REGULATORY SUPPORT DOCUMENT

EMISSIONS STANDARDS FOR HEAVY-DUTY CLEAN-FUEL FLEETS

U.S. Environmental Protection Agency

Regulatory Development and Support Division

Draft
May, 1993

Table of Contents

List of Tables

List of Figures

1.0 Introduction

This document is intended to provide technical, environmental and economic analyses of the heavy-duty portion of the Clean-Fuel Fleet program. The heavy-duty portion of the fleet program applies to only light heavy- and medium heavy-duty vehicles and the engines designated for use in these vehicles. EPA is proposing to set a heavy-duty clean-fuel fleet vehicle standard of 3.5 g/Bhp-hr non-methane hydrocarbon (NMHC) + oxides of nitrogen (NOx). Credit generating standards for the fleet program are also being proposed. Technological discussions of NMHC and NOx formation and control, calculations of environmental benefits and an assessment of costs and cost effectiveness are contained in separate chapters.

Chapter 2 contains an assessment of technologies available for reducing NMHC and NOx emissions in conventionally-fueled heavy-duty vehicles as well as technologies capable of meeting the credit generating standards. First the formations of NMHC and NOx in gasoline engines and the impacts of gasoline engine design are discussed. Next, emissions formation and control in diesel engines are covered. Finally, alternative fuel technologies and their emissions capabilities are presented.

Chapter 3 contains a discussion of the environmental benefits expected from this program. The chapter begins with a presentation of the vehicle demographics used in the calculations. This is followed with a discussion of how new emissions factors applicable to the vehicles covered by these standards were derived. Finally, the emissions benefits are presented and discussed.

Chapter 4 begins with an estimate of the costs associated with meeting these standards. Expected costs for research, development and testing are combined with certification costs and the anticipated incremental hardware and operating costs to derive both manufacturer and consumer costs associated with this program. These costs are then combined with the emissions estimates from chapter 3 in a calculation of the 22-year cost effectiveness of the heavy-duty portion of the Clean-Fuel Fleet program.

Chapter 2
Technology Assessment

2.0.1 **Introduction**

Internal combustion engines produce hydrocarbon[1] and oxides of nitrogen (NOx) emissions through a series of complex related processes which also control the production of other pollutants such as CO and particulates as well as the power output and efficiency of the engines. Hydrocarbon (HC) emissions generally result from the incomplete combustion of the fuel, while NOx results from the reaction of oxygen and nitrogen present in the combustion air. The reactions which produce NOx occur much more rapidly under conditions of high temperature and pressure.

Engine design and operations which affect emissions of HC and NOx will be discussed for both heavy-duty diesel and gasoline engines as well as for alternative fuel technologies. Other emission control technologies such as catalytic aftertreatment will also be discussed. The purposes of these discussions are to: 1) provide background information regarding the fundamentals of the technologies, 2) describe the technologies which are being commonly used today, 3) describe innovative technologies which may be used by clean-fuel fleet vehicles, and 4) identify the approaches that are most likely to be used by manufacturers to comply with the clean-fuel fleet vehicle standards. The discussions in this chapter will be qualitative in nature and generally do not include predictions of emissions reductions likely to result from use of a particular technology.

2.0.2 **Gasoline Engines**

2.0.2.1 Fundamentals of Gasoline Engines Which Impact NMHC + NOx emissions

NMHC and NOx emissions from gasoline engines (i.e., spark-ignited, otto cycle) are impacted by the following characteristics of the engine and its operation: air-to-fuel ratio, ignition timing, and combustion chamber design. Adjustments or variations to these parameters can substantially affect the performance as well as the emissions of gasoline engines.

2.0.2.1.1 Air-to-Fuel Ratio

---

[1] For simplicity, the term hydrocarbon (HC) is used throughout this chapter to describe general effects in emissions control. The term non-methane hydrocarbon (NMHC) is used for clarity when discussing the emissions standards or specific emission levels. The discussions using the term HC, therefore, should be considered to be equally applicable to NMHC emissions.

Emissions from gasoline engines are extremely sensitive to the ratio of fuel and air in the combustion system. A critical parameter then in the performance and emissions characteristics of gasoline engines is the excess air factor designated as λ. An excess air factor of 1.0 indicates the engine is operating at stoichiometric conditions while λ values of more than 1.0 indicate there is excess air in the combustion chamber. The current strategy, especially with the presence of three-way catalytic converters, is to attempt to keep λ at 1.0.

The air-to-fuel ratio, since it affects nearly all the operational parameters of the engine, is a primary design element in the operation of a gasoline-fueled engine. Proper air-to-fuel ratio control is critical in controlling both the engine out emissions of hydrocarbons (HC) and NOx and, as will be discussed in a later section, in the performance of catalytic converter aftertreatment devices. In principle, as λ is increased (i.e., leaner air-to-fuel ratio), HC emissions decrease due to the increasing availability of oxygen for more complete combustion. NOx emissions, on the other hand, show slight increases in engine-out emissions levels at λ values slightly above 1.0 and decreasing levels at higher values of λ.

NOx values increase at λ values slightly greater than 1.0 due to the increased availability of oxygen and nitrogen to react to form NOx. As λ increases, the additional air has a competing effect on NOx; by adding mass to absorb the heat of combustion, it lowers the peak temperatures and pressures, which leads to a decrease in the rate of formation of NOx. Also as λ increases, HC emissions begin to increase slowly at first and then rapidly as the lean misfire point is approached. Within reasonable limits, however, the effects of air-to-fuel ratio on engine-out emissions of HC are much less than the effects on engine-out NOx emissions.

Engines using lean air-to-fuel ratios also tend to show greater thermal efficiencies due to factors such as lower heat losses and the ability to use higher compression ratios (lean fuel mixtures are less susceptible to autoignition). At higher values of λ, however, the power output per volume can drop off despite the increase in thermal efficiency due to the lower fuel content. This effect can be offset by either using lean burn only at partial load conditions or by turbocharging the intake mixture to pack more air and the same quantity of fuel into the cylinder at a higher initial pressure.

2.0.2.1.2 Ignition Timing

Control of the timing of the ignition spark is important in controlling both NOx and HC emissions as well as in maximizing the work output of the engine. Delaying the ignition as much as possible reduces the amount of NOx produced by reducing both the peak temperatures and pressures of the combustion cycle and the length of time that the gases are exposed to high temperatures and pressures. Retarding the ignition timing can also increase the work output of the engine by reducing the amount of extra work the piston must do during the final stages of compression after the combustion has already begun. If the ignition timing is retarded too much, however, the combustion process begins late, resulting in somewhat incomplete combustion. Under these conditions, the power output drops and under conditions of greater timing retard the HC emissions can go up. Ideally, to minimize the NOx and HC emissions and to maximize the fuel economy of the engine, the combustion process needs to be optimized so that the ignition timing can be delayed to as close to the point in time when the piston reaches top dead center and to have as much of the combustion as possible take place just after the piston reaches top dead center.

2.0.2.1.3 Combustion Chamber Design

Combustion chamber parameters can affect the peak temperatures and duration of the combustion process, which in turn impact on the level of NOx emissions and the amount of work produced. The primary goals in the design and operation of the combustion chamber are to maximize the amount of work and power output by the combustion process (which also implies maximum combustion of the HC) while minimizing the production of NOx, the amount of wear on the engine and the likelihood of autoignition (knocking).

Reducing the combustion time is an important goal in chamber design. Shorter combustion time allows the timing to be retarded, which thereby reduces the formation of NOx and HC, while still allowing the combustion to proceed to completion earlier in the expansion stroke (thereby capturing more of the energy of combustion). Decreasing the combustion time can be accomplished by making design changes to the combustion chamber which minimize the distance the flame front needs to travel and/or increases the flame speed. Flame speed can be increased by increasing the turbulence in the chamber. In addition to decreasing emissions and increasing the percentage of the fuel burned near the optimal point in the process, "fast-burn" techniques also reduce the tendency of the engine to knock by reducing the amount of time available for the unburned fuel to auto-ignite. Therefore, compression ratios can be increased which in turn further increases the efficiency of the engine.

2.0.2.2 Current Gasoline Emissions Control Technology

All heavy-duty gasoline engines certified for model year 1992 were equipped with exhaust gas recirculation (EGR), and almost all were equipped with some form of catalytic converter and electronic engine controls. Most were equipped with three-way catalytic converters (converters which are capable of both reducing NOx emissions and oxidizing HC and CO emissions). These technologies are described below. It is also worth noting that some current engines are already very close to complying with the proposed NMHC+NOx emission standard of 3.5 g/Bhp-hr for heavy-duty clean-fuel fleet vehicles. Three of the gasoline-fueled engines families certified for the 1992 model year had HC+NOx emissions of 4.0 g/Bhp-hr or less, including one with HC+NOx emissions of 3.6 g/Bhp-hr.

2.0.2.2.1 Exhaust Gas Recirculation

From a NOx control standpoint, it is desirable to have some inert gases in the cylinder to take up some of the heat of combustion. The recirculation of exhaust gases can provide these inert gases. Recirculating exhaust gases is a more effective means of NOx emissions control than using additional air to absorb the heat of combustion (leaning out the air-to-fuel ratio) since the water and CO_2 in the exhaust gases have high heat capacities which make the exhaust gases more effective at absorbing the excess heat of combustion. Thus by using EGR, the peak temperatures can be reduced further before the volume of inert gases reach the point of interfering with the combustion process. Furthermore, recirculated exhaust gases do not add the excess oxygen. Modest levels of excess air can lead to increases in the engine-out levels of NOx emissions.

In some instances, exhaust gas recirculation can lead to a reduction in engine-out HC emissions. However, EGR normally has very little effect on HC emissions. At high levels of EGR (i.e. >25%), the combustion process can become unstable, just as in the case of too much excess air. Under these conditions, the HC emissions begin to rise sharply.

2.0.2.2.2 Aftertreatment Systems

2.0.2.2.2.1 Catalytic Converters

Catalytic converters are an important means of further reducing the emissions of gasoline engines. As already noted, heavy-duty gasoline engine systems are usually equipped with catalytic converters which remove HC, CO and NOx from the exhaust stream. Others use catalysts that are designed only to oxidize the HC and CO.

In three-way or oxidation/reduction catalysts, the HC and CO are oxidized to either less complex intermediate products or CO_2 and water vapor, while NOx is reduced to N_2 and oxygen. The reduction of NOx is accomplished by simultaneously utilizing the oxygen from the NOx molecules to oxidize the remaining HC and CO in the exhaust. This results in partial oxidation of the HC and CO. Further oxidation may be achieved using an oxidation catalyst. However, if there is excess oxygen in the exhaust stream, the HC will preferentially react with the free oxygen rather than the oxygen contained in the NOx molecules thereby leaving the NOx molecules relatively unaffected. On the other hand, if there is not sufficient oxygen available in the exhaust stream, the HC will not be oxidized or will be only partially oxidized due to the lack of oxygen. Therefore, the performance of three-way catalytic converters is very sensitive to the air-to-fuel ratio in the engine.

This problem can be partially overcome by using a catalytic converter that consists of two separate beds (a reduction catalyst followed by an oxidation catalyst) and injecting extra air between the two beds. This allows the air-to-fuel ratio to be run slightly on the rich side to ensure that good conversion of the NOx will be achieved in the first bed. However, this technique results in a decrease in fuel economy because of the slightly rich calibration. Furthermore, the injection of too much air into the second bed has the potential for cooling the gases down to the point that the catalytic converter can lose some of its effectiveness.

Each catalytic converter design has its advantages and disadvantages. The best approach for a given engine design is determined based upon the composition and level of the engine-out emissions.

