures and cooling systems, work cycles on component heat loads with independent coolers, interaction of different cooling systems, interaction of controls, etc.), and potential use of complex controls with conflicting requirements and potential instabilities.

General simulation and modeling needs include:

- Simulation and prediction of heat loads (steady-state, work cycle, transient);
- Simulation and prediction of underhood heat transfer and temperatures;
- Simulation and prediction of cooling system performance (fluid/ thermal systems and air subsystems), including rapid analysis, synthesis, and optimization of cooling systems; and
- Integration of cooling system and machine performance.

Technical Target. The technical target is to create, design, analyze, simulate, and test technologies that enable cost-effective development of complex machine thermal and cooling systems within a several-week product development cycle.

Heat Load Prediction

Prediction of heat loads is a fundamental input for machine thermal management and cooling system design. Diesel engine cooling is typically 60–70% of overall machine heat loads, with significant cooling required for various powertrain elements, hydraulic systems, and cab HVAC systems. Emissions systems result in a new element of engine cooling for charge air and/or EGR. The heat load of many components depends on the component installation design, system design, and operation over typical work cycles.

Status: Engines. Engine heat loads are generally determined on the basis of specific engine performance tests under limited conditions of engine load, speed, and ambient conditions, for example. Engine cycle simulations based on lumped parameter (one-dimensional) gas dynamics can be used to predict engine performance and, with measured exhaust temperatures, engine heat loads. These models, in turn, can be used with empirical data to define heat loads and heat load splits to the engine jacket water, lube systems, and charge air systems. Such models can predict heat load variations with some engine parameters, such as speed and load or altitude, and over a machine work cycle. These types of models have been used extensively for analyzing engine performance trade-offs, but not for predicting heat load.

More detailed three-dimensional models are also used, but they are generally for localized design issues. Detailed CFD combustion models represent the state of the art in engine performance simulation. Detailed finite element analysis models (FEA) can be used for both structural and thermal work, but they are generally targeted toward prediction of thermal stresses and fatigue, not heat transfer from the engine. FEA models are often steady state, but they are beginning to be used for transient analysis of thermal test cycles in light-duty applications. The calculations model a three-dimensional geometry and are often labor- and computer-intensive and do not provide a detailed analysis of the fluid side (coolant or oil).

Status: Powertrain. Most predictions of powertrain heat loads are based on historical information. Changes in the overall system configuration, components, or machine operation (due to changes in powertrain configuration, machine application, operator control systems, etc.) generally require machine build and cooling tests over work cycles to accurately identify heat loads. Numerical CFD models are applied to improve fluid flow efficiencies but have not been generally applied to predict the amount of heat generated from pumping losses, torque converter losses, windage losses, and clutch losses. FEA structural models have been used for localized cooling, but not for overall component heat load prediction via coupling to a coolant model or to the environment via a free or forced convection model. These coupled models could include either lumped parameter models or CFD models of the internal fluid flow and of the external free/forced surface convection (natural cooling).

Status: Hydraulic Systems. Most predictions of hydraulic heat loads are based on historical information. Changes in the overall system configuration, components (such as pumps, motors, and valves), installation of these components, or operation of these components (e.g., due to changes in the component, machine configuration, machine application, operator controls, automation) generally require machine build and cooling tests completed over work cycles to accurately identify heat loads.

Lumped parameter steady-state and transient models of hydraulic systems are frequently used to analyze and design hydraulic systems, their components, and integration into machine systems. These models are often used to analyze performance (speed and force), stability, and efficiency. These models are also used to estimate heat generated due to inefficiencies in the hydraulic system, but methods have not been developed to accurately quantify the heat load imposed on the cooling system, which requires the prediction of heat transferred from these components to the environment (conduction and convection) and to the machine as a heat sink (conduction). Another aspect is the modeling and validation of transient heat loads.

Status: HVAC Systems. These heat loads are often estimated on the basis of historical experience with existing systems, expected cab heat loads, and typical machine applications. Use of one-dimensional tools that can model the HVAC system, including two-phase flow, is emerging.

