Multiyear Program Plan
Advanced Petroleum-Based Fuels (APBF) RD&T for Compression-Ignition, Direct-Injection Engines and Emission Control Systems

Office of Advanced Automotive Technologies
Office of Heavy Vehicle Technologies
Energy Efficiency and Renewable Energy

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Executive Summary

This document is the Multiyear Program Plan (MYPP) for the U.S. Department of Energy's (DOE) Advanced Petroleum-Based Fuels (APBF) Program. This document lays out the research, development, and testing (RD&T) plans for fiscal years 2000 through 2004 of DOE's Office of Advanced Automotive Technologies and Office of Heavy Vehicle Technologies in collaboration with industry, academia, and other government agency partners. The APBF Program covers RD&T on advanced petroleum-based fuels for compression-ignition, direct-injection (CIDI) engines and emission control systems for on-road vehicles (i.e., vehicles spanning from automobiles, light trucks, and Class 7 and 8 heavy trucks).

The mission of the APBF Program is to identify and document the capability that cost-effective, advanced petroleum-based fuels and non-petroleum blending components have to enable light-duty vehicles and heavy-duty engines to meet future emissions standards while maintaining continuous improvement in engine efficiency and durability. As such, the APBF Program is an enabling program. The results will be used by DOE's CIDI engine and emission control R&D programs to enable these programs to meet their technical targets for emissions and efficiency.

The principal outputs of the APBF Program will be data, recommendations to the automotive CIDI and heavy-duty engine programs to meet respective light-duty and heavy-duty emissions targets, and an improved understanding of the effects of fuel and lubricant properties on engine emissions and exhaust emission control as well as on energy efficiency. The relationships between fuel and lubricant properties, emissions, and efficiency will be documented from the program database of results. Assessments will be provided for: (1) economics of fuel production, (2) compatibility of fuels with existing infrastructure for delivering and storing fuel, (3) health and safety properties of the liquid fuels, (4) consumer acceptance issues (e.g., odor and noise), and (5) life-cycle emissions of greenhouse gases and criteria pollutants.

The technical approach has four major experimental tasks: fuel and lubricant property effects on engine-out emissions and on emission control (e.g., exhaust emission control system) performance, data-derived model development and validation, and vehicle compatibility testing. A systems approach will be implemented to examine the effects of fuel, engine operations, and emission control systems on reduction of nitrogen oxides (NO_x) and particulate matter (PM) emissions. Periodic system analysis will be conducted for three specific platforms: automobile, light truck, and heavy-duty engine. These analyses will be used to monitor progress towards meeting targets for emissions reduction and to guide the RD&T along the optimal pathways towards the program goals. Supporting analyses will assess health and safety, consumer acceptance, infrastructure, and economics. The supporting analyses will leverage as much information as possible from ongoing government and industry programs.

The technical approach is designed to overcome technical barriers related to fuel and lubricant effects on emissions and engine and emission control performance. Overcoming these barriers will lead to attainment of the technical targets established for the program. Attainment of these targets will enable DOE's engine and emission control R&D to meet their objectives and achieve DOE's vision for energy efficient, environmentally sustainable transportation.

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1.0 Introduction

This document is the Multiyear Program Plan (MYPP) for the U.S. Department of Energy's (DOE) Advanced Petroleum-Based Fuels (APBF) Program. The APBF Program MYPP lays out the research, development, and testing (RD&T) plans of DOE's Offices of Advanced Automotive Technologies (OAAT) and Heavy Vehicle Technologies (OHVT) for fiscal years 2000-2004.

1.1 Purpose of the Multiyear Program Plan

This MYPP directs RD&T on advanced petroleum-based fuels for compression-ignition, direct-injection (CIDI) engines and their emission control systems for light-duty vehicles and heavy-duty engines (HDE). It will be used by DOE as a framework for collaborative fuels RD&T with the private sector and other government agencies. Major stakeholders assisting in review of the plan and in conducting RD&T are: energy companies, automobile manufacturers, engine manufacturers, emission control manufacturers, the U.S. Environmental Protection Agency (EPA), and the U.S. Department of Commerce.

1.2 Program Mission

The mission of this program is to identify and establish the capability of advanced petroleum-based fuels and non-petroleum fuel blending components to enable light-duty CIDI vehicles and heavy-duty CIDI engine technologies to:

- maintain continuous improvement in engine efficiency and durability
- meet projected emission standards in the period 2000 to 2010
- meet additional potential constraints (e.g. emissions of toxics, ultrafine particulate matter (PM), greenhouse gases)

1.3 Nature of Advanced Petroleum-Based Fuels

Advanced petroleum-based fuels are envisioned by DOE to have properties that enable the next generation CIDI engines and emission control systems to meet future applicable emission standards and operate with high energy efficiency. An advanced petroleum-based fuel may consist of a highly refined petroleum base blended with non-petroleum derived blending components. These blending components could be derived from renewable resources such as biomass. As a system, advanced petroleum-based fuels, CIDI engines, and emission control devices have the potential to: (1) decrease consumption of imported petroleum, (2) improve emissions performance of existing vehicles, and (3) open pathways to meet future emission standards. Fuel formulations for advanced CIDI engines and their emission control systems will be:

- suitable for compression ignition engines
- widely available in commerce
- compatible with infrastructure for liquid fuels
- cost effective
- safe for the public and the environment

1.4 Expected Products and Outcomes of DOE Sponsored RD&T

The expected products of the APBF Program are:

- Data on:
  - Tailpipe emissions reduction achievable through advanced fuel formulations

  - Effects of new fuel blending components and advanced fuel formulations on (1) engine-out emissions and (2) performance of emission control devices
  - Effects of advanced lubricants on both engine and emission control system operations
  - Engine efficiency and fuel economy for CIDI engine programs
- Empirical relationships between fuel properties and emissions
- Supporting analyses of:
  - Cost of producing different fuel options being investigated
  - Benefit-to-cost tradeoffs for emission reduction
  - Safety and health properties of fuel constituents
  - Combustion kinetics and emission forming mechanisms

The U.S. EPA is now engaged in three major regulatory actions for which the APBF Program will provide timely information:

- Model year (MY) 2004 emission standards for heavy-duty engines (implementation scheduled in MY 2002 as a result of the Consent Decree between the EPA, Department of Justice, and the manufacturers of heavy-duty engines)
- Proposed heavy-duty engine and vehicle standards that will take effect in 2007
- Highway diesel fuel sulfur control requirements

The Advanced Notice of Proposed Rulemaking for regulation of diesel fuel quality was published in May 1999, and the Final Proposed Rule was released in May 2000. The technology review for the MY 2004 heavy-duty engine emissions standards took place in 1999, and a Final Rule was released in October 1999. EPA may engage in a technology review for the MY 2007 heavy-duty engine standards and the diesel fuel sulfur control requirements during the 2003-2004 time period.

Thus, key time periods for RD&T results from the APBF Program are:

- 2000 to 2004 for potential technology reviews for the proposed MY 2007 heavy-duty engine emission standards and diesel fuel sulfur requirements which affect light duty (i.e., meet Tier 2)
- 2004 to 2010 for data on other potential emission constraints to guide government and industry in preparing for future CIDI fuels beyond 2010

The emphasis of the APBF Program is on two time periods driven by anticipated regulatory measures with an ongoing lesser effort preparing for the longer-term. Data collected will establish the relationships between fuel and lubricant properties and (1) engine operation and emissions and (2) efficacy and durability of emission control systems. These results will provide valuable information within the context of the regulatory environment (see Figure 1).

1.5 Relationship of the MYPP to Other DOE Programs and Documents

This MYPP serves to define the program elements of the *OAAT R&D Plan* [1] and the *OHVT Technology Roadmap* [2][*] programs. This MYPP covers RD&T on fuels and lubricants within the context of the R&D programs conducted by OAAT and OHVT on engines and emission control systems for vehicle platforms spanning automobiles through heavy vehicles. As such, it is complementary to DOE's technical roadmap on CIDI engines and emission control systems. [3,4]

[*]Numbers in brackets refer to the references listed at the end of the MYPP

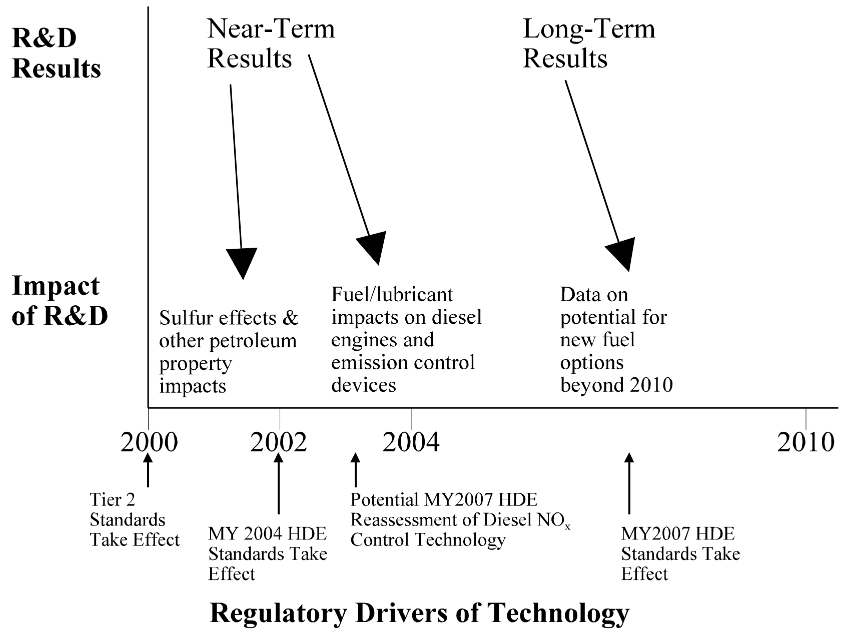

Figure 1: **Timeline for APBF RD&T Results**

1.6 Basis for the MYPP

This MYPP has, as its foundation, the following principles:

- Over the next three decades, motor vehicle fuels for CIDI engines will be predominantly based on petroleum-derived components
- Both petroleum-based and non-petroleum-based components will be evaluated as blending options for advanced petroleum based fuels
- Non-petroleum-based components will include liquids derived from Fischer-Tropsch processing as well as renewable sources
- Fuels will be compatible with compression ignition engines
- Fuels will be applicable for engines across a range of vehicle platforms spanning automobiles through heavy-duty vehicles
- Results from the RD&T program conducted over the period 2000-2004 will be available for consideration for near-term and longer-term needs in the regulatory environment of the United States
- Industry participates in the development of the MYPP by means of review and comment
- The technical approach in this MYPP is designed to overcome technical barriers to achieving a series of technical targets. Meeting the targets will achieve the mission of the APBF Program.
- The APBF Program is an enabling technology program. The results will enable DOE's CIDI engine and emission control R&D programs to meet their technical objectives

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2.0 Status of CIDI Engines, Emission Controls, and Fuels

The United States faces major challenges in meeting its growing needs for personal mobility and commercial transport on our roadways. These challenges encompass our continued dependence on imported petroleum for motor vehicle fuels and the impacts of their use on public health and the environment. The situation that we face, which has led DOE to establish the APBF Program, is summarized in this section.

2.1 Motor Vehicle Fuels and Emissions

The U.S. transportation sector is 97 percent dependent upon petroleum fuels [5]. Petroleum imports are projected to increase from about 52 percent of domestic consumption in 1998 to 64 percent in 2020 [6]. As a consequence, DOE's Office of Transportation Technologies has established its RD&T programs to achieve its vision that "*within the first decade of the 21st century, the United States will turn the corner in the growth of petroleum use for highway transportation*"[7]. A key aspect of DOE's strategy is to develop, in partnership with industry, more fuel-efficient power systems (i.e., engine-fuel-emission control system) that will penetrate the marketplace. By virtue of their inherent high-efficiency, CIDI engine technologies are the focus of DOE's RD&T for both light and heavy-vehicle platforms, and represent a key technology to enable the Partnership for a New Generation of Vehicles' (PNGV) goal of up to 80 miles per gallon (mpg) (gasoline equivalent) for a mid-size vehicle. Fuel formulations to enable CIDI engines to meet their emissions and efficiency targets are the focus of the APBF Program.

2.2 CIDI Engines

2.2.1 Heavy-Duty Diesels

Due to their high efficiency and reliability, diesel engines are the dominant power source for heavy-duty trucks and for city and intracity buses in the United States, and they are the preferred power source for commercial surface transportation worldwide. CIDI engines are the most efficient energy conversion devices currently available, with very large units (e.g., land-based and marine engines) exceeding 50 percent thermal efficiency. Turbocharged diesels for highway trucks are now offered that exceed 46 percent efficiency, an improvement of about 40 percent relative to diesel engines of the late 1970s (see Figure 2). The diesel-engine industry believes that heavy-duty diesel engine efficiency can be increased to 50 percent in the next few years, even with accelerated implementation of stricter emissions regulations.