2.0.2.2.2.2 Electronic Controls

Recent advances in electronic controls have made it possible to achieve very tight control over engine parameters such as the air-to-fuel ratio and ignition (spark) timing. This improvement in the controllability of the combustion process minimizes the excursions of these engines in non-optimized operating ranges which result in both increased emissions and decreased performance.

The most significant advantage to using electronic controls is that it provides a means by which the air-to-fuel ratio can be adjusted to ensure that the concentration of oxygen in the exhaust is at a level which leads to the optimum efficiency of a three-way catalyst under a broad range of operating conditions. By installing oxygen sensors in the exhaust stream near the catalytic converter, the system can diagnose whether or not the proper air-to-fuel ratio is being maintained. Using these feedback signals, the engine computer can then adjust the air-to-fuel ratio rapidly to compensate if the exhaust stream does not contain the optimal level of oxygen.

2.0.2.3 Future Gasoline Emissions Control Technology

Due to the 1998 4.0 g/Bhp-hr NOx standard, general improvements can be expected to current gasoline emissions control technology such as exhaust gas recirculation, catalytic converters (likely catalyst improvements), and especially electronic controls. Additional emission control of gasoline engines may occur with other emission control technologies that are under development:

electrically-heated catalytic converters, close-coupled catalytic converters, and lean-burn calibration.

2.0.2.3.1 Electrically-Heated Catalytic Converters

Catalytic converters require fairly high temperatures to be effective. Heat is provided by the exhaust and from the reactions of the HC in the catalyst bed. Following a cold start, there is a delay before the catalytic converter becomes effective, while it heats up to its operating temperature; once the converter reaches the desired operating temperature, it performs well with very high efficiency. Electrically heating catalytic converters at vehicle start-up can reduce the delay before the converters become effective. This approach may also be of value to the emissions control strategy for light and medium duty vehicles. Electrically-heated catalytic converters are made of metals rather than ceramics, thus, these converters experience less cracking and are more durable than other catalytic converters. However, some electrically-heated catalytic converters are susceptible to aluminum washcoat degradation. This technology is currently available. Other catalyst bed improvements are also available which could improve emission reductions efficiency.

2.0.2.3.2 Close-Coupled Catalytic Converters

Another approach that can be used to minimize the delay is to install the converter very close to the engine, so that the exhaust gases contacting the catalyst are hotter. However, these close-coupled catalytic converters are more susceptible to thermal degradation because they are continually exposed to significantly higher temperatures than converters located further away from the engine. By installing converters only slightly closer to the engine than current converters so that the exhaust gases contacting the catalyst are only at a slightly higher temperature, smaller emission benefits may occur. Closed-coupled catalytic converters will be available for the 1994 model year due to the California LEV standards. Insulating exhaust pipes may provide similar benefits at lower costs.

2.0.2.3.3 Lean-Burn Calibration

While the air-to-fuel ratios of current engines are generally calibrated at stoichiometry, there would be potentially significant benefits with leaner calibrations. Leaner air-to-fuel ratios could lead to lower engine-out HC, CO, and perhaps NOx emissions, as well as a decrease in fuel consumption. On the other hand, there can be a loss of power and problems with ignition and flame propagation. Also, leaner combustion would lead to leaner exhaust which would present the additional challenges of developing catalysts and oxygen sensors that work well under such conditions. It is likely that lean-burn calibration would only be used on engines with advanced electronic feedback controls. The availability of this technology is uncertain at this time for heavy duty engines.

2.0.2.4 Expected Approaches for Clean-Fuel Gasoline Engines

Overall, given that emissions from some current gasoline-fueled engines are already very close to those required by the proposed standard, it is expected that optimization of existing technologies will be adequate to allow a significant number of gasoline-fueled engines to comply with the clean-fuel fleet standard, and that dramatic changes will not be necessary. Engine changes, such as but not limited to changes in the EGR system, combustion chamber design improvements, and tighter control over the air-to-fuel ratio, are expected to provide much of the necessary reductions in NMHC+NOx emissions for many engines. Slightly leaner calibrations may be used under some conditions; however, very lean calibrations should not be necessary.

Additional reductions will also likely come from upgraded exhaust aftertreatment systems. It is expected that all gasoline engines in the Clean Fuel Fleet program will be equipped with three-way catalysts; and that these catalysts will be slightly more effective than those currently being used, through either optimization of the catalytic materials, increases in the catalyst loading and/or bed size or exhaust pipe insulation. The Agency does not currently expect that electrically-heated or close-coupled catalysts will be necessary in order for most gasoline-fueled engines to comply with the proposed standards.

The docket contains further supporting material on the feasibility of the proposed NMHC + NOx emission standard for heavy-duty engines.[1]

2.0.3 **Diesel Engines**

2.0.3.1 Technical Background/Fundamentals of Diesel Engines Which Impact NMHC + NOx Emissions

In diesel engines, NOx is formed in the early phases of combustion where temperatures and pressures reach a peak. In diesel engines, as fuel is injected into the combustion chamber it mixes with hot compressed air already present, and after a brief period known as ignition delay, this fuel-air mixture ignites. In this premixed burning phase, the fuel-air mixture burns in an uncontrolled manner, which causes a rapid rise in cylinder pressure and heat release, until the mixing controlled combustion phase (diffusion-controlled burning) takes control of the combustion process. Once diffusion-controlled burning begins, fuel essentially burns as it is injected, allowing partially burned droplets and particulates to be consumed as oxygen becomes available at local combustion sites. It is believed that most of the NOx is formed during the period before diffusion takes control of combustion.[2] Therefore, anything which can be done to reduce the temperatures during this uncontrolled burning phase will tend to reduce the formation of NOx.

Hydrocarbons are the result of incomplete combustion of the fuel. Because of the lean combustion technology used in diesels, out hydrocarbon emissions tend to be inherently low. However, controls that reduce NOx often have an adverse effect on HC emissions since they are inversely related to oxygen availability and peak conbustion temperature.

2.0.3.1.1 Fuel System

The fuel system in a diesel engine is responsible for controlling both the amount of fuel delivered to the cylinder and the timing of the fuel delivery. Since the fuel is injected into an air mass that is already compressed and has consequently been heated to a temperature above the auto-ignition point for the fuel, the injection timing determines when combustion will begin and serves some of the same functions in diesel engines as ignition (spark) timing does in gasoline engines. There are two types of injection systems available for diesel engines: direct and indirect injection.

Diesel engines can use either direct injection (DI) or indirect injection (IDI) combustion systems. Direct injection engines inject the fuel into a hollow in the piston and have the air/fuel mixing controlled by swirling motions in the intake air and the momentum and spray characteristics of the fuel jet. Indirect injection engines, on the other hand, inject the fuel into a pre-chamber and accomplish most of the air/fuel mixture through turbulence created by the expansion out of the chamber. Since indirect injection engines do not expose the bulk of the initial uncontrolled burning to as much oxygen, they have somewhat lower NOx emissions rates.[3]

The primary disadvantage of engines using IDI technology is that they are less fuel efficient than DI engines due to heat and frictional losses in the pre-chamber. However, indirect injection technology has low initial costs which make it well suited for small high-speed diesel engines where the fuel consumption is least significant.[4] In addition, IDI is a useful option for small diesels because it helps address problems with air utilization due to their small cylinder volume.[3] Concerns about the fuel economy penalties, however, are leading some manufacturers to use alternative methods of controlling NOx emissions.

2.0.3.1.2 Air System

Air system improvements also show promise for NOx and HC control. By increasing the mass of gases contained in the cylinder, the temperature rise can be decreased which results in reduced NOx formation. If some of the extra gas is oxygen, the increased oxygen availability will result in more complete combustion reducing HC and particulate emissions. Cooling of the intake air will further reduce the in-cylinder temperatures resulting in reductions in NOx formation.

2.0.3.2 Current Diesel Emissions Control Technology

Current emissions control for diesel engines is generally based upon optimization of engine parameters such as ignition timing, injector nozzle and cylinder design, and air intake. Nearly all of the light and medium heavy-duty engine families certified in 1992 used turbochargers with aftercooling. A very small number of current light and medium heavy-duty engine families use electronic controls, but most use mechanical controls. The use of mechanical controls is probably the most significant limitation of current diesel emission control. While some mechanical improvements are still being made, it is generally true that emissions from mechanically controlled engines have been optimized nearly as much as is possible without the development of dramatically new technologies, or reductions in fuel economy. For example, NOx emissions could be reduced from current levels by retarding the injection timing, but this would lead to reduced fuel economy and increased HC and PM emissions (which would increase the need for exhaust aftertreatment). The following sections discuss some of the currently technologies which affect diesel emissions.

2.0.3.2.1 Retarded Injection Timing

Retarding the injection timing is a well-known and proven technique for significantly reducing NOx emissions. The primary mechanism for reducing NOx emissions by this technique is the reduction in the duration of uncontrolled burning. However, retarded timing has undesirable effects, particularly when used alone. Retarding the timing significantly will increase particulate and hydrocarbon emissions and decrease fuel economy due to reduced time for the fuel and initial combustion products to mix with the excess air in order to burn.[5] The regulatory pressures on particulate emissions and the market pressures on fuel economy combine to limit the use of retarded timing in controlling NOx emissions.

2.0.3.2.2 Injection Pressure

Injection pressure increases in DI engines can be used to limit particulate emissions and speed up the completion of injection. Increased injection pressure increases the air/fuel mixing in direct injection engines because of increased air entrainment into the fuel spray and higher turbulence therein (less condensation is likely to occur). This has little direct effect on NOx formation; however, it does lead to a decrease in particulate formation. Furthermore, an injection pressure increase will shorten the duration of the injection.[6] The combination of reduced particulate formation and shortened injection duration should allow the timing to be retarded without incurring other impacts. Hydrocarbon emissions are insensitive to injection pressure at full-load, and only increase slightly under half-load high speed conditions.[7]

2.0.3.2.3 Injector Nozzle Holes and Diameters

Nozzle characteristics are important to optimize for emissions and performance reasons, particularly for direct injection engines. Decreasing the nozzle hole diameters increases the injection duration without increasing the ignition delay; therefore, the maximum heat release in the pre-mixed burning phase decreases. In addition, reducing the hole size better atomizes the fuel allowing more complete burning. For these reasons, smoke can be decreased without an increase in NOx by decreasing the nozzle diameter.[2] Changing the number of holes in the injection nozzle may be used to affect the spray characteristics of the fuel. Hydrocarbon emissions are only slightly affected by the number of holes; however, CO and smoke have been found to be least sensitive to injection pressure for a 6-hole injector.[8]

2.0.3.2.4 Intake Air Turbocharging

Turbochargers are used to force additional air (mass) into the combustion chamber allowing a shorter ignition delay and more complete burning of a given amount of injected fuel. Therefore, turbocharging may be used to reduce HC emissions at partial loads which increases the capability of retarding timing (lower NOx).[8] As with other lean burn systems the addition of additional air to make the mixture even leaner results in reduced cylinder temperatures. This change has a direct positive impact on NOx emissions.

2.0.3.2.5 Aftercooling

If the intake air is turbocharged, the temperature will rise during compression. Cooling the intake air after it has been turbocharged will help lower the in cylinder temperature, and therefore reduce NOx formation.[5] There are several approaches to aftercooling, including air-air and air-liquid aftercoolers. By using air-to-air aftercoolers, some manufacturers have been able to reduce the temperature of the turbocharged intake air to about ten or fifteen degrees Fahrenheit above the ambient air temperature.

