EPA

Final Regulatory Impact Analysis: Control of Emissions of Air Pollution from Highway Heavy-Duty Engines

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September 16, 1997

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CHAPTER 1: INTRODUCTION

This chapter presents a summary of the Regulatory Impact Analysis (RIA) that follows. It begins with a brief description of the Statement of Principles, which established the framework for the rule, as well as the provisions of the final rulemaking itself. The Environmental Protection Agency (EPA) finalized several provisions that were not specifically described in the Statement of Principles. This is followed by a brief summary of each of the chapters of the RIA including health and welfare benefits, industry characterization, technological feasibility, economic impact, environmental impact and cost-effectiveness.

I. Overview of the Statement of Principles and Rulemaking

Over the last 20 years, emissions from highway heavy-duty engines have been reduced as a result of changing emission standards and related requirements. Although previously promulgated standards for control of emissions of oxides of nitrogen (NOx) and hydrocarbons (HC) are expected to lead in the short term to reductions in emissions of these ozone precursors, there is concern that the fleets' emission levels will increase in the future. According to various studies, NOx levels in the U.S. are showing a downward trend today, but factors such as the growth in the number of vehicles and driving activity in the near future will likely result in total NOx emissions that will exceed current levels. Many states will need reductions in NOx and HC to achieve ozone attainment in the future and there is concern that some areas considered attainment areas today may go into nonattainment in the future. Moreover, some nonattainment areas expected to reach attainment may return to nonattainment, thus reversing the positive impact that past regulations will have on people's health and the environment.

With these reasons in mind EPA, the California Air Resources Board, and highway heavy-duty engine manufacturers signed the Statement of Principles in 1995 to pursue a large reduction in NOx emissions from highway heavy-duty engines. This historic accord has given government and industry the opportunity to agree on common goals with mutually beneficial results. The SOP included the following new standards which would apply to all highway heavy-duty engines, including those that use diesel, gasoline, alternative fuels, or fuel blends:

1) a combined NMHC plus NOx standard of 2.4 g/bhp-hr, or

2) a combined NMHC plus NOx standard of 2.5 g/bhp-hr, with a cap of 0.5 g/bhp-hr on NMHC emissions.

The Statement of Principles also contained several key provisions in addition to the standards. Signatories recognized the importance of maintaining emission controls throughout the life of the engine and agreed to develop appropriate measures to ensure that emission-control improvements are maintained in use. Signatories agreed to work cooperatively to develop an improved national averaging, banking, and trading program that would create more incentive for the early introduction of technologies and provide manufacturers with flexibility that may be critical in making the standards feasible in 2004. Furthermore, the Statement of Principles discusses the need to review in 1999 the technological feasibility of the standards and their appropriateness under the Clean Air Act (CAA). The document also recognizes the benefits of harmonizing California and federal emission standards for highway heavy-duty engines. Also, the SOP outlines a plan for developing technology that reduces NOx emissions to 1.0 g/bhp-hr and PM to 0.05 g/bhp-hr while maintaining performance, reliability, and efficiency of the engines.

The Notice of Proposed Rulemaking (NPRM) proposed the new standards contemplated in the SOP for highway heavy-duty engines beginning in 2004. Furthermore, the NPRM proposed a number of changes to the averaging, banking and trading program (ABT) to ease the transition to the new standards and provide an incentive for the early introduction of technology. In response to the general provisions in the Statement of Principles regarding in-use emission controls, EPA proposed a series of updates to current regulations to further encourage highly durable emission-control technologies. For the final rule, several of the proposals were modified in response to comments received by the Agency. The reader is directed to the preamble for the NPRM and or the Summary and Analysis of Comments for the final rule for a complete description of these proposals.

For the final rule, EPA is finalizing the standard of 2.4/2.5 g/bhp-hr NMHC plus NOx contained in proposal for diesel-cycle engines. For otto-cycle engines (e.g., gasoline-fueled engines), EPA is not finalizing any new standards in this rule. Therefore, this RIA does not contain information regarding the effect of the standards on otto-cycle engines.

The final rule also contains modified ABT provisions for heavy-duty diesel engines, which increase industry compliance flexibility and respond to the need to promote the early introduction of new emission control technology, as well as to obtain early emission reductions. EPA is not finalizing new ABT provisions for otto-cycle engines because no new standards are being adopted for those engines. In summary, engine manufacturers will be able to generate credits under the new program beginning with the 1998 model year for use only in 2004 and later model years. The credits in the modified program will have unlimited life, as opposed to the three year credit life contained in the current program. Also, engines with certification levels at or below a certain cut point are able to generate undiscounted credits. Credits generated by engine families certified above the specified cut point are discounted by 10 percent for purposes of banking and trading. The current averaging, banking, and trading program is being retained for engine using credits before 2004, and for otto-cycle engines which cannot earn credits in the modified program, as noted above. In 2004, the cut-point is adjusted to reflect the implementation of the new standard.

EPA finalized several provisions to help ensure in-use durability. First, EPA is increasing the useful life period for heavy heavy-duty diesel engines to 435,000 miles. This new period represents a 50 percent increase and is more representative of the durability of current and future heavy heavy-duty diesel engines. In addition, longer allowable maintenance intervals are being finalized for some critical emission-control components, including exhaust gas recirculation systems, catalysts, and other add-on emissions control components. Generally, the maintenance intervals for the components are set at 100,000 miles for light heavy-duty diesel engines and 150,000 miles for medium and heavy heavy-duty diesel engines. Warranty regulations were also revised to better reflect current industry practices.

Other provisions address the period after the manufacturer's responsibility for emission control ends, including engine rebuilding. One of those provisions requires engine manufacturers to establish a section in the owners manual for add-on components that includes recommendations for maintenance and diagnosing malfunction. In addition, all on-board monitoring used to satisfy the engine's allowable maintenance must not be designed to turn off after the end of the useful life. Finally, EPA is establishing provisions to address engine rebuilding which specify what actions are needed to ensure proper operation of emissions control components and ensure that rebuilding does not result in loss of emissions control. Removal or disabling of emissions related components, resulting in a higher emitting vehicle, would be considered tampering. Please refer to the final rule documents for more detailed information on the requirements, especially the provisions regarding ABT, durability, allowable maintenance, and rebuilding.

II. Summary of the RIA

A. Chapter 2—Health and Welfare Concerns

Chapter 2 provides an overview of the health and environmental effects associated with ozone and particulate matter. As part of the legally-required periodic review of the ozone and PM air quality standards, EPA has recently assessed the impacts of ozone and PM on human health and welfare, taking into account the most relevant, peer-reviewed scientific information available. Chapter 2 reviews some of EPA's key concerns at this time, as compiled in the Agency's Criteria Documents and Staff Papers for ozone and PM. The chapter also provides national NOx and VOC emissions inventories and emissions trends.

B. Chapter 3—Industry Characterization

EPA, California, and the engine manufacturers acknowledged in the Statement of Principles the benefits of harmonizing California and federal emission regulations. Chapter 3 discusses the need for such harmonization and the problems that manufacturers face when designing and selling different engines in order to meet different emission standards. The chapter also presents an overview of the type of vehicles and the major manufacturers that are affected by the rule. All diesel engines used in highway vehicles with a gross vehicle weight rating of 8,500 lbs or greater will be subject to the new standards and provisions. The eleven manufacturers currently selling heavy-duty engines in the U.S., nine of which are diesel engine manufacturers directly affected by the new standards. These engines are used in vehicles that range in from Class 2B through Class 8 heavy-duty vehicles. Also included are buses and motor homes.

Recent sales trends show that diesel engines are playing an increasingly prominent role in all heavy-duty vehicle categories, especially Classes 5 through 8. In addition, data indicate that sales have increased for Classes 3 and 4 in the last few years, while sales of Class 5 engines have decreased rapidly.

Chapter 3 also gives an overview of engine rebuilding practices. Heavy-duty engines are often rebuilt because it is more economical than buying a new engine. These rebuilds extend engine life far beyond the "useful life". An EPA study found that currently most rebuilt engines exhibit emissions at or below certification levels for that model year. Virtually all heavy heavy-duty diesel engines are rebuilt at least once during their lifetime; between 220,000 and 250,000 of these engines are rebuilt each year. Medium heavy-duty diesel engines, which in some cases are not designed for rebuilding, are not rebuilt as often; only about 83,000 of these engines, or less than ten percent of the population, are rebuilt each year. Light heavy-duty diesel engines and heavy-duty gasoline engines are usually not rebuilt. About 40,000 heavy-duty gasoline engines, close to one percent of the total population, are rebuilt each year.

C. Chapter 4—Technological Feasibility

To achieve the proposed standards, heavy-duty diesel engine manufacturers will need to consider a combination of new and existing emission control devices. Chapter 4 presents the technologies available and discusses their potential for helping to reach the proposed emission levels. Emission control devices such as exhaust gas recirculation (EGR), advanced fuel injection and charge air systems can help reduce NOx plus NMHC levels to 2.4 g/bhp-hr in heavy-duty diesel engines.

Even though engine manufacturers have been successful in the past in meeting more stringent emission standards, lower levels will present a technological challenge. The difficulty of decreasing NOx without increasing PM has led manufacturers to explore the possibility of using aftertreatment devices in combination with other engine technologies. EGR, which is currently used in gasoline engines, is a potential technology for further emission reductions in the future from diesel engines.

D. Chapter 5—Economic Impact

The costs associated with the development of emission-control devices were estimated first by considering which emission-control devices would be more likely to help reduce NOx plus NMHC levels to those proposed for the year 2004. The primary technologies for controlling emissions from diesel engines are EGR, combustion chamber optimization and fuel system upgrades. The secondary technologies, or those that are expected to play a minor role in controlling NOx emissions, include variable-geometry turbochargers, advanced oxidation catalysts, and lean NOx catalysts.

Total costs were estimated from the cost differential that is expected from engines that will comply with 1998 standards to those that will comply with 2004 standards. Cost calculations were made separately for the three categories of heavy-duty diesel vehicles and urban buses due to their differences in cost, durability, expected mileage accumulation and sensitivity to fuel penalty. The total life-cycle cost per engine included the total manufacturer cost plus the operating costs over the life of the engine. The manufacturer cost consisted of the projected emission control devices and estimated variable costs (components, assembly labor and overhead) and fixed costs (tooling, research and development, and certification).

Table 1-1 summarizes the estimated increases in the purchase price of heavy-duty engines in the years 2004, 2006, and 2009. Long-term cost estimates shown in the table reflect a reduction from initial costs because fixed costs are recovered after five years. In addition, technology and production learning curves reduce costs as manufacturers gain experience in production. In addition to the increased purchase price, operating expenses are expected to increase to account for effects on oil changes and rebuild practices. The estimated net present value of these changes for each engine is $10, $60, $130, and $125 for light, medium, and heavy heavy-duty vehicles, and urban buses, respectively.

Table 1-1
Estimated Incremental Impact on
Heavy-Duty Diesel Engine Purchase Price

Service Class	Model Year		
	2004	2006	2009
Light heavy-duty	$258	$224	$109
Medium heavy-duty	$397	$355	$136
Heavy heavy-duty	$467	$411	$180
Urban Bus	$406	$361	$143

E. Chapter 6—Environmental Impact

Estimates show that emissions from heavy-duty diesel vehicles account for about 10 percent of the total 1990 inventory of NOx emissions and 1.3 percent of total volatile organic carbon emissions. Trends demonstrate that present NOx standards will help reduce emissions over the next several years, but the increase in the number of vehicles and driving activity will result in total NOx emission levels that are expected to surpass current levels by the year 2020. NMHC projections show that the proposed standard would have a small effect in the NMHC inventory because only about ten percent of heavy-duty diesel engines sold in 1994 emit HC at levels of 0.5 g/bhp-hr or more.

Additional data presented in Chapter 6 show that the proposed standards would result in NOx reductions that exceed one million tons by the year 2020, or nearly a five percent reduction of the total NOx inventory. In addition, it is estimated that NMHC would be reduced by 16,400 tons per year in 2020, or less than one percent of the total inventory in the U.S. It is projected that, as a result of the proposed standards, about half of the emission benefits will occur in attainment areas, one quarter will occur in marginal and moderate nonattainment areas, and one quarter in serious, severe, and extreme nonattainment areas.

Other environmental impacts discussed include the reduction in the concentration of secondary nitrate particles as a result of lower NOx standards. It is estimated that the equivalent particulate emission reductions could be as high as 44,000 tons if there is a 2.0 g/bhp-hr NOx standard highway heavy-duty diesel engines. These NOx, and consequently particulate, reductions would also result in less acid deposition and less nitrogen present in estuaries.

F. Chapter 7—Cost-Effectiveness

Chapter 7 presents an analysis of the per-vehicle cost-effectiveness of the standards for new heavy-duty diesel engines. The analysis relies on cost and emissions information described in Chapters 5 and 6, estimating cost-effectiveness in terms of dollars per ton of total emission reductions. Cost-effectiveness is a tool used for comparing the cost and benefits of a given measure relative to the costs and benefits of other control programs. In this case, the comparison is for urban ozone nonattainment area control programs. The cost-effectiveness analysis for the new engine standards was performed for all diesel heavy-duty vehicles, with a separate calculation for three individual categories of heavy-duty diesel vehicles (light, medium, and heavy). A fleet cost-effectiveness analysis is also presented covering 30 model years after the new engine standards would take effect. Three sensitivity analyses look at the effect of fuel economy penalty, increased maintenance costs, and increased technology costs on cost-effectiveness.