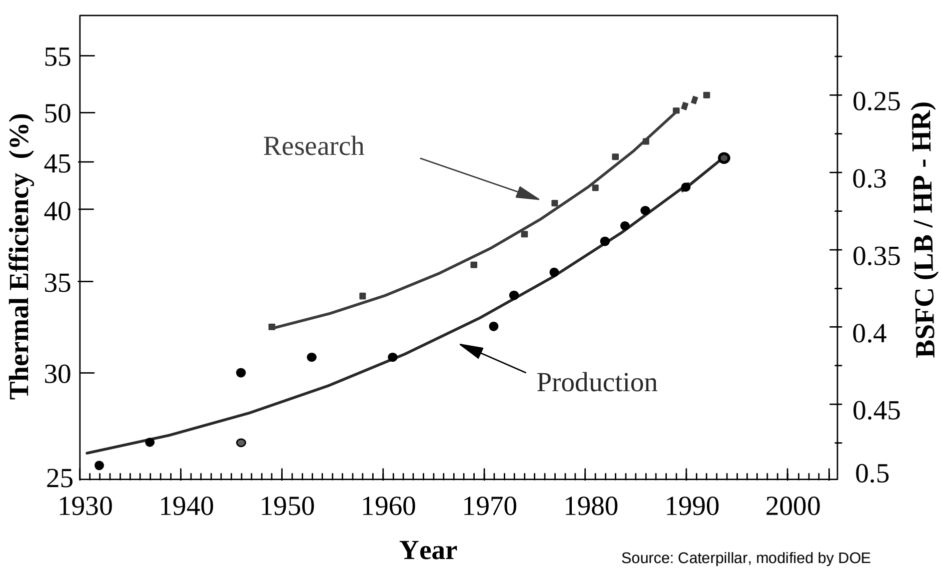
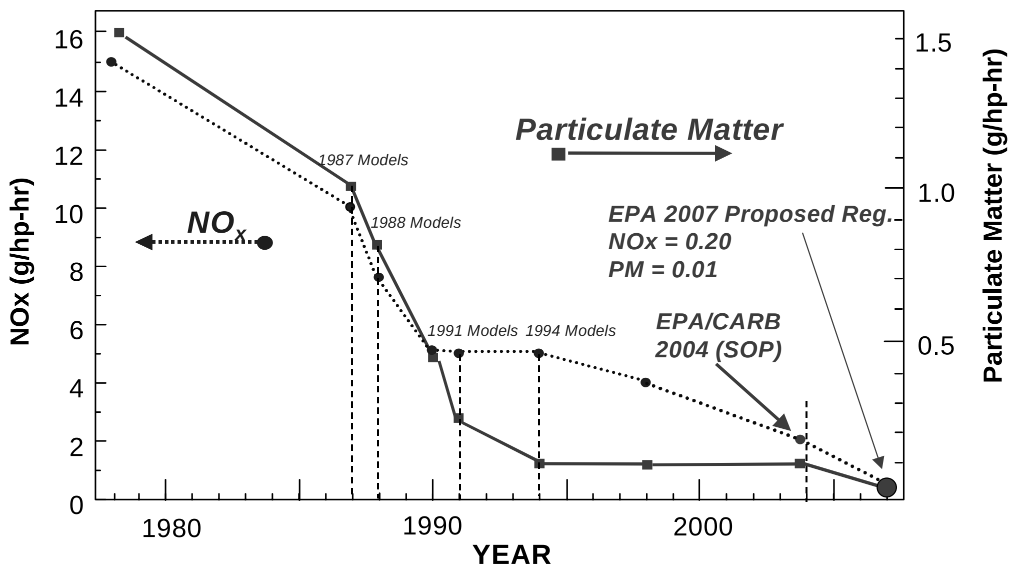


Figure 2: Diesel Cycle Engine Efficiency Development History

Today's heavy-duty diesel engine emissions are regulated to 4.0 g/bhp-hr of NO_x and 0.10 g/bhp-hr of PM (<0.05 g/bhp-hr of PM for transit buses), which represent significant reductions from uncontrolled engines. To date, progress in emission control has been achieved primarily through retarding fuel injection timing, increasing the injection pressure, and other design changes (see Figure 3). In 1996, the EPA, the State of California, and major engine manufacturers prepared a "Statement of Principles (SOP)" [8] that required further reductions to 2.4 g/bhp-hr of NO_x plus non-methane hydrocarbons (NMHC) or 2.5 g/bhp-hr of NO_x plus NMHC with a maximum of 0.5 g/bhp-hr of NMHC by 2004 (see Table 1). These emission levels are believed to be achievable through the use of cooled exhaust gas recirculation (EGR), though durability is a concern with the current level of sulfur in the fuel, and efficiency is significantly degraded. Recent action by the EPA and Department of Justice resulted in a "Consent Decree" with the diesel engine manufacturers that moves the SOP requirements up to the year 2002. (The EPA has proposed more stringent heavy-duty diesel standards to go into effect in model year 2007 which will likely require the use of exhaust emission control devices of some type.) [9] A consensus about testing protocols to indicate achievement of Tier 2 standards has not yet been formed.



Source: Cummins, modified by DOE

Figure 3: Evolution of Heavy-Duty Diesel Cycle Engine Emissions Control

Table 1. Heavy-Duty Engine Emission Regulations and DOE Research Goals

	(All units in g/bhp-hr)				
	HC	**HC+NO_x**	**CO**	**NO_x**	**PM**
Current	1.3	-	15.5	4.0	0.10 (0.05 for Transit Buses and California)
2004 Option 1[1]	0.5	-	15.5	2.5	0.10 (0.05 for Transit Buses and California)
2004 Option 2[1]	-	2.4	15.5	-	0.10 (0.05 for Transit Buses and California)
DOE Heavy-Duty Diesel Research Goals	-	-	-	0.2	0.01

[1] To be implemented in 2002 as part of the "Consent Decree"

2.2.2 Light-Duty Diesels

In light-duty applications (automobiles and light trucks), the use of CIDI engines is much less prevalent than in highway trucks, but the fuel conservation potential is high when substituting for conventional spark ignition (SI) engines. A sampling of data from CIDI diesels of approximate size and power for light trucks gives a range of peak efficiencies of 38-42 percent compared to mid-20's for gasoline-engine light trucks. Although direct comparisons to SI vehicles are few, CIDI engines typically provide a 35-40 percent fuel efficiency improvement (energy basis) over spark-ignition gasoline engines. For automobiles and light trucks, the shortcomings of the CIDI that have slowed its market acceptance are its lower power density and higher initial cost (which offsets fuel cost savings from improved efficiency). The development of electronic controls and related improvements for fuel injection have greatly reduced the once objectionable diesel noise and exhaust odor.

Emission control strategies are similar to those described for heavy-duty diesels with the exception that EGR is already used on many light-duty diesels. As seen in Table 2, diesel vehicles have traditionally been given relaxed standards relative to gasoline vehicles in part because so few light-duty diesels were being sold. This situation will change with the implementation of the proposed Tier 2 emissions regulations [10] which anticipate much larger light-duty diesel vehicle sales. The Tier 2 emissions regulations represent a large step requiring more than 90 percent reduction in NO_x and PM. In addition, the Federal Test Procedure (FTP) becomes more stringent for model year 2000 vehicles through the addition of the "US06" cycle that incorporates higher speeds and accelerations, and the "SC03" cycle that simulates the use of the air conditioning system. Both of these new cycles will likely increase emissions of NO_x and particulates from light-duty diesel vehicles, thus increasing the severity of the FTP for emissions certification. A consensus about testing protocols to indicate achievement of Tier 2 standards has not yet been arrived at.

The DOE research goals listed in Table 2 are RD&T goals and are not meant to be suggestive of possible emissions standards beyond current Tier 2 standards. The full useful life NO_x goal of 0.07 g/mi was chosen from the fleet average of the Tier 2 standards. The PM research goal of 0.01 g/mi was chosen because it is the fleet average and the most stringent PM standard for any Tier 2 vehicle except for zero-emission vehicles. In this case, the research goal includes deterioration because there are multiple PM reduction technologies and their deterioration rates are not known well enough to assume a meaningful value to set a research goal without deterioration.

Table 2. Light-Duty Gasoline and Diesel Vehicle Full Useful Life Emission Standards and DOE Research Goals

	Range, Automobiles through LDT4 (g/mi)			
	THC	CO	NO_x	PM
Tier 1 (Gasoline)	0.31 to 0.56[1]	4.2 to 7.3	0.6 to 1.53	0.10 to 0.12
Tier 1 (Diesel)	0.80	4.2 to 7.3	1.0 to 1.53	0.10 to 0.12
Tier 2 (Gasoline and Diesel)[2]	0.070[3]	2.1	0.04	0.01
DOE Automotive/ Light-Duty Truck (LDT) Research Goals[4]	-	-	0.07	0.01

[1] Measured as NMHC
[2] Emissions (Bin 4) believed to be representative of the typical light-duty vehicle in 2009
[3] Measured as NMOG
[4] The DOE research goals listed in Table 2 are RD&T goals and are not meant to be suggestive of possible emissions standards beyond 2004.

2.3 Emission Controls

The greatest single challenge for CIDI technology in both light- and heavy-duty applications is the control of NO_x and PM emissions. There are three approaches to reducing NO_x and PM emissions from CIDI engines: (1) minimizing the pollutants coming out of the engine (engine-out emissions), (2) reducing the emissions after they leave the engine (exhaust emission control), and (3) modifying fuel properties (the subject of the APBF Program) to reduce engine-out emissions and enable improved exhaust emission control devices.

2.3.1 Engine-Out Emissions Reduction

Significant reductions in emissions have been achieved through combustion modifications by optimizing fuel and air handling systems. In general, NO_x control is achieved by burning as much of the fuel as possible in cooler, diluted regimes. High temperatures and complete mixing favor reduced PM, hence NO_x and PM reductions are usually a compromise. Electronic fuel injection control and cooled-EGR have been most effective at reducing engine-out emissions, though combustion chamber design, incorporation of turbocharging, and detail improvements have also contributed. It is generally acknowledged that these engine modifications will be sufficient to allow heavy-duty CIDI engines to meet the 2004 standards, but they will not be sufficient for light-duty CIDI engine vehicles to meet the proposed Tier 2 standards, or for heavy-duty CIDI engines to meet more stringent standards beyond 2004.

Emissions of PM from CIDI engines originate from lube oil as well as from fuel combustion. Although this effect is markedly less, it is nonetheless important if the new, more stringent proposed regulations are to be met.

2.3.2 Exhaust Emission Control Systems

Control of NO_x and PM from CIDI engines will likely be the most critical factor in achieving the Tier 2 standards for light-duty vehicles and the 2004 standards for heavy-duty CIDI engines. The widespread consensus in the industry and the research community is that exhaust emission control devices and fuel changes will be needed to meet the Tier 2 standards and heavy-duty CIDI engine standards beyond 2004.

The exhaust emission control devices that are being developed to reduce NO_x in the exhaust gases include the following:

- NO_x Adsorbers
- Lean NO_x Catalysts
- Non-Thermal Plasma Catalysts
- Selective Catalytic Reduction (SCR)

All these devices, with the possible exception of high temperature SCR, require diesel fuel with very low sulfur content (on the order of 15 ppm or less), and SCR has the drawbacks of requiring development of a distribution system for the nitrogen carrier (urea or ammonia) and enforcement of its use.[9]

The exhaust emission control devices that are being developed to reduce PM in the exhaust gases include the following:

- Oxidation Catalysts
- Particle Filters
- Continuously Regenerating Diesel Particle Filters
- Catalyzed Diesel Particle Filters

Other exhaust emission control devices may be developed that are sulfur tolerant. While most of the above listed PM reduction devices do not require very low sulfur fuel, they will be more durable with very low sulfur fuel. Both the NO_x and PM emission control devices will also produce sulfate particles from the sulfur in the fuel downstream of the devices, especially if platinum is used in the devices and high temperatures are employed. Meeting the Tier 2 PM emission standard may depend on very low sulfur fuel not because of device deterioration, but because of sulfate production downstream of the device.

2.4 Fuels for CIDI Engines

Diesel fuel is usually produced by combining two or more refinery streams, often directly from the distillation of crude oil. Diesel fuels in the U.S. are most often defined by American Society of Testing and Materials (ASTM) specifications. These ASTM specifications define allowable ranges for select physical and chemical properties such as flash point, sulfur content, kinematic viscosity, and cetane number. These specifications are broad enough that no two fuels have identical composition. There are five ASTM designations of diesel fuel — two of which are intended for on-highway service. The one most widely used for transportation vehicles is 2-D, though 1-D is used in cold climates because of its superior cold temperature properties and for certain applications (i.e., urban transit buses) where its propensity to produce less smoke is valued. Most states have adopted the ASTM standards as requirements for diesel fuel sold for transportation vehicle use. Recently, several oil companies have been marketing a premium grade of diesel fuel primarily to the heavy-duty market. However, a new wave of advanced light-duty diesels entering the market may create the demand for a diesel fuel tailored to their need for quiet and low odor operation while meeting stringent emissions standards for PM. Such a fuel could be envisioned to differ significantly from diesel fuel (2-D or premium) that is also adequate for heavy-duty vehicles. Whether or not several grades of diesel fuel (similar to those for gasoline) develop remains to be seen.

2.4.1 Specifications and Properties for Emissions Control

Since 1990, the EPA has required that all diesel fuel sold for use in on-road vehicles have no greater than 500 ppm sulfur content (the resulting average is about 340 ppm). Current EPA proposed regulations require diesel fuel for use in highway vehicles to have a sulfur content no greater than 15 ppm beginning June 1, 2006. In addition, the fuel must have either a maximum aromatic content of 35 percent or a minimum cetane number of 40. In contrast, diesel fuel sold for off-road use has a sulfur limit of 5,000 ppm. Since 1993, the California Air Resources Board (CARB) has required that in addition to limiting sulfur content to 500 ppm, diesel fuel sold in California for both on-road and off-road diesel vehicles must have 10 percent maximum aromatic content (20 percent for small refiners; alternative formulations with higher aromatic content are allowable if they are proven to produce the same or lower emissions). The California South Coast

Air Quality Management District is currently proposing to limit the sulfur content of both on-road and off-road diesel fuel to 15 ppm starting July 1, 2003.[22] These limits on diesel fuel properties are intended to reduce emissions of NO_x and PM. In addition to these changes, increasing cetane number, reducing density, and reducing the maximum boiling temperature also reduces NO_x and PM emissions from diesel engines. Emissions of hydrocarbons and carbon monoxide from diesel engines are inherently low and typically do not represent a constraint to diesel engines.

2.4.2 Potential Options for Advanced Fuel Formulations

While sulfur content, aromatic concentration (or density), and the cetane number of diesel fuels are widely recognized as fuel properties that affect engine-out emissions, there has been less focus on other controllable fuel properties such as the boiling point distribution, fuel viscosity, and molecular structural variations in relation to emissions reductions. In addition, preliminary studies with oxygen-containing materials have shown substantial potential to reduce emissions of PM and NO_x (to a lesser extent). It appears that significant engine-out emission reductions are possible through modifications of diesel fuel properties beyond those mandated by the EPA and CARB to date.