2.0.3.2.6 Cylinder Design

The combustion chamber shape may be optimized in order to promote mixing with enhanced turbulence. Enhanced turbulence can reduce particulate and hydrocarbon emissions through better mixing but has a tendency to increase NOx emissions through the increased heat release. A reentrant chamber has a small lip around the top of the bowl cut into the piston. This combustion geometry has been found to reduce particulate emissions and the sensitivity of particulate emissions to timing retardation.[6] Since the sensitivity of particulate emissions to timing retardation is reduced, the timing can be retarded to reduce NOx emissions in many cases to the point that there is a reduction of NOx emissions at either the same level of particulate emissions or even with a reduction of particulate emissions.

Valve timings and, particularly for direct injection engines, degree of swirl can also be critical. Control of these events to optimize air/fuel mixing minimizes the formation of pollutants. Swirl increases the mixing of the air and fuel in the combustion chamber, and the degree of swirl depends on both air patterns and cylinder geometry. It is difficult to incorporate a degree of swirl which will achieve good mixing at all operating conditions. Although increasing the swirl in the combustion chamber may be used to reduce particulate emissions,[12] the NOx, smoke, and fuel consumption may increase.[8] Experiments on engines equipped with a two position variable swirl device have shown simultaneous reductions in both particulate emissions and NOx emissions by allowing the engine to be optimized for NOx or particulate emissions reductions at operating conditions under which formation of either of these pollutants is of particular concern.

2.0.3.3 Future Diesel Emissions Control Technology

Future emission control for diesel engines will be based upon further optimization of engine parameters such as injection timing, injection pressure, injector nozzle and cylinder design, air intake, and aftercooling. Additional diesel emission control may occur with the following new emission control technologies among others: exhaust gas recirculation, electronic controls, particulate trap-oxidizers, catalytic oxidizing converters, catalytic NOx reduction, and variable compression ratio.

2.0.3.3.1 Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is a proven NOx control strategy for gasoline engines (see above discussion). Previously, EGR has not been necessary in diesel-cycle engines due to the availability of other approaches, such as increased air mass charging, to accomplish similar objectives. However, with the practical limits of these approaches now being faced, the increased heat capacity of recirculated exhaust may now provide a valuable advantage. The higher levels of particulate emissions traditionally found in diesel engines also led to concerns that recirculation of exhaust gases would lead to decreased engine durability. With the advent of diesel engines with low engine-out particulate emissions and diesel fuel sulfur control, however, EGR is becoming more feasible for diesel engines.

Exhaust gas recirculation reduces the temperature of the cylinder by adding inert gases to expand to do work. This can increase PM emissions, especially at full load, due to the lack of oxygen present in the combustion chamber which results in incomplete combustion. Moderate EGR rates (5-15%) have been shown to bring NOx down into the 1.9 - 3.4 g/Bhp-hr range. This may be done without increasing particulates significantly or de-rating the engine by using electronically-controlled EGR (see discussion below). In addition with a NOx reduction engines using EGR have shown significantly better fuel economy than engines using timing retard. More research must still be done to demonstrate the full potential of EGR.[9]

2.0.3.3.2 Improved Turbocharging

Two improvements to intake air turbocharging which are being developed may result in significant emissions reductions. The first is the variable geometry turbocharger (VGT), which allows a more optimized flow of air into the engine, such as more air at high loads. VGT would not directly impact NOx emissions, but would decrease particulate emissions and fuel consumption, thereby allowing further retard of the injection timing. It also provides a means of controlling cylinder pressures for engines using EGR. The second approach called turbo expanding involves over-compressing the intake air, then expanding it to a lower pressure after the charge is cooled by the aftercooler. The result is a reduced intake temperature, and thus lower NOx emissions.

2.0.3.3.3 Injection Rate Shaping

Injection rate shaping is a very promising technology for reducing NOx emissions without adversely affecting other performance parameters. The basic approach is to reduce the amount of fuel injected in the early phases of injection so that the amount of fuel which undergoes premix burning reactions is reduced. Preliminary testing and even production system development has begun in earnest over the last few years.

Results from the Ricardo HDD engine research program demonstrate that rate shaping may be used to achieve very low NOx levels without a penalty in fuel economy or particulate emissions.[10] By injecting the fuel with a "gradual rise and a sharp cut" as opposed to a constant injection, the NOx is reduced because of a lower heat release during the pre-mixed burning phase where NOx is formed.[2] In addition, a clean injection cut-off will reduce smoke and HC emissions by avoiding the poorly atomized end of injection.[8]

2.0.3.3.4 Electronic Controls

One historical problem with managing the engine operation parameters is the inherent problem that mechanical controls have only a limited ability to adjust the operating parameters to match the optimal conditions for any given speed and load condition. An engine set up to produce low emissions at one set of conditions may have relatively high emissions at some other sets of operating conditions. These problems are especially pronounced in the smaller diesel engines affected by new clean-fuel fleet vehicle regulations.

The advent of electronic engine control devices will allow more flexible control of engine operation. Electronic controls are expected to be installed on essentially all heavy-duty diesel engines by 1994 in order to both achieve improved engine performance and to assist in achieving compliance with the 1994 emission standards. Through the use of electronic controls and the advent of advanced fuel delivery systems, it will become possible to store a map of the optimum operation parameters and then to control the engine operation at these conditions over a wide range of operating modes thereby reducing some of the needs to make design trade-offs in cases where engine operation parameters optimized for one operating condition may not be appropriate for other operating conditions.[8] Among the parameters that could be controlled electronically are injection timing, injection rate, and EGR rate.

One example of the use of electronic control would be to use it to significantly retard injection timing under most operating conditions except high loads, where the need for both particulate control and high power is significant. Similarly, EGR rates could be reduced at high loads to decrease the impact on particulate emissions. It may also be possible to use exhaust gas sensors for oxygen and/or NOx in a closed-loop control system to correct for in-use deterioration. EPA believes that, of the technological advances expected in the next several years, electronic controls have the greatest potential for improving the emissions and fuel economy of diesel engines.

2.0.3.3.5 Aftertreatment Devices

Aftertreatment devices have not yet come into widespread use on diesel engines. Up to the present time, emissions control strategies for most diesel engines have relied on technologies which control engine out emissions. However, both particulate trap oxidizer systems and flow through catalytic oxidizers are under development and expected to be available for wide-scale commercial production if necessary to comply with the 0.10 g/Bhp-hr PM standard for the 1994 model year. In addition, there is active research ongoing in the area of catalytic converters capable of reducing NOx emissions in lean exhausts. These are discussed below.

2.0.3.3.5.1 Particulate Trap-Oxidizers

A trap-oxidizer system primarily affects PM and HC emissions. This method of aftertreatment consists of a durable particulate filter (trap) which collects particulate emissions in the exhaust stream. Developers of these systems claim that collection efficiencies of 80 percent or greater can be achieved. Since collection of the particulates without a system for eventual removal would quickly plug the traps and shut down the engine, some method of regenerating the filter by burning off (oxidizing) the particulates is required. The traps must be regenerated before the systems become plugged to the extent that back pressures in the exhaust system rise too much, but too frequent regenerations increase the amount of energy which must be put into the systems to effect the regeneration.

Trap-equipped urban bus engines have been certified recently, but manufacturers remain reluctant to rely on these systems because of their relatively high costs and remaining concerns over the durability of the systems. However, these systems should be available for use prior to 1998, if needed.

2.0.3.3.5.2 Catalytic Oxidizing Converters

Catalytic oxidizing converters greatly reduce HC emissions. Reductions of as much as 40 or 50 percent of the engine out HC emissions may be seen from the designs likely to be available prior to 1998. Since catalytic converters may see widespread use in the control of particulate emissions, large reductions in HC emissions will result as a corollary benefit. The catalytic converter avoids the problem of regeneration due to its flow-through design and some believe this is a simpler, more cost efficient and more durable method of aftertreatment than particulate traps. However, its major drawback is sulfate production. This problem is expected to be managed with the low sulfur fuels being mandated for sale beginning in October of 1993.[9]

2.0.3.3.5.3 Catalytic NOx Reduction

Aftertreatment devices to control NOx emissions in lean exhausts are not available at this time, although research on promising technologies is progressing in Japan and Germany.[11] The only aftertreatment device to be demonstrated to date involves the injection of ammonia or urea into the exhaust stream to consume NOx. However, there are no acceptable methods to ensure that there will always be a supply of ammonia or urea to keep these devices operating. Therefore, actual in-use emissions reductions cannot be relied on and use of these devices could be problematic. There is also concern about harmful effects from the emissions of ammonia.

Passive flow-through catalytic converters to reduce NOx emissions in lean-burn exhausts are under investigation. These devices appear to operate by simultaneously reducing NOx and oxidizing HC or particulates with the oxygen produced from the NOx. However, the development of useful devices is still some years away and availability of these devices for the 1998 model year can not be assumed.[8]

2.0.3.3.6 Variable Compression Ratio

Increasing the compression ratio in the engine reduces white smoke and hydrocarbon emissions. There is, however, an optimum point at which a further increase in the compression ratio causes an increase in particulate emissions.[12] A prototype diesel engine has been developed that had a variable compression ratio. NOx and NMHC emissions from this engine were very low. This technology thus may become available to reduce particulates without increasing NOx.[13]

2.0.3.4 Expected Approaches for Clean-Fuel Diesel Engines

Diesel engines will need to make changes to comply with the proposed clean-fuel fleet emission standard for NOx and NMHC, but this should be feasible for a significant number of engines. It is expected that electronically controlled EGR will be necessary, and that highly optimized electronic control of injection timing and rate shaping will also be incorporated. Some catalytic aftertreatment may be used to control NMHC and PM emissions, since engine-out emissions of NMHC and PM could increase as a result of timing retard. EPA does not expect that catalytic aftertreatment will be used to reduce NOx emissions. It is not clear, at this time, how fuel economy will be affected, since electronic controls, EGR, and improved turbocharging can improve fuel economy, while timing retard will have a negative impact. Manufacturers will be faced with a decision of how to best trade off improvements to the engines with increases in fuel consumption, in order to control emissions in the most cost effective manner.

The docket contains further supporting material on the feasibility of the proposed NMHC + NOx emission standard for heavy-duty engines.[1]

2.0.4 **Alternative Fuel Technologies**

While alternative fuel technologies are certainly viable candidates for use in clean-fuel fleet vehicles, the proposed emission standards are not set at a level which will require their use. It will be difficult, however, for most diesel engines, and possibly some types of gasoline engines, to reach the proposed credit-generating standards. Alternative fuel technologies such as methanol- and gaseous-fueled engines are expected to meet these standards while electric vehicles are viewed as being the only technology capable of meeting the proposed zero emission vehicle standards. The docket contains further supporting material on the feasibility of the proposed credit level NMHC + NOx emission standards for heavy-duty engines.[1]

2.0.4.1 Methanol

Methanol is an attractive fuel from an emissions standpoint. Its lower flame temperature leads to an inherent reduction in the formation of NOx emissions. Exhaust emissions of NMHC (more appropriately called organics for methanol-fueled engines) are generally comparable to those of similar petroleum-fueled engines. Nevertheless, methanol-fueled engines can still provide some benefit with respect to organic emissions for two reasons. First, organic emissions from methanol-fueled engines, while not necessarily less than those from engines using conventional petroleum fuels, tend to be less reactive in the processes which form ozone, and thus can have a less significant impact on ambient air quality. It should be noted, however, that this benefit is difficult to quantify. Second, non-exhaust (e.g., evaporative) emissions of organics are much lower than those from gasoline-fueled vehicles due to the lower vapor pressure of methanol.