The cost-effectiveness of the new engine standards is analyzed by two cost-effectiveness scenarios. The first scenario presents the nationwide cost-effectiveness, in which the life-cycle costs are divided by the lifetime NOx plus NMHC emission benefits. The second scenario presents a regional ozone strategy cost-effectiveness, in which life-cycle costs are divided by the discounted lifetime NOx plus NMHC emission benefits after adjusting for the fraction of emissions that occur in the regions expected to impact ozone levels in ozone nonattainment areas. Based on the two cost-effectiveness scenarios, the range in the cost-effectiveness results for 2009 and later model year heavy-duty diesel vehicles is \$100 to \$200 per ton.

CHAPTER 2: HEALTH AND WELFARE CONCERNS

I. Background

As part of the legally-required periodic review of the ozone and PM air quality standards, EPA has recently assessed the impacts of ozone and PM on human health and welfare, taking into account the most relevant, peer-reviewed scientific information available. The paragraphs below review some of EPA's key concerns at this time, as compiled in the Agency's Criteria Documents and Staff Papers for ozone and PM. The Criteria Documents are prepared by the Office of Research and Development consist of EPA's latest summaries of scientific and technical information on each pollutant. The Staff Papers on ozone and PM are prepared by the Office of Air Quality Planning and Standards and summarize the policy-relevant key findings regarding health and welfare effects.

A. Ozone

Over the past few decades, many researchers have investigated the health effects associated with both short-term (one- to three-hour) and prolonged acute (six- to eight-hour) exposures to ozone. In particular, in the past decade, numerous controlled-exposure studies of moderately-exercising human subjects have been conducted which collectively allow a quantification of the relationships between prolonged acute ozone exposure and the response of people's respiratory systems under a variety of environmental conditions. To this experimental work has been added field and epidemiological studies which provide further evidence of associations between short-term and prolonged acute ozone exposures and health effects ranging from respiratory symptoms and lung function decrements to increased hospital admissions for respiratory causes. In addition to these health effects, daily mortality studies have suggested a possible association between ambient ozone levels and an increased risk of premature death.

Most of the recent controlled-exposure ozone studies have shown that respiratory effects similar to those found in the short-term exposure studies occur when human subjects are exposed to ozone concentrations as low as 0.08 ppm while engaging in intermittent, moderate exercise for six to eight hours. These effects occur even though ozone concentrations and levels of exertion are lower than in the earlier short-term exposure studies and appear to build up over time, peaking in the six- to eight-hour time frame. Other effects, such as the presence of biochemical indicators of pulmonary inflammation and increased susceptibility to infection, have also been reported for prolonged exposures and, in some cases, for short-term exposures. Although the biological effects reported in laboratory animal studies can be extrapolated to human health effects only with great uncertainty, a large body of toxicological evidence exists which suggests that repeated exposures to ozone causes pulmonary inflammation similar to that found in humans and over periods of months to years can accelerate aging of the lungs and cause structural damage to the lungs.

In addition to the effects on human health, ozone is known to adversely affect the environment in many ways. These effects include reduced yield for commodity crops, for fruits and vegetables, and commercial forests; ecosystem and vegetation effects in such areas as National Parks (Class I areas); damage to urban grass, flowers, shrubs, and trees; reduced yield in tree seedlings and non-commercial forests; increased susceptibility of plants to pests; materials damage; and visibility. Nitrogen oxides (NOx), a key precursor to ozone, also results in nitrogen deposition into sensitive nitrogen-saturated coastal estuaries and ecosystems, causing increased growth of algae and other plants.

B. Particulate Matter

Particulate matter (PM) represents a broad class of chemically and physically diverse substances that exist as discrete particles (liquid droplets or solids) over a wide range of sizes. Human-generated sources of particles include a variety of stationary and mobile sources. Particles may be emitted directly to the atmosphere or may be formed by transformations of gaseous emissions such as sulfur dioxide or nitrogen oxides. The major chemical and physical properties of PM vary greatly with time, region, meteorology, and source category, thus complicating the assessment of health and welfare effects as related to various indicators of particulate pollution. At elevated concentrations, particulate matter can adversely affect human health, visibility, and materials. Components of particulate matter (e.g., sulfuric or nitric acid) contribute to acid deposition.

Key EPA findings can be summarized as follows:

1. Health risks posed by inhaled particles are affected both by the penetration and deposition of particles in the various regions of the respiratory tract, and by he biological responses to these deposited materials.

2. The risks of adverse effects associated with deposition of ambient particles in the thorax (tracheobronchial and alveolar regions of the respiratory tract) are markedly greater than for deposition in the extrathoracic (head) region. Maximum particle penetration to the thoracic regions occurs during oronasal or mouth breathing.

3. The key health effects categories associated with PM include premature death; aggravation of respiratory and cardiovascular disease, as indicated by increased hospital admissions and emergency room visits, school absences, work loss days, and restricted activity days; changes in lung function and increased respiratory symptoms; changes to lung tissues and structure; and altered respiratory defense mechanisms. Most of these effects have been consistently associated with ambient PM concentrations, which have been used as a measure of population exposure, in a large number of community epidemiological studies. Additional information and insights on these effects are provided by studies of animal toxicology and controlled human exposures to various constituents of PM conducted at higher than ambient concentrations. Although mechanisms by which particles cause effects are not well known, there is general agreement that the cardio-respiratory system is the major target of PM effects.

4. Based on a qualitative assessment of the epidemiological evidence of effects associated with PM

for populations that appear to be at greatest risk with respect to particular health endpoints, the EPA has concluded the following with respect to sensitive populations:

a. Individuals with respiratory disease (e.g., chronic obstructive pulmonary disease, acute bronchitis) and cardiovascular disease (e.g., ischemic heart disease) are at greater risk of premature mortality and hospitalization due to exposure to ambient PM.

b. Individuals with infectious respiratory disease (e.g., pneumonia) are at greater risk of premature mortality and morbidity (e.g., hospitalization, aggravation of respiratory symptoms) due to exposure to ambient PM. Also, exposure to PM may increase individuals' susceptibility to respiratory infections.

c. Elderly individuals are also at greater risk of premature mortality and hospitalization for cardiopulmonary problems due to exposure to ambient PM.

d. Children are at greater risk of increased respiratory symptoms and decreased lung function due to exposure to ambient PM.

e. Asthmatic individuals are at risk of exacerbation of symptoms associated with asthma, and increased need for medical attention, due to exposure to PM.

5. There are fundamental physical and chemical differences between fine and coarse fraction particles and it is reasonable to expect that differences may exist between the two subclasses of PM_{10} in both the nature of potential effects and the relative concentrations required to produce such effects. The specific components of PM that could be of concern to health include components typically within the fine fraction (e.g., acid aerosols, sulfates, nitrates, transition metals, diesel particles, and ultra fine particles), and other components typically within the coarse fraction (e.g., silica and resuspended dust). While components of both fractions can produce health effects, in general, the fine fraction appears to contain more of the reactive substances potentially linked to the kinds of effects observed in the epidemiological studies. The fine fraction also contains the largest number of particles and a much larger aggregate surface area than the coarse fraction which enables the fine fraction to have a substantially greater potential for absorption and deposition in the thoracic region, as well as for dissolution or absorption of pollutant gases.

With respect to welfare or secondary effects, fine particles have been clearly associated with the impairment of visibility over urban areas and large multi-state regions. Fine particles, or major constituents thereof, also are implicated in materials damage, soiling and acid deposition. Coarse fraction particles contribute to soiling and materials damage.

Particulate pollution is a problem affecting localities, both urban and non-urban, in all regions of the United States. Manmade emissions that contribute to airborne particulate matter result principally from stationary point sources (fuel combustion and industrial processes), industrial process fugitive particulate emission sources, non-industrial fugitive sources (roadway dust from paved and unpaved roads, wind erosion from cropland, etc.) and transportation sources. In addition to manmade emissions, consideration must also be given to natural emissions including dust, sea spray, volcanic emissions, biogenic emanation (e.g., pollen from plants), and emissions from wild fires when assessing particulate pollution and devising control strategies.

II. National NOx and VOC Emission Trends

Figure 2-1 shows projected total NOx emissions over the time period 1990 to 2020, including a breakdown between stationary and mobile source components over the same period.[1] Figure 2-2 presents similar data for VOC emissions for the period 1990 to 2010. As the figures show, a similar pattern is projected for both of these ozone precursor emissions. Initially, the projections indicate that national inventories will decrease over the next few years as a result of continued implementation of finalized stationary and mobile source NOx control programs called for in the Clean Air Act. After the year 2000, however, when the implementation of these Clean Air Act programs is largely completed and the pressure of growth continues, these downward trends are expected to reverse, resulting in rising national VOC and NOx emissions.

Figure 2-1

Figure 2-2

III. Contribution of Heavy-Duty Vehicles to National NOx and VOC Emissions

Highway heavy-duty vehicles represent about 12 percent of nationwide NOx emissions and are an important source of VOC and PM emissions throughout the country. This section reviews EPA's current estimates of the contribution of heavy-duty vehicles to the nation's major air pollution problems now and into the future. The projections that follow incorporate the emission reductions from all national emission control programs for stationary and mobile sources for which final regulations had been promulgated at the time of the proposal.

A. National Mobile Source NOx Emission Trends

Figure 2-3 shows the total mobile source NOx inventory by emission source (light-duty vehicles, heavy-duty vehicles, and nonroad engines) projected over the next 25 years.[2] For light- and heavy-duty vehicles the figure shows a decline in emissions over the next decade as current programs phase in. The figure also shows, however, that this current downward trend is projected to end, resulting in a return to current levels in the absence of further controls. Nonroad emissions are projected to rise throughout the period.

B. National Mobile Source VOC Emission Trends

Figure 2-4 shows the total national mobile source VOC inventory by emission source.[3] As with the NOx emission projections in Figure 2-5, this figure shows that light-duty vehicle emissions can be expected to decline for some years, but then begin rising in the 2005 time frame. VOC emissions from heavy-duty vehicles and nonroad sources are projected to rise gradually throughout this period.

Figure 2-3

Figure 2-4

Chapter 2 References

1.See Chapter 6 for a discussion of the modeling assumptions used in generating emission inventories.

2. U.S. Environmental Protection Agency Contract No. EPA68-300-35, E. H. Pechan.

3.U.S. Environmental Protection Agency. (1994) National Air Pollutant Emissions Trends, 1900-1993. Research Triangle Park, NC: Office of Air Quality Planning and Standards. EPA Report No. EPA-454/R-94-027.

CHAPTER 3: INDUSTRY CHARACTERIZATION

In any evaluation of the impact of emission standards it is essential to have a thorough understanding of the affected industries. This assessment is important to better understand the industry's ability to comply with the new standards, both monetarily and physically. The purpose of this chapter is to characterize the affected industries: who the engine and equipment manufacturers are, what they produce, their degree of vertical integration, and their size and financial standing. Although gasoline -fueled engines are not affected by the new standards, information is provided on those engines and engine manufacturers to provide a complete picture of the heavy-duty engine industry.

I. National Uniformity of Standards

The Clean Air Act allows California to set its own heavy-duty engine emission standards and provides the opportunity for other states to adopt these standards by adopting the California program. However, truck and engine manufacturers have long called for uniform emission standards throughout the country.[a] The advantage of uniform standards is apparent when one considers a scenario of varying standards across different states or regions.

Without uniform standards, engine manufacturers would have to develop and produce two or more different models of the same engine for different areas of the country. This would add expense in design, manufacturing, and certification of the engines and would increase the complexity of marketing as manufacturers determine how many engines they must produce for each market. An alternative for the engine manufacturers would be to produce their engines to meet the most stringent standard in the country so their engines could be sold anywhere. This approach would simplify the production and marketing of low-emitting engines, but may increase the price of engines and result in a competitive disadvantage compared with manufacturers that produce engines designed to meet the less stringent standards.

Engine manufacturers also face potential problems with nonuniform standards. The same basic engine model engineered to meet different emission standards may require a different packaging approach for the vehicle manufacturer. Thus, from a business perspective there are benefits to uniform national standards if they can be justified from air quality and cost-effectiveness perspectives. Sales and marketing of these vehicles will be more complex, since manufacturers will have to plan how to distribute their engine sales. More importantly, the sale of one type of engine will be closed to other markets with more stringent standards. Thus, the manufacturers will have to keep track of two or more different sales figures. Vehicle marketers in the area with more stringent standards may

[a]As will be seen later in this chapter while some manufacturers do make both trucks and engines, usually engine and truck manufacturers are separate entities, one serving as supplier and the other as customer.

be at a disadvantage as users purchase higher emitting vehicles in other states or move operations to areas where standards are less stringent.

II. Engine Manufacturers

A. Highway Vehicles Involved

This rulemaking would apply to diesel vehicles with a gross vehicle weight rating (GVWR) of 8,500 pounds or greater (Classes 2B through 8). Table 3-1 shows a breakdown of the vehicle classes and their GVWR. This rulemaking also includes buses and motor homes with a GVWR in excess of 8,500 lbs. For heavy-duty diesel vehicles, EPA categorizes Classes 2B through 5 as light heavy-duty, Classes 6 and 7 as medium heavy-duty, and Class 8 as heavy heavy-duty. For heavy-duty gasoline engines, Classes 2B and 3 are light heavy-duty and Class 4 and bigger are heavy heavy-duty.