Reducing the sulfur content of diesel fuel to 15 ppm has the potential to enable several exhaust emission control technologies that could significantly lower emissions of NO_x and PM. Additional fuel modifications could further decrease engine-out emissions and make exhaust emission control devices more effective, less costly, or both. Adding oxygenated or high hydrogen content components made from natural gas or renewable resources has the potential not only to reduce emissions, but to reduce petroleum consumption by diesel vehicles and lessen the greenhouse gases emitted from the use of diesel fuel. Looking beyond the Tier 2 and ultimate heavy-duty CIDI engine standards, fuel formulation could have significant impacts on the emissions of currently unregulated toxics and ultrafine particles.

2.4.3 Health and Safety of Liquid Fuels

Diesel fuel is regulated and meets all applicable health and safety requirements. Storage and handling procedures have been built around the relatively low volatility of diesel fuel. New options for diesel fuels must be examined to assure that they can be handled and used safely by the public. A recent review of the safety and industrial hygiene issues (e.g., fire safety; chemical decomposition hazard; exposure by inhalation, ingestion, skin absorption) related to potential blending components for advanced petroleum-based fuels concluded that, for many of them, insufficient information is currently available to determine their health and safety properties.[11]

2.5 Fuel Production and Reserves

The U.S. transportation sector consumes about two-thirds of the nation’s oil demand. In 1998, 52 percent of U.S. petroleum consumption was met by imports, contributing to the Nation’s trade deficit and representing a major transfer of wealth from the United States to oil exporting countries. With petroleum demand projected to grow and domestic production projected to decline, the Energy Information Administration (EIA) predicts that imported petroleum will account for 64 percent of domestic petroleum consumption by 2020 based on the reference case. The import shares of total consumption in 2020 is 59 percent in the high oil price case and 69 percent in the low oil price case.[6] This will make the U.S. increasingly vulnerable to fuel shortages and price spikes with their associated economic impacts. CIDI engines in both light- and heavy-duty vehicles are estimated to contribute 25 percent of all the transportation fuel savings by 2020 for all the petroleum fuel reductions, according to estimates for the Office of Transportation Technologies (OTT) [12].

2.6 Global Considerations

Fuel properties around the world are moving in the same direction (though at different speeds) to allow engines to produce lower emissions. For diesel fuel, the trends are for lower sulfur content, lower aromatic content, higher cetane number, and lower maximum boiling temperature. The western European countries are moving the fastest towards “cleaner” diesel fuels because of the high number of diesel passenger cars there and because their refineries are configured to produce the necessary diesel fuel. In Europe, 28 percent of the passenger cars are diesel, compared with 2 percent in the U.S. and 14 percent worldwide [13]. These European countries are moving towards a 50 ppm sulfur limit for diesel fuel by 2005, which England implemented in the latter part of 1999. Germany has announced it will move to 50 ppm sulfur diesel fuel by 2001, four years ahead of the EU requirement, and they are in favor of 10 ppm sulfur diesel fuel over the longer term (2007).[23] Sweden, Denmark, and England all have requirements for “City Diesel” with sulfur content of 10 ppm maximum. The EU currently has a “Call for Evidence” out (to close July 31, 2000) to explore whether to reduce the January 1, 2005 requirement for 50 ppm sulfur content gasoline and diesel fuel to some lower level [24].

European refineries are better configured to produce very low-sulfur diesel fuel compared to U.S. refineries for two reasons:

- European refineries produce a higher proportion of diesel fuel compared to gasoline
- Most European refineries have higher hydrocracking capacity than U.S. refineries

Similar to the situation with fuel properties, vehicle emission standards are becoming more stringent around the world, and as a result, less difference is seen among them. Increasingly, vehicle emission control technology is developed for the world market, instead of specific countries. Converging fuel properties will enable this approach and allow the benefits of reduced emissions to be accrued by countries worldwide. Numerous U.S., European, and Japanese vehicle and engine manufacturers have recognized the benefits of common fuel specifications and have proposed worldwide specifications for gasoline and diesel fuel called the World-Wide Fuel Charter [14].

2.7 Economics

Petroleum fuels currently enjoy a competitive advantage over alternative fuels and natural gas derived liquid fuels. Investments in engine, emission control, and fuel technologies to reduce emissions while maintaining or improving engine efficiency will require economic trade-offs that are not sufficiently understood and must be addressed.

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3.0 Potential for CIDI Technologies Enabled by Advanced Fuels

Research activities supporting CIDI technologies and their corresponding emission control systems are intended to result in more efficient and less polluting personal mobility and commercial transport on roadways. Changes in fuel formulation have the potential to enable further reductions in emissions while simultaneously increasing engine efficiency.

3.1 Improved Public Health and Environment

Because of the large number of gasoline-fueled, spark-ignition vehicles in the U.S. contributing to pollution, the EPA regulated them first, and emission control technology development has focused on these vehicles and achieved very substantial results. Emission controls for diesel engines and vehicles have lagged behind because the regulations were not as stringent as those for gasoline vehicles. Because of increased sales of diesel vehicles and reduced emissions from gasoline vehicles, diesel vehicles have become significant contributors to the NO_x and PM from transportation vehicles. By 2010, the EPA predicts that diesel engines will account for 53 percent of the NO_x and 70 percent of the PM_{10} (PM comprised of particles less than 10 μm in diameter) emissions from transportation vehicles.[10] In addition, there is significant concern among health professionals that emissions of ultrafine particles and air toxins pose public health risks and perhaps should be regulated. CARB has recently classified PM emissions from diesel engines as a toxic air contaminant and will determine what additional steps are necessary to further reduce the public's exposure in California. The EPA has similar concerns about PM and toxic emissions from diesel engines, especially if there is substantial penetration of diesel engines into the light-duty vehicle market.

3.2 Improved Energy Efficiency and Reduced Petroleum Consumption

CIDI engines are used in the vast majority of heavy trucks that carry freight in the U.S. The diesel engine displaced the gasoline-fueled spark ignition engine in this application because it is much more fuel efficient and durable. It would clearly be undesirable for heavy-duty vehicles to revert to using gasoline-fueled spark ignition engines because of the increase in petroleum fuel use, much higher carbon monoxide (CO) emissions, and the need to design numerous new engines. Therefore, it is essential that suitable fuels are available for the existing population of diesel engines and to allow high-efficiency CIDI engines to be used in heavy trucks meeting stringent current and future emission regulations. Such fuels should not be a hindrance to achieving additional engine efficiency gains in the future. The White House has proposed the "21st Century Truck Initiative" which partners major medium- and heavy-duty truck and engine makers with government agencies to develop commercially viable truck and propulsion systems technology that will dramatically cut fuel use and emissions of trucks and buses while enhancing safety, affordability, and performance.

In the light-duty sector, CIDI engines have found a niche in pickup trucks where their high efficiency and high torque make them popular for heavy-duty towing and hauling. In such applications, the fuel savings compared to gasoline engines with similar power are dramatic (30 to 40 percent). Many sport-utility vehicles (SUVs) in the U.S. are based on pickup chasses and use the same or similar gasoline engines. Given the large production volume of SUVs, the potential fuel savings are significant if CIDI engines are used. Advanced petroleum-based fuels that allow CIDI engines to meet emissions regulations and customer requirements, such as low odor and noise could result in 30 to 40 percent per-vehicle reduction in petroleum consumption.

Use of CIDI engines could have similar fuel efficiency gains as cited for light-duty trucks when used in passenger automobiles. For example, the 1999 model year Volkswagen Jetta is available with several different engines including a CIDI engine. The CIDI engine version uses 38 percent less fuel (energy, based on city cycle fuel economy) than their gasoline engine version. Also, the CIDI engine in hybrid configuration is considered likely to be the only internal combustion engine capable of meeting the PNGV goals for increased fuel economy. In a hybrid configuration, CIDI engines would use a motor operating either in parallel or series configuration with rechargeable storage batteries. The PNGV program may also be expanded to include light trucks.

3.3 Reduced Emissions of Greenhouse Gases

The only significant greenhouse gas emission from CIDI engines using diesel fuel is carbon dioxide. In vehicles such as SUVs where CIDI engines could replace gasoline engines, the savings in carbon dioxide emissions are 20 to 25 percent per mile. For heavy-duty vehicles that already use CIDI engines, further increases in engine efficiency are anticipated that will reduce the per-mile emissions of carbon dioxide from these vehicles. (However, in the interim, it is acknowledged that heavy-duty engines will experience a decrease in efficiency to meet the 2004 emission standards.) Should the U.S. agree to a binding Kyoto Protocol agreement, the EIA predicts that the price of gasoline would rise to about $2.00 per gallon and gasoline consumption would be reduced by 3 to 18 percent.[15] Vehicles with CIDI engines using advanced petroleum-based fuels could become a popular choice among other high fuel economy vehicle technologies such as reduced vehicle size and weight to reduce emissions of greenhouse gases and achieve the PNGV fuel economy goal.

3.4 Improved U.S. Economic Competitive Position

The U.S. is home to several diesel engine manufacturers who sell diesel engines around the world. Most of the engines designed for highway use are sized for heavy-duty trucks. However, U.S. diesel engine manufacturers are now applying their considerable engine design expertise to build CIDI engines for light-duty vehicles, primarily pickups and SUVs. In addition, auto manufacturers are designing small CIDI engines for passenger automobile use. In Europe and Japan, automobile manufacturers already offer CIDI engines in their passenger cars and light trucks. Enabling and enhancing U.S. manufacturers' ability to build advanced CIDI engines and emission control systems keeps them competitive with European and Japanese manufacturers and expands the possibilities for exporting U.S. made vehicles.

4.0 Technical Targets for DOE's APBF Program

DOE's APBF Program has seven technical targets. This section of the MYPP summaries the targets, rationale for their selection, and the approach to monitoring progress towards their attainment.

4.1 Description of Targets

The Department of Energy's research targets for NO_x and PM emissions for both light- and heavy-duty on-highway CIDI vehicles are depicted in Tables 1 and 2 (see Section 2). To achieve these targets, the APBF Program has identified seven technical targets (labeled T1-T7) that are to be achieved through the modification of fuels and lubricants for CIDI engines. Attainment of these targets will (1) assist in achieving emission reductions to meet near-term emission standards, (2) document fuel property effects on emissions to direct future mid-term enhancements of fuels to meet emissions standards with minimal to no penalty on efficiency, and (3) provide a foundation for the longer-term development of new formulations of petroleum-based fuels.

The technical targets for the APBF Program have been established to enable CIDI engine and emission control programs to meet their research goals for emissions with minimal impact on the efforts to increase the efficiency of CIDI engines (see Tables 1 and 2). Advanced petroleum-based fuels for CIDI engines and emission control systems, if they meet these seven technical targets, will not only enable CIDI engine technology to meet future emission regulations, but will also provide opportunities for substantial improvements in energy efficiency and decreased greenhouse gas emissions in the transportation sector.

T1. **Engine-out Emissions Reduction:** Advanced petroleum-based fuels should reduce engine-out emissions to enable light- and heavy-duty vehicles to meet emission goals established by DOE CIDI engine programs with minimal or no efficiency penalties.

T2. **Enable and Enhance Emission Control Technologies:** Advanced petroleum-based fuels should enable the use of exhaust emission control system technologies for meeting light- and heavy-duty CIDI emissions targets. The fuel should contribute to improving the performance of exhaust emission control system technologies, through increases in device conversion efficiency, by being the source of effective reductants for emission control devices, and by facilitation of component durability goals through reduction of deterioration factors.

T3. **Health and Environmental Effects:** The effect of fuel changes should not cause any significant increase in composite risk compared to current diesel fuels with regard to unregulated health impacts such as air toxins, ultrafine particles, groundwater contamination, and handling safety.

T4. **Reduced Life-Cycle Criteria and Greenhouse Emissions Per Diesel-Equivalent Gallon:** Emissions of greenhouse gases (expressed as CO_2-equivalent) and criteria emissions per diesel-equivalent gallon of fuel shall not be greater than those from conventional diesel fuel.

T5. **Enable Engine Efficiency Increases Through Favorable Composition and Properties:** Advanced petroleum-based fuels should reduce petroleum consumption in the transportation sector, compared to conventional diesel fuel in comparable vehicles. This target includes favorable changes to fuel composition and properties that will enable achievement of the DOE CIDI light-duty vehicle and heavy-duty engine targets.

T6. **Fuel Price Impacts:** Any fuel changes or reformulation should provide a foundation for engines and vehicles to have fuel related operating costs competitive with current fuels. Increases in the price of the fuel due to composition or property changes should be the same or less than the price differential being asked for premium diesel fuel. At present, this differential is roughly 5 percent of the retail price which is also representative of the cost increase of reformulated gasoline (RFG) compared to conventional gasoline.

T7. **<u>Cost Effective Emission Reduction</u>:** Emission reduction benefits resulting from a fuel change, expressed as cost per ton of NO_x + NMHC emission reduction, shall be comparable to the costs for Tier 2 emissions controls as calculated by the EPA. For LDVs, this cost is $4,900/ton while for LDT1s, the cost is $3,100.[25]

The technical targets are quantified and criteria for attainment are provided in Table 6, as appropriate. The targets are not mutually exclusive; attainment of one target may affect attainment of one of more of the other targets.

4.2 Rationale for Emissions Reduction Targets and Pathway

The Office of Heavy Vehicle Technologies and the Office of Advanced Automotive Technologies have established overall "tailpipe" emissions and fuel economy goals for advanced heavy-duty diesel engines and advanced light-duty vehicles. Overall emissions targets are expected to be achieved through a power system (engine, emission control systems, and fuels formulation) approach. Fuels formulation affects both engine-out emissions as well as exhaust emission control device performance. For the APBF Program, it was desirable to establish targets for the progress toward tailpipe emissions goals that could be attributable to fuel formulation. Two sets of research targets have been established by DOE for its programs—one for heavy-duty engines and one for light-duty vehicles (see Tables 1 and 2). The logic and procedure for establishing the emission reduction pathways was essentially the same for both light-duty vehicles and heavy-duty engines. This was accomplished by conceiving a pathway from a baseline emissions level to the overall emissions target, which delineates the respective contributions of engine technology, fuel formulation, and exhaust emission control devices. For light-duty vehicles, two pathways are presented—one for a light-duty truck and one for a PNGV-type passenger car to illustrate the differences in stringency between the two.