Both otto-cycle and diesel-cycle methanol-fueled engines and vehicles are under development currently. While it is expected that otto-cycle technology will be capable of meeting the proposed credit standards by 1998, these vehicles are being developed primarily for light-duty uses. Diesel-cycle engines, however, because of their inherent fuel economy advantages, are more likely to see applications in heavy-duty vehicles. Recently, Detroit Diesel certified the first heavy-duty diesel cycle methanol engine for commercial sale. This engine was recertified for the 1993 model year as having NMHC+NOx equivalent emissions of 1.8 g/Bhp-hr, CO emissions of 2.1 g/Bhp-hr and particulate emissions of 0.03 g/Bhp-hr. As can be seen, this engine is already in compliance with the proposed credit standard. This particular engine is a heavy heavy-duty engine intended for use in urban buses, but the technology should be transferrable to other engines more likely to be used in the Clean Fuel Fleet program.

2.0.4.2 Natural Gas

Natural gas, in either the form of compressed natural gas (CNG) or liquified natural gas (LNG), is likely to be used as an alternative fuel in some light and medium heavy-duty vehicles for use in the Clean Fuel Fleet program. Indeed, experimental delivery vans converted from gasoline to CNG are being used by several delivery fleets due to its potential for fuel cost savings. Moreover, Cummins has recently certified a CNG-fueled L-10 bus engine with the State of California. Two types of CNG-fueled engines are being developed: stoichiometric (i.e., converted gasoline engines) and lean-burn (e.g., the Cummins L-10 bus engine).

EPA analyzed the emissions characteristics of CNG-fueled vehicles and engines in an April 1990 special report.[14] Stoichiometric engines, which are the type of engines being used by delivery vans, were projected in that report to have emissions of 0.88 g/Bhp-hr NMHC+NOx, 7.4 g/Bhp-hr of CO, 0.01 g/Bhp-hr of particulate and 0.0006 g/Bhp-hr of formaldehyde for optimized engines. Projections for optimized lean-burn engines, which are favored for use in heavy heavy-duty applications (greater than 26,000 lbs GVWR) for fuel economy reasons, indicated that NMHC+NOx emissions of 4.06 g/Bhp-hr, CO emissions of 1.5 g/Bhp-hr, particulate emissions of 0.05 g/Bhp-hr and formaldehyde emissions of 0.03 g/Bhp-hr can be achieved using traditional technology. However, the Cummins L-10 engine that was recently certified had emissions that were much lower than those projected for such a lean-burn engine: NMHC+NOx emissions of 2.6 g/Bhp-hr, CO emissions of 0.4 g/Bhp-hr, and particulate emissions of 0.02 g/Bhp-hr. While neither the projected emissions, nor the emissions from the Cummins L-10 engine, would comply with all the credit standards, it is expected that the standards could be met by engines using more advanced technology. Although the L-10 engine is for heavy heavy-duty applications, the L-10 engine demonstrates that it ought to be feasible to meet the clean-fuel fleet vehicle standards with light and medium heavy-duty vehicles. Lean-burn CNG engines will need to improve the control of NOx and/or NMHC emissions in order to meet the credit standards, but it is likely that this would be accomplished by incorporating the advances in NOx control which are being developed to comply with the 4.0 g/Bhp-hr standard for all heavy-duty engines. Stoichiometric technology will also require minor advances, such as slightly higher catalyst loadings, in order to comply with these standards by 1998.

2.0.4.3 Liquefied Petroleum Gas

Liquefied Petroleum Gas (LPG) is another gaseous fuel which expected to be used to some extent in the Clean Fuel Fleet program. It is a very clean-burning and economical fuel, and has been the most widely used alternative fuel for many years. Most of the incentive for its use has come from its economic advantages, and there is only a limited amount of emissions data available, especially for heavy-duty vehicles. In general, emissions from LPG-fueled engines should be similar to the emissions from CNG-fueled engines, except for NMHC which could be slightly higher from LPG-fueled engines. This is because NMHC emissions are generally due to unburned fuel, and LPG is largely a non-methane fuel (unlike CNG which is comprised mostly of methane). As with CNG-fueled vehicles, it is expected that LPG-fueled heavy-duty engines will also be able to comply with the credit standards with similar control approaches. EPA plans to release a report on LPG fuels and vehicles in the next few months.

2.0.4.4 Electric Vehicles

EPA anticipates that electric vehicle technology will be required for a vehicle to comply with the zero standards. While light and medium heavy-duty vehicles may be better equipped to handle the bulk and mass of the necessary batteries, the additional batteries, limited driving range, and operating expenses will probably still make electric vehicle technology an unpopular choice. Advances in technology and market incentives for credits, however, may combine to make such technology viable at some point in time.

2.0.5 Summary

The proposed clean-fuel fleet vehicle standards should be achievable using a wide range of technologies. Gasoline-fueled engines should be able to reach compliance with the standards through the further optimization of technologies already in use. Diesel engines will significant developmental work, including the introduction of new technologies such as EGR for diesels. EPA also believes that optimized electronic controls for fuel will be required for all diesel engines in this program but much of this will be incorporated meet the 4.0 g/Bhp-hr NOx standard. Optimized (or in some cases non-optimized) alternative fuel technologies capable of meeting the clean-fuel fleet vehicle standards are already available.

Credit-generating standards may be achievable in some cases using conventional fuel technologies and will certainly be achievable using alternative fuels. These standards might be achievable with highly advanced gasoline engines using electrically heated catalytic converters and possibly even by diesel engines using optimized EGR and electronic fuel control should they become available. A methanol engine which meets all of the proposed credit standards has already been certified, and natural gas-fueled engines appear to be promising candidates also. Zero-emitting vehicles will probably require electric vehicle technology.

REFERENCES

1. Presentation to EPA Office of Mobile Sources on developments in automotive emission control technology, Manufacturers of Emission Controls Association (MECA), May 11, 1993 (found in the docket for this rulemaking).

"Regulatory Impact Analysis, Oxides of Nitrogen Pollutant Specific Study and Summary and Analysis of Comments," EPA Office of Mobile Sources, March 1985.

"Final Regulatory Support Document and Summary and Analysis of Comments on the NPRM -- 1993 Model Year Bus Particulate Standard, 1994 and Later Model Year Urban Bus Particulate Standard, Urban Bus Test Procedures, and 1998 and Later Model Year Heavy-Duty Engine NOx Standard," EPA Office of Mobile Sources, February 1993.

Acurex Environmental Project Under Contract with California Air Resources Board, "Technical Feasibility of Reducing NOx and Particulate Emissions Form Heavy-Duty Engines," Acurex Environmental Project 8450, Contract No. A132-085, July 27, 1992.

"Draft Regulatory Support Document -- 1994 and Later Model Year Urban Bus Particulate Standard, Urban Bus Retrofit/Rebuild Program, 1998 and Later Model Year Heavy-Duty Engine NOx Standard," EPA Office of Mobile Sources, May 1991.

2. Research work done by Wade et. al., 1987; Cartellieri and Wachter, 1987.

3. "Feasibility of Controlling Emissions form Off-Road, Heavy-Duty Construction Equipment," Energy and Environmental Analysis, Inc., December 1988.

4. "Feasibility and cost-Effectiveness of Controlling Emissions from Diesel Engines in Rail, Marine, Construction, Farm, and other Mobile Off-Highway Equipment," Radian Corporation, February 1988,

5. "Mobile-Source NOx Emissions Sources and Control Options," US EPA, November 1990.

6. "Combustion Chamber Shape and Pressurized Injection in High-Speed Direct Injection Diesel Engines," M. Ikegami, M. Fukuda, Y. Yoshihara, J. Kaneko, SAE Paper 900440.

7. "Application of a High Flexible Electronic Injection System to Heavy Duty Diesel Engine," R. Racine, M. Miettaux, Y. Drutel, J. Heidt, SAE Paper 910184.

8. "The Effect of Injection Parameters and Swirl on Diesel Combustion with High Pressure Fuel Injection," S. Shundoh, T. Kakegawa, K. Tsujimura, SAE Paper 910489.

9. "The Low NOx Engine," J. Needham, D. Doyle, A. Nicol, SAE Paper 910731.

10. "Injection Timing and Rate Control--A Solution for Low Emissions," J. Needham, M. May, D. Doyle, S. Faulkner, SAE Paper 900854.

11. Ward's Engine and Vehicle Technology Update, "Lean-Burn Catalysts Under Development" April 15, 1991.

12. "Technology for Meeting the 1991 U.S.A. Exhaust Emission Regulations on Heavy Duty Diesel Engine," K. Mori, H. Kamikubo, T. Kawatani, T. Obara, I. Fukano, K. Sugawara, SAE Paper 902233.

13. "The Development of a Novel Variable Compression Ratio, Direct Injection Diesel Engine," R. Sobotowski, B. Porter, A. Pilley, SAE Paper 910484.

14. Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel, Volume II Heavy-Duty Vehicles, Special Report Office of Mobile Sources, Environmental Protection Agency, April 1990

Chapter 3
Environmental Benefits

3.0.1 Introduction

The environmental benefits of the use of heavy-duty clean-fuel fleet vehicles which meet the proposed combined 3.5 g/Bhp-hr NMHC+NOx standard have been estimated by comparing the total emissions from clean-fuel fleets which are covered by this program to what the emissions from these same heavy-duty fleets would be in the absence of a fleet program. Projections have been made of the number of vehicles which will be affected by these requirements, the number of miles each of these vehicles travel during a year, and the emission factors for clean-fuel and 1998 "baseline" vehicles.

3.0.2 Calculation Method

Efforts were made to estimate emissions in a manner consistent with the methodology used in the MOBILE4 computer model. These estimates will be updated using MOBILE5 for the final version of this document accompanying the final rule on heavy-duty standards. The same basic approach of multiplying deteriorated emission factors by the total number of vehicle miles traveled to estimate the total emissions was used. Some departures from the MOBILE4 methodology were necessary, however. MOBILE4 lumps all heavy-duty vehicles together for emissions calculations purposes. In these calculations, the affected vehicles were broken up into light heavy-duty (8,501-19,500 lbs gross vehicle weight (GVW)) and medium heavy-duty (19,501-26,000 lbs GVW) vehicle subclasses since these subclasses are the ones affected by the Clean-Fuel Fleet program and they vary distinctly from the heavy heavy-duty (greater than 26,000 lbs GVW) subclass and each other in terms of population growth, usage, and engine type. Separate emissions factors thus had to be generated for both light heavy- and medium heavy-duty gasoline and diesel engines. Furthermore, the fleet vehicle miles traveled (VMT) and age distribution of vehicles were modified to reflect information about the operations of fleet vehicles. In the methodology employed for these calculations, the fleet specific VMT is converted to a per-vehicle VMT and is then broken down into light heavy- and medium heavy-duty vehicle subclasses.

3.0.3 Discussion of Data

3.0.3.1 Light and medium heavy-duty fleet vehicle demographics

Several factors about fleet vehicle demographics control the results of the emissions inventory modeling. Because of the specialized nature of the analysis of fleet emissions, heavy-duty fleet vehicles have been distinguished by heavy-duty subclass (i.e., light heavy or medium heavy-duty) and engine type (i.e., otto-cycle or diesel-cycle). The characteristics of these four subclasses will be discussed in order to provide the background data necessary to make the emissions inventory calculations and to interpret the results of the emissions inventory modeling.