Table 3-1
Vehicle Class and GVWR Breakdown

Vehicle Class	2B	3	4	5	6	7	8
GVWR (lbs.)	8,501 - 10,000	10,001 -14,000	14,001 - 16,000	16,001- 19,500	19,501- 26,000	26,001- 33,000	33,000+

B. Sales

According to the Power Systems Research (PSR) Database, which compiles a list of the sales data for all engines sold in the United States, there were 11 manufacturers of engines for vehicles in the heavy-duty vehicle categories listed above doing business in the United States in 1994.[b] Table 3-2 contains a list of those manufacturers, the number of engines sold in the United States (both diesel and gasoline), and the vehicle categories involved. Six other foreign manufacturers certified heavy-duty diesel engines for sale in the U.S. in 1994. These included Hino, Isuzu, Mitsubishi, Nissan, Perkins, and Renault.

As Table 3-2 shows, the six major manufacturers in these categories: Caterpillar, Cummins, Detroit Diesel, Ford, General Motors, and Navistar account for over 80 percent of the total engines sold in the United States. Only General Motors makes both gasoline and diesel engines. Chrysler and Ford use diesel engines produced by other manufacturers in their vehicles. Only one manufacturer, Cummins, produces engines in all three diesel engine categories. A few manufacturers certified alternative-fueled engines.

[b]Power Systems Research is a company that tracks the sales and populations of vehicle and engines in the highway as well as nonroad areas.

Table 3-2
1994 Engine Manufacturer Sales

Engine Manufacturer	Vehicle Class Categories							
	2B*	3 & 4**	5	6	7	8	Bus	Motor Home
Caterpillar				4,977	13,059	57,043	2,192	194
Chrysler	50,000	3,596						24
Cummins	43,000	3,765	656	1,143	32,499	79,588	10,593	8,812
Detroit Diesel						51,371	4,527	282
Ford	198,000	3,237		154	6,732	554	40	10
General Motors	234,000	16,699		3,071	6,283		1,922	20,630
Hercules							10	
Mack						25,815		
Mercedes Benz				20	144	89		
Navistar	116,000	17,462	199	1,974	37,029	6,470	18,120	
Volvo					671	2,466		
TOTAL	641,000	44,759	855	11,339	96,417	223,396	37,404	29,952

*Class 2B engine sales are based on EPA estimates of manufacturer sales.
**Classes 3 and 4 are presented together because PSR combined them in its database.
SOURCE: PSR Database, 1995.

Figures 3-1 through 3-8 illustrate sales trends for the years 1980 through 1994 (except for motor homes, which are 1985 through 1999) for gasoline and diesel engines separately.[1] In studying these figures, some important trends become apparent. First, the general trend of heavy-duty engine sales is upward. There are periods of downward trends that correspond to downward turns in the economy, but nevertheless, the overall trend has been toward increased sales.

Second, as shown in Figure 3-8, while the trend of duty engine sales over the last four years is upward, this is dominated by an increase in diesel engine sales. The gasoline engine sales have actually been decreasing over the years (although the level of gasoline engine sales has leveled off in the past few years), thus it is evident that dieselization of the heavy-duty vehicle market has been taking place. In other words, an even greater percentage of heavy-duty vehicles is diesel-powered and, if present trends continue, diesel engines will take on an increasingly important role in the future.

A final point that can be derived from the graphs is that there is an apparent migration across truck classes. Figures 3-2 and 3-3 show a dramatic decrease in sales for truck Classes 5 and 6. Since the sales for all other classes (both above and below Classes 5 and 6) are showing increases, it is not possible to determine whether this is a net upward (toward higher GVWR) or a downward (toward lower GVWR) migration. However, the most reasonable assumption is that the migration is occurring in both directions to some degree. Possibly with the Class 5 vehicles migrating to the Class 4 level and the Class 6 vehicles migrating up to class 7.

To form a better picture of the types of engines that are presently being sold for various vehicle classes, it is important to understand these engines' power and torque requirements. Table 3-3 provides the range of peak horsepower and torque of the engines in each vehicle class for the 1994 model year. Except for Class 5, which has extremely small sales in comparison with other classes, there is a general increase in the average horsepower and torque as the GVWR increases. Buses and motor homes, as one would expect, vary considerably in size and thus utilize a broad range of engine power and torque.

Table 3-3
Rated Horsepower and Torque Ranges for Gasoline and Diesel Heavy-duty Engines

	Class 2B	Classes 3&4	Class 5	Class 6	Class 7	Class 8	Buses	Motor Homes
Peak HP Range	135 - 210	100 - 300	160 - 190	160 - 300	160 - 300	190 - 500	121 - 450	160 - 450
Peak Torque Range (ft-lbs.)	253 - 400	184 - 644	542 - 658	514 - 1288	514 - 1288	499 - 2509	245 - 1966	407 - 1966

SOURCE: PSR Database, 1995.

C. Engine Manufacturer Profiles

This section develops a profile of the individual engine manufacturers that may be affected by the new emission standards for heavy-duty engines. Gasoline-fueled engine manufacturers are also included. The discussion includes the financial standing of the organization, its size, and other industries in which it is involved. This information was derived from the 1995 InfoTrac Database. A later section discusses the situation for vehicle manufacturers, some of which also manufacture engines. Table 3-4 summarizes manufacturers' product offerings for the different fuels and engine sizes.

Table 3-4
1994 Heavy-Duty Engine Categories
for Each Manufacturer (G=Gasoline, D=Diesel)

Manufacturer	Light	Medium	Heavy
Caterpillar		D	D
Chrysler	G		
Cummins	D	D	D
Detroit Diesel			D
Ford	G		
General Motors	G, D	D	G
Mack			D
Mercedes Benz		D	
Navistar	D	D	
Renault		D	
Volvo		D	D

1. Caterpillar, Inc.

Caterpillar produces a large number of engines that are used in highway applications, primarily truck Classes 6 through 8. Caterpillar is also well known as one of the larger manufacturers of nonroad equipment and engines for equipment used in construction, forestry, and farming to name a few. This vertical integration in the nonroad market is not paralleled on the highway side; Caterpillar sells its highway engines to other companies that manufacture and sell the trucks and buses in which their engines are used.

Caterpillar employs about 54,000 people worldwide, with its main office located in Peoria, Illinois and with several plants in the United States, Brazil, Australia, France, Switzerland, Mexico, Belgium, Japan, Hong Kong, Singapore, Italy, and Indonesia. Caterpillar's Engine Division employs about 8,000 people. Caterpillar sells products under three different trade names: Cat and Caterpillar, used for engines, earthmoving equipment, construction and material handling machinery and lift trucks; and Solar, which is used for their line of turbine engines.

Caterpillar is involved in several businesses other than its engine and nonroad equipment manufacturing, as evidenced by its diverse list of subsidiaries, including Caterpillar Financial Services Corporation, Defense Products, Service Technology Group, Caterpillar Logistics Services, Inc., Caterpillar Paving Products, Inc., Caterpillar Venture Capital, Inc., Caterpillar World Trading Corporation, Caterpillar Insurance Services, Inc., Solar Turbines, Inc., and Caterpillar Industrial Products, Inc.

Caterpillar, Inc., the parent company, had total revenues in fiscal year 1994 of $14.3 billion, while the Engine Division had a total revenue of $1.3 billion, or about nine percent of the parent company's.

2. Chrysler Corporation

Chrysler Corporation is a well known manufacturer of passenger cars and trucks. Chrysler also produces gasoline engines for Class 2B through Class 4 highway vehicles (between 8,500 and 16,000 lbs GVWR). Chrysler produces the vehicles in which these engines are used, such as their heavier Dodge Ram pickups, wagons and vans with a GVWR above 8,500 lbs.

Chrysler is also involved in several other business areas. Its subsidiaries manufacture adhesives, automotive parts, boats, chemicals, outboard motors, automotive testers, tractors, and military vehicles. Chrysler is also involved in automotive rental and financial services. As of 1994, Chrysler had approximately 121,000 employees with a total sales revenue of $52.2 billion. Because Chrysler does not report separately the heavy-duty vehicle or engine manufacturing information, data about engine revenue was not available.

3. Cummins Engine Company

Cummins Engine Company makes engines for all the vehicle classes affected by the new emission standards. The information for the engine populations produced by Cummins includes those engines manufactured by Consolidated Diesel Company, a private subsidiary of Cummins. Cummins' headquarters is located in Columbus, Indiana and Consolidated Diesel is located in Whitakers, North Carolina.

Cummins manufactures primarily diesel engines and the associated parts, but also produces some of their own other systems such as turbochargers, electronic control systems, and alternators that may be marketed to its competitors. Consolidated Diesel manufactures diesel engines for sale under the Cummins label. They also produce nonroad engines of Cummins design for Case, a well known nonroad equipment manufacturer.

In 1994 Cummins Engine company employed approximately 25,600 people and had revenues of $4.7 billion, primarily from the sale of engines and parts. Consolidated Diesel, during that same time period, employed 1,500 people and had revenues of $520 million.

4. Detroit Diesel Corporation

Detroit Diesel Corporation is a major player in manufacturing engines for Class 8 trucks and buses. Manufacturing these heavy duty engines and engine parts appears to be the main thrust of

Detroit Diesel's business. Its headquarters is located in Detroit, Michigan.

Detroit Diesel is owned by Penske Corporation, which is involved in many business areas, including car and truck rentals. As of 1994, Detroit Diesel employed approximately 5,400 people and had annual sales revenue of $1.7 billion. Detroit Diesel is the parent company of Detroit Diesel Remanufacturing West located in Salt Lake City, Utah. As the name would imply, this company remanufactures of diesel engines. In 1994, it employed 218 people and had revenues of $31 million. Detroit Diesel in 1995 bought VMI, a manufacturer of diesel engines for passenger cars.

5. Ford Motor Company

Ford Motor Company, best known for its production of passenger cars and light trucks, also produces both engines and vehicles for several models of heavy-duty gasoline trucks. Ford buys engines from manufacturers of diesel engine manufacturers for its line of heavy-duty diesel trucks.

Ford is involved in a number of other businesses including, motor vehicle parts and accessories manufacturing and financial services. Ford owns at least a portion of several other businesses throughout the world, including other automobile manufacturers. It maintains production at many assembly and manufacturing plants in the United States and throughout the world. In 1994, Ford employed 337,778 people, and had a total sales revenue of $128.4 billion. No information was available to show how much of this revenue was from its heavy-duty engine manufacturing operations.

6. General Motors Corporation

General Motors Corporation (GM), with its headquarters in Detroit, Michigan, is a major player in heavy-duty engine manufacturing, producing a large market share of the engines in Class 2B through Class 6 truck categories. GM also produced almost 70 percent of the engines for motor homes in 1994. It is the only manufacturer that produces both gasoline and diesel heavy-duty engines. GM also manufactures the chassis for many of the heavy-duty trucks and motor homes for which they manufacture engines. GM is involved several other business areas as well, most importantly as a major manufacturer of passenger cars and trucks and replacement parts for their products. GM is involved in motor vehicle financing and also owns a data and electronics firm. GM owns part or all of many companies throughout the world, some of which are also involved in the automobile manufacturing industry. In 1994, General Motors employed 692,800 people throughout the world and had sales revenues of about $124 billion.

7. Hercules Engine Company

Hercules engine company plays a very small role in the heavy-duty engine manufacturing industry, having produced only 10 bus engines in 1994. Most Hercules engines are for nonroad purposes and are used predominantly in generator sets and forklifts.

Hercules is a privately held company with headquarters in Canton, Ohio. In 1994 it employed

300 people and produced $55.0 million in sales revenue.

8. Mack Trucks, Inc.

Mack Trucks, Inc. is located in Allentown, Pennsylvania. It produces and sells truck chassis under the Mack label. These chassis are predominantly of the Class 8 type, but they also make truck chassis in the Class 6 and 7 weight classes. The Powertrain Division, located in Hagerstown, Maryland, produces engines for Class 8 trucks only.

Mack Truck was recently purchased by Renault, a major European automobile manufacturer. Mack Trucks employed 5,459 people in 1994 and had sales revenue of $970 million. The Powertrain Division employed 1,500 people of the total and accounted for $220 million of total Mack Truck sales.

9. Mercedes Benz of America

Mercedes Benz of America is a subsidiary of Daimler Benz, which is located in Europe. The heavy-duty engines produced by Mercedes Benz are only a small portion of its market, evidenced by the fact that Mercedes Benz of North America had a total sales revenue in 1994 of $2.2 billion while employing 1,400 people. Mercedes Benz is also a producer of passenger cars powered by diesel and gasoline engines.

10. Navistar International Corporation

Navistar is a large stand-alone company based in Chicago, Illinois. It is a major manufacturer of light and medium heavy-duty engines, except for those used in motor homes. Navistar is also involved in the manufacturing of truck and bus bodies. The main company, Navistar International Corporation, is listed primarily as a builder of truck and bus bodies as well as being involved as a financial holding company.

Navistar International Transportation, a subsidiary founded in 1987, manufactures motor vehicles and car bodies. Its division, Navistar International Transportation Corporation, Engine and Foundry Division, manufactures heavy-duty diesel engines. The overall parent company, Navistar International Corporation, employed 14,910 people in 1994 and had 1994 sales revenues of $5.3 billion.