Barriers. Barriers include the following:

- Inadequate experience, test data, and calibration factors to predict engine heat loads using one-dimensional gas dynamics models.
- Excessive time and cost, plus limited experience using numerical methods for predicting engine heat generation, conduction, and convection into various cooling fluids and into the environment.
- Inadequate models of powertrain losses, heat generation, dispersion of the heat throughout the transmission or gear case, and convection into the cooling fluids or environment.

- Inadequate models of hydraulic components to determine inefficiencies and heat generated.

- Inadequate models of conduction/convection from hydraulic thermal sources into other machine elements.

- Definition of machine work cycles and conditions for adequate, accurate heat load generation.

- Lack of efficient, timely methods for integration or co-simulation of complex engine, powertrain, and hydraulic heat generation phenomena with three-dimensional CFD and/or FEA models into one-dimensional system lumped parameter models.

Approach. The approach involves the following activities:

- Extensive use of commercial one-dimensional tools and methods to model various heat-generating elements is required.

- Component tests to develop semi-empirical relationships are required under various component operating conditions and boundary conditions.

- Controlled experiments in component test laboratories and then on machines are essential to validate these tools and understand their capabilities and deficiencies.

- Use of numerical models to understand and refine one-dimensional models in critical areas of heat conduction and convection is required.

- Definition of machine work cycles and component operation cycles is vital to establish both average and work cycle component heat loads.

In addition, CFD or convection factors could be used to determine the amount of heat naturally convected from hydraulic components, as they are less massive and have higher surface area than an engine or transmission. FEA could be used to determine conduction from the hydraulic component if mounted onto massive machine structures (heat sinks). Both CFD methods and FEA methods should be developed to predict heat transfer from large components, such as engines and transmissions.

Underhood Thermal Simulation

Increased underhood temperatures are resulting from better sealed engine compartments because of sound regulations, increased congestion from larger exchangers, air-to-air charge air cooling, exhaust systems incorporating aftertreatments, potential EGR coolers, electronic components, lower hood lines, and increased underhood thermal sources (exhaust surface area, heat-generating catalysts, additional heat from EGR and charge-air systems, etc). High underhood temperatures result in unacceptable underhood component temperatures and increased heat transfer to fuel systems, adjacent cabs, enclosure cooling fluid systems, and adjacent cooling air subsystems. Underhood thermal simulation is used to predict and modify underhood ventilation systems to obtain acceptable component temperatures and to understand and mitigate adverse thermal effects on other machine systems.

Status. Underhood thermal models for off-highway equipment have not been rigorously developed since engine compartments have generally been open, ventilated by the main cooling fan, and contained less-critical components. Some three-dimensional CFD models for compartment airflow have been developed, some CFD temperature work has been done, and some techniques could be borrowed from extensive underhood CFD thermal modeling in the automotive industry. However, unlike the automotive problem, separate off-highway machine engine compartments operate under conditions of maximum heat load without ram air and have extensive, complex, hot surfaces that provide the bulk of underhood heat. Lumped parameter models have been made for cooling systems (heat loads and cooling components), but they generally lack effects of heat transfer into and out of a closed engine compartment.

Barriers. Barriers include the following:

- Models for convective heat transfer from engine, exhaust, and other critical underhood heat transfer components are not well developed for low airflow velocities.

- The overall flow path may be very complex where the engine compartment is open to other internal machine compartments.

- CFD models are not timely and are too expensive for modeling dozens of unique product types, product sizes, and enclosure configurations for relatively low- volume machines.

- Required detail for CFD models of complex engine and exhaust geometry is not well defined.

Approach. The approach involves the following activities:

- Develop CFD thermal models that include adequate and validated methods to model convective heat transfer from hot components (engine, exhaust) to cooler components within a relatively sealed engine compartment with low flows (no ram air).

- Evaluate and model effects of radiation heat transfer, especially for extensive underhood exhaust systems.

- Validate overall model for steady-state and work cycle engine operations.