EPA has estimated that, in 1989, there were 305,000 light heavy-duty and 668,000 medium heavy-duty vehicles operating in fleets of ten or more heavy-duty vehicles in areas affected by the fleet provisions.[1] Based on information available from EPA's MOBILE4 emissions model, the light heavy-duty fleet population is projected to grow at a rate of 2.75 percent per year while the population of medium heavy-duty fleet vehicles is projected to decline at a rate of 1.11 percent per year.[2] It is also estimated that heavy-duty fleet vehicles are replaced every six years and that 80 percent of the vehicles operating in fleets of ten or more heavy-duty vehicles in affected areas will actually be covered by the program. (Twenty percent of such vehicles are assumed not to be covered because they are not centrally fueled or capable of being centrally fueled or are exempt under the CAA fleet program.) Combining these data and assumptions with the fact that 50 percent of the purchases of affected heavy-duty fleets will be required to be clean-fuel fleet vehicles starting in 1998, it is projected that 8,516 light heavy-duty and 11,124 medium heavy-duty clean-fuel fleet vehicles will be required to be purchased in 1998.[3] The results of this projection of the number of light heavy-, medium heavy- and total heavy-duty vehicles affected by the Clean-Fuel Fleet Program from 1998 through 2020 are shown in Table 3-1.

TABLE 3-1: HEAVY-DUTY CLEAN-FUEL FLEET VEHICLE POPULATION

	Acquisitions						IN-USE Vehicles						Total	Total
	LHDV Acquisitions			MHDV Acquisitions			LHDV IN-USE			MHDV IN-USE			New	IN-USE
Year	Otto-Cycle	Diesel-Cycle	Total	Otto-Cycle	Diesel-Cycle	Total	Otto-Cycle	Diesel-Cycle	Total	Otto-Cycle	Diesel-Cycle	Total	Acquisitions	Vehicles
1998	5,961	2,555	8,516	3,337	7,787	11,124	5,961	2,555	8,516	3,337	7,787	11,124	19,640	19,640
1999	6,126	2,625	8,751	3,300	7,700	11,000	12,087	5,180	17,267	6,637	15,487	22,124	19,751	39,391
2000	6,294	2,698	8,992	3,264	7,615	10,879	18,381	7,878	26,259	9,901	23,102	33,003	19,871	59,262
2001	6,467	2,772	9,239	3,227	7,530	10,757	24,849	10,649	35,498	13,128	30,632	43,760	19,996	79,258
2002	6,645	2,848	9,493	3,192	7,447	10,639	31,494	13,497	44,991	16,320	38,079	54,399	20,132	99,390
2003	6,828	2,926	9,754	3,156	7,364	10,520	38,322	16,424	54,745	19,476	45,443	64,919	20,274	119,664
2004	7,015	3,006	10,021	3,121	7,282	10,403	39,375	16,875	56,250	19,259	44,939	64,198	20,424	120,448
2005	7,209	3,089	10,298	3,086	7,202	10,288	40,458	17,339	57,797	19,046	44,440	63,486	20,586	121,283
2006	7,407	3,174	10,581	3,052	7,121	10,173	41,570	17,816	59,386	18,834	43,946	62,780	20,754	122,166
2007	7,610	3,262	10,872	3,018	7,043	10,061	42,713	18,306	61,019	18,625	43,459	62,084	20,933	123,103
2008	7,820	3,351	11,171	2,984	6,964	9,948	43,888	18,809	62,697	18,418	42,975	61,393	21,119	124,090
2009	8,035	3,443	11,478	2,952	6,887	9,839	45,095	19,326	64,421	18,214	42,498	60,712	21,317	125,133
2010	8,256	3,538	11,794	2,919	6,810	9,729	46,336	19,858	66,194	18,011	42,027	60,038	21,523	126,232
2011	8,483	3,499	11,982	2,999	6,736	9,735	47,610	20,268	67,878	17,924	41,561	59,485	21,717	127,363
2012	8,716	3,460	12,176	3,082	6,661	9,743	48,920	20,554	69,473	17,954	41,101	59,055	21,919	128,528
2013	8,956	3,422	12,378	3,167	6,587	9,754	50,265	20,714	70,979	18,103	40,645	58,748	22,132	129,727
2014	9,202	3,384	12,586	3,254	6,514	9,768	51,647	20,747	72,394	18,372	40,196	58,568	22,354	130,962
2015	9,455	4,052	13,507	2,761	6,441	9,202	53,068	21,355	74,423	18,182	39,749	57,931	22,709	132,354
2016	9,715	4,007	13,722	2,837	6,370	9,207	54,527	21,824	76,351	18,100	39,309	57,409	22,929	133,760
2017	9,982	3,963	13,945	2,915	6,299	9,214	56,026	22,288	78,314	18,016	38,872	56,888	23,159	135,202
2018	10,257	3,919	14,176	2,995	6,229	9,224	57,567	22,747	80,314	17,929	38,440	56,369	23,400	136,683
2019	10,539	3,875	14,414	3,077	6,160	9,237	59,150	23,200	82,350	17,839	38,013	55,852	23,651	138,202
2020	10,829	4,641	15,470	2,611	6,092	8,703	60,777	24,457	85,234	17,196	37,591	54,787	24,173	140,021

TABLE 3-2: VEHICLE MILES TRAVELLED BY CLEAN-FUEL FLEET LHDVs/MHDVs

Year	Vehicle Miles Travelled (million miles)						Total Vehicle Miles Travelled (million miles)
	LHDV			MHDV			
	Otto-Cycle	Diesel-Cycle	Total	Otto-Cycle	Diesel-Cycle	Total	
1998	107	46	152	121	282	403	555
1999	216	93	309	240	560	801	1109
2000	328	141	469	358	836	1194	1664
2001	444	190	634	475	1108	1584	2218
2002	563	241	804	591	1378	1969	2773
2003	685	293	978	705	1644	2349	3328
2004	704	302	1005	697	1626	2323	3328
2005	723	310	1033	689	1609	2298	3331
2010	828	355	1183	652	1521	2173	3356
2015	948	382	1330	658	1438	2096	3426
2020	1086	437	1523	622	1360	1983	3506

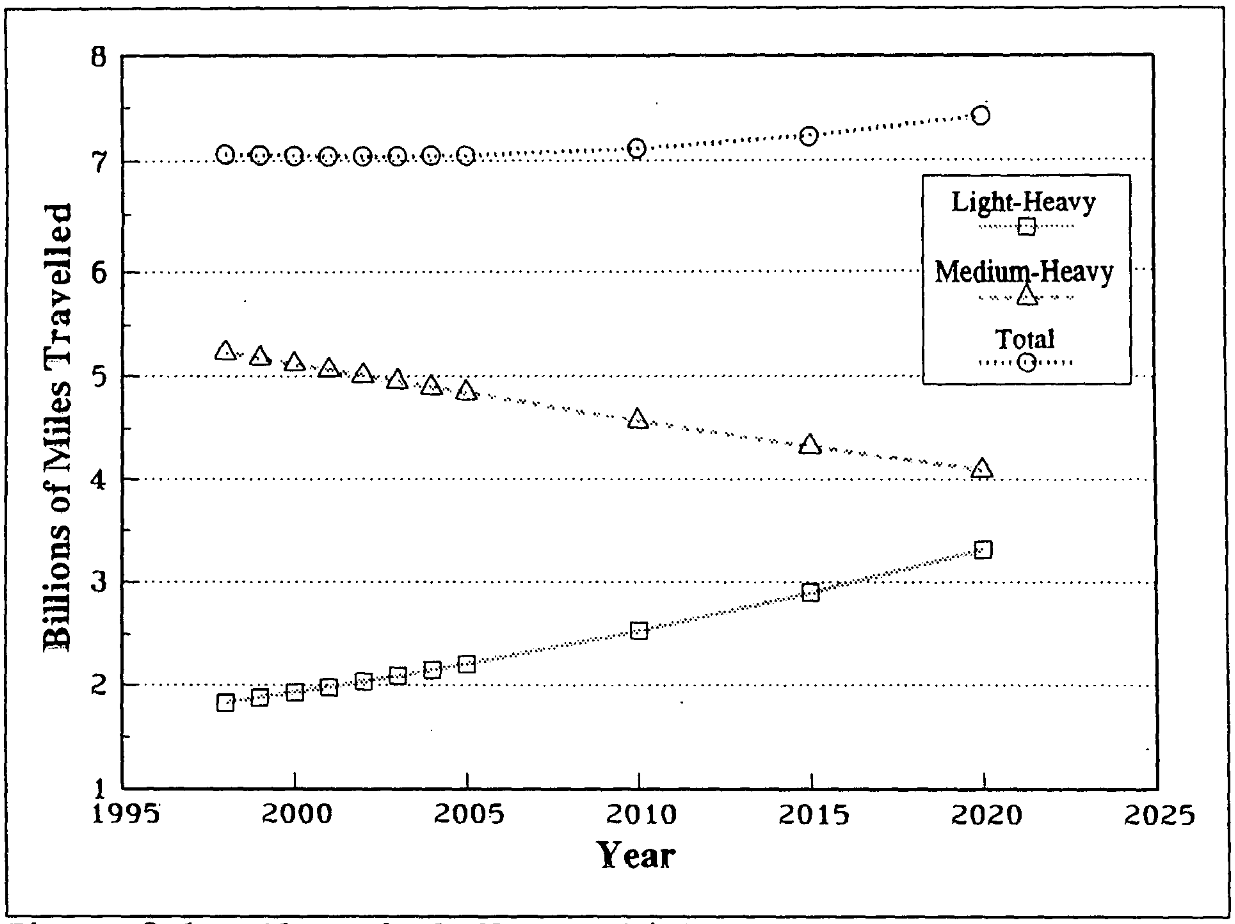

Figure 3-1 - Clean-fuel fleet vehicle VMT

Information about fleet operating practices and data available from MOBILE4 were combined to calculate annual vehicle miles traveled (VMT) by the clean-fuel fleet vehicle population. For simplicity, it was assumed that all fleet vehicles within a given class travel the same number of miles per year regardless of age. Since light heavy- and medium heavy-duty fleet vehicles are both projected to accumulate their average fleet life miles within six years, the annual VMT per vehicle for each class was calculated by averaging the VMT per vehicle projections for the first six years of each class as published in the User's Guide to MOBILE4. It was further assumed that the VMT/vehicle data will remain constant from year to year. Using this methodology, it is projected that light heavy-duty fleet vehicles will travel 17,870 miles per year and medium heavy-duty fleet vehicles will travel 36,190 miles per year.

The projections of the total number of vehicle miles traveled by heavy-duty vehicles affected by the Clean-Fuel Fleet program are shown in Table 3-2 and Figure 3-1. It can be seen that, due to the simultaneous growth in light heavy-duty fleet vehicles and the decline in the population of medium heavy-duty fleet vehicles, the number of light heavy-duty vehicles is projected to surpass the number of medium heavy-duty vehicles by approximately the year 2008. The total number of vehicles increases throughout the time period evaluated. However, due to the fact that medium heavy-duty fleet vehicles accumulate approximately twice as many miles per vehicle each year as light heavy-duty fleet vehicles (see previous paragraph), medium heavy-duty fleet vehicles together accumulate more miles each year than the light heavy-duty fleet vehicles even out to the year 2020.

In order to understand some of the complexities of the results which will be shown later, it is important to understand some of the contrasts between light heavy- and medium heavy-duty vehicles and between otto-cycle (gasoline) and diesel-cycle engines. As has already been pointed out, the population of light heavy-duty vehicles is growing while the population of medium heavy-duty vehicles is declining. Furthermore, it has also been stated that medium heavy-duty vehicles travel about twice as many miles in a year as do light heavy-duty vehicles. Another important contrast between light heavy and medium heavy-duty vehicles is the mix of engine types these vehicles use. It is estimated that 70 percent of the light heavy-duty vehicles use gasoline powered otto-cycle engines with the remainder being primarily diesel-cycle engines. For medium heavy-duty vehicles, the engine mix is nearly the opposite of the engine mix for light heavy-duty vehicles (30 percent otto-cycle and 70 percent diesel-cycle).[2]

The distinction between engine type mixes becomes particularly critical when the contrasts in emission factors between gasoline and diesel powered vehicles are taken into account. Diesel engines typically emit higher levels of NOx than do gasoline engines while simultaneously emitting lower levels of HC due to the fact that diesel engines use lean-burn modes of operation and consequently have relatively low engine-out HC emissions levels. Today's diesel engines are not equipped with catalytic converters to reduce the engine-out HC and NOx emissions as are gasoline engines.