11. Volvo GM Heavy Truck Group

The Volvo GM Heavy Truck Group presently produces a very small percentage of the engines for Classes 7 and 8 engines. While GM owns approximately 13 percent of the company, it is owned primarily by Volvo, the Swedish automobile manufacturer. The Heavy Truck Group manufactures Volvo trucks as well as diesel engines. Located in Greensboro, North Carolina the Heavy Truck Group employs 4,200 people and had sales revenues in 1994 of $1.0 billion, most of which can be attributed to its vehicle sales and not engine production, since the number of engines produced was relatively small.

III. Vehicle Manufacturers

A. Heavy-duty Vehicle Use

Heavy-duty vehicles are sold for many different commercial purposes. Table 3-5 lists the primary products carried by trucks and the approximate number of trucks used for these purposes by weight class. The table shows that trucks transport a very wide range of commodities.

The trucking industry is divided into two basic carrier categories: local and intercity. Carriers are considered local if they conduct 50 percent or more of their business in a metropolitan area. Intercity carriers (otherwise known as line haul or over-the-road) conduct pickup and delivery between metropolitan areas. The intercity carriers currently account for 29 percent of all intercity freight in terms of ton-miles, second only to railroad freight transport. These trucks compete with railways, inland waterways, pipelines and domestic airways for freight transportation. Figure 3-9 shows that trucks have gained an increasing role in the competition for carrying intercity freight. Thus, as the amount of intercity commerce dependent on trucks increases, the importance of trucks to the nation's commerce becomes more apparent.

B. Sales

The American Automobile Manufacturers Association (AAMA) provides a listing of trucks sold by make and GVWR. Table 3-6 shows the sales information for 1993. Note that these numbers do not entirely match the information on engine sales from Table 3-2 for those manufacturers who make both engines and truck bodies. These may have several causes. First, there can be some differences in apparent engine and vehicle sales attributed to one company if that company makes both engines and vehicles; this company will not necessarily make all of its engines for its own vehicles, nor will it use only its engines in its manufactured vehicles. Also, not all engines may be made for new vehicles. Some engines are manufactured and sold as replacement engines.

Table 3-5
Number of Heavy-Duty Vehicles by Products Carried (Thousands)

Products	Class 2*	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8
Farm Products	182.6	58.2	30.7	39.6	147.5	77.8	197.7
Live Animals	155.1	53.1	12.9	16.1	29.8	14.4	35.5
Animal Feed	92.6	14.5	7.7	6.8	17	7.2	28.4
Mining Products	4.1	3.6	NA	0.9	4.6	2.2	24.7
Raw Forest Products	36.7	8	6.7	6.7	11.4	5.9	58.9
Lumber & Wood Prod.	80.7	13.3	8.8	9	20.8	10.2	43.9
Processed Food	130.1	32.4	11.2	16.3	48.9	44.1	182
Textile Mill Products	57.1	11.9	3.1	4.1	7.8	5	18.4
Building Materials	162.8	52.6	31.1	25.6	87.1	49.7	306.7
Household Goods	13.3	3.7	2.6	4.9	11.3	3.8	24.4
Furniture/Hardware	37.2	13.6	3.6	8.5	8.4	3.3	20.2
Paper products	59.1	9.8	2	7.2	10.8	5	52.5
Chemicals	60.4	13.9	6.6	6.1	30.3	11.3	49.8
Petroleum	50.8	10.1	8.5	9.8	40.7	23.7	65
Plastics/Rubber	26.3	4.3	2.1	2.2	4.8	2.6	18.2
Primary Metal Prod.	57.0	8.7	4	4.3	9.8	3.6	49.3
Fabricated Metal Prod.	45.3	1.3	6.2	6.7	14.7	5.8	29.7
Machinery	129.7	24.3	12	8.8	27.8	14.7	67.6
Transportation Equip.	102.2	59.2	21.5	10.6	18.1	9.6	57.7
Glass Products	1.4	0.7	NA	NA	1.8	NA	4.8
Misc. Manufacturing Prod.	58.9	8.1	NA	7	9.3	4.6	27.5
Industrial "waste" water	NA	NA	NA	NA	NA	0.9	5.1
Scrap, Refuse, Garbage	34.5	13.4	10.5	9.6	18.9	13.3	64.2
Mixed Cargoes	66.4	30.2	14.3	15.8	26.6	13.4	107
Craftsman's Equip.	548.3	68.5	15.4	16.6	33.8	16.4	13.3
Recyclables	7.5	3.1	1.8	2.1	7.1	3.9	16.1
Personal Transport	1920.9	84.8	18.5	11.1	14.2	1.2	NA
Passengers	111.5	6.5	NA	NA	NA	0	0
Totals	4232.5	611.8	241.8	256.4	663.3	353.6	1568.6

*Includes vehicles from 6,000 to 10,000 lbs. GVWR. The new standards apply to diesel vehicles above 8,500 lbs. GVWR. These numbers were included for completeness.

SOURCE: 1992 Census of Transportation, United States Truck Inventory and Use Survey, U.S. Department of Commerce.

C. Equipment Manufacturer Profiles—United States and Worldwide

Truck manufacturers vary greatly in size and structure. Manufacturers selling the greatest volume of trucks in the United States are large, international corporations. Of these larger corporations, affected heavy-duty vehicles make up a small portion of total corporate revenues. Corporations such as Ford, Chrysler, General Motors, Mitsubishi, and Nissan gain the largest share of revenues from automotive sales, financial services and electronics. Their diverse array of products are sold throughout the world. Parts and dealerships are often supplied by many independent, unrelated sources.

Truck manufacturers such as Mack, Kenworth, Peterbilt, and Freightliner, while smaller and specializing primarily in the making of trucks and truck parts, are subsidiaries of larger, international corporations. For example, Mack Truck Inc. was entirely purchased in 1990 by Renault.[2] Similarly, Freightliner is associated with Daimler-Benz.

Other companies, such as Western Star, Bluebird, Oshkosh, and Flxible sell specialized vehicles (i.e. school buses, dump trucks, city transit buses). Market share and total revenue are much smaller than the largest truck manufacturers. These smaller companies invariably purchase their engines from another company, rather than bear the costs of producing them in house.

Table 3-7 lists the majority of truck manufacturers producing Class 2B through Class 8 trucks. The table also provides information regarding the size of the companies and lists and other business interests.

Table 3-6
Factory Sales of 1993 Complete Heavy-Duty Vehicles

Manufacturer	Vehicle Category								Total
	2B*	3	4	5	6	7	8	Bus	
Chrysler	52,297	13,826							66,123
Ford	218,960		21,455		5,708	24,408	16,407	3,055	289,993
Freightliner					492	2,869	37,667		41,028
Mercedes Benz					1	4			5
General Motors	160,070		7,894	2	8,620	16,427		3,030	196,043
Kenworth						124	17,873		17,997
Mack					675	461	16,662		17798
Navistar					7,474	32,809	32,582	14,665	87,530
Peterbilt						97	15,778		15,875
Volvo GM						684	19,376		20,060
Western Star							1,045		1,045
Hino Diesel		1	258	291	472	339			1,361
Isuzu Truck		5,811	3,235	1,451	1,394	217			12,108
Mitsubishi Fuso		2,421		930	715	303			4,369
Nissan Diesel		724	475	770	807	246			3,022

*Class 2B sales were estimated as 35 percent of total Class 2 sales for each manufacturer.
SOURCE: AAMA Motor Vehicle Facts and Figures, 1994 Edition.

Table 3-7
Truck Manufacturers' Parent Company Profile

Parent Company	Truck Manufacturers	Total Revenues in 1994	Total Employees in 1994	Other Business Interests
Chrysler	Dodge, Jeep	$52.224 billion	121,000	Automotive, Financial, Electronics
Daimler-Benz	Freightliner	about $100 billion	326,400	Automotive, Electronics, Space Tech., Defense Tech.
Ford Motor	Ford	over $130 billion	337,778	Automotive, Financial, Auto Rental
General Automotive	Flxible	$220 million (only Flxible)	1000 (only Flxible)	
General Motors	GMC, Chevrolet	$123.1 billion	692,800	Automotive, Financial, Insurance, Electronics, Locomotives
Hino Motors	Hino Diesel	$5.1 billion	9,151	Buses
Isuzu Motors	Isuzu Truck	$10.87 billion		Automotive, Parts, Buses
Mitsubishi	Mitsubishi Fuso	Over $100 billion	Over 70,000	Automotive, Raw Materials
Navistar International	Navistar International	$4.69 billion	13,612	Buses, Ambulances, Financial
Nissan Motor	Nissan Diesel	—	143,754	Automotive
Oshkosh Truck	Oshkosh Truck	—	2,400	Truck Trailers, Fire Trucks
Paccar	Kenworth, Peterbilt	$4.285 billion	over 10,000	Parts, Winches, Oil Well Equip.
Renault	Mack Truck	$970 million (Mack only)	5,459 (Mack only)	
Volvo GM	Volvo		73,641	Automotive, Buses, Marine, Food, Energy
Western Star*	—	—	—	—
Other	Bluebird, Novabus, more			

*Data not available.
SOURCE: DIALOG Database.

D. Future Truck Sales

In attempting to determine the behavior of future sales of trucks there are a few clues provided in the engine sales data from Figures 3-1 through 3-7. First, the PSR database provides projections for sales for the year 1995. In most cases, a slight increase in sales from 1994 to 1995 is predicted with the exception being Class 8 trucks and buses, but in these cases these are not severe drops and may be caused by a market surplus from extremely vigorous sales in the previous few years as the country pulled out of a recession.

To some degree heavy-duty vehicle sales are a subject to the fluctuations of the economy just as the automotive industry is. This is particularly evident when viewing Figure 3-8, which clearly shows the downward trend of sales and a subsequent recovery corresponding to two major recessions of the recent past: the recessions of the early 1980s and the early 1990s. However, throughout the time period shown on the figure there has been a general increase of sales.

As was previously discussed, another factor that can affect relative sales is the migration of sales from one vehicle class to another. Possible illustrations of this point are shown in Figures 3-1 and 3-2 and also in Figures 3-3 and 3-4.

The trend of dieselization will also play an important role in future sales of heavy-duty vehicles. The apparent result, of course, is that fewer gasoline heavy-duty vehicles will be sold in the market. Classes 5 and 8, for example, no longer have any sales of gasoline powered vehicles and other classes show trends in that direction. Diesel vehicles generally are more economical to operate and should show an even increased share of the market in the future provided they retain the economical advantage over gasoline in the heavy-duty truck classes.

Sales of trucks in the 1990s have, in general, gradually increased each year after a series of fluctuations during the 1980s. Figures and predictions for 1994 and 1995 have also generally followed the gradual increase, according to AAMA and individual manufacturer's reports. Market data from individual manufacturer's reports also supports a continuation of gradual growth. However, a complete sampling of truck manufacturer's growth predictions was not available.

A more detailed history of truck sales is provided in Table 3-8 below. The data through 1993, was provided by AAMA and excludes import truck sales. The data for 1994 and 1995 is based on engine manufacturer submittals to EPA of heavy-duty engine production. Note that the total number of heavy-duty vehicles sold in 1994 was about 300,000 higher than in 1993 and sales continued to increase in 1995. The sales increase was apparent throughout all vehicle classes, especially for the light and heavy heavy-duty trucks.

Table 3-8
New Retail Domestic Truck and Bus Sales*

YEAR	Vehicle Class							Total
	2B**	3	4	5	6	7	8	
1980	341,185	3,510	195	2,309	89,764	58,436	117,270	612,669
1981	297,482	748	12	1,916	71,993	51,402	100,334	523,887
1982	336,372	1,062	9	1,434	44,214	62,488	75,777	521,356
1983	422,310	145	2	1,159	46,532	59,383	81,647	611,178
1984	428,483	6,019	4	5,417	55,482	78,479	137,693	711,577
1985	448,075	10,854	0	5,081	48,358	96,973	133,581	742,922
1986	424,782	11,558	0	5,905	44,796	100,713	112,871	700,625
1987	411,278	14,007	2,129	8,185	44,282	102,583	131,156	713,620
1988	466,585	14,228	21,181	8,268	53,599	103,042	148,361	815,264
1989	454,087	19,161	27,031	7,243	39,128	93,446	145,068	785,164
1990	383,942	20,873	27,453	5,055	38,209	85,345	121,324	682,201
1991	306,690	21,256	23,829	3,301	22,445	72,598	98,711	548,830
1992	357,381	25,519	25,631	3,589	27,725	73,229	119,057	632,131
1993	431,335	26,947	33,317	4,288	26,642	80,793	157,886	761,208
1994 (gasoline)	light		heavy					
	413,679		51,129					464,808
1994 (diesel)	light				medium		heavy	
	256,339				130,543		189,928	576,810
1995 (gasoline)	light		heavy					
	483,928		59,811					543,739
1995 (diesel)	light				medium		heavy	
	279,789				139,895		217,247	636,931

*Any differences between the sales figures in this table and the numbers from Figures 3-1 through 3-8 are explained by the fact that the numbers from the Figures represent the total engine sales in the United States both domestic and imported, while the sales up through 1993 in this table are representative of AAMA member United States domestic vehicle production.

**Sales for class 2b were assumed to represent 35 percent of the total class 2 sales.

SOURCES: AAMA Motor Vehicle Facts and Figures (1994 edition), and engine manufacturer submittals to EPA.

With these factors in mind it is still not easy to determine any long-term sales trend for the heavy-duty vehicle market. It has been shown that diesel engines are gaining prominence over gasoline engines in the heavy-duty engine market; the economy has a critical effect on this highly cyclical industry; and there may be some reapportioning of sales from some weight classes to another. But overall the trend has been, and should continue to be, towards increasing sales in this industry. The degree of increasing sales may vary for each weight class. Figure 3-8 provides a composite picture of the sales history of heavy-duty engines (except for class 2B, which is excluded because of uncertainties with the data). This figure illustrates the overall industry trends of cyclical sales periods, with clear long-term growth.