The pathways for emission reduction are presented in Tables 3, 4, and 5 for the light-duty truck case, PNGV-type passenger car case, and heavy-duty engine case, respectively. In each of these tables, the first row provides the baseline values of NO_x and PM.[*] The other rows represent the relative contributions of additional engine development, fuel reformulation, and enablement of exhaust emission control devices by lowering the sulfur content of the fuel. The following subsections provide descriptions and assumptions for the parameters in the pathway tables.

<u>4.2.1 Selection of Baseline</u>

The baselines for emissions and fuel economy for light-duty vehicles are an advanced light truck platform, achieving 30 mpg (approximately 25 mpg gasoline equivalent) combined city/highway mileage, and an advanced automobile meeting the PNGV target of up to 80 mpg, both using state-of-the-art CIDI engines. The emissions data for these baselines were derived from modern CIDI passenger car data. The light truck has the greater emissions reduction challenge compared to passenger car light-duty vehicles.

The baseline for heavy-duty engines is representative of current production engines with emissions of 4.0 g/hp-hr NO_x and 0.10 g/hp-hr PM. It is recognized that an NO_x+HC level of 2.5 g/hp-h has been achieved on near-term prototype engines for the 2002 consent decree heavy-duty regulations. These emission baselines assume using 300 ppm sulfur certification diesel fuel.

[*] It is assumed that meeting the NO_x and PM emission regulations will be the primary force guiding emission control system development for CIDI engines. Emissions of NMHCs and CO are assumed to be controlled to within standards given the emission control technologies being developed to control NO_x and PM.

4.2.2 Improvements in Engine Technology Other than Fuels

In parallel to RD&T on fuels and emissions controls, engine technology is advancing and achieving reductions in emissions through the application of such systems as EGR, improved fuel systems, and improved controls. Given the tradeoff between NO_x and PM, we assume that engine designers will choose to minimize engine-out NO_x, without an increase in PM. The estimates for the emissions reductions from engine development are derived from recent progress and reports on prototype engines. The combination of advanced engines, coupled with fuel impacts, set the requirements for exhaust emission control device emission reduction.

4.2.3 Estimates of Fuel Impacts on Engine-Out Emissions

NO_x reduction attributable to fuel effects, based on existing data from higher emitting engines, supports small potential reductions in engine-out NO_x (approximately 10 percent) through hydrocarbon reformulation alone with the potential for further reductions from oxygenates. Higher and lower NO_x reductions are likely dependent on the specific engine design. No reduction in NO_x from fuel reformulation is assumed for the light-duty engines, and 10 percent reduction is assumed from fuel reformulation for heavy-duty engines

PM reduction from fuel reformulation and the use of oxygenates, based on data from older engines, supports reductions in engine-out PM by up to 70 percent. In addition, since at these low PM emissions levels the oil consumed can represent as much as one-third of the total mass, a reduction in the oil contribution to PM is assumed. Lessor reductions in PM are likely from state-of-the-art CIDI engines. Reductions of PM due to fuel reformulation are assumed to be 20 and 25 percent for heavy-duty engines and light-duty vehicles, respectively.

4.2.4 Fuel-Enabled Exhaust Emissions Control

Based on existing data and projections of technology improvement, low-sulfur fuel is expected to enable NO_x adsorbers or other NO_x control technologies having effectiveness of 80 percent or more reduction in NO_x emissions. Similarly, the performance of diesel particle filters is expected to be enhanced with reduced sulfur. There are some claims and evidence that selective catalytic reduction (SCR) NO_x control is less sulfur sensitive than other NO_x emission control devices. Even so, a complete exhaust emissions control system will likely require devices such as oxidation catalysts that are sulfur sensitive. Given the sizeable infrastructure issues, plus lack of certainty on sulfur effects, the APBF Program has chosen not to base the technical target and pathway to it on a fuel path that allows only SCR to have a chance of success. Note that with respect to all fuel effects (in this case sulfur), the APBF Program is to determine the required fuel characteristic (e.g., sulfur content) to achieve the fuel portion of the CIDI goals, whereas other RD&T programs are responsible for developing the base technology for CIDI emission control devices.

Using fuel reformulation, on-board reforming, and other fuel-related means, the APBF Program hypothesizes that the effectiveness of NO_x exhaust emission control can be improved to between 80 and 90 percent (needed for the light-duty truck and heavy-duty engine cases to meet their NO_x emission targets). The subsequent question is whether or not this level of NO_x aftertreatment is feasible. If not, then either the overall targets cannot be met or engine-out emissions targets must be adjusted. Based on limited data, mostly at steady state, plus the current performance levels that have been achieved in SI engine aftertreatment, up to 90 percent effectiveness is believed feasible, though maintaining this level of effectiveness over the full useful life may prove equally challenging. Estimating how much of this can be directly attributed to the fuel formulation as opposed to independent advancement of the adsorber or catalyst technology is very speculative. For heavy-duty engines, durability and robustness requirements may call for an alternative to adsorbers.

Fuel (and lubricant) optimization is expected to help increase PM filter efficiency by 5 percent, and improve durability.

Table 3. Emissions Reduction Pathway for Engine+Fuel+Emissions Control
Light-Duty Truck Case (~30 mpg)

State of Technology	NO_x (g/mile)	PM (g/mile)	Absolute Improvement (g/mile)	Percent Improvement (%)	Comments
Baseline — Light Truck	1.0	0.08	0	0	Scaled from emissions index of a modern CIDI engine.
Engine Development[1]	0.6	0.08	0.4 for NO_x 0 for PM	40 0	Maximum NO_x reduction chosen without increase in PM. Assumes cooled EGR, advanced controls. Estimates supported by preliminary data.
Fuel Reformulation Effect on Engine-Out Emissions	0.6	0.06	0 for NO_x 0.02 for PM	0 25	Estimates supported by preliminary data.
Exhaust Emission Control Devices	0.07	0.01	0.53 NO_x 0.05 PM	88 83	NO_x adsorber is the assumed technology for reducing NO_x; catalyzed soot filter to reduce PM.[1] Includes fuel impacts on emission control devices.
Target	0.07	0.01			**Targets Met**

[1]It is acknowledged that considerable development work remains before the engine, NO_x control, and particle filter technology can meet the expected performance and durability levels over light-duty driving cycles. Those development efforts are underway in complementary projects.

Table 4. Emissions Reduction Pathway for Engine+Fuel+Emissions Control
Advanced Automobile Case (80 mpg PNGV-Type Gasoline Equivalent)

State of Technology	NO_x (g/mile)	PM (g/mile)	Absolute Improvement (g/mile)	Percent Improvement (%)	Comments
Baseline — PNGV-Type Passenger Car	0.40	0.04	0	0	Scaled from emissions indexes of current CIDI engines.
Engine Development[1]	0.36	0.04	0.04 for NO_x 0 for PM	10 0	Advanced combustion, improved fuel injection, optimum use of EGR.
Fuel Reformulation Effect on Engine-Out Emissions	0.36	0.03	0 for NO_x 0.01 for PM	0 25	Estimates supported by existing data
Exhaust Emission Control Devices	0.07	0.01	0.29 for NO_x 0.02 for PM	81 67	NO_x adsorber and Catalyzed Soot Filter[1;] includes fuel impacts on emission control devices.
Research Target	0.07	0.01			**Targets Met**

[1]It is acknowledged that considerable development work remains before the engine, NO_x control, and particle filter technology can meet the expected performance and durability levels over light-duty driving cycles. Those development efforts are underway in complementary projects.

Table 5. Emissions Reduction Pathway for Engine+Fuel+Emissions Control
Heavy-Duty Engine Case

State of Technology	NO_x (g/hp-h)	PM (g/hp-h)	Absolute Improvement (g/hp-h)	Percent Improvement (%)	Comments
Production — Heavy-Duty Highway Truck	4.0	0.10	0	0	Urban bus engines meet 0.05 g/hp-h PM
Baseline 2002 Engine Technology, EGR, Fuel Control[1]	2.5 NO_x+ HC	0.10	1.5 for NO_x 0 for PM	60 0	Maximum NO_x reduction chosen on PM tradeoff. Estimates supported by existing data. Required starting in 2002.
Fuel Reformulation Effect on Engine-Out Emissions	2.25	0.08	0.25 for NO_x 0.02 for PM	10 20	Estimates supported by existing data
Stretch Engine Technology, EGR, and Advanced Engine Controls	1.5	0.05	0.75	33 37	Probable lower limit for engine-out NO_x in DI diesel. PM control includes use of an oxidation catalyst.
Fuel Sulfur Enabled Exhaust Emission Control, Minimum Required	0.20	0.01	1.3 for NO_x 0.04 for PM	87 80	NO_x adsorber or SCR catalyst is the assumed NO_x reduction technologies.[1] Catalyzed soot filter assumed to reduce PM. Includes fuel impacts on emission control devices.
Research Target	0.2	0.01			**Targets Met**

[1]It is acknowledged that considerable development work remains before the engine, NO_x control, and particle filter technology can meet the expected performance and durability levels over light-duty driving cycles. Those development efforts are underway in complementary projects.

4.3 Rationale for Target T7: Cost Effective Emission Reduction

The cost effectiveness targets are based on the costs associated with LDVs and LDT1s meeting the Tier 2 emission standards using 30 ppm sulfur RFG without applying learning curve effects and including capital cost amortization.[25] This basis was chosen because it can be used to quickly compare the costs of fuel reformulation using existing refineries without doing extensive analysis to estimate long-term changes to the refinery system and how those changes might affect long-term fuel costs.

4.4 Monitoring Progress Towards Attaining Targets

Throughout the APBF Program, systems analyses will be conducted regularly using data from several DOE programs on the effects of fuel, engine operations, and emission control systems on emissions of NO_x and PM from CIDI engines. These analyses will be conducted for the three specific platforms selected at the beginning of the program: automobile, light truck, and heavy-duty engine. The results of the systems analyses will be compared with the pathways summarized in Tables 3-5 for emission reduction and used to guide the RD&T activities. The emission reduction pathways are and will remain flexible in order to optimize attainment of program goals.

4.5 Technical Targets Table

The technical targets *attributable only to the fuel portion* of the pathways (presented in Tables 3, 4, and 5) needed to meet the DOE research targets are quantified in Table 6. In order for the DOE research targets to be met, these targets will have to be met along with the engine and exhaust emission control device developments listed in the pathways. These targets represent goals for fuel development that are near the maximum that may be expected through fuel reformulation.

In general, technical targets for a given technical area (e.g., fuels) that is focused on technology development are usually expressed in terms of parameters that pertain directly to that technical area. For example, in the case of fuels, parameters such as cetane number or index, density, viscosity, or latent heat would be expected. However, at this point in the APBF Program, the appropriate fuel parameters and their required values are not known. The major objective of the fuels technical area is to characterize the implications of fuel formulations on engine and power system performance and to develop associated predictive models. Accordingly, the related technical targets are expressed in terms of emissions performance of engine and emission control system performance.

Table 6. Technical Targets, Values, and Criteria for Attainment

I.D.	Target Description	Target Value	Criteria	Rationale
T1	Engine-out emission reduction, light-duty vehicle (LDV)	Reduce engine-out PM by 0.01 g/mi (25%)	Demonstrate LDV goals over the FTP. Provide proof of durability to satisfy EPA full useful life requirements.	Supports progress toward LDV emissions targets of 0.07 g/mi NO_x and 0.01 g/mi PM. Target is based on existing data.
	Engine-out emission reduction, light-duty truck (LDT)	Reduce engine-out PM by 0.02 g/mi (25%)	Demonstrate LDT goals over the FTP. Provide proof of durability to satisfy EPA full useful life requirements.	Supports progress toward LDT emissions targets of 0.07 g/mi NO_x and 0.01 g/mi PM. Target is based on existing data.
	Engine out emission reduction, heavy-duty engine (HDE)	Reduce engine-out NO_x by 0.25 g/hp-hr (10%) Reduce engine-out PM by 0.02 g/hp-hr (20%)	Demonstrate goals using the heavy-duty diesel engine transient cycle. Provide proof of durability to satisfy EPA full useful life requirements.	Supports progress toward overall HDD emissions targets of 0.2 g/hp-hr NO_x and 0.01 g/hp-hr PM. Baseline is 2.5 g/hp-hr NO_x and 0.10 g/hp-hr PM
T2	Enable advanced NO_x control, LDV application* Enable advanced exhaust PM control devices*	Fuel technology enabler for NO_x conversion of up to 90% for final tailpipe emissions of 0.07 g/mile. Ensure PM filter effectiveness of up to 85% by lowering regeneration temperature to achieve tailpipe target of 0.01 g/mile.	Demonstrate goals over FTP cycle. Provide proof of durability to satisfy EPA full useful life requirements	Low sulfur enables technology such as adsorbers, with NO_x conversion of ~80%. Fuel reformulation to improve effectiveness to up to 90%. Low sulfur fuel permits more active catalyst in diesel particle filters (DPF) and reduces sulfate PM. Fuel reformulation to lower engine-out PM. Necessary to achieve 0.01 g/mi PM.