- Use the validated three-dimensional CFD approach and experimental design methods to develop more general one-dimensional surrogate models and/or develop efficient means to couple these models into lumped parameter machine thermal simulations or into rapid cooling system models. Apply knowledge from automotive and/or on-highway truck industry as appropriate.

Cooling System Models

Cooling system models generally include the heat loads as inputs and model the fluid system, heat exchanger, air system, and fan.

Status. Cooling system models generally include the heat loads as inputs and model the fluid system, heat exchanger, air system, and fan. These models generally rely on lumped parameter air system and fluid system approaches coupled to component performance data for heat exchangers and fans. Fan and exchanger data are often obtained under standard, ideal conditions and de-rated for the machine installation, on the basis of experience. These models are primarily used for analysis, rather than design synthesis or direct design optimization. Commercial codes are available to facilitate these models (e.g., KULI and FLOWMASTER).

Three-dimensional CFD models may be needed to model the air system, especially where flow distributions to different heat exchangers are critical or where installation geometry is restrictive and complex. Surrogate fan models are used to represent the fan as a source of flow and pressure and to provide a more realistic flow distribution “input” to the air system model. CFD models remain expensive and not very timely, especially where a large number of alternatives are under consideration.

Fan sound power is estimated on the basis of experience or proprietary equations, along with standard tests of sound power (e.g., fan operated with free inlet and free outlet).

The final prediction of machine “ambient temperature capability” is much improved, but it often lacks sufficient accuracy to avoid some machine redesigning, building, and testing to achieve the required cooling within more stringent and precise constraints on fan sound power, package size, and emissions cooling.

Barriers. Barriers include the following:

- Ability to parametrically synthesize designs and optimize cooling system parameters concurrent with component parameters is limited because of the use of component models consisting of component-specific laboratory data.

- Adequate models do not exist for installation effects (e.g., flow distribution, temperature distribution, turbulence, etc.) on fan performance, exchanger performance, and sound levels

- Accurate models for air systems using CFD are time-consuming, expensive, and lack adequate fan models.

- Application of computational aeroacoustics or other time-based CFD methods is cost-prohibitive in terms of understanding fundamental fan aeroacoustics and installation effects on aeroacoustics and developing acoustic improvements to the fan and installation.

Approach. The approach involves the following activities:

- Develop math models of component performance as a function of component parameters.

  - Quantify, via experiments, typical installation effects on fan performance, fan noise, exchanger restriction, and exchanger thermal performance.

  - Develop math models for installation effects (de-rating factors for fan performance, fan noise, exchanger restrictions, and/or exchanger performance) or for installed component performance.

  - Use designed experiments for test rigs with fans and exchangers.

  - Consider using off-line CFD models and designing experiments over the design space to develop surrogate models for fan performance, fan noise, and airflow distributions.

- For overall air systems or unique air systems, develop faster CFD methods, such as improved meshing methods, machine air system templates, parametric CFD methods, and use of digital fluid dynamics (finite different methods).

  - Develop standard methods for co-simulation of lumped parameter system models and localized three-dimensional CFD models to enable rapid analysis and improved accuracy for critical, complex air system elements.

  - Demonstrate and develop optimization methods.

  - Integrate cooling system model with overall machine thermal simulation model (next section).

- Develop standard definitions of product work cycles suitable for use in cooling system design.

  - Collect ongoing machine temperature data for critical components, fluids, and ambient conditions.

- Instrument and test machines to define operation, performance, and corresponding heat loads and temperatures.

Machine Thermal Systems Simulation

Overall machine thermal simulation is essential to model heat loads, underhood thermal effects, cooling fluid/thermal systems, cooling air systems, and various machine temperatures in the context of various machine applications, operation, work cycles, and performance levels. This enables design, control, and optimization at the overall machine systems level for both machine and cooling system design and performance. These models may include the engine, powertrain, implements, machine/soil interaction, soil/rock, operator, automated control system, and thermal models.