IV. Engine Rebuilding

Some of the provisions of this rule address issues related to engine rebuilding practices. The provisions detail what the Agency would consider a violation of the tampering prohibitions established in the Clean Air Act. Essentially, the provisions were adopted to ensure that emissions controls are not removed or otherwise dismantled during the process of rebuilding an engine. The requirements are consistent with current customary rebuilding practices. Engine rebuilders customarily rebuild to original specifications and restore engines to like new condition. As such, the provisions do not place new requirements or burdens upon rebuilders but only emphasize rebuilder's obligations under the CAA. To better understand the engine rebuilding industry, EPA contracted with ICF incorporated to conduct an industry characterization.[3] EPA has also conducted a study of engine rebuild practices as required under Section 202(a)(3)(D) of the Clean Air Act.[4] The following contains a summary of ICF's findings. The reader is directed to the ICF report as well as the EPA study for further details regarding rebuild industry characteristics and rebuild practices.

A. Light Heavy-Duty Diesel Engines and Heavy-Duty Gasoline Engines

It is estimated that it will take the average light heavy-duty diesel engine eight years to reach the point of needing to be rebuilt or replaced. After this relatively long period of time the truck body deteriorates to a point where it is no longer practical to rebuild the engine. Engine manufacturers have stated that there is no real demand for rebuilding these engines and, in fact, light heavy-duty diesel engines are not designed to facilitate rebuilding.

Similarly, heavy-duty gasoline engines are rarely rebuilt. On the rare occasion that these engines are rebuilt, it is generally only when a premature failure takes place. Approximately one percent of heavy-duty gasoline engines, or about 40,000 units, are rebuilt each year.

B. Medium and Heavy Heavy-Duty Diesel Engines

The vast majority of engine rebuilding occurs with class 6-8 heavy-duty diesel trucks and buses, which typically fall into EPA's medium and heavy heavy-duty engine subclasses. Trucks in these classes are designed to last for many years and the engines are usually designed with replaceable cylinder liners (sleeved) which allows the engines to be rebuilt easily and several times, as necessary. Table 3-9 contains general information regarding the class 6-8 truck population. The table shows a population trend toward larger vehicles, with a decreasing Class 6 population and increasing Class 7 population. Because a minority of class 6 and 7 engines are not sleeved and because they accumulate mileage at a slower pace, rebuilding in those classes is common but not as prevalent as with class 8 trucks.

Table 3-9
Heavy-duty Diesel Engine Population and Rebuild Estimates

Truck Class	1990 Population	1995 Population	2000 Projected Population	1995 Average Mileage to Overhaul	1995 Number of Rebuilds
6	464,993	354,370	283,630	297,654	37,149
7	685,832	793,540	972,370	411,300	45,795
8	1,411,409	1,650,112	1,817,860	511,119	243,490

SOURCE: DataMac database, MacKay & Company, 1995

The cost of engine rebuilding is typically in the range of $6,500 - $8,500 for class 8 engines and $4,000 - $5,500 for class 6 and 7 engines, which compares very favorably with the cost of a new engine which ranges from about $12,000 for classes 6 and 7 to about $22,000 for class 8. The cost varies depending on the extent of the rebuild process. Rebuilding will most always include replacing cylinder components and other engine component such as camshafts, as needed. If the engine is removed from the vehicle (out-of-frame rebuild) more parts will be replaced than if the engine is rebuilt while remaining in the vehicle. The ratio of in-frame to out of frame rebuilds was about 2:1 in 1995. Engine rebuilding may also include rebuilding the fuel system and additional components such as the turbocharger, especially during an out-of-frame rebuild. ICF confirmed EPA's earlier findings and the comments received by EPA that it is standard rebuild industry practice to rebuild to original engine specifications, regardless of what type of company is conducting the rebuild. By rebuilding to original specifications, the rebuilder ensures proper engine operation and durability.

Engine rebuilding is triggered by a variety of criteria depending the owners preferences for addressing the issue. Primarily, rebuilding is triggered by a loss of performance such as a decrease in power or increase in fuel or oil consumption. Also, it is common for rebuilding to occur when the engine has had a catastrophic failure. Although rebuilding is not usually a scheduled maintenance event, some fleets may monitor mileage, and use mileage as a criteria for when to rebuild an engine.

C. Rebuilding Industry Characterization

Engine are rebuilt by the following groups: vehicle owners/fleet operators, truck dealerships, engine distributors, independent garages, and factory remanufacturers. Factory remanufacturers refers to large factory engine rebuilders that perform engine rebuilds in an assembly-line style operation. Engine cores are shipped to the remanufacturer as they are traded-in and the owner is supplied with a remanufactured engine. The remanufacturer disassembles the engine completely and then rebuilds it in an assembly-line operation. There are remanufacturers that are operated by the engine manufacturers (OEMs) and there are independent facilities. Most other types of rebuilders are custom rebuilders that work on engines individually as they need to be rebuilt. Table 3-10 shows the number of rebuilds performed by each group and the number of companies in each group.

Table 3-10
Engine Rebuilders

Rebuilder	Total Annual Rebuilds	Number of Companies
Engine Distributor	22,900	180
Truck Dealer	61,200	1,800
Vehicle Owner	175,600	407,800
Independent Shop	33,100	2,800
OEM Factory Remanufacturer	21,900	6
Independent Factory Remanufacturer	2,600	4

Using \$25 million in revenues as a threshold to differentiate between large and small businesses, all independent garages and the large majority of truck dealerships are small businesses which may perform engine rebuilds as a source of revenue. Independent garages, truck dealerships and engine distributors typically offer a wide range of engine and vehicle related services including engine rebuilding. ICF estimated that there are perhaps 400 to 500 independent shops which rely on heavy-duty engine rebuilding as a key source of revenue, performing 40 to 50 rebuilds each per year on average. Other shops perform heavy-duty engine rebuilds infrequently. Likewise, truck dealerships and engine distributors offer a wide range of engine and vehicle related services. ICF estimated that for truck dealerships, engine rebuilding represents about 7 percent of revenue and about 20 percent of total dealer profit. ICF also reported that smaller truck dealers focus on preventative maintenance rather than engine rebuilding.

Engine distributors are licensed by the original engine manufacturer and provide new engines, remanufacturered engines, parts, and OEM-warrantied engine rebuilds. Historically, distributorships were established by Class 8 engine manufacturers to sell and service engines and most of the major OEMs have 25 to 40 distributorships nationwide. Class 8 vehicles are more likely than class 6 or 7 vehicles to be designed to be equipped with engines from several different manufacturers. Distributors seek to secure large volume engine orders and also provide engine servicing.

For truck fleets, rebuilding is an expense rather than a revenue source. ICF found that fleets begin to have their own maintenance facilities at about 10 vehicles, but small fleets typically do not conduct many rebuilds. Large fleets often have rebuilding facilities and conduct the bulk of the fleet rebuilds. However, some large fleets sell their vehicles before the engine need to be rebuilt and also it is becoming more common to out-source rebuilds as the time before the rebuild point increases. Rebuilding is increasing in complexity with the addition of new technologies such as electronic controls which also steers fleets in the direction of out-sourcing.

Table 3-11
Fleet Rebuilding Estimates

Trucks in Fleet	Number of Fleets	Number of Vehicles	Rebuilds per Year
1-9	366,375	661,964	72,627
10-24	25,051	383,486	
25-99	12,547	350,657	102,936
100-499	2,947	313,473	
500+	855	1,088,770	

Figure 3-1

Figure 3-2

Figure 3-3

Figure 3-4

Figure 3-5

Figure 3-6

Figure 3-7

Figure 3-8

Figure 3-9

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CHAPTER 4: TECHNOLOGICAL FEASIBILITY

The purpose of this chapter is to discuss the feasibility of further reductions in highway heavy-duty diesel engine emissions beyond the 1998 federal emission standards. EPA anticipates that, by 2004, heavy-duty diesel production engines will be capable of greatly reduced exhaust emissions with little or no penalty for fuel consumption or durability. This conclusion is based on publicly available data on laboratory prototype systems, technology proven in other applications, the availability of substantial lead time, and the application of sufficient research and development funds.

The following sections describe the key technology that may be used to control emissions from highway heavy-duty engines by the 2004 model year. Technological projections are based on information on current developments. This chapter also discusses some strategies for continued emission control development beyond 2004. The organization of this discussion is divided into five main topics: background, engine controls, aftertreatment, developmental technology, and fuels.

I. Background

Heavy-duty diesel engine manufacturers have been very successful in lowering particulate matter (PM) and oxides of nitrogen (NOx) levels concurrently to meet increasingly stringent EPA emission standards. EPA standards have required a reduction in NOx emissions of over 50 percent (10.7 g/bhp-hr to 5.0 g/bhp-hr) and PM reduction of over 80 percent (0.60 g/bhp-hr to 0.10 g/bhp-hr) largely within the last five years. Engine manufacturers have been able to achieve the majority of these reductions using engine technology, with minimal reliance on exhaust aftertreatment technology. Today's heavy-duty diesel engines are also well below the standards for hydrocarbons (HC) and carbon monoxide (CO). Over this same period, engine manufacturers have been able to provide their customers with increased fuel economy and improved engine durability. Based on a review of current emissions research, EPA believes that emission control improvements from engine design changes have not yet leveled off.

Simultaneous control of NOx and PM presents a particular challenge. PM results from the incomplete evaporation and combustion of fine fuel droplets. High combustion temperatures cause nitrogen in the intake air (and to a lesser degree in the fuel) to combine with available oxygen to form NOx. NOx emissions are controlled primarily by lowering peak combustion chamber temperatures. However, simply lowering combustion temperatures can lead to an increase in PM formation because PM is less thoroughly oxidized at lower temperatures. NOx control strategies such as retarding fuel injection timing by themselves are limited because they cause an increase in PM. Engine manufacturers have had to devise more sophisticated emission control strategies due to this trade-off. Engine manufacturers have used a variety of technologies, often balancing their effects and optimizing among them to achieve the emission standards.

Lowering both NOx and PM has been accomplished primarily through improvements to the combustion chamber, intake air system, fuel injection system, and the use of electronic controls. NOx has been controlled substantially through charge air cooling, i.e., cooling the intake air by passing it through a heat exchanger. The key to PM control has been improved mixing of the fuel and air within the cylinder through the use of higher fuel injection pressures to better atomize the fuel and through better combustion chamber design. Improved turbocharger control and cylinder ring design for decreased oil consumption have also been important. Fuel injection control has been critical for both PM and NOx reduction. It is very important to ensure that the appropriate amount of fuel is injected at the appropriate time. Many engines are now equipped with electronically controlled fuel injection, lowering emissions and providing better fuel economy. Some engines are also equipped with oxidation catalysts for additional PM control.

It appears that manufacturers will rely on a variety of technologies to achieve the 1998 NOx standard of 4.0 g/bhp-hr. It is likely that manufacturers will continue refining the above technologies to continue to meet the standards. Chapter 5 includes detailed assumptions about these baseline technologies.

Engine manufacturers, independent laboratories, universities, and government laboratories are conducting substantial research on a variety of engine-based and aftertreatment technologies to control emissions, as well as fuel and fuel additive innovations and changes. This chapter examines their efforts to reduce NOx emissions below the 1998 standard of 4.0 g/bhp-hr while maintaining PM emissions levels at or below 0.10 g/bhp-hr. These technologies are examined below in detail because they are likely to continue to be very important. Also, some technologies not yet being used widely on production heavy-duty diesel engines, such as EGR, NOx reduction catalysts, and split fuel injection are reviewed. Such technologies could be very helpful in reaching NOx levels substantially lower than 4.0 g/bhp-hr.

It should also be noted that in addition to their own programs, engine manufacturers have been participating in significant cooperative research projects with goals similar to EPA's goals. The Department of Energy is coordinating a heavy-duty diesel engine program with emission goals of 2.5 g/bhp-hr for NOx and 0.05 g/bhp-hr for PM by 2000 on a test engine. Most domestic manufacturers are participating in this program, which began in 1994 and has an estimated annual budget ranging from $6 million to $10 million for emissions research and development alone.[c] Also, sixteen engine manufacturers are funding a cooperative research and development program at Southwest Research Institute (SwRI) called the Clean Heavy-duty Diesel Engine Program. The program is looking at engine technology and has goals of 2.0 g/bhp-hr for NOx and 0.05 g/bhp-hr for PM. The program has finished the first five years with encouraging results.[d]

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[c]The overall annual budget ranges from $12 to $20 million and covers fuel efficiency improvements and alternative fuels R&D.

[d]Under the agreement, no one may release or discuss actual results for two years after the program concludes. There has been and will be a lot of research and development progress that is not published.

Indications are that NOx and PM control technologies have not yet reached their potential. Current published research shows that NOx levels of 2.0 g/bhp-hr with a PM level of 0.10 g/bhp-hr can almost be achieved in laboratory diesel engines now. Unpublished and confidential research such as that done at SwRI probably represent even more advanced research efforts. For the 2004 time frame, these and other technologies could be optimized to meet and possibly exceed future emission targets.