Table 6. Technical Targets, Values, and Criteria for Attainment

I.D.	Target Description	Target Value	Criteria	Rationale
T2	Enhance performance of exhaust emission control, HDE	Enable increased NO_x conversion efficiency of high temperature NO_x catalyst up to 90%, for tailpipe NO_x of 0.2 g/hp-hr PM-80% effective for tailpipe target of 0.01 g/hp-hr	Demonstrate goals on heavy-duty FTP. Provide proof of durability to satisfy EPA full useful life requirements	Enables NO_x devices to bring heavy-duty engine system to 0.2 g/hp-hr NO_x.
T3	Health and Environmental Effects: • Unregulated toxics and ultra-fine particles	By independent analysis	No significant increase in composite risk compared to conventional fuels	Numeric values for targets not established because of the variety of issues and biologic end points potentially involved. Issues specific to particular fuel options will be assessed.
	• Groundwater contamination potential	By independent analysis		
	• Health & safety effects of fuel	By independent analysis		
T4	Life-Cycle Greenhouse and Criteria Emissions	No Increase	Full fuel cycle including FTP tests for criteria emissions.	APBF should not cause an increase in greenhouse or criteria emissions.
T5	Enable Engine Efficiency Increases Through Favorable Composition and Properties	Up to 80 mpg in PNGV-type passenger car (LDV goal)		OAAT R&D Plan
		35% increase in fuel economy relative to similar gasoline LDT (LDT goal)		OHVT Roadmap
		50% thermal efficiency (HDE goal)	Identify fuel by 2004 for DOE engine RD&T to demonstrate by 2006.	OHVT Roadmap

Table 6. Technical Targets, Values, and Criteria for Attainment

I.D.	Target Description	Target Value	Criteria	Rationale
T6	Fuel Price Increase	5% of retail price of diesel fuel. Vehicle cost impacts to be insignificant	Engineering cost assessment.	Similar to premium diesel fuel and typical of the additional cost to make RFG
T7	Cost Effective Emission Reduction	$4,900 per ton of emission reduction for LDVs and $3,100 for LDTs	Full useful life emissions estimated using the FTP	Emission reduction costs shall be cost competitive with those needed to meet Tier 2 regulations

* HC and oxygen content may be tailored for emission control system.

5.0 Technical Barriers To Be Overcome

The technical barriers to the development and implementation of APBF for next generation CIDI engines and emission control systems are discussed below. These technical barriers inhibit identification of optimal fuel properties and formulations. Because fuels are an enabling technology for CIDI engines and emission control systems, these barriers also inhibit optimization of the CIDI engine-fuel-emission control system. These barriers (labeled B1-B9) are listed without regard to their relative severity or program emphasis.

B1. **Fuel Property Effects on Engine Emissions and Efficiency:** Data and models for engine-out emissions and efficiency based on fuel properties are limited in scope, have unexplained differences among various engine types, and do not adequately account for the effects fuel's physical properties have on the dynamic operation of the fuel injection systems. This is particularly true for advanced engines and new fuel options. Also, most of the models do not account for the confounding effects of lubricating oil consumption on emissions. The lack of accurate and comprehensive models is a barrier to determining optimal fuel properties and formulations for CIDI engine applications and designing and developing CIDI engines that can make the best use of APBF.

B2. **Fuel Property Effects on Exhaust Emission Control System Technology:** Data on the effect of fuel properties (other than sulfur) on exhaust emission control systems are very limited. In addition, test procedures to measure exhaust emission control system effectiveness need to be established to measure the impact of fuel properties. The lack of adequate data and test procedures to evaluate the effects of fuels on exhaust emission control system technology hinders assessment of various advanced fuel options and is a barrier to the development of advanced CIDI engines.

B3. **Emission Control System Degradation:** Fuel properties affect the deterioration rates and durability of exhaust emission control system devices and components. While some information is known about how fuel properties affect emission system durability, much is unknown. This is a barrier to determining optimal fuel properties for emission control systems. Emission control systems that do not significantly degrade in use are needed for optimization of CIDI engine combustion and emission system design to meet current and future full useful life emissions regulations for engines and vehicles operating on various advanced fuel options.

B4. **Sulfur Impacts:** Sulfur from the fuel and consumed lubricating oil adversely affects many exhaust emission control system devices and affects the durability of other systems such as cooled EGR systems. Data on the magnitude of the impacts as a function of specific sulfur concentration are lacking, as well as on other issues such as reversibility following exposure to fuels with high sulfur levels. This lack of data inhibits informed choices about the trade-offs between refinery investments for cleaner fuels versus the additional cost of engine emission control systems.

B5. **Toxic Emissions:** Data are limited on the impact that petroleum fuel and non-petroleum components have on toxic emissions as defined by the Clean Air Act Amendments of 1990. Emissions of additional compounds that could be considered toxins are coming under increasing scrutiny by regulators who are likely to propose new regulations including them in the future. The lack of data about toxic emissions from existing fuels and engines is a barrier to determining the desirable characteristics of advanced petroleum-based fuels and any non-petroleum fuel components. Thus the benefits of various fuel formulation and engine/emission system control options cannot be determined at this time.

B6. **Ultrafine Particles:** The study of ultrafine particles (i.e., particles of diameter < 50 nm) is immature, and diesel engines are believed to be significant contributors to the existing ambient inventory of ultrafine particles. The formation mechanism of ultrafine particles is not known with certainty, but evidence exists that the way in which exhaust gases are diluted with the air has a significant impact on the number of ultrafine particles that are produced. Likewise, the role of exhaust emission control system devices in the formation of ultrafine particles is not well-defined. However, they have been shown to cause increases in the number of ultrafine particles while reducing particulate mass emissions. The effects of fuel properties (petroleum-based and non-petroleum) on the formation of ultrafine particles are also not well established. The lack of knowledge in these areas inhibits the creation of advanced petroleum-based fuels that could have significant impact on ultrafine emission formation from CIDI and existing diesel engines.

B7. **Advanced Fuel Production and Costs:** Data on refinery economics and processing strategies are insufficient to compare options for APBF CIDI fuels. Non-petroleum advanced fuel components typically have little or very preliminary production economics data. Insufficient advanced fuel production and cost data are a barrier to making informed decisions about the commercial viability of advanced petroleum-based CIDI fuels.

B8. **Health, Safety, and Regulatory:** Sparse and incomplete data exist about health, safety, and regulatory issues for most non-petroleum fuel components that might be used in APBF CIDI fuels. Without a fairly thorough knowledge of these issues, it is difficult to screen out those components with undesirable characteristics. This lack of information raises a barrier to the investigation of potential non-petroleum fuel components that could have substantial emissions and energy efficiency benefits. Should desirable advanced fuels have health, safety, or regulatory issues, they will need to be resolved to the extent required by regulatory bodies to allow their sale and use in motor vehicles.

B9. **Infrastructure Impacts:** Little is known about the technical and economic impacts of non-petroleum fuel components of APBF CIDI fuels on the distribution, storage, and retailing infrastructure. Should the characteristics of non-petroleum fuel components cause advanced petroleum-based CIDI fuels to have compatibility or fungibility problems, barriers are raised to their widespread use. Solutions to these problems may include the addition of storage capacity in the system, which while solving a technical problem creates an economic barrier. Advanced petroleum-based fuels will not be successful commercially unless they can be distributed, stored, and sold in a manner that meets regulations and is acceptable to consumers.

Table 7 cross-references the technical targets identified in Section 4 and the technical barriers (B1 - B9). A complete description of the technical targets is provided in Table 6.

Table 7. Technical Target and Barrier Cross-Reference

Technical Targets	Technical Barriers *
T1. Engine-Out Emissions Reduction	• B1. Fuel Property Effects on Engine Emissions and Efficiency • B5. Toxic Emissions • B6. Ultrafine Particles
T2. Enable and Enhance Emissions Control Technologies	• B2. Fuel Property Effects on Exhaust Emission Control System Technology • B3. Emission Control System Degradation • B4. Sulfur Impacts • B5. Toxic Emissions • B6. Ultrafine Particles
T3. Health and Environmental Effects	• B5. Toxic Emissions • B6. Ultrafine Particles • B8. Health, Safety, and Regulatory
T4. Reduced Life-Cycle Criteria and Greenhouse Emissions Per Diesel-Equivalent Gallon	• B1. Fuel Property Effects on Emissions and Efficiency
T5. Enable Engine Efficiency Increases Through Favorable Composition and Properties	• B1. Fuel Property Effects on Emissions and Efficiency • B7. Advanced Fuel Production and Costs • B8. Health, Safety, and Regulatory • B9. Infrastructure Impacts
T6. Fuel Price Impacts	• B7. Advanced Fuel Production and Costs • B8. Health, Safety, and Regulatory • B9. Infrastructure Impacts
T7. Cost Effective Emission Reduction	• B4. Sulfur Impacts • B7. Advanced Fuel Production and Costs • B8. Health, Safety, and Regulatory • B9. Infrastructure Impacts

* The barriers are arbitrarily numbered and are not ranked in any particular order.

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6.0 Technical Approach

The technical approach for RD&T over the 2000-2004 time period for DOE's APBF Program is summarized in this section of the MYPP. This approach addresses the barriers identified in Section 5, which when overcome will lead to attainment of the technical targets identified in Section 4. Attainment of these targets will achieve the mission of the APBF Program.

The technical approach is comprised of nine tasks as seen below. Major tasks (Tasks 2, 3, 4, 9) in terms of resource requirements are highlighted in bold. Supporting analyses, which will require fewer resources and will involve little (Tasks 7, 8) or no experimentation (Tasks 1, 5, 6) are not bold.

Task 1. Screening

Task 2. Fuel and lubricant properties — engine-out emissions

Task 3. Fuel and lubricant properties — exhaust emission control system and emissions

Task 4. Develop empirical relationships

Task 5. Refinery and fuel processing economics

Task 6. Infrastructure

Task 7. Vehicle materials compatibility

Task 8. Safety, health, and consumer acceptance aspects of liquid fuels

Task 9. Validation and testing of the empirical relationships

Results from the APBF Program will be utilized by DOE's CIDI engine and emission control programs for both light and heavy-duty vehicles. The principal products will consist of data and empirical relationships linking fuel and lubricant properties to emissions and engine output. These data will be consistent with the requirements of other DOE Programs to facilitate their use in engine and vehicle models.

An initial screening of potential fuels and blending components, as well as lubricants, in Task 1 will provide candidates for testing in Tasks 2 and 3. The effects of fuel and lubricant properties on engine-out emissions (Task 2) and emission control performance (Task 3) will be documented.

A systems analysis for emission reduction including the engine, emission control system, and fuel will be conducted in Task 4 to guide the identification of the most promising fuel formulations. Emissions and energy efficiency data will be generated, and empirical relationships linking fuel and lubricant properties to emissions and energy efficiency will be developed. These data will be supplied to DOE's engine and emission control programs on an on-going basis, and they in turn will provide frequent feedback on engine and emission control system developments. Through this iterative process, optimum combinations of engine, emission control system, and fuel formulation will be identified.

Periodically, as new candidate fuels are identified and shown to yield promising emission reduction potential, a suite of supporting analyses (Tasks 5-8) will be conducted to identify issues that could affect the use of candidate fuels in the marketplace. Findings will be communicated to pertinent DOE programs and industry. Any "show stoppers" that are identified will terminate further testing of that candidate fuel.

Task 9 will validate the empirical relationships, demonstrate fuels and lubricants in vehicles, and prioritize the most promising fuel and lubricant options. The work breakdown structure for the APBF Program (see Figure 4) graphically depicts each of these tasks with their major elements.

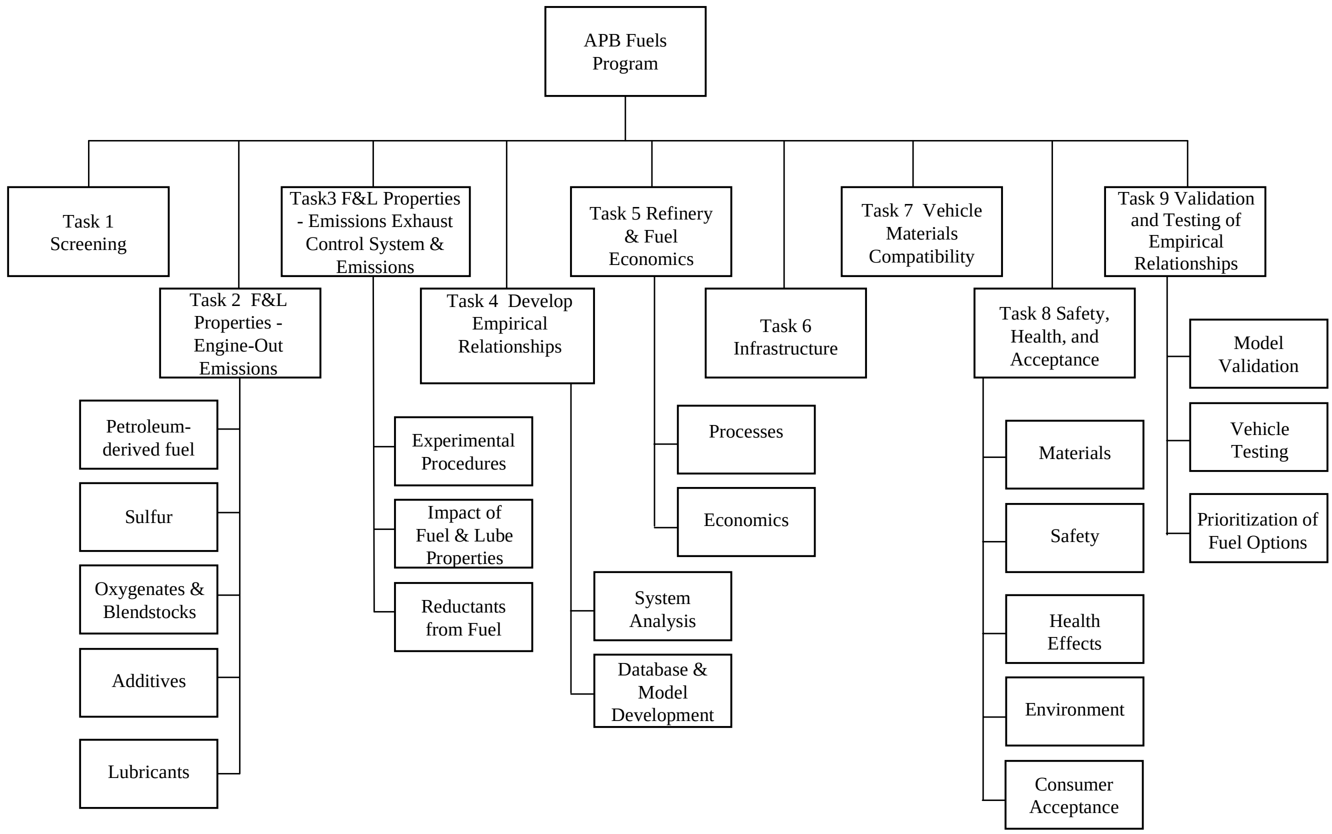


Figure 4: Work Breakdown for the APBF Program

6.1 Task 1 - Screening

In Task 1, a list of advanced petroleum-based CIDI fuels will be generated and assessed for four principal factors prior to extensive testing under the program. The factors to be considered will include:

- General characteristics for combustion in a CIDI engine
- Safety and health properties
- Production and distribution issues
- Environmental transport and fate properties

This initial list will be updated as necessary based on results and developments in CIDI engine design and emission control systems from the CIDI Combustion and Emission Control R&D Program and from the OHVT Heavy-Duty Engine R&D Program.