3.0.3.2 Emission Factor Calculations

In order to calculate the emissions inventories for the desired scenarios, emission factors and deterioration rates for light heavy-duty and medium heavy-duty vehicles are needed. In this analysis, all the vehicles are either gasoline- or diesel-powered so emission factors for only these two fuel types will be needed. It is expected that some alternative-fueled vehicles will be produced, but that the numbers will be sufficiently small, and certification emission levels and deterioration characteristics sufficiently similar, so as to not substantially impact the results of this analysis.

3.0.3.2.1 1998 and Later Baseline Emission Factors

Determination of the environmental impacts of fleet vehicles requires estimates of emission factors for in-use vehicles. For this analysis, data is used that projects that in-use 1998 and later heavy-duty vehicles will behave similarly to certification vehicles, and that they will meet their respective standards (intermediate useful life and full useful life standards) in use. In order for this approach to be valid, it would be necessary for there to be an extensive inspection and maintenance program, as well as an active field enforcement program, for heavy-duty vehicles. Both of these seem reasonably likely, especially in the areas that will be affected by the fleet program. As will be discussed later, a similar approach is also being used for heavy-duty clean-fuel fleet vehicles. Since the same approach is being used for both baseline and clean-fuel fleet emission factors, these assumptions should not significantly impact the calculation of incremental benefits even if the assumptions were to be somewhat in error. The 1998 baseline vehicle emission factors are derived from 1991 sales-weighted certification emissions, taking into account the effects of new emission standards. The 1991 certification emissions rates are shown in Table 3-3.

NMHC estimates for pre-1998 vehicles were derived from MOBILE4 projections. Non-methane hydrocarbon (NMHC) emission factors were estimated at 95 percent of the total hydrocarbon emission factor for diesel engines and at 75 percent of the total HC emission factor for gasoline engines.[4] For gasoline engines the same deterioration rates for HC emission factors are applied to the NMHC emission factors since present catalytic converters have little effect on methane emissions.

Table 3-3 Sales-Weighted 1991 Light and Medium Heavy-Duty Certification Values

Sales-Weighted Heavy-Duty Certification Values (g/Bhp-hr)			
Vehicle class	THC	NMHC (estimate)	NOx
Light Heavy-Duty Diesel	0.56	0.54	4.44
Medium Heavy-Duty Diesel	0.41	0.39	5.01
Light Heavy-Duty Gasoline	0.45	0.34	3.87
Medium Heavy-Duty Gasoline	0.79	0.59	3.84

The most significant standard affecting 1998 baseline heavy-duty vehicles is a reduction in the NOx emission standard from 5.0 to 4.0 g/Bhp-hr beginning in that model year. Light and medium heavy-duty diesel engines currently exceed this level and will therefore require new compliance effort. Although the sales-weighted certification values for NOx emissions from 1991 heavy-duty gasoline engines are numerically low enough on average to just meet the 1998 4.0 g/Bhp-hr NOx standard, the relatively small compliance margins and the fact that some engine families do not meet the standard indicates that further reductions are needed. Manufacturers will likely incorporate compliance margins of 10 to 15 percent for certification vehicles to allow for production variability and in-use operation. Thus, in-use emissions may be under the standard on average. For this analysis, however, average NOx emissions will be modeled as being at the level of the 4.0 g/Bhp-hr standard at the end of the vehicle's useful life.

Hydrocarbon standards for 1998 heavy-duty engines will be the same as for current engines. Heavy-duty diesel NMHC emissions may drop if catalytic converters achieve a significant penetration into the light heavy- and medium heavy-duty diesel engine market for particulate control. This is because, in addition to providing particulate control, these catalytic converters are expected to reduce HC emissions. However, it is also possible that engine-out HC emissions will be allowed to rise somewhat in the presence of the catalyst in order to provide more control flexibility for NOx. This would result in little or no net reduction of NMHC for 1998 baseline vehicles. For this analysis, 1998 baseline diesel NMHC will be modeled as being at a level equivalent to the 1991 NMHC levels.

Hydrocarbon emissions from heavy-duty gasoline vehicles are also projected to comply with the applicable HC standards in use. Light heavy-duty gasoline vehicles are assumed to comply with the 1.1 g/Bhp-hr HC standard for vehicles 14,000 lbs GVW and under, and medium heavy-duty gasoline vehicles are assumed to comply with the 1.9 g/Bhp-hr HC standard for vehicles over 14,000 lbs GVW. Given the Mobile model vehicle grouping scheme laid out in the beginning of this chapter for light and medium heavy-duty vehicles, these assumptions could introduce some analytical error into the analysis, since some light heavy-duty gasoline vehicles (those between 14,000 and 19,000 lbs GVW) could emit up to the 1.9 g/Bhp-hr standard. However, this should not introduce significant error into the analysis since there are few gasoline vehicles in this weight range. For this analysis, as with diesels, 1998 baseline gasoline NMHC will modeled as equivalent to 1991 NMHC levels since some reductions in NOx emissions will be needed in 1998.

The deterioration rates for heavy-duty diesel engines are based on the assigned deterioration factors for heavy-duty diesel engines with aftertreatment, and the deterioration rates for gasoline engines are based on the assigned deterioration factors for light-duty gasoline trucks with three-way catalysts.[5] For this analysis, the estimated zero-mile emission factors are back-calculated by using the emission projections estimated above and the respective deterioration factors. These estimated zero-mile emission factors and deterioration rates for 1998 baseline vehicle engines are presented in Table 3-4. The deterioration factors presented in Table 3-4 are the additive equivalents of the multiplicative deterioration factors, divided over the useful life.

Table 3-4 1998 Model Year Baseline Emission Factors

	Zero Mile EF (g/Bhp-hr)		Deterioration Rate (g/Bhp-hr/10,000mi)	
Vehicle	NMHC	NOx	NMHC	NOx
L-H diesel	0.42	3.33	0.011	0.061
M-H diesel	0.30	3.33	0.005	0.036
L-H gasoline	0.20	3.33	0.013	0.061
M-H gasoline	0.35	3.33	0.022	0.061

3.0.3.2.2 Projections for 1998 Clean-Fuel Fleet Emission Factors

Emission factors and deterioration rates for clean-fuel fleet heavy-duty vehicles were estimated using the following methodology. The clean-fuel engine emission factors are based on the projection that average NMHC + NOx emissions will comply with a combined 3.5 g/Bhp-hr NMHC+NOx standard at the end of the vehicle's useful life. The vehicles' emissions are also assumed to deteriorate in a manner consistent with baseline vehicles, and thus the same assigned deterioration factors were used for the clean-fuel fleet vehicles as for the baseline vehicles. However, since the end-of-useful-life projections are different between these two types of vehicles, the multiplicative deterioration factors will result in different additive deterioration rates.

With a combined NMHC + NOx standard manufacturers can get the required reductions from NMHC and NOx. Each engine family is likely to use a different mix, but in most cases reductions in both pollutants are expected. This analysis assumes that the end of life NMHC level for clean-fuel engines will be 30 percent lower in 1998 than in 1991. This is based on the NMHC reduction expected from improved catalysts in gasoline and diesel applications. To estimate NOx levels for 1998 clean-fuel engines, the just-calculated 1998 NMHC level is subtracted from the proposed NMHC+NOx standard of 3.5 g/Bhp-hr. Zero-mile emissions are estimated by back-calculating using the emissions projections estimated above and the respective deterioration factors. Table 3-5 contains the projected zero-mile in-use emission factors and deterioration rates for heavy-duty clean-fuel fleet vehicles.

Table 3-5 1998 Heavy-Duty Clean-Fuel Fleet Vehicle Emission Factors

	Zero Mile EF (g/Bhp-hr)		Deterioration Rate (g/Bhp-hr/10,000mi)	
Vehicle	NMHC	NOx	NMHC	NOx
L-H diesel	0.29	2.60	0.008	0.047
M-H diesel	0.21	2.69	0.003	0.029
L-H gasoline	0.14	2.72	0.009	0.049
M-H gasoline	0.24	2.57	0.016	0.047

3.0.4 **Environmental Impacts**

Based on the baseline and clean-fuel fleet vehicle emission factors developed above, emission inventory estimates have been calculated for NMHC and NOx emissions from heavy-duty fleet vehicles. Historically, carbon monoxide emissions and particulate emissions from diesel engines have been directly proportional to HC emissions and inversely proportional to NOx emissions. However, the introduction of new technologies such as catalytic converters, rate-shaped electronically-controlled unit injectors and exhaust gas recirculation will change the relationships between pollutant emissions rates in ways which can not be accurately predicted. Therefore, projections of emission inventories will be made only for NMHC and NOx, the primary pollutants targeted by the clean-fuel fleet requirements.

The inventories of NMHC and NOx emissions from heavy-duty clean-fuel fleet vehicles 1998 baseline vehicles have been calculated for the years during which these standards are being phased in and for every five years beyond that until the year 2020. In general, for each vehicle subclass these per-vehicle emission benefits were calculated by subtracting the clean-fuel fleet vehicle emission factors from the baseline emission factors for the respective pollutants and then multiplying the result by the estimated vehicle miles traveled by all clean-fuel fleet vehicles in that vehicle subclass during each year. The overall emission benefits results from light heavy-duty and medium heavy-duty vehicles were then combined for each year and are presented in Table 3-6 according to engine type.

As demonstrated in Table 3-6, the emission inventories and benefits climb rapidly during the first six years as the fleet is turned over; after 2003, however, the emissions inventories and benefits become relatively constant. After 2003 diesel-cycle NOx benefits begin to decline as otto-cycle benefits increase due to the gradual replacement of medium heavy-duty vehicles by light heavy-duty vehicles which are mostly otto-cycle vehicles.

Table 3-6 Nationwide Emissions Inventories of Fleets Covered by the Clean-Fuel Fleet Program

	NMHC Emissions Benefit (tons per year)			NOx Emissions Benefit (tons per year)		
calendar year	Otto-Cycle	Diesel-Cycle	Total	Otto-Cycle	Diesel-Cycle	Total
1998	26	60	86	206	415	621
1999	60	124	184	429	850	1,278
2000	101	193	294	667	1,304	1,971
2001	149	266	415	922	1,779	2,701
2002	204	345	548	1,192	2,273	3,465
2003	266	428	693	1,479	2,787	4,266
2004	265	425	689	1,479	2,766	4,245
2005	264	422	686	1,480	2,745	4,224
2010	261	408	669	1,490	2,648	4,138
2015	260	397	657	1,513	2,563	4,076
2020	261	387	648	1,550	2,492	4,042
Total	5,251	8,286	13,537	30,462	53,923	84,385

This analysis generates emission reductions based on the assumption that the end of life NMHC level for clean-fuel engines will be 30 percent lower than the end of life NMHC level for 1998 baseline engines and the remainder of the required reduction comes from NOx. There are any number of potential approaches which could be used to meet the NMHC + NOx levels of the proposed standard. For example, another possibility is that otto-cycle engine NMHC levels increase over 1991 levels under pressure from the 4.0 g/Bhp-hr NOx standard and diesel-cycle NMHC emissions decrease as a result of the particulate matter control technology discussed in Chapter 2. Thus, a different set of NMHC benefits would be expected for clean-fuel heavy-duty engines. Assuming the NMHC + NOx split for 1991 engines the NMHC benefit for otto-cycle would be about 28,000 tons (an increase) but for diesel-cycle engines the benefits would drop to about 1,200 tons. NOX benefits would essentially be the same.