II. Engine Controls

For the purpose of this discussion, engine combustion technology has been separated from exhaust aftertreatment technology. However, in actual heavy-duty vehicle design, both types of technology may be used together. This section will discuss several engine emission control technologies and their interactive effects on emissions and performance. For simplicity and clarity, each technology is first described individually. After the technologies are described, emissions data from various technology combinations will be presented.

A. Combustion Optimization

Several parameters in the combustion chamber of a heavy-duty diesel engine affect its efficiency and emissions. These engine parameters include: charge air and peak cylinder temperature and pressure, turbulence, valve and injection timing, injection pressure, fuel spray geometry and rate, combustion chamber geometry, air-fuel ratio, compression ratio, and exhaust in the cylinder. As the engine operates under changing load and speed, the effects of these parameters will change.

Many technologies that are designed to control the engine parameters listed above have been investigated. However, a positive influence on one parameter may have a negative influence on another. For example, decreasing combustion temperature will retard NOx formation but will increase HC and PM due to incomplete combustion. Therefore, combinations of technologies are often used to optimize the engine parameters. To attain significant reductions in HC and NOx from 1998 levels without penalties in other emissions or performance, a combination of approaches will be necessary.

1. Timing retard

The effects of injection timing in diesel engines on emissions and performance are well established.[1,2,3,4] Retarded timing is an inexpensive method of reducing NOx emissions and is already used to some degree. NOx is reduced because the premixed burning phase is shortened and because cylinder temperature and pressure are lowered. Too much timing retard results in undesirable increases in HC, CO, PM, and fuel consumption. These increases are due to the end of injection being later in the combustion stroke, shortening the time for fuel to burn, and due to the lower temperature and pressure in the cylinder. Technologies that can offset the negative effects of retarded timing will be discussed in further detail below.

2. Compression ratio

Compression ratio is another engine design parameter that impacts emission control. In general, higher compression ratios cause a reduction in PM emissions and improved fuel economy, but also cause an increase in NOx emissions. However, higher compression ratios require a stronger engine structure, which may increase weight and cost. The increased engine weight and frictional losses somewhat offset the fuel economy benefit of higher compression ratios, especially at very high compression ratios. Conversely, lower compression ratios generally cause a reduction in NOx emissions while causing an increase in PM emissions and decreased fuel economy. Also, low compression ratios can lead to problems with starting a cold engine if the cylinder pressure and temperature are not high enough to create ignition.

3. Combustion chamber geometry

Manufacturers have achieved significant emission reductions through changes to the combustion chamber. Additional modifications to the combustion chamber may provide further improvements in emission control. Combustion chamber parameters of interest include (1) the shape of the chamber and the location of the fuel injector, (2) volume of crevices, and (3) the compression ratio. The introduction of ceramic coatings to surfaces of the combustion chamber is another possible modification in the experimental stage.

Efforts to redesign the shape of the combustion chamber and the location of the fuel injector have been directed primarily at optimizing the relative motion of the air and the injected fuel. The goal is to limit the formation of NOx without an increase in PM, or conversely, to reduce PM without an increase in NOx. Reductions in both NOx and PM may be possible with some combustion chamber configurations currently under development. However, significant problems in the areas of structural durability and emission control durability have been attributed to these configurations. Additional benefits can be realized in the form of reduced HC and CO emissions, accompanied by little or no penalty in fuel efficiency. Costs would be limited primarily to initial fixed costs such as research and development and tooling changes, which would not be very large if spread over many engines.

The location of the top piston ring relative to the top of the piston has undergone significant investigation. The location of piston rings has been modified to reduce the crevice volume, while retaining the durability and structural integrity of the piston and piston ring assembly. Improvements result in reduced HC emissions and, to a lesser extent, in reduced PM emission. Costs associated with a relocation of the top ring can be substantial. Raising the top piston ring requires modified routing of the engine coolant through the engine block and lube oil routing under the piston to prevent the raised ring from overheating. Also, the machining needed for the engine block would likely require more precise tolerances.

4. Swirl

Increasing the turbulence of the intake air entering the combustion chamber (i.e., inducing swirl) can reduce PM emissions from diesel engines by improving the mixing of air and fuel in the combustion chamber. Historically, swirl was induced by routing the intake air to achieve a circular motion in the cylinder. Manufacturers are, however, increasingly using "reentrant" piston designs, in which the top surface of the piston is cut out to allow fuel injection and air motion in a smaller cavity in the piston to induce additional turbulence. The effect of swirl is often engine-specific, but some general effects may be discussed.

At low loads, increased swirl will reduce HC, PM, and smoke emissions and fuel consumption due to enhanced mixing of air and fuel. NOx is increased slightly at low loads as swirl increases. At high loads, swirl causes slight decreases in PM emissions and fuel consumption at the cost of severe increases in NOx emissions due to the higher temperatures associated with enhanced mixing and reduced wall impingement. In addition, HC emissions may actually be increased due to overmixing. These statements are based on data from an engine running at an intermediate speed (63% of rated).[5] A higher pressure fuel system can be used to offset some of the negative effects of swirl, such as increased NOx, while enhancing the positive effects such as a reduction in soot.[6]

Another study used a small auxiliary combustion chamber with its own fuel injector to induce turbulence late in the combustion period. Because the initial period of combustion was not disturbed, the mixing in the combustion chamber aided in the combustion of unburnt hydrocarbons without increasing peak cylinder temperatures. Therefore, smoke, PM and fuel consumption were reduced without an increase in NOx emissions. In addition, thermal efficiency was improved at high loads.[7]

B. Electronic Control

Many heavy-duty diesel engines are using open-loop electronic control to meter fuel flow and injection timing. This control allows the fine tuning that is necessary to fully optimize engine combustion for low emissions and fuel consumption. Several open-loop and closed-loop systems have been developed for diesel engines.[8] Especially when aftertreatment is used, closed loop control will become important for the efficient operation of diesel engines. Closed-loop control logic is discussed, in some detail, later in this chapter.

C. Charge Air Compression

Charge air compression is used in almost all current heavy-duty diesel engines. The original purpose was to increase power output from a given displacement engine. By forcing more air into the cylinder, more fuel can also be added at the same air fuel ratio, resulting in higher power. Boost air may also be used to reduce fuel consumption and emissions of smoke and soot by increasing the pressure and the amount of excess air in the cylinder. However, this increase in pressure and in oxygen and nitrogen availability may result in an increase in NOx emissions.[9,10]

Turbocharging is the most common method used for increasing boost pressure into the cylinder for four-stroke diesel engines. A turbocharger makes use of the waste energy in the exhaust gas to compress the intake charge. The exhaust gas drives a turbine linked to a centrifugal compressor that boosts the intake air pressure. Two-stroke diesel engines often use a positive-displacement pump to scavenge the cylinder and increase air flow into the engine. Positive-displacement pumps are very effective at increasing the cylinder charge, but they can cause a loss in efficiency since they are mechanically driven by the drive shaft.

1. Turbo-compounding

At rated power, a typical diesel engine loses about 30 percent of its energy through the exhaust. Even for turbocharged engines, much of this energy is not used since extra exhaust energy is passed through a waste-gate. Turbo-compounding refers to using a high pressure turbine and feeding extra energy back to the crankshaft. This is most efficient for engines operating at nearly constant high loads and high engine speeds. Test data have reported up to 15 percent increase in shaft power and 3-11 percent lower specific fuel consumption. Due to the high speed of the turbine; however, it is difficult to couple the power turbine to the drive shaft. This is especially difficult when the turbine and shafts must be matched over a wide range of operating speeds. There are some durability issues due to the need for a fluid coupling to protect high-speed gears by absorbing crankshaft vibrations.[11]

2. Variable geometry turbocharger

A turbocharger may have a lag time associated with its response. As a result, during transient operation, too little intake air compression may occur at the beginning of an acceleration, while an excessive boost may remain at the start of the next steady-state operation. In addition, a given turbocharger optimized for high loads may have compromised efficiency at low loads. A variable geometry turbocharger may be used to increase the boost response rate and provide appropriate air/fuel ratios for varying loads and speeds. In one study, with the addition of electronic controls and a variable geometry turbocharger, a heavy-duty diesel engine achieved a 37 percent reduction in HC and a 34 percent reduction in PM emissions without an increase in NOx over a portion of the heavy-duty Federal Test Procedure (HD-FTP).[12]

D. Charge Air Cooling

One negative effect of charge air compression is that the intake air temperature increases substantially. As the intake air heats up, it expands, causing a somewhat lesser amount of charge to be forced into the cylinder. In addition, an increase in charge temperature results in higher NOx formation and engine durability problems. To solve these problems, charge air cooling is used. Charge air cooling results in decreased smoke, HC, NOx, and PM emissions and fuel consumption, especially at high loads where most NOx is created.[13]

Charge air cooling is accomplished with aftercoolers on diesel truck engines. There are two types of aftercoolers, each with unique characteristics: air-to-liquid aftercoolers and air-to-air aftercoolers. The first manufacturers to introduce charge air cooling used air-to-liquid aftercoolers, with the engine coolant as the cooling medium. Air-to-liquid aftercoolers using engine coolant can lower the intake air temperature only to a level near the operating temperature of the engine. However, the temperature of the charged intake air, and thus the level of emission control, remains relatively constant over a wide range of ambient temperatures.

Air-to-air aftercoolers use a stream of outside air flowing through the device to cool the intake air. By using ambient air, an air-to-air aftercooler can cool the compressed intake air to a temperature approaching that of the ambient air. Manufacturers are now extensively using air-to-air aftercoolers, because the more effective cooling contributes to lower NOx emissions. Intake air temperature from an air-to-air aftercooler is highly dependent on ambient temperature. NOx control would, therefore, be most effective in low ambient temperatures. However, unless manufacturers limit the effectiveness of cooling in winter conditions, very low intake air temperatures may lead to increased PM emissions. Converting to an air-to-air aftercooling strategy introduces a moderate cost penalty.

Another possibility for getting more cooling than the conventional air-to-liquid aftercooler is an air-to-liquid aftercooler using a separate coolant system. Such a system would cool intake air temperatures almost as effectively as an air-to-air aftercooler and could reduce seasonal variations in intake air temperature. Introducing a separate liquid system for aftercooling would be more complex and costly than either of the other systems.

E. Advanced Fuel Injection

Emission control in a diesel engine may be improved through advances in fuel injection design. Design variables for a fuel injector include injection pressure, number of nozzle holes, nozzle hole size and shape, and fuel spray angle. In addition, the control of rate of fuel injection adds greater dimension to the design of a low-emission engine.

1. Increased injection pressure

Increased fuel injection pressure achieves better atomization of the fuel droplets and enhances mixing of the fuel with the intake air. This combination of reduced droplet size and improved mixing leads to more complete combustion, decreased unburnt hydrocarbons, and decreased formation of PM. NOx emissions have been observed to increase due to higher cylinder pressures.[14] A drawback of higher injection pressures is the cost involved in reinforcing the fuel injection system and possibly the engine to deal with higher pressures, which might otherwise cause a decrease in durability.

Higher fuel injection pressures also decrease the duration of the injection. Because the duration of injection is shortened with high injection pressures, the start of fuel injection is delayed causing lower combustion temperatures and reduced NOx. Decreasing the duration of injection avoids the HC, PM and fuel economy penalties of retarded injection timing, because the termination of fuel injection is not delayed.[15] Nozzle geometry is used to optimize the fuel spray pattern for a given combustion chamber design, to improve mixing with the intake air, and to minimize fuel condensation on the combustion chamber surfaces.[16]

2. Rate shaping

Manufacturers can achieve greater control of the combustion process by controlling the rate at which fuel is injected throughout the combustion process. This is commonly referred to as rate shaping. Rate shaping may be performed mechanically or electronically through the use of pilot injection or multiple injections.

NOx and PM emissions may be improved by varying the rate at which fuel is injected into the cylinder. A low rate pilot injection may be used at the beginning of combustion to minimize peak temperatures and pressures and to stabilize combustion. Pilot injection shortens the ignition delay, therefore shortening the pre-mixed burning phase of combustion where most NOx is formed. At low loads, NOx, PM, and fuel consumption can be reduced with some penalty in smoke. Particulate formation is reduced due to a reduction of the soluble organic fraction (SOF). At retarded timing, this reduction in SOF outweighs the increase in soot. At advanced timing, the SOF decrease is approximately the same as the soot increase.[17]

Multiple injections may be used to shape the rate of fuel injection into the combustion chamber. Two or three bursts of fuel can come from a single injector during the injection period. The amount of fuel injected during each burst may be varied as well as the duration between bursts. This sort of rate shaping has been shown to be capable of reducing PM without increasing NOx. Because this strategy is most effective in conjunction with retarded timings, NOx can be reduced through timing retard without an increase in PM. Multiple injections can be optimized to have little effect on fuel consumption by controlling the total time from start of the first injection until the end of the last injection.[18]

F. Exhaust Gas Recirculation

1. Hot EGR

Exhaust gas recirculation (EGR) is probably the most important diesel engine control technology for obtaining significant NOx reductions below 1998 levels. Under this approach, a portion of the exhaust gas is routed into the intake manifold. This has the effect of reducing peak temperatures, and thus reducing NOx formation in the cylinder. However, PM emissions and fuel consumption can be increased, especially if EGR is used at high loads. This strategy for NOx control is currently used in most European light-duty diesel engines.[19] At least one heavy-duty diesel engine using EGR will be marketed in the 1996 model year.