6.2 Task 2 - Fuel & Lubricants Properties – Engine-Out Emissions

In Task 2, data will be gathered, through testing, on the effects of fuel and lubricant properties on engine-out emissions. Detailed experimental plans will be prepared and coordinated among test laboratories concerning experimental design, test articles, test protocols, and measurements to be made. The results of Task 2 will be provided to DOE's CIDI engine

RD&T programs (both light- and heavy-duty) as information to enable the engine/emission control programs to meet their targets.

Standard test protocols for light-duty and heavy-duty engine dynamometer emission tests will be agreed to and used throughout the APBF Program. A standard protocol for translating emission levels obtained from light-duty engine tests (i.e., g/bhp-hr) to equivalent tailpipe emissions levels (g/mi) will also be agreed to and used. In the first year of the program, an assessment will be made of the need for development of a new engine dynamometer test protocol, and a new protocol will be developed should DOE and industry agree that this is warranted.

The data to be collected from the baseline fuel list includes correlations of fuel properties with NO_x and PM emissions, quantification of the potential for oxygenates to reduce NO_x and PM, and the impact of sulfur on fuel lubricity. The effect of lubricant composition on PM emissions will be determined. Where justified, fuel additives will be evaluated.

The bulk of the emission testing in Tasks 1, 2 and 9 will consist of measurements of engine-out emissions and emission levels following emission control systems. In addition, research on in-cylinder processes through use of research engines and combustion simulation devices will be conducted to elucidate the mechanisms that control emission levels.

6.2.1 Petroleum-Derived Fuel

Numerous studies have examined the impacts of fuel properties such as cetane number, density, aromatic, branching, and saturated ring structures on emissions from a variety of diesel engines.[16, 17] Recent work [18, 19] has indicated that the ratio of hydrogen to carbon in fuels provides a better prediction of particulate emissions than other correlating fuel properties, at least in light-duty diesel engines. There has been only limited work examining other fuel properties such as viscosity and boiling range.

While the data indicate general agreement, several issues are apparent. Some engines are more responsive to fuel property changes than others. Fuel injection systems, as would be expected for complex precision hydraulic devices, have altered injection characteristics as fuel physical properties change, confounding the fuel property combustion impacts. Alterations in the start of injection, injection duration and rate shape, total delivery volume, and fuel droplet characteristics not only affect engine power but also impact emissions in a design-dependent way.

The following work will be conducted:

- Data will be gathered, through testing, on the impacts of fuel properties other than cetane number, aromatics, and density on efficiency and criteria emissions, particularly in current production and advanced engine designs
- Data will be gathered, through testing, on fuel property impacts on polyaromatic hydrocarbon emissions

6.2.2 Sulfur Reduction

Sulfur in the fuel has been shown to interfere with the functioning of certain types of catalytic exhaust emission control system devices, particularly NO_x adsorber catalysts and lean-NO_x reduction catalysts. Sulfur reduction may be needed to enable the use of certain other devices. As identified later in the discussions on fuel impacts on exhaust emissions control system devices, fuel sulfur reduction should be investigated. Sulfur reduction can also provide benefits of reduced engine oil degradation, as well as reduced engine deposits and wear.

Sulfur reduction has been associated with reduced lubricity in diesel fuel, leading to increased fuel injection system wear. While sulfur compounds provide little lubricity, many of the deep sulfur removal refinery processes also remove the trace levels of nitrogen or oxygen-containing compounds which form lubricious surface films. At sulfur levels below 30 ppm, more effective fuel lubricity additives may be needed. The effect of reduced sulfur on fuel lubricity will be measured, and lubricity additive effectiveness will be evaluated if they are required.

In addition, sulfur has been implicated as a possible factor in the formation of ultrafine PM. The impacts of fuel sulfur on the formation of ultrafine PM will be evaluated.

6.2.3 Oxygenates and Other Blendstocks

Oxygen-containing components in diesel fuel have been shown to substantially reduce particulate emissions, in some cases accompanied by small but statistically significant reductions in NO_x. Results also suggest that the molecular structure of the oxygenated species substantially affect the results. A variety of oxygen containing materials are potentially available for blending with diesel fuel including plant-derived "bio-diesel," oxygenates from tailored gas-to-liquid processes, and a wide variety of oxygenated chemicals available in the marketplace.

Other potential blending components for diesel fuels include what are referred to as gas-to-liquid products, an example of which is Fischer-Tropsch liquids. These products, classically all paraffins, have high hydrogen to carbon ratios and, in several studies, have substantially reduced diesel particulate emissions.

Much work needs to be done on how to best utilize such materials to maximize emission benefits, and how to incorporate such materials into a diesel fuel production process. Research on the use of such unconventional diesel fuel components will include testing of:

- Impacts on regulated and unregulated emissions
- Impact on engine efficiency
- Opportunities for such fuel components to be used in the existing diesel engine fleet
- Mechanisms of how oxygenated materials reduce particulate emissions
- Increased engine wear with oxygen containing fuels (e.g., low molecular weight alcohols in gasoline have been shown to increase wear under operating conditions that lead to the formation and condensation of organic acids)

6.2.4 Fuel Additives

Fuel additives for emission reduction have been investigated with limited success. Additives are attractive because of their ease of use, their ability to be easily introduced within the existing infrastructure, and their potential cost effectiveness. Particularly for the reduction of PM emissions, areas which may offer some potential include additives for surface tension modification, combustion catalysts, or reaction modifiers. Water emulsified in fuel has been proposed for NO_x reduction. However, the track record in this area is discouraging. Fuel additives will be tested only if compelling data are provided to justify their inclusion in the testing program.

6.2.5 Lubricants

While oil consumption has long been recognized as a contributor to emissions of PM, engine oil may become a greater concern as fuel-derived PM emissions are reduced through combustion and fuel improvements. Fuel modifications often require corresponding reformulation of engine oils. Sulfur reduction will provide benefits independent of the exhaust emission control system. Potential benefits include reduced engine oil degradation, reduced engine deposits and wear, and reduced sulfur related engine-out particulate emissions. The widespread use of EGR with consequent increased levels of particles and acids will add a significant additional stress to the oil. The following tests will be conducted on lubricants:

- The contribution of lubricants to both the soluble and insoluble fraction of PM emissions will be assessed
- Approaches to reducing the contribution of engine oil to PM, whether through oil consumption reduction or oils that are less likely to produce PM, will be investigated
- The impacts of fuel changes on engine lubricant requirements will be evaluated

6.3 Task 3 - Fuel & Lubricant Properties – Exhaust Emission Control System & Emissions

The focus of Task 3 is to determine the interactions between fuel constituents and emission control devices (principally exhaust emission control system). The task consists of the following major elements:

- Generate data on the effects of sulfur and trace-level fuel constituents (~1-500 ppm) on emission control devices
- Develop data on the effects and synergies of major fuel components (over 1 percent) on emission control devices

The primary emission control devices to be studied in the test matrix include NO_x catalysts, NO_x adsorbers, oxidation catalysts, DPF, SCR, and EGR components. Others may be added as their development matures. Detailed experimental plans will be prepared and coordinated among test laboratories concerning experimental design, test articles, test protocols, and measurements to be made.

The key interactions with the exhaust emission control system include enhancement of system performance by strategically formulating the fuel, as well as understanding the components of the fuel that degrade emission control systems.

6.3.1 Develop/Standardize Procedures for Determining Fuel Effects on Exhaust Emission Control System

Experiments with emission control prototypes such as catalysts and adsorbers have frequently produced confounding results because of inconsistent protocols, methods, and instruments among laboratory sites. In this program, a "standard procedures" paper will be generated that prescribes the preferred conditions for the evaluation of the emission reduction performance as affected by fuel constituents. Among the important parameters to be documented and held consistent among test articles and laboratory are exhaust gas constituents, temperature, and space velocity. Teams presently conducting research on exhaust treatment devices have developed preliminary "standard" practices that could be adapted for this program. The recommended practice also includes the break-in ("degreening") period for a device as well as the emission measurement instruments themselves. This sub-task will:

- Develop standardized, accelerated aging tests with variable fuel properties

6.3.2 Determine Interactions of Fuel and Lubricant Constituents on Emission Control Devices (performance, deactivation mechanisms, regeneration potential)

Trace-level fuel components Because of the preponderance of evidence that sulfur is a poison to most emission control exhaust treatment technologies, the highest priority will be given to it.[20] The principal unknowns are (1) how far must sulfur really be reduced to enable emission controls, (2) what impact does sulfur have on device durability, (3) what is the role of lube oil sulfur, (4) is regeneration or sulfur-resistance achievable, (5) does sulfur play a role in the apparent formation of ultrafine PM in catalysts and filters, and (6) what's the conversion percentage of sulfur to sulfate PM by emissions control devices? Sulfur is expected to have a deleterious effect on cooled-EGR systems on certain engines. Efforts in FY 2000 and beyond will build on an existing effort, the Diesel Emissions Control Sulfur Effect (DECSE) project. Additional emphasis is expected on sulfur's influence on PM and on the lubricant sulfur. The activities that will be conducted as part of this sub-task include:

- The mechanisms of degradation and sensitivity to fuel sulfur will be determined
- The relation between exhaust emission control system performance/durability and sulfur levels will be further developed for the fuel and the lubricant
- The impact of representative cetane enhancers such as 2-ethylhexylnitrate and di-tertiary-butyl peroxide on the exhaust treatment devices will be documented
- The impact of non-sulfur fuels and lubricants trace materials in additive packages will be determined and recorded

Major Fuel Blend Components The second major path in relating fuel properties to emission control devices is examining the influences of major fuel constituents such as hydrocarbon groups and oxygenates. These fuel constituents may further be manifested in measured physical properties such as "natural" cetane number, distillation characteristics, viscosity, surface tension, etc. However, the key effect of major fuel constituents is via the exhaust species they produce, which will have a pronounced effect on the performance and longevity of exhaust emission control system devices. The exhaust PM, hydrocarbon (HC) species, partially oxidized species, and various oxides of nitrogen can all affect NO_x and PM control technologies. Certain exhaust constituents (e.g., C_{12} n-alkanes, alcohols, olefins) are more effective than others (branched alkanes) as reductants for NO_x conversion.[21] The better reductants are several times more effective than the worst, and thus are significant in overall engine/emission control system efficiency. Hence a fuel formulation strategy might target maximizing the optimal species in the exhaust. The activities that will be conducted as part of this sub-task include:

- The RD&T program will systematically characterize exhaust species as related to fuel constituents, and further determine the response of emission control devices to those species
- Attention will be given to the role of major fuel components in the formation of ultrafine particles in exhaust emission control system devices

6.3.3 Determine the Potential for Fuels Formulated for On-board Processing of Reductants

Generally, diesel fuel is not the most effective reductant for NO_x exhaust emission control system. Therefore, onboard processing of a portion of an engine's fuel flow has been considered for generating optimal reductants. An extreme example was an experiment to generate ammonia from fuel (on-board) for use in an SCR system. Less complex onboard processing may include partial oxidation or merely distilling light components of the fuel. Little work has been done to tailor the primary fuel to carry a reductant that can then be easily recovered for use in the exhaust emission control system.

- The potential to produce effective reductants from diesel fuel will be evaluated based on input from the CIDI Engine and Emission Control R&D Programs as to the properties of optimum reductants.

6.4 Task 4 - Develop Empirical Relationships

The relationships between fuel and lubricant properties on emissions with respect to engine operation and emission control system performance will be documented in this task, providing a major product from the APBF Program.

Data generated in Tasks 2 and 3 will provide a significant data set that can be utilized to develop predictive tools for estimating the effects that fuel property variations can have on engine-out emissions control system performance. This activity will consolidate the fuels and emissions data collected from the literature and developed during the course of this program, and develop empirical relationships that describe the combined emissions response of engines and exhaust emission control system to changes in fuel properties.

Analysis of the potential emission levels of criteria pollutants from LDVs, LDTs, and HDEs will be conducted in a systems analysis covering fuel, engine, and emission control systems. These analyses will (1) guide the course of testing, (2) assess progress towards achieving the technical targets, and (3) provide input to DOE's engine and emission control programs.

- The Advisor model, developed by DOE for automobiles, will be enhanced to facilitate analysis of emission reduction and efficiency improvement for a typical PNGV vehicle, light truck, and heavy-duty engine powertrain. The Advisor model will incorporate information on fuels, engines, and emission control technologies together as a system.
- Empirical relationships among fuel properties, engine characteristics, fuel injection parameters, and combustion phenomena will be derived to predict effects on engine-out emissions.

- Fuel properties, engine operating characteristics, and exhaust gas composition will be used to model exhaust emission control device effectiveness.
- Outputs will be shared with the CIDI Combustion and Emission Control R&D Programs and the OHVT Heavy-Duty Engine R&D Programs.

6.5 Task 5 - Refinery and Fuel Processing Economics

Task 5 is a supporting task that will assess the potential economic viability of potential APBF. Potential new diesel fuel components include Fischer-Tropsch (F-T) products, diesel oxygenates, processed diesel components with very low sulfur concentrations, reductants, and revised petroleum components. The benefits from revising diesel fuel will come at a cost during production. The balanced nature of fuels production in the refinery will result in compensatory changes elsewhere to accommodate those changes desired for diesel fuel.