Either the scenario laid out in section 3.0.3.2 or that discussed above is conceivable and depending on what strategies are used a range of values is the best estimate at this time. Based on the scenarios above, the 22-year total of emission benefits for otto-cycle engines range from 5,300 to 28,000 tons of NMHC benefits and from 30,500 to 31,000 tons of NOx benefits. The 22-year total of emission benefits for diesel-cycle engines range from 1,200 to 8,300 tons of NMHC benefits, and from 52,700 to 53,900 tons of NOx benefits. Combined benefits range from 14 to 29 tons of NMHC and 83 to 84 tons of NOx.

References

1. "Highway Statistics, 1989," U.S. Department of Transportation, Federal Highway Administration, 1989.

2. "User's Guide Mobile 4.0," Terry Newell, Test and Evaluation Branch, Environmental Protection Agency, PB 89 164271. The document is available from EPA's Emission Planning and Strategies Division.

3. U.S. Environmental Protection Agency, Office of Mobile sources, "Estimated Number of Fleet Vehicles Affected by the Clean Fuel Fleet Program," Memorandum from Sheri Dunatchik to Docket A-91-25, June 11, 1991.

4. "Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel; Volume II: Heavy-Duty Vehicles," Office of Mobile Sources, EPA, April 1990.

5. EPA Office of Mobile Sources Advisory Circular 51C, as revised February 26, 1987. The document is available from EPA's Certification Division.

Chapter 4
Costs and Cost Effectiveness

4.0.1 Introduction

This chapter describes EPA's analysis of the economic impact of the Clean-Fuel Fleet program on heavy-duty vehicles. The purpose of this analysis is to estimate of the per-vehicle costs, the total cost, and the cost effectiveness of the proposed program. To do this, it is necessary to make several assumptions about how manufacturers will choose to comply with the program. The Agency recognizes that manufacturers may deviate from the control techniques assumed here, and that such deviations could lead to different costs. Nevertheless, in the absence of better information, EPA believes that these approaches are technically reasonable and that they result in reasonably accurate estimates of the costs associated with this program.

It should also be noted that this analysis does not assume that all current light-heavy and medium-heavy duty vehicle engine families will comply with the standards of this program, but rather that only those engine families which could comply with relatively minor changes would be produced for the clean-fuel fleet vehicle program. This is important because costs would be significantly higher if it were necessary that all light-heavy and medium-heavy duty vehicle engine families comply with the standards. However, this is not the case, and given the small size of the affected market, there should be a significant incentive to modify only those engine families for which costs were relatively small or demand was larger from a nationwide perspective.

4.0.2 Costs

4.0.2.1 Operating Costs

Increased operating costs can arise from three sources; increases in fuel consumption, increases in maintenance costs and decreases in engine life. Increased fuel consumption has traditionally been a potential problem in engines designed to reduce NOx emissions. This reduction in fuel economy is usually a side effect of retarding the timing of the combustion (i.e., spark timing in otto-cycle engines or fuel injection timing in diesel-cycle engines). It is not clear at this time, however, whether engine manufacturers will need or choose to sacrifice fuel economy to reduce NOx emissions. Historically, manufacturers have been reluctant to do so and have sought other technologies which reduce NOx emissions without increased fuel consumption. Up to a one percent increase in fuel consumption is possible if manufacturers choose emission control approaches which have an adverse effect on fuel consumption. However, based on the technology being developed to meet the 4.0 g/Bhp-hr NOx standard (see Chapter 2 of this document), it is more likely that NMHC+NOx emissions will be reduced through the addition of emission control hardware without a fuel economy penalty.

Since engines for heavy-duty clean-fuel fleet vehicles are not expected to have significantly different designs than the engines designed to meet the 1998 heavy-duty NOx standard, they are not expected to be less durable or more expensive to maintain than their general-use counterparts. Therefore, EPA does not anticipate that heavy-duty clean-fuel engines or vehicles will be any more expensive to operate than their contemporary general use counterparts and therefore that all costs will be associated with engine and emission control modifications.

4.0.2.2 Engine Costs

Engine costs consist of four elements: research and development (R&D) costs, additional hardware requirements, added manufacturing costs and engine certification costs. Additional hardware and added manufacturing are variable costs included in the price of each engine purchased. Engine certification and R&D costs are fixed costs paid up-front by the engine manufacturer and recovered through additional costs added to each engine over a period of time. For purposes of this analysis, the certification costs will be recovered on a yearly basis, while the R&D costs will be amortized over a period of five years using a rate of return of 10 percent. (Since this analysis was performed, EPA's Office of Policy, Planning, and Evaluation has recommended that a rate of return of 7 percent be used for this type of analysis. The analysis performed for the final RIA will use this value.)[1]

4.0.2.2.1 Otto-Cycle Heavy-Duty Engines

4.0.2.2.1.1 Hardware Costs

Gasoline (otto-cycle) heavy-duty engines are not expected to require the development of new hardware to meet the heavy-duty clean-fuel fleet vehicle emission standard. However, as discussed in Chapter 2, some will require improvements in the existing hardware. Nearly all otto-cycle heavy-duty engines currently have electronically controlled fuel injection and three-way catalytic converters capable of both reducing NOx emissions and oxidizing HC emissions, with oxygen sensors and feedback controls. Compliance with the clean-fuel fleet vehicle standards, however, may require higher catalyst loadings, which would increase catalyst costs. Other improvements or minor modifications may or may not increase the manufacturing costs. In order to take these potential costs into account, engine production cost increases will be estimated at $50 per engine. This is conservative given that current NMHC+NOx certification levels are already close to the standard (see Table 3-3) and the need for all heavy-duty engines to meet the 4.0

g/Bhp-hr NOx standard in 1998.

4.0.2.2.1.2 Development Costs

In order to comply with the heavy-duty clean-fuel fleet vehicle standard, some otto-cycle heavy-duty engines will require minor improvements to existing systems beyond those needed to achieve compliance with the 1998 4.0 g/Bhp-hr NOx standard. It is expected that some combination of better air/fuel handling, improved catalytic converter technology, exhaust pipe insulation and enhanced exhaust gas recirculation will be the main compliance strategies. In order to make the design changes necessary, EPA estimates that the calibrations and other development efforts will cost approximately $30,000 per engine family.[2]

4.0.2.2.1.3 Certification Costs

To certify an engine family, manufacturers must perform emission tests on a representative engine from that family and submit the results to EPA; this only need occur once for each engine family at the beginning of its production, with certification being carried over in each subsequent year for about 80 percent of families. Recordkeeping and reporting requirements accompany new certification and annual recertification. EPA has estimated that the cost of certification testing for heavy-duty gasoline engine families is about $200,000 per family[3] and the cost for reporting and recordkeeping is about $100,000 per family certified or recertified.[4] In addition to these costs, manufacturers must pay a certification fee of $12,500 for each heavy-duty engine family. Thus the total certification costs for each heavy-duty gasoline engine family are projected to be about $312,500.

4.0.2.2.2 Diesel-Cycle Heavy-Duty Engines

4.0.2.2.2.1 Hardware Costs

Manufacturers will apply refined or improved control technologies that will allow compliance without an increase in fuel consumption. As was discussed in Chapter 2, it appears likely that further optimization of the technology that will be available as a result of the 1998 4.0 g/Bhp-hr NOx and 1994 0.10 g/Bhp-hr PM standards will allow manufacturers to meet the clean-fuel fleet vehicle standards for many engine families. Technologies which are expected to be used in some conventional diesel engines to comply with the 1998 4.0 g/Bhp-hr NOx standard include improved electronic engine controls and exhaust gas recirculation, and some of the other technologies discussed in Chapter 2. Particulate trap oxidizers and catalytic oxidizing converters (to reduce PM and HC emissions) should make a broad penetration into the heavy-duty diesel engine market in order to facilitate compliance with the 0.10 g/Bhp-hr PM standard. Clean-fuel diesel engines are expected to be optimized versions of the cleanest of these conventional engines, and may also include advanced turbocharging and catalytic converters (for NMHC control).

By basing the clean-fuel diesel engines on only the cleanest conventional diesel engine families, manufacturers will be able to minimize costs. EPA estimates that the additional manufacturing cost of the improved control system hardware for heavy-duty clean-fuel vehicle engines, which will improve emissions while maintaining the same fuel consumption, will be about $100 dollars per engine more than the costs associated with the cleanest 1998 baseline engines. This $100 is roughly equivalent to the lifetime cost of a one percent increase in fuel consumption (i.e., $ 100 fuel economy penalty) for light- and medium-heavy duty diesel vehicles. Thus, in order to avoid the fuel economy penalty, manufacturers would likely make the necessary hardware changes at a cost ($100) equivalent to the amount the consumer would spend in lifetime operating costs.

4.0.2.2.2.2 Development Costs

As with otto-cycle engines, diesel-cycle engines are expected to require additional development beyond that required for engines meeting the 1998 4.0 g/Bhp-hr NOx standard. It is expected that several additional calibrations will be required. These calibrations will require design changes and engine modifications. The cost of these calibrations and other development is estimated to be about $100,000 (in 1992 dollars) for each engine family.[2]

4.0.2.2.2.3 Certification Costs

As with otto-cycle engines, HDD engine manufacturers will incur costs for certification of engines for clean-fuel vehicles as well as the associated reporting and recordkeeping requirements. EPA estimates that these costs are $260,000[5] per family for certification testing and $78,000 per family certified for reporting and recordkeeping. (The estimated reporting and recordkeeping costs for diesels are less than those for otto-cycle engines because information collection for evaporative testing does not exist for diesels.)[4] As was the case with gasoline engines, EPA projects that about 80 percent of the families will be recertified each year using carryover provisions and that 20 percent will engage in new certification and the accompanying testing. The recordkeeping and reporting costs cited above apply to each family each year as does the certification fee of $12,500. Thus the total certification costs for each heavy-duty diesel engine family is projected to be about $350,500.

4.0.2.3 Aggregate Costs

As was discussed above, heavy-duty clean-fuel fleet vehicles are not expected to have any increases in operating costs over general heavy-duty vehicles; thus, essentially all the costs of this program should come from increased engine/vehicle costs. Since the number of clean-fuel heavy-duty engines required to be purchased will be relatively small, the per engine and total costs of this portion of the Clean-Fuel Fleet program will be a strong function of how many engine families are developed and certified for this program. For this analysis, it is estimated that a total of six light and medium heavy-duty otto-cycle and twelve light and medium heavy-duty diesel-cycle engine families will be certified for participation in the Clean-Fuel Fleet program. For comparison, in 1991 a total of nine otto-cycle and fourteen diesel-cycle light or medium heavy-duty engines were certified. If significantly fewer engine families are certified, costs will be less than those estimated here.

In addition, to be conservative this analysis has assumed that full certification costs will be incurred for each engine family certified, even though most families will probably be able to be certified based on California test data. In such cases, separate federal testing would probably not be necessary and the certification testing costs correspondingly lower.