Status. Lumped parameter machine simulation is often done by using flexible modeling codes that simulate overall machine dynamics, such as DADS or ADAMS, or simulate performance and dynamics (including engine, powertrain, and hydraulic system dynamics), such as SIMULINK or EASY5. Additionally, these models can aid in the simulation and analysis of controls. These models could be used for thermal analysis concurrently with machine dynamics and performance analyses, given available heat load models, heat dissipation models, and acceptable cooling system component models.

Barriers. Barriers include the following:

- Adequate models or required test data for heat loads and underhood thermal management may not be available for the particular machine systems model.

- Overall systems model is complex and may require co-simulation with subsystem models for adequate model speed and component model accuracy.

- Models of thermal systems dynamics (machine thermal inertias, cooling thermal inertias, and thermal control systems) are not generally available.

- Models of thermal system controls require validation.

- Operator effects on machine operation and heat loads are significant and are not modeled.

Approach. The approach involves the following activities:

- Demonstrate the ability and gaps for an overall machine system thermal model by using a lumped parameter code suitable for modeling machine dynamics, machine performance (engines, powertrains, hydraulics, work cycles), and machine cooling.

- Benchmark the model speed, accuracy, and timeliness and improve those parameters.

- Develop methods to co-simulate or exchange data with other three-dimensional tools and one-dimensional subsystem models to improve accuracy and minimize cost of overall systems modeling.

- Conceive of thermal dynamics models of thermal system and cooling system components and perform real-time instrumented machine tests to validate these models.

- Improve the fidelity of engine, powertrain, and hydraulics dynamics models and transient heat generation, especially for highly transient heat loads, such as braking, flow over relief valves, and other stall phenomena.

- Work toward developing a virtual machine performance and cooling systems model.

- Long term, develop operator models by using artificial intelligence or develop machine simulators that allow operator-in-the-loop simulations.

- Use these methods to define work cycles for new machine types, new machine configurations, new powertrain concepts, and new operator controls.

- Use these work cycles and machine thermal simulations to derive new work cycle heat loads. This allows proper development of cooling systems without building and testing a new machine.

2.6.8 References

SAE: Society of Automotive Engineers

SAE, 2000, Proceedings 5th Vehicle Thermal Management Systems Conference, SAE p. 363, Nashville, TN, May 14–17.

USDOE: U.S. Department of Energy

USDOE, 2000, "Technology Roadmap for the 21st Century Truck Program" [url http://www-db.research.anl.gov/db1/ohvt/document/DDD/62.pdf (as of December 1, 2001)], Dec.

3 SCHEDULE AND MILESTONES

The program schedule and milestones developed by the groups are given in Table 3.1. The milestones are general; more specific milestones will be developed after a more detailed assessment of technology options early in the program.

On the basis of input from the industrial participants, initial estimates of resource needs for FY 2003 are listed in Table 3.2. For industry to meet the goals described in this roadmap, it is likely that this level of funding needs to be sustained for at least for five years (FY 2003–2007).

TABLE 3.1 Off-Highway Program Schedule and Milestones

Program Element	2006	2010
Engine/Aftertreatment and Fuels/Lubes	Maintain Tier 2 fuel efficiency while meeting Tier 3 emission standards	Improve fuel economy by 5% compared with Tier 2 products; meet Tier 4 emission standards, non-petroleum fuel-capable where appropriate
Machine System		Reduce system loads by 21%
Thermal Management		Provide a 65% increase in cooling capacity

TABLE 3.2 Initial Resource Needs, Off-Highway Research and Development

Category	Recommended Government Funding, FY 2003[26] (in $ millions)
Engine	
Systems analysis/performance measures	0.5
Emissions controls	5.0
Systems	
Systems analysis	0.5
All-electric accessories/replace hydraulics	1.5
Noise, vibration, harshness/thermal cycles	3.5
Thermal management	3.0
Auxiliary systems optimization	0.5
Sensors/diagnostics	0.5
Hybrid systems	0.75
Fuels	
Improved fuels and lubes	0.5
Propulsion materials	1.5
High-strength weight-reduction materials	0.5
Total	18.25

[26] Assumes 50% cost-share by industry.

APPENDIX:

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