6.5.1 New Kinds of Processes

Any significant revision of diesel fuel characteristics means adding and/or changing several refinery processes. The call for dramatically lower sulfur concentrations opens the door for new sulfur removal technologies. Though there are proposals for new catalysts and conditions to achieve deeper sulfur removal, their effect on the delicate balance in the refinery needs further study. Similarly, while the push for F-T products has produced many reports of hoped-for plants, their construction still awaits. Even now, refineries generate byproducts that could contribute to an F-T products pool, but since F-T products always include both low-quality gasoline and waxes that would require further processing to make diesel components, the integration of F-T products into the diesel mix requires a complex strategy that has not yet been devised. Oxygenates for diesel fuel would be needed in such quantities and with such specifications that they would become refinery-made products following the model of methyl tertiary butyl ether (MTBE). These options will be explored in coordination with the DOE Ultra-Clean Transportation Fuels Program which is jointly managed by DOE's Offices of Energy Efficiency and Fossil Energy. Activities to be conducted include:

- Identifying economic processes for sulfur reduction
- Describing potential refinery operations for producing oxygenates
- Comparing marginal costs of F-T options for refining, including needed upgrading
- Determining strategies for diesel fuel boiling range adjustment

6.5.2 Cost Assessments for Diesel Fuel Reformulation

A refinery model is a mathematical interrelation of individual operating costs for the various processes and upgrading steps making up a refinery. The model takes into account the properties of crude oil, refined products, and the mix of product volumes called the product slate. The refinery model yields the changed investment and operating costs for diesel fuel when any specifications or constraints are changed. Such changes are rarely continuous functions. For example, as sulfur concentration might be lowered, step changes in cost could occur because new techniques are invoked as progressively lower concentrations of sulfur are specified. Similarly, a step change would occur with the addition of a new component, such as an oxygenate. A refinery model provides a more realistic understanding of changes and their costs and benefits than can be obtained otherwise, and the results are crucial to the overall cost/benefit analysis. This global assessment of the costs of revising diesel fuel must be independent of organizations that may have proprietary interests in the outcome. Work in this area is ongoing at DOE and includes using a typical refinery model geared to changes in diesel fuel to: (1) include new processing steps and components to revise diesel, (2) conduct case studies for suggested changes in diesel composition, and (3) make sensitivity studies to identify the range of probable costs.

Assessments to be conducted will include:

- Leveraging existing refinery modeling efforts to assess the potential costs of producing new fuel formulations for commercial use for the fuels being tested in the APBF Program

- Identifying fuel properties that are most economical to adjust for emission testing

A promising new petroleum-based fuel or reformulation must be able to use the existing infrastructure for transport, storage, and distribution, not cause any significant vehicle materials incompatibilities, or cause unacceptable health and environmental hazards. The following three tasks address these issues and serve as a screen through which all new petroleum-based fuels and reformulations must pass to be considered practical candidates for widespread use by the public.

6.6 Task 6 - Infrastructure

Task 6 is a supporting task that will assess the compatibility of potential APBF with current infrastructure for producing, transporting, and storing fuel.

The definition of advanced petroleum-based fuels used in this program plan precludes those fuels that would need storage, distribution, and retailing infrastructure different from the ones currently in place for conventional petroleum fuels. However, some advanced petroleum-based fuels may have an impact on certain elastomers or components used in the existing infrastructure that might require updates to function reliably with expected durability. Therefore, the primary objective of this task is to assess whether or not any impacts on the existing infrastructure are likely, and if so, what measures would need to be taken to mitigate these effects. The infrastructure components that will be evaluated include storage tanks, pumps, flow meters, valves, floating roof seals, tank trailers, dispensers, dispenser hoses, and dispenser nozzles. The following activities will be conducted for each candidate fuel:

- Assessment of the compatibility of advanced petroleum-based fuels with current infrastructure for producing, transporting, and storing fuel
- Identify measures needed to mitigate adverse impacts

6.7 Task 7 - Vehicle Materials Compatibility

In Task 7, assessments will be made of the compatibility of vehicle fuel system, engine, and emission control system components with fuels and lubricants. Work in this task will be undertaken to address specific issues that are identified during the course of the program.

Similar to the technical approach for infrastructure explained in Section 6.6, it is assumed that advanced petroleum-based fuels will not need an entirely new fuel system onboard the vehicle. It is possible that some properties of advanced petroleum-based fuels might cause materials compatibility problems or result in the need for minor modifications to existing onboard fuel systems. Working with vehicle manufacturers, estimates will be made of the potential effect of fuel options on the cost of producing vehicles. Some examples of these potential problems and modifications include: (1) incompatibility with fuel system metals and elastomers, (2) inadequate lubricity for fuel injection systems, and (3) requirement for a vapor control system (some advanced petroleum-based fuels may have a significant vapor pressure which would cause evaporative emissions if used in vehicles without evaporative emission control systems).

Laboratory studies will focus on material compatibility, lubricity, and other pertinent issues using tests consistent with industry practice. This work will serve to identify potential issues that manufacturers of vehicle systems need to consider. Fuel options will be screened for corrosion of metal and degradation of polymer components. This includes consideration of: (1) elastomers used in o-ring seals, tubing, and hoses, and (2) component failure and permeation. Results of the compatibility assessments will be provided to DOE’s engine and emission control programs. Work under Task 7 will include:

- Identifying potential materials compatibility issues
- Assessing the potential importance of these issues through limited screening tests
- Providing assessments to DOE engine and emission control programs for disposition

6.8 Task 8 - Safety, Health, and Consumer Acceptance Aspects of Liquid Fuels

Task 8, a fourth supporting task, will assess the current state of knowledge on health and safety properties of liquid fuels. Also, potential issues of consumer acceptance of odor and combustion noise will be assessed.

Current storage and handling procedures for compression-ignition fuels have been built around the properties of diesel fuel, especially its relatively low volatility. New fuel options must be examined to ensure that they can be handled, used safely, and accepted by the public. A recent review of the safety and industrial hygiene issues (e.g., fire safety, chemical decomposition, inhalation, ingestion, and skin absorption exposure) related to potential blending components for advanced diesel fuels concluded that for many potential substances insufficient information is currently available to determine their health and safety properties.[10]

The technical targets for addressing these barriers are that the new fuels (1) present no greater overall safety, health, and environmental risks than current diesel fuels, (2) have no serious "show stopper" hazards, and (3) reduce the overall risk to public health compared to current diesel fuel.

The general technical approach for evaluating the magnitude of these potential safety, health, environmental, and acceptance barriers and identifying ways to overcome barriers that are considered to be unacceptable is to: (1) identify the hazard, (2) survey the available knowledge on the hazard, (3) consider the likelihood of occurrence of the hazard, (4) consider the potential consequences of the hazard, (5) make an estimate of the overall risk, (6) compare this risk to the current diesel fuel baseline, (7) identify changes that can reduce either the likelihood or the consequences of the hazard, and (8) consider whether those changes are economically and operationally feasible.

- Safety, health, and acceptance of candidate fuels will be determined as necessary.

6.8.1 Potential Materials Compatibility Barriers

While materials compatibility is often considered primarily an operational issue, problems with materials compatibility can directly affect the ability of the fuel delivery infrastructure and the vehicle fuel system to contain the fuel. Accidental fuel releases often cause safety, health, or environmental risks. Investigation of any issues associated with materials compatibility will be addressed in Task 7.

6.8.2 Safety

The safety hazards of liquid fuels are principally fire safety hazards. Knowledge of the fuel's physical and combustion properties can be used effectively to predict fire safety risk. The following elements of fuel flammability will be examined as possible technical barriers:

- Fuel volatility, as measured by vapor pressure or flash point
- Flammable range of the fuel, including
  - Temperature limits of flammability of vapors in fuel tanks
  - Vapor density and the dispersion rate of vapors released in the air
- Potential for accidental ignition of fuel, including spark ignition and autoignition, as well as the possible formation of explosive peroxides
- Fuel burning rate (Higher burning rates increase the fire hazard.)
- Flame radiation effects. Lower flame radiation reduces the potential for damage to people and property, but very low flame radiation can result in flame visibility concerns

6.8.3 Human Health Effects

The consideration of human health hazards is multi-dimensional. There can be many different organs in the body effected, resulting in many possible biologic end-points which may be associated with either acute or chronic effects. Moreover, the potential for adverse health effects may vary with the route of exposure, whether by inhalation, ingestion, or dermal exposure.

- A literature review of the following sources will be conducted to identify potential human health effects: National Institute of Occupational Safety and Health (NIOSH) Registry of Toxic Effects of Chemical Substances (RTECS), American Council of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs), and Health Sciences Data Base (HSDB).
- The degree of exposure associated with various fuel-related activities, such as vehicle fueling, vehicle repair, and fuel handling will be considered.

6.8.4 Environment

Fuels spills and accidental releases can affect the environment. Because of the importance of water in the environment, knowledge of the transport and fate of fuel constituents in surface and ground water is important. The environment is diverse, so a range of approaches is required. These approaches will utilize standard protocols that allow for comparison with other substances. The potential harm to the environment from spills and accidental releases will be evaluated by assessing the following for each candidate fuel:

- Water and air diffusivity
- Biodegradability
- Vapor pressure
- Octanol-water partition coefficient
- Henry's Law Constant
- Transformation rates

6.8.5 Consumer Acceptance

In order to gain a wide consumer acceptance of diesel-powered vehicles, the three major nuisances — visible smoke, odor, and noise have to be ameliorated. The visible smoke problem is addressed in this program explicitly in both Tasks 2 and 3. However, there is little attention given to the odor and noise characteristics of these new fuels. The following will be done as part of Tasks 2 and 3.

- Noise will be measured and assessed where indications are that it may be a problem.
- Odor will be assessed through analysis of hydrocarbon speciations.

6.9 Task 9 - Validation and Testing of the Empirical Relationships

Throughout the early part of the program, as sufficient information becomes available, the benefits of the emissions reduction potential of several fuels will be identified. Benefits will be validated for individual pollutants in terms of quantity of emissions reduced. The validation of these benefits will be conducted in laboratories and in the field with industry collaborations.

Work under Task 9 will integrate results from Tasks 1-8 to (1) validate the empirical models of fuel and lubricant properties with emissions and efficiency, (2) test new fuels in vehicles, and (3) prioritize fuel options for DOE's engine and emission control programs.

6.9.1 Model Validation

Predictive models inspire little confidence without some accompanying validation of their output. Therefore, selected fuels and lubricants will be recommended from Tasks 1-8 for model validation. These fuels and lubricants will be produced and tested to produce data that can be compared to the outputs of the empirical models developed under Task 4. Work will include:

- Producing fuels and lubricants for testing in a variety of engines with emission control systems
- Comparing the data to results from the emissions models developed under Task 4
- Determining, by modeling, the contribution of fuel, engine operation, and emission control systems to reduction of NO_x and PM emissions for the three platforms: automobile, light truck, and heavy-duty engine
- Providing validated model relationships to DOE's engine and emission control programs

6.9.2 Vehicle Testing

Entire systems will be evaluated in light- and heavy-duty vehicles by means of on-road testing to see if technical targets are achieved. These field evaluation tests will focus on demonstrations of the effectiveness and durability of fuel/hardware systems in service. Information on operations, emissions, and economics will be gathered and reported for the three platforms: automobile, light truck, and heavy-duty engine.

Early demonstrations will be based upon ongoing work under DOE's heavy vehicle fuels utilization program and will include demonstration of highly refined diesel fuel (e.g., ARCO EC Diesel) in heavy trucks.

Field evaluations will include:

- Establishing appropriate fuel hardware systems for field evaluation
- Testing fuel/engine/emission control systems in vehicles
- Reporting results for operations, emissions, and economics compared to the APBF targets
- Providing feedback to model development and validation

6.9.3 Prioritization of Fuel Options

In Task 9, comprehensive assessment of fuel options will be conducted using the output of Tasks 2-8. Potential implementation costs will include such factors as production and distribution of fuel, emission control hardware, advanced vehicle engine and fuel systems, and fuel economy (including emission control system requirements). This assessment of fuel options will not be a detailed, definitive evaluation. Modest program resources will be expended to provide guidance to DOE and its industry collaborators on the relative merits of potential fuel options.

6.10 Linking RD&T Elements to Barriers and Program Results

Table 8 lists the tasks, the expected outputs and the barriers that are addressed. Task 1, which is not listed in Table 8, will prioritize potential fuel constituents for investigation in the other tasks.