4.0.2.3.1 Manufacturer Costs

Based on the development costs projected above, the total cost of developing six otto-cycle engine families will be approximately $180,000; the total cost of developing twelve heavy-duty diesel-cycle engine families will be approximately $1,200,000. Similarly, the first-year certification costs for six otto-cycle and twelve diesel-cycle engine families will be $1,200,000 and $3,120,000, respectively. For subsequent years, this analysis assumes that one otto-cycle engine family and two diesel-cycle engine families will be recertified with emission testing required each year (approximately 20 percent); certification costs would then total $200,000 per year and $520,000 per year, respectively. Annual reporting, recordkeeping, and certification fees for all families amount to $675,000 for otto-cycle engines and $1,086,000 for diesel-cycle engines. The fixed costs to manufacturers for developing each engine family are presented in Table 4-1.

The total costs to manufacturers will consist of these fixed costs of developing and certifying each engine family combined with the variable costs of manufacturing the engines. Using the projections of the number of clean-fuel fleet vehicles required to be purchased from Table 3-1 in chapter 3, the yearly variable costs to manufacturers from hardware and production costs can be calculated (per vehicle production + hardware cost * number of vehicles). These costs have been analyzed through the year 2020 (the first 22 years that the standard is in effect).

Table 4-1 Manufacturer Fixed Costs for Heavy-Duty Clean-Fuel Engines

	Number of Families	Total Develop. Costs ($)	Total First-Year Cert. Costs ($)	Total Annual Cert. Costs ($)	Total Annual Recording Reporting & Fees Costs ($)
Otto-cycle	6	180,000	1,200,000	200,000	675,000
Diesel-cycle	12	1,200,000	3,120,000	520,000	1,086,000

In order to calculate the total aggregate costs to manufacturers, all costs are discounted to the first year of the standard, 1998. Research and development costs will be assumed to occur in the second year before the standard goes into effect (1996). Initial costs for certifying (and fulfilling reporting/recordkeeping requirements) for all engine families certified as clean-fuel vehicles is assumed to occur in 1997, with full recertification occurring annually thereafter for only one otto-cycle family and two diesel-cycle families, as described above. The assumed chronology for the incurring of costs for research, development, and testing (RD&T), certification and reporting, and for the hardware costs is presented in Table 4-2. The present value costs to manufacturers accrued during the first 22 years of the standard discounted to 1998 (in 1992 dollars) are also presented in Table 4-2. The total present value costs to manufacturers of the first 22 years of the program discounted to 1998 (in 1992 dollars) is approximately $15.9 million for otto-cycle engines and approximately $31.8 million for diesel-cycle engines.

Table 4-2 Costs to Manufacturers

	Otto-Cycle		Diesel-Cycle	
Year	RD&T/ Cert.	Hardware	RD&T/ Cert.	Hardware
1996	$180,000		$1,200,000	
1997	$1,875,000		$4,206,000	
1998	$875,000	$464,900	$1,606,000	$1,034,200
1999	$875,000	$471,300	$1,606,000	$1,032,500
2000	$875,000	$477,900	$1,606,000	$1,031,300
2001	$875,000	$484,700	$1,606,000	$1,030,200
2002	$875,000	$491,800	$1,606,000	$1,029,500
2003	$875,000	$499,200	$1,606,000	$1,029,100
2004	$875,000	$506,800	$1,606,000	$1,029,000
2005	$875,000	$514,800	$1,606,000	$1,029,100
2010	$875,000	$558,700	$1,606,000	$1,034,900
2015	$875,000	$610,800	$1,606,000	$1,049,400
2020	$875,000	$672,000	$1,606,000	$1,073,300
1998 NPV	15,941,600		31,826,900	

4.0.2.3.2 Costs to Users

Since clean-fuel heavy-duty vehicles are not expected to have different fuel consumption or maintenance costs than general use light and medium heavy-duty vehicles, the only cost to the consumer will be the first cost of purchasing the vehicles. In addition to the cost for hardware changes, consumers will also have to pay for the amortized cost of the research, development, and testing as well as for the retail price mark-up.

Manufacturers are expected to recover the development costs and first-year certification costs over the first five years of engine sales. By amortizing these costs over the predicted sales during the first five years of the program, EPA has calculated that the development costs and first-year certification costs of these engine families will add an average of $62 to the manufacturer's cost of a clean-fuel heavy-duty otto-cycle engine and $152 to the manufacturer's cost of a clean-fuel heavy-duty diesel engine, respectively.

Adding on the estimated additional certification, hardware and manufacturing costs for both otto- and diesel-cycle heavy-duty clean-fuel engines and factoring in an estimated 29 percent retail price mark-up it is estimated that these engines will cost about $250 more per otto-cycle engine and $482 more per diesel-cycle engine than for engines that would be used in general heavy-duty vehicles during the first five years of the program. During the remaining years of the program (from year 2003 to 2020), clean-fuel otto-cycle engines are estimated to cost an additional $147 to $178, and clean-fuel diesel-cycle engines are estimated to cost an additional $322 to $338 in 1992 dollars. (These additional costs for clean-fuel engines are different from year to year due to variations in the projected number of clean-fuel fleet vehicles required to be purchased (see Table 3-1).)

This analysis generates additional costs for clean-fuel fleet vehicles that may be overly conservative since as described above it assumes that the manufacturers will have to incur costs for certification testing on all engine families. Without the certification testing, these engines would cost about $165 more per otto-cycle engine and $306 more per diesel-cycle engine than for engines that would be used in general heavy-duty vehicles during the first five years of the program. During the remaining years of the program (from year 2003 to 2020), clean-fuel otto-cycle engines are estimated to cost an additional $129 to $152, and clean-fuel diesel-cycle engines are estimated to cost an additional $265 in 1992 dollars.

Table 4-3 presents total consumer cost projections through the year 2020, along with the aggregate cost, expressed in 1992 dollars discounted to the year 1998. As the table shows, costs in the first five years of the program are marginally higher than in successive years because development costs are being recovered during this period. The 22-year present value costs of the fleet program range from $15.4 to $20.6 million for otto-cycle engines and from $28.4 to $41.1 million for diesel-cycle engines.

Table 4-3 Costs to Consumers

Year	Otto-Cycle	Diesel-Cycle
1998	$2,300,600	$4,978,100
1999	$2,316,600	$4,973,500
2000	$2,333,300	$4,970,000
2001	$2,350,500	$4,966,800
2002	$2,368,400	$4,965,000
2003	$1,772,700	$3,399,200
2004	$1,782,500	$3,398,900
2005	$1,792,800	$3,399,300
2010	$1,849,500	$3,406,700
2015	$1,916,700	$3,425,300
2020	$1,995,600	$3,456,300
1998 NPV	$20,564,700	$41,056,700

4.0.3 **Cost Effectiveness**

The cost effectiveness of the heavy-duty portion of the Clean-Fuel Fleet program was calculated using a 22-year cost effectiveness method. The 22-year cost effectiveness analysis is performed by discounting both the total consumer costs and the total benefits of the first 22 years of the program to 1998 and dividing the costs by the benefits. Since the costs have been estimated separately for otto-cycle and diesel-cycle engines, their cost effectiveness will be analyzed separately also. It should be noted that for otto-cycle engines which have both NMHC and NOx emissions reductions, the costs have been divided evenly between NMHC and NOx.

The 1998 present value for the 22 years of emission reductions are calculated from the data in Table 3-6 of chapter 3. As discussed in Chapter 3, this analysis generates emission benefits for clean-fuel fleet vehicles that may be overly conservative. The 22-year present value emission benefit for diesel-cycle engines ranges from 500 to 3,100 tons of NMHC emission reductions and 19,600 to 20,100 tons of NOx emission reductions. For otto-cycle engines, the 22-year present value benefit ranges from 1,900 to 10,200 tons of NMHC emission reductions and 11,000 to 11,300 tons of NOx emission reductions. For diesel-cycle engines the minimal NMHC reduction is not used in the cost effectiveness analysis, and thus, the cost effectiveness for diesel-cycle engines will be calculated by assigning all costs to NOx reduction.

The 22-year cost effectiveness, in dollars per ton, can now be calculated by dividing the present value costs by the present value emission benefits. The costs of the otto-cycle and diesel-cycle engines are divided evenly between the NMHC and NOx benefits. The 22-year cost effectiveness for otto-cycle and diesel-cycle engines is presented in Table 4-4. This analysis generates 22-year cost effectiveness projections for clean-fuel fleet vehicles that may be overly conservative. The 22-year cost effectiveness for otto-cycle engines ranges from $800 to $5,500 per ton of NMHC emission reductions and $700 to $900 per ton of NOx emissions reductions. For diesel-cycle engines, the resulting 22-year cost effectiveness is $6,700 per ton of NMHC emission reductions and ranges from $1,000 to $1,400 per ton of NOx emission reductions. The relatively high cost effectiveness of NMHC control and low cost effectiveness of NOx control is a result of the cost allocation method used. Given the nature of the standard (NMHC + NOx) and the large number of possible ways to split controls and control costs undue importance should not be placed on the numerical values derived. A simple reallocation of costs or assumed change in NMHC/NOx control fraction would change the cost effectiveness value. Given, the depth of analyses possible at this time any change probably would not be meaningful until further information becomes available.

Table 4-4 Cost Effectiveness in $/ton (1998 Present Value)

	Otto-Cycle	Diesel-Cycle
Costs ($)	**15** - 21 million	**28**- 41 million
NMHC (tons)	1,900 - **10,200**	**500** - 3,100
NOx (tons)	11,000 - **11,300**	**19,600** - 20,100
NMHC Cost Effectiveness ($/ton)	**800** - 5,500	**n/a** - 6,700
NOx Cost Effectiveness ($/ton)	**700** - 900	1,000 - **1,400**

4.0.4 **Summary**

The total cost of the heavy-duty Clean-Fuel Fleet program to consumers is estimated to be approximately $4.7 to $7.3 million per year during the first five years of the program (1992 dollars), and approximately $4.3 to $5.5 million per year after that. Estimates of the cost effectiveness of this program range from $800 to $5,500 per ton for NMHC control and range from $700 to $1,400 per ton for NOx control.

As was presented above there are a number of different ways costs and benefits could be developed and attributed and each scenario would yield a different value for each entry in Table 4-4. EPA recognizes that each of the values in Table 4-4 has validity based on the analysis presented above; further information and reanalysis is needed in the final rule to refine the estimates. For purposes of this report the figures presented in bold type will be carried forward in further analysis. However, the other values also have validity and merit equal consideration.

References

1. "OMB Presentation and Discussion on OMB Circular A-94 Regarding Discount Rates and Benefit-Cost Analysis," Memorandum from Brett Snyder to Addressees, EPA Office of Policy, Planning and Evaluation, March 23, 1993.

2. Based on calibration estimates from the "Gaseous Emission and Particulate Emission Regulations," 50 FR 10606, EPA Office of Mobile Sources, March 15, 1985

3. "Regulatory Impact Analysis, Oxides of Nitrogen Pollutant Specific Study and Summary and Analysis of Comments," EPA Office of Mobile Sources, March 1985.

4. "Information Collection Request Supporting Statement; Clean Fuel Fleet Emission Standards, Conversions, and General Provisions," EPA Office of Mobile Sources, August 1992 Draft.

5. "Final Regulatory Support Document and Summary and Analysis of Comments on the NPRM -- 1993 Model Year Bus Particulate Standard, 1994 and Later Model Year Urban Bus Particulate Standard, Urban Bus Test Procedures, and 1998 and Later Model Year Heavy-Duty Engine NOx Standard," EPA Office of Mobile Sources, February 1993.

"Draft Regulatory Support Document -- 1994 and Later Model Year Urban Bus Particulate Standard, Urban Bus Retrofit/Rebuild Program, 1998 and Later Model Year Heavy-Duty Engine NOx Standard," EPA Office of Mobile Sources, May 1991.