EGR reduces NOx by reducing the peak temperature in the combustion chamber. By diluting the charge with inert gas, the adiabatic flame temperature is reduced. This has the opposite effect of increasing oxygen availability during combustion. The recirculated gas also reduces peak combustion temperature by absorbing some of the heat of combustion. This reduction in temperature leads to decreased NOx formation and an increase in HC and PM emissions.[20] At light loads (10-15 percent or less), the potential adverse effects of EGR on fuel consumption, PM level, and engine durability are minimal.

2. EGR cooling

There are several methods of controlling the PM emissions attributed to EGR. One method is to cool the exhaust gas recirculated to the intake manifold. With EGR cooling, a much higher amount of exhaust gas can be added to the intake charge. At light loads, there can be a small NOx penalty due to increased ignition delay, but at high loads, some additional NOx reduction may result from EGR cooling.[21] Another method to offset the negative impacts of EGR on PM is through the use of high intake air boost pressures. By turbocharging the intake air, exhaust gas can be added to the charge without reducing the supply of fresh air into the cylinder.[22]

3. Soot removal in recirculated gas

The main challenge still remaining with EGR in heavy-duty diesel engines is the possible negative effects of soot from the exhaust stream being routed into the inlet stream. Soot may form deposits in the intake system, which could cause wear on the turbocharger or decrease the efficiency of the aftercooler. As the amount of soot in the cylinder increases, so does the amount of soot that will work its way past the piston rings into the lubricating oil. Soot acts as an abrasive in the oil and increases engine wear, especially in the cams. One study showed that 15 percent EGR had a significant effect on heavy-duty engine durability.[23] The EGR fraction is defined as the mass flow rate of the recirculated gas divided by the mass flow rate of the total intake charge.

A low-voltage soot removal device that reduces the soot in the recirculated gas by 50 to 84 percent has been developed. Engine wear was shown to be greatly reduced as a result of this device. Testing was performed at 30 percent EGR.[24] Another strategy for particle-free EGR is to recirculate the exhaust gas after it has passed through a particulate trap. Traps typically can remove more than 90 percent of particulate matter, whereas some designs have achieved a 99 percent particle collection efficiency.[25,26]

One study discusses a technology package designed to solve the problems of minimizing the amount of intake charge displaced by exhaust gas and of fouling of the turbocharger and intercooler.[27] This technology package uses a variable geometry turbocharger, an EGR control valve, and a venturi mixer to introduce the recirculated gas into the inlet stream after the intake air is charged and cooled. The VGT is used to build up pressure in the exhaust stream. Once the pressure is high enough, the EGR control valve is opened and the recirculated gas is mixed in to the high pressure inlet stream in a venturi mixer. Although the recirculated gas is cooled, this cooling is minimal to prevent both fouling in the cooler (due to condensation) and a large pressure drop across the cooler.

Several bypass filtration designs exist to filter smaller particles out of engine oil.[28] With bypass filtration, a portion of the oil is run through a secondary unit which results in well filtered oil. This type of filtration system could be used to minimize negative effects of soot in the oil that is associated with high levels of EGR. At least one of design claims efficiencies of up to 99% in capturing 1-micron particles. Another design is capable of removing water as well as particles less than 1 micron in size. To accelerate vaporization of impurities and to maintain oil viscosity, a heated diffuser plate is used in a third design.

A hybrid EGR system is also being studied as a potential solution to durability problems associated with recirculated diesel exhaust.[29] In this system, a small gasoline engine is used to drive the supercharger for a larger diesel engine. A portion or all of the gasoline engine exhaust can then be fed into the intake stream of the diesel engine. Because of the lack of sulfuric acid and the very low carbon content in the gasoline engine exhaust, the problems of wear and erosion of parts in the diesel engine associated with EGR are alleviated. Another bonus of this system is that the boost pressure is independent of the load and speed of the diesel engine. Therefore, there is more flexibility in optimizing the emissions and fuel consumption of the diesel engine. The study referenced above showed that the hybrid EGR system had about the same fuel consumption as a conventional EGR engine, but with a larger NOx decrease.

G. Technology Combinations

Several manufacturers and institutions have been working on the challenge of achieving further diesel emission reductions by using combinations of the engine-based technologies described above. This section describes the test results obtained from each of these combinations. A summary of the results described in this section is presented in Table 4-1. When comparing the technology combinations in Table 4-1, note that the emission results for any two of the combinations presented are not necessarily determined by the same test cycle. Also note that none of these strategies include the effects of particulate traps or lean NOx catalysts on emissions. As discussed below, aftertreatment devices could result in additional emission reductions.

Table 4-1
Reported Emissions from Various Technology Combinations

Technology Combination (Focus on Engine Controls)	Test Procedure	HC g/bhp-hr	NOx g/bhp-hr	PM g/bhp-hr
Multiple injection and EGR	6 modes	—	3.7	0.11
Fuel injection and geometry	2 modes	—	3.5	0.10
Electronic unit injection, and EGR	17 modes	—	3.6	0.08
On/off cooled EGR and catalyst	transient	—	2.8	0.10
EGR and cooled boost air	1 mode	1.0	1.8	—
Cooled EGR and cooled boost air	3 modes	0.16	1.9	0.22
Cooled EGR and cooled boost air	3 modes	—	2.3	0.12
Cooled EGR and boost air, swirl	3 modes	0.10	1.9	0.13
Mult. inj., EGR, and cooled boost	1 mode	—	2.2	0.07
VGT, cooled EGR, venturi mixer	13-mode	—	1.8	0.08
EGR, rate shaping, and catalyst	transient	2.54 (HC+NOx)		0.13
EGR, optimized fuel and air systems	study	0.30	2.0	0.15[e]

1. Multiple fuel injection and EGR

EGR and several multiple fuel injection strategies were studied by instrumenting a single cylinder version of a heavy-duty on-highway engine.[30] A fuel system was used that was capable of four independent injections at pressures ranging from 2,900 to 17,000 psi. A six mode simulation of the HD-FTP was used for this study since a transient test was considered inconvenient for the research environment. Over the six mode test, using four injections and EGR, the engine produced NOx and PM levels of 3.7 and 0.11 g/bhp-hr, respectively. When operating at 75 percent load and intermediate speed, emissions levels of 1.6 g/bhp-hr NOx and 0.11 g/bhp-hr PM were achieved.

2. Fuel injection and geometry

Effects of fuel injection pressure, rate shaping, timing, nozzle geometry, and spray angle were studied on a single-cylinder diesel engine operating at 75 percent and 25 percent of peak torque at 1600 RPM.[31] At 75 percent load, an intermediate injection pressure was combined with a nozzle

[e]This study reports 0.05 g/bhp-hr PM with the use of a particulate trap.

using sharp-edged orifices and a 125 degree spray angle to achieve NOx and PM levels of 3.5 and 0.05 g/bhp-hr respectively. The fuel consumption was slightly increased (1 to 2 percent) due to the added timing retard used to control NOx. The same nozzle geometry was used at 25 percent load; however, a lower injection pressure was used combined with rate shaping to control the premix burn mode. NOx and PM levels of 3.8 and 0.2 g/bhp-hr were achieved. Note that these low emission levels are without the help of EGR. HC emissions were not measured.

3. Electronic unit injection and EGR

A single cylinder diesel engine with a swept volume of approximately two liters was used as an experimental engine for the purposes of emisssion design work for heavy-duty diesel engines.[32] An off-the-shelf electronic unit injection (EUI) system was modified by increasing the injection pressure from 23,200 to 27,600 psi, reducing the spray holes from 0.20 to 0.18 mm, and opening the spray cone from 155 to 158 angle degrees. The EUI system was designed to respond to electronic control of the injection timing and fuel quantity. Exaust was drawn from the outlet plenum chamber and introduced into the inlet plenum chamber in a simple EGR system. The engine was tested over 17 steady state modes and the results were weighted in order to simulate what the results would be on the HD-FTP. The final weighted results were 3.6 g/bhp-hr NOx and 0.08 g/bhp-hr PM.

4. On/off cooled EGR and oxidation catalyst

A heavy-duty diesel engine was equipped with a simple on/off cooled EGR system and operated over the transient heavy-duty highway Federal Test Procedure (HD-FTP).[33] Over the test cycle EGR was varied from 0 percent at idle to 25 percent during periods of high speed and load. With the addition of an oxidation catalyst, this engine was capable of reducing NOx to 2.8 g/bhp-hr without raising PM above 0.1 g/bhp-hr. HC emissions were not reported.

5. EGR and aftercooled boost air

A single-cylinder diesel engine was equipped with EGR and tested for emissions and fuel consumption for several injection timings and EGR ratios at an intermediate speed.[34] Tests were run using both replaced and additional EGR. Replaced EGR means that the recirculated gas replaces some of the intake air. Additional EGR is achieved by using a supercharger to charge the intake air so that a constant amount of fresh air enters the cylinder at each EGR ratio.

When 33 percent additional EGR was added to the intake charge, the NOx emissions were about 1.8 g/bhp-hr without a significant increase in fuel consumption due to EGR. PM emissions were not reported, but no significant increases in HC or smoke were observed when compared to engine operation without EGR. In addition, further work showed that increased intake boost pressure results in an enhancement of diffusion combustion, reduced ignition delay, and reduced premixed burning.

6. Cooled EGR and intercooled boost air I

In an attempt to develop a low NOx truck engine, cooled EGR was added to a six cylinder, turbocharged and intercooled, diesel, direct injection engine.[35] This engine was tested for emissions and fuel consumption over three modes of the European R-49 13-mode test procedure. The predicted R-49 emission results showed that the engine was capable of NOx emissions as low as 1.9 g/bhp-hr without a significant increase in fuel consumption. PM and HC emissions for this calibration were 0.22 and 0.16 g/bhp-hr respectively.

7. Cooled EGR and intercooled boost air II

Cooled EGR was applied to a heavy-duty diesel engine with engine out emissions meeting the US 1994 emission standards.[36] The exhaust gas was routed downstream of the intercooler to prevent fouling. This engine was tested for NOx and PM at a low, an intermediate, and a high load (at intermediate speed). These modes were selected for their significance in the US HD-FTP. At low load, NOx and PM levels of 2.0 and 0.15 g/bhp-hr were achieved with 30 percent EGR. Medium load NOx and PM levels of 2.3 and 0.12 g/bhp-hr were achieved with about 7 percent EGR. At high load and 5 percent EGR, NOx and PM levels were 2.6 and 0.10 g/bhp-hr respectively. HC results were not reported.

8. Cooled EGR, aftercooled boost air, and swirl optimization

A single-cylinder diesel engine was equipped to have boost pressures and temperatures equivalent to a typical multi-cylinder turbocharged and aftercooled heavy-duty diesel engine.[37] Because the European R-49 13-mode test procedure is biased towards peak torque, the swirl ratio was optimized for high load operation. This study showed that NOx and PM emissions of 1.9 and 0.13 g/bhp-hr respectively, are possible through the use of cooled EGR. At these NOx and PM levels, HC stayed constant at 0.10 g/bhp-hr. Although only three modes of the R-49 were tested, the final results are a projection of the full test. Boost pressures would have had to be increased 10 percent to maintain air-fuel ratios if the EGR were uncooled.

9. Multiple injections, EGR, and intercooled boost air

Emissions and fuel economy testing was performed on a single-cylinder diesel engine at 75 percent of peak torque at 1600 rpm.[38] This engine was equipped with simulated turbocharging and intercooling. Multiple injections were used as an injection rate shaping strategy aimed at controlling the combustion process. The fuel was injected at pressures up to 120 MPa at a spray angle of 125 degrees. Retarded timing and uncooled EGR were also applied to this engine. Through the combination of 6 percent EGR and triple injection, NOx and PM levels of 2.2 and 0.07 g/bhp-hr were achieved. There was some sacrifice in fuel consumption due to the retarded timing. This study suggests that, by controlling the PM levels with multiple injections, engine durability problems associated with EGR (i.e., lubrication oil contamination) may be reduced. HC emissions were not measured.

10. VGT, cooled EGR and a venturi mixer

This study focused not only on significantly reducing NOx and PM from a heavy duty diesel engine but also on developing an EGR system that would be practical for real world use.[39] The engine used for this research was a six cylinder, turbocharged and intercooled engine with a rated power of 420 hp. The main emission control used in this research was EGR. However, the paper really focuses on how the EGR is applied.

Several difficulties were overcome. To avoid fouling of the turbocharger and intercooler, and to minimize the mass of air displaced through EGR, the exhaust gas is recirculated downstream of the intake air charging and cooling. This is accomplished through the use of a variable geometry turbocharger and a venturi mixing unit. By closing the VGT, pressure builds up in the exhaust gas; through the use of an EGR valve the exhaust gas can be released to the intake stream once the pressure is high enough. The mixing venturi provides suction of the recirculated gas thus minimizing the pressure loss in the EGR circuit. Some EGR cooling was performed, but this was minimized to prevent fouling of the EGR cooler (through condensation) and to minimize the pressure loss in the EGR circuit.

Final emission results were reported as 1.8 g/bhp-hr NOx and 0.08 g/bhp-hr PM. These results are based on the 13-mode steady-state test procedure used for European emission standards (ECE R49).

11. EGR, rate shaping, and catalyst

One heavy-duty diesel engine manufacturer presented intial results from a program which has the goal of building a diesel engine that can achieve the 2004 emission levels finalized today using current technology.[40] The technical approach was as follows: 1) advanced fuel system with rate shaping capability, 2) state of the art combustion system with EGR, 3) electronically modulated air flow management with improved volumetric efficiency, 4) reduced mechanical parasitic, 5) calibration optimization, and 6) a 1994 model year catalytic convertor. The results at this stage of the program are 2.54 g/bhp-hr HC+NOx and 0.126 g/bhp-hr PM. These results are based on the HD-FTP using low sulfur fuel designed for use in California.