Table 8. Technical Approach Will Produce Results Targeted to Overcome Barriers

Program Result	Barrier Addressed	Element of Technical Approach
Data on:		
– Engine-out emissions	B1, 5, 6	Task 2
– Emission control performance	B2-6	Tasks 3, 7
– Tailpipe emission reduction potential	B1-6	Tasks 4, 9
– Lubricant effects	B1-6	Tasks 2, 3, 9
Data-derived models	B1-6	Task 4, 9
Economics of fuel production	B4, 7, 8, 9	Task 5
Benefit/cost for emissions reduction	B4, 7, 8, 9	Tasks 6, 7, 9
Safety, health, and acceptance of liquid fuels	B5, 6, 8	Task 8

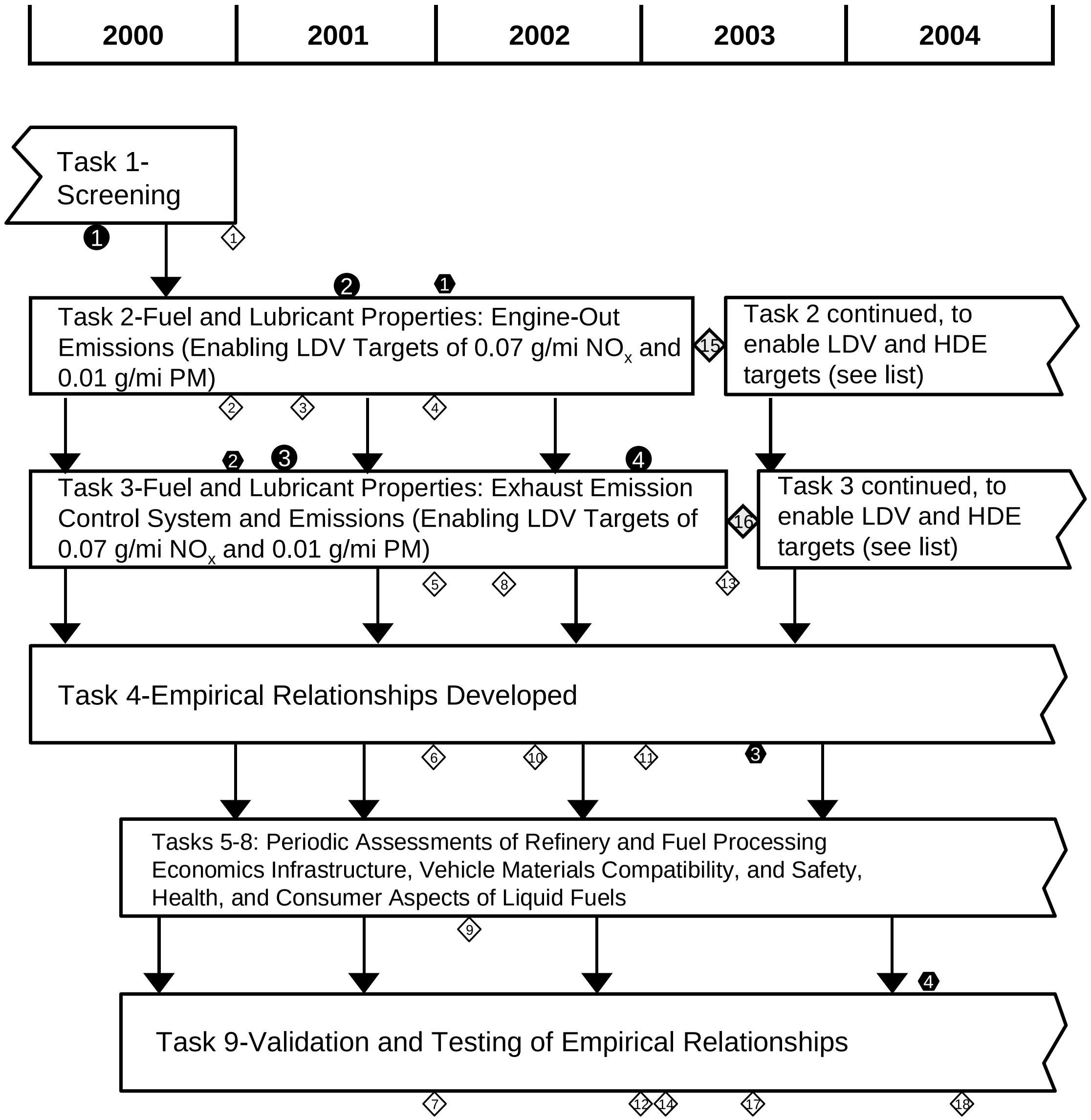
7.0 Schedule and Milestones

The schedule and milestones for the APBF Program are depicted in Figure 5.

Table 9. Advanced Petroleum-Based Fuels Program Milestones

Milestone	Task	Milestone Description	Estimated Date (CY) Q=Quarter
1	1	Complete initial list of fuel formulations for CIDI Engine Testing	4Q, 2000
2	2	Quantification of lubricants to PM and NO_x emissions completed	4Q, 2000
3	2	Fundamental combustion analysis results for oxygenates completed	1Q, 2001
4	2	Fuel impacts on criteria emissions, toxics, and PM completed for initial list of fuel formulations	4Q, 2001
5	3	Effects of major fuel components characterized on emission control technologies	4Q, 2001
6	4	Data collection for oxygenates completed	4Q, 2001
7	9	Validation of empirical relationships through system testing of petroleum components completed	4Q, 2001
8	3	Ultra-fine PM characterized	2Q, 2002
9	5-8	Assessments of initial list of test fuels for economics, infrastructure and vehicle compatibility, health and safety, consumer acceptance, life-cycle greenhouse and criteria gases, and cost effectiveness of emission reductions completed.	1Q, 2002
10	4	Empirical relationships completed for initial list of fuels	2Q, 2002
11	4	Effectiveness of onboard processes to produce NO_x reductants determined	4Q, 2002
12	9	Validation of empirical relationships through system testing of oxygenates completed	4Q, 2002
13	3	Fuel sulfur impact on emission control technologies characterized for LDVs and HDEs (effectiveness and durability)	2Q, 2003
14	9	Advanced fuel(s) to enable full useful life emissions of 0.07 g/mile NO_x and 0.01 g/mile PM for a PNGV-type CIDI passenger car demonstrated	4Q, 2002
15	2	Go/no-go. Continue collection of engine-out emissions data on fuel and lubricant properties to enable targets of 0.03 g/mile NO_x and 0.01 g/mile PM for LDVs, and 0.2 g/bhp-hr NO_x and 0.01 g/bhp-hr PM for HDEs	1Q, 2003
16	3	Go/no-go. Continue collection of exhaust emission control system data on fuel and lubricant properties to enable targets of 0.03 g/mile NO_x and 0.01 g/mile PM for LDVs and 0.2 g/bhp-hr NO_x and 0.01 g/bhp-hr PM for HDEs	2Q, 2003

Milestone	Task	Milestone Description	Estimated Date (CY) Q=Quarter
17	9	Validation of empirical relationships for reformulated diesel fuels to enable 0.07 g/mile NO_x and 0.01 g/mile PM emissions targets completed	2Q, 2003
18	9	Effects of fuel properties on toxic emissions characterized for the most promising LDV and HDE exhaust emission control devices	2Q 2004



Milestones

1. Complete initial list of fuel formulations for CIDI Engine Testing.
2. Quantification of lubricants to PM and NO_x emissions completed.
3. Fundamental combustion analysis results for oxygenates completed.
4. Fuel impacts on criteria emissions, toxics, and PM completed for initial list of fuel formulations.
5. Effects of major fuel components characterized on emission control technologies.
6. Data collection for oxygenates complete.
7. Validation of empirical relationships through system testing of petroleum components completed.
8. Ultra-fine PM characterized.
9. Assessments of initial list of test fuels for economics, infrastructure and vehicle compatibility, health and safety, consumer acceptance, life-cycle greenhouse and criteria gases, and cost effectiveness of emission reductions completed.
10. Empirical relationships completed for initial list of fuels.
11. Effectiveness of onboard processes to produce NO_x reductants determined.
12. Validation of empirical relationships through system testing of oxygenates completed.
13. Fuel sulfur impact on emission control technologies characterized for LDVs and HDEs (effectiveness and durability).
14. Advanced fuel(s) to enable full useful life emissions of 0.07 g/mile NO_x and 0.01 g/mile PM for a PNGV-type CIDI passenger car demonstrated
15. Go/no-go. Continue collection of engine-out emissions data on fuel and lubricant properties to enable targets of 0.03 g/mile NO_x and 0.01 g/mile PM for LDVs, and 0.2 g/bhp-hr NO_x and 0.01 g/bhp-hr PM for HDEs
16. Go/no-go. Continue collection of exhaust emission control system data on fuel and lubricant properties to enable targets of 0.03 g/mile NO_x and 0.01 g/mile PM for LDVs, and 0.2 g/bhp-hr NO_x and 0.01 g/bhp-hr PM for HDEs
17. Validation of empirical relationships for reformulated diesel fuels to enable 0.07 g/mi NO_x and 0.01 g/mi PM emissions targets completed.
18. Effects of fuel properties on toxic emissions characterized for the most promising LDV and HDE exhaust emission control devices

Technology Area Output

1. Data on hydrocarbon fuels and lubricants and effects on engine-out emissions to the light- and heavy-duty CIDI engine and vehicle programs.
2. Data on sulfur effects on emissions and fuel property effects on NO_x generation and control to the light- and heavy-duty CIDI engine and vehicle programs.
3. Fuel properties to meet Tier 2 regulations to the light- and heavy-duty CIDI engine and vehicle programs.
4. Empirical relationships between fuel properties and CIDI engine and vehicle emissions to the OAAT vehicle programs.

Supporting Input

1. Input from current literature on the effects of fuels on emissions.
2. Advanced CIDI engines with lower engine-out NO_x and PM emissions from CIDI light- and heavy-duty engine programs.
3. Enhanced PM measurement techniques (from CIDI Program).
4. Advanced NO_x control technology from CIDI Program.

Figure 5. Advanced Petroleum-Based Fuels R&D Network

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8.0 Management Plan

Execution of the MYPP is principally being undertaken through the APBF-Diesel Emission Control (DEC) Program. The APBF-DEC Program is being overseen by a government-industry Steering Committee consisting of DOE, EPA, engine and automobile manufacturers, energy companies, and manufacturers of emission control systems (Figure 6).

Fulfilling the MYPP principle of conducting R&D on fuels within a systems context, three work groups in the APBF-DEC program are defining and directing R&D on fuel and lubricant effects:

1. Fuels, engines, selective catalytic reduction/diesel particle filter (DPF) technologies
2. Fuels, engines, NO_x adsorber/DPF technologies
3. Lubricant effects

These three systems groups are being supported by work groups on: unregulated emissions, experimental design and data analysis, fuel and lubricant provision, and communications.

DOE is supplementing APBF-DEC with supporting R&D through its National Laboratories and independent contractors.

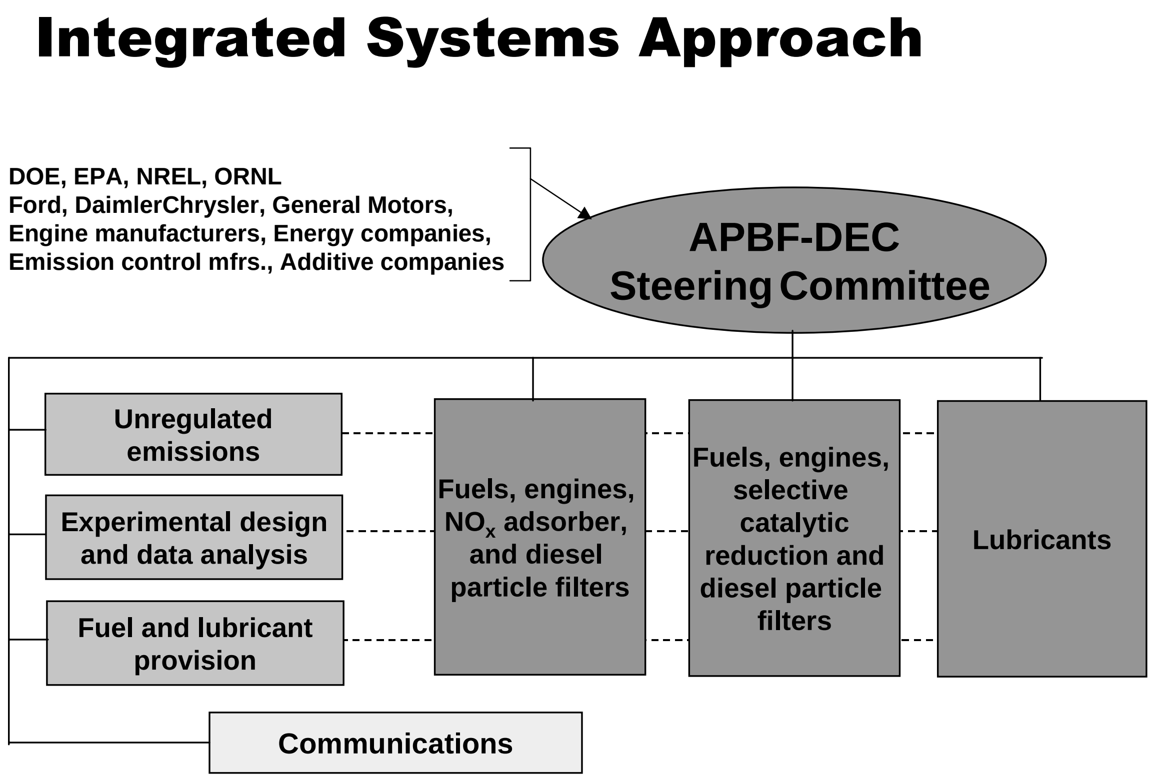

Figure 6: APBF-DEC Management Structure

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Glossary

ACGIH	American Council of Governmental Industrial Hygienists
APBF	Advanced Petroleum-Based Fuels
ASTM	American Society of Testing and Materials
BSFC	Brake specific fuel consumption
CARB	California Air Resources Board
CIDI	Compression-ignition direct-injection
CO	Carbon monoxide
DECSE	Diesel Emissions Control-Sulfur Effect
DOE	Department of Energy
DPF	Diesel particle filter
EGR	Exhaust gas recirculation
EIA	Energy Information Administration
EPA	Environmental Protection Agency
F-T	Fischer-Tropsch
FTP	Federal test procedure
FY	Fiscal year
g/bhp-hr	Grams per brake horsepower-hour
HC	Hydrocarbon
HDE	Heavy-duty engine
HSDB	Health Sciences Data Base
MPG	Miles per gallon
MTBE	Methyl tertiary butyl ether
MY	Model year
MYPP	Multiyear program plan
NIOSH	National Institute of Occupational Safety and Health
NMHC	Non-methane hydrocarbons
NO_x	Nitrogen oxides
OAAT	Office of Advanced Automotive Technologies

OHVT	Office of Heavy Vehicle Technologies
OTT	Office of Transportation Technologies
PM	Particulate matter
PNGV	Partnership for a New Generation of Vehicles
RFG	Reformulated gasoline
RTECS	Registry of Toxic Effects of Chemical Substances
SCR	Selective catalytic reduction
SI	Spark-ignition
SOP	Statement of Principles
SUV	Sport-utility vehicle
TLVs	Threshold Limit Values

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