12. EGR with optimized fuel and air systems

A study of feasible NOx and PM levels from heavy-duty diesel engines was contracted by the California Air Resources Board (CARB).[41] This study concluded that, with the application of EGR to a 1994 production heavy-duty diesel engine and an optimization of fuel and air systems, emission levels can be reduced significantly. Emission levels of 2.0 g/bhp-hr NOx and 0.15 g/bhp-hr PM were reported to be feasible without a significant increase in HC (<0.3 g/bhp-hr) or fuel consumption. Through the use of aftertreatment, the particulate emissions could be reduced to 0.05 g/bhp-hr.

H. Crankcase Emission Control

When ignition occurs inside the combustion chamber in internal combustion engines, the increase in cylinder pressure pushes a small amount of gases past the piston rings (blowby) and into the crankcase. To prevent the crankcase from becoming pressurized, the gases must be vented from the crankcase. A regulation requiring manufacturers to close the crankcase (preventing these gases from being vented to the atmosphere) was the first measure used for reducing pollution from cars and trucks in the U.S. In 1963, California adopted a resolution requiring closed crankcases in all light-duty vehicles. Later, manufacturers installed crankcase emission control devices in all light-duty vehicles and trucks to be sold in the U.S. A method known as a positive crankcase ventilation (PCV) was used to recirculate blowby gases back to the intake manifold and control their flow through the use of a valve. The most common PCV system used is one in which the air from the crankcase is drawn through a hose from the air cleaner to one of the valve covers or to a crankcase inlet below the intake manifold.[42] Therefore, the blowby gases are reintroduced into the cylinder. Closed crankcases using PCV systems have been used in gasoline vehicles since the late 1960s and are also required in today's naturally aspirated diesel engines.[43]

Few studies have been conducted with the purpose of investigating crankcase emissions from heavy-duty diesel engines. Table 4-2 summarizes crankcase emission data from one study where three engines were tested:[44]

Table 4-2
Crankcase Emission Data

Pollutant	Crankcase Emission Levels (g/bhp-hr)	Percent of Corresponding Exhaust Emissions	Percent of 2004 Standard Finalized Today[f]
HC	0.005 - 0.013	0.2 - 4.1	1.0 - 2.6
NOx	0.001 - 0.009	0.01 - 0.1	0.05 - 0.45
PM	—	0.9 - 2.9	—

A more recent study done by Southwest Research Institute in 1993 provided similar crankcase emission data from one heavy-duty diesel engine: 0.01 g/bhp-hr NOx, 0.01 g/bhp-hr HC, and 0.01 g/bhp-hr PM.[45] Even though these numbers might not appear very significant, one has to take into consideration that crankcase emissions increase with engine life, which today, with proper maintenance, can approach one million miles before rebuilding for line-haul trucks.[46] None of the engines reported had more than 500,000 miles. Presently EPA is conducting testing on a few heavy-duty diesel engines to obtain more crankcase emission data.

Currently, turbocharged diesel engines are not required to provide crankcase emission controls. The problem with recirculating blowby gases in turbocharged engines is that the durability of turbocharger components and aftercooler effectiveness can be affected by the recycling of gases

[f]For simplicity, standards were assumed to be 2.0 g/bhp-hr for NOx and 0.5 g/bhp-hr for HC.

that contain particulate matter and other potentially damaging particles. Routing gases to the intake manifold after the compressor would require a pump due to the higher pressure there. One solution to this problem has been applied to a new heavy-duty diesel engine. The 1994 Navistar T444E had a closed crankcase in which the gases were recirculated to the intake manifold and a woven wire element was installed in order to collect the oil and prevent it from reaching the turbocharger compressor. According to Navistar, durability test data showed no deterioration of the turbocharger as a result of the recirculation of crankcase gases.[47] Other studies have shown the possible connection of increased blowby gases with the presence of EGR in diesel engines.[48] Although not conclusive, the results might suggest that the increase in crankcase gases are due to higher wear of the piston rings, likely caused by abrasive particles present in the recirculated gases.

Though still undergoing development, another method of separating particulate matter from the crankcase gases going through the turbocharger is the inertial separator. Inertial separators centrifuge particles to a collecting zone, drain them to the bottom and collect them in a reservoir.[49] One problem with this option is its low separation efficiency of around seven percent. Other filtering methods are also being studied, but none of them seem to be more efficient and economical than the PCV system with a filtering element to remove the particulate. One concern, however, has to do with the efficiency of the filter as the particulate accumulates and any required maintenance to replace it.

III. Aftertreatment

As described in the introduction section, engine manufacturers have been very successful in developing a mix of technologies to lower PM and NOx concurrently while continuing to improve fuel economy and engine durability. Although EPA is not proposing a reduction in the highway heavy-duty engine PM standard beyond the level of 0.10 g/bhp-hr (0.05 g/bhp-hr for urban buses), PM control will continue to be very important. PM will remain a primary consideration along with fuel economy and engine durability in the development of engines with lower NOx emissions. As discussed above, HC emissions control has not been a primary focus for diesel engines due to their relatively low HC emissions levels. With a NOx plus NMHC standard, HC emissions levels would become a greater consideration in the packaging of technologies to meet overall emission targets. Exhaust aftertreatment technologies for PM and NOx control are discussed in this section and any effect of these technologies on HC is also noted.

A. Particulate Matter Control

Two aftertreatment technologies have received the most attention and use for particulate control, the flow-through oxidation catalyst and the particulate trap. The oxidation catalyst provides relatively moderate overall PM reductions by oxidizing a portion of the particulate as the exhaust passes through it. Oxidation catalysts are relatively inexpensive and are now being used by engine manufacturers on some engines to meet the current 0.10 g/bhp-hr PM standard (0.05 for urban buses).

Particulate traps capture a very high percentage of the particulate and hold it until the PM can be removed. Removing the PM from the trap, termed trap regeneration, is most often accomplished by oxidizing (i.e., burning) the PM. Because diesel exhaust almost never reaches the high temperatures needed to ignite the PM, oxidation requires either an external heat source or a catalyst material to lower the oxidation temperature of the PM. Particulate traps have not gained wide acceptance and use due to several concerns that have not yet been overcome, including high cost, system complexity, fuel economy penalty, and trap durability. Also, engine manufacturers have not needed the very high level of PM control provided by traps to meet current standards. Although initial trap designs, with regeneration, may be too complex, second generation designs are being pursued.

1. Oxidation catalyst

As mentioned above, engine manufacturers have started to use oxidation catalysts in cases where engines have needed help meeting the particulate standards. For the 1994 model year, about 30 percent of engine families certified were equipped with oxidation catalysts (with the exception of urban buses, all of these were either light or medium HDDEs). Another 30 percent of the engine families were certified to PM levels above the 0.10 g/bhp-hr standard through the averaging, banking and trading program. As these families are redesigned or retired, the percentage of engine families equipped with oxidation catalysts may change.

Flow-through oxidation catalysts oxidize both gaseous hydrocarbons and the portion of PM known as the soluble organic fraction (SOF). The SOF consists of hydrocarbons adsorbed to the carbonaceous solid particles and may also include hydrocarbons that have condensed into droplets of liquid.[50] The carbon portion of the PM remains essentially unaffected by the catalyst. In recent years, SOF has been reduced through new piston ring designs for oil control and fuel injection and combustion chamber modifications for more complete combustion of the fuel. The amount of SOF varies widely among engines but SOF often makes up 30 to 60 percent of the total mass of PM. Catalyst efficiency for SOF varies with exhaust temperature in the range of about 50 percent conversion at 150°C to more than 90 percent above 350°C.[51] Typically, exhaust temperatures during the HD-FTP fluctuate between 100°C and 400°C. The reduction in total particulate mass provided by catalysts is relatively modest both because the efficiency is low at low exhaust temperatures and because catalysts oxidize only the SOF and not the carbon portion of the PM.

Improvements in catalyst technology have been hindered to some degree by sulfur contained in the fuel, even with the low sulfur fuel currently required by EPA. Especially at higher exhaust temperatures, catalysts oxidize sulfur dioxide to form sulfates, which contribute to total PM emissions. Catalyst manufacturers have been successful at developing catalyst formulations that minimize sulfate formation.[52] Catalyst manufacturers have also compromised in the placement of the catalyst such that the exhaust is warm enough to achieve the needed SOF reduction but not so warm as to cause substantial sulfate formation.[53] Manufacturers have noted that fuel with sulfur concentrations lower than 0.05 weight percent would permit the use of more active, higher efficiency oxidation catalysts.

Oxidation catalyst development and use is likely to continue. Although it is still too early to know exactly what combinations of technologies will be used to meet the 1998 standards of

4.0 g/bhp-hr NOx and 0.10 g/bhp-hr PM it is very likely that oxidation catalysts will be used at least in some cases. Urban buses are also likely to meet their PM standard of 0.05 g/bhp-hr using in-cylinder modifications and oxidation catalysts. Future improvements in oxidation catalysts will likely provide marginal improvements in overall PM reductions and such refinements may prove to be valuable to engine manufacturers.

2. Particulate trap

The promise of particulate reductions of greater than 90 percent and the 1994 and later PM standard of 0.10 g/bhp-hr prompted the development of particulate trap technology in the late 1980s. Particulate trap filters that capture a high percentage of the PM in the exhaust stream were developed. These initial particulate trap filters needed to be regenerated (cleaned) after a period of time because the filters eventually began to fill up, creating unacceptable backpressure on the engine. For the first generation of trap systems, regeneration was often accomplished by heating the exhaust with an electric heater or fuel burner to oxidize the particulate. The Donaldson Company led U.S. trap system development with an electronically controlled system consisting of dual ceramic monolith filters and electrical heating elements to regenerate the trap. In the 1992 and 1993 model years, some urban bus engines equipped with the Donaldson system were EPA-certified and sold in limited numbers. Engine manufacturers have been able to meet the 1994 particulate standards with engine modifications and using oxidation catalysts where necessary and no trap-equipped engines were certified for the 1994 model year.

Several companies and universities are developing a new generation of trap technologies have the potential to be simpler, more reliable, and less expensive than previous systems. The majority of research and development is focused on devising new methods for trap regeneration. A number of active and passive trap regeneration methods are in various stages of development and testing.

Active regeneration generally involves the triggering of a trap regeneration mechanism at fairly regular intervals based on an exhaust backpressure threshold for the engine. One example of a newer approach for active regeneration is reverse pulse air regeneration, which uses compressed air to blow PM out of the trap and into a separate container.[54] The PM can then be burned by heating the container either on or off the vehicle. By blowing out the trap rather than burning the PM within the filter, the filter is not subjected to extreme temperature gradients that can lead to ceramic filter melting or cracking. As part of the Department of Energy programs described previously, Cummins Engine Company is working on a microwave trap regeneration system that provides more uniform heating of the trap core, avoiding extreme temperature gradients.[55] The system uses a ceramic paper core that is about 80 percent efficient. Cummins also reported that engine backpressure was below target.

Many regeneration techniques being researched involve using catalyst materials that lower the PM oxidation temperature to the range normally experienced in diesel exhaust. The addition of a catalyst often provides HC reductions as well. Such systems are often called passive regeneration systems because they do not require some action to take place for regeneration at regular intervals, such as heating the PM or blowing the PM out of the trap. Instead, regeneration occurs somewhat continuously depending on the exhaust gas temperature. Catalysts both in the form of coatings and fuel additives are being developed. Johnson-Matthey has developed a system that places a catalyst at the inlet facing of the trap filter such that the exhaust flows though the catalyst before entering the filter. This system is currently being field tested.[56] The catalyst will oxidize sulfur and Johnson-Matthey is requiring the use of fuel with a sulfur level much lower than EPA specifications. Fuel additives including a cerium-oxide additive developed by Rhone-Poulenc and a copper-oxide additive developed by Lubrizol Corporation also lower PM ignition temperatures.

Catalyst materials bring down the temperatures needed for oxidation, but still may be challenged to reach the very low exhaust temperatures of diesel engines, which have been further reduced by the use of air-to-air aftercooling. For systems using catalysts, it will be necessary to optimize the system for the specific engine application under real world operating conditions. For example, it would be important to know what percentage of the time the vehicles' exhaust temperature will exceed the ignition temperature of the PM in the presence of the catalyst. If the temperature remains lower than the PM ignition temperature for long periods of time, say during idle and low load conditions, the PM will continue to accumulate in the trap. When ignition temperature is reached, there may be too much PM in the trap, causing overheating and trap filter damage. It may be necessary to have a back-up active regeneration system in some cases.

In addition to trap regeneration, trap filters continue to be an area of significant research. Research is focused on developing more durable filter materials that can withstand the very high temperatures experienced during some forms of trap regeneration. Examples of these filter materials include glass fiber pads sandwiched between wire mesh for support, porous and corrosion resistant metal fibers, and silicon carbide. Filter development is also focused on reducing the amount of exhaust backpressure and associated fuel economy loss caused by the trap. Additionally, there are problems with ash in the exhaust stream, which the trap captures along with the particulate matter. The ash does not oxidize during trap regeneration and over time builds up within the trap. Eventually, the filter must be cleaned or replaced.

In the long term, traps may be among the mix of technologies considered by engine manufacturers in meeting future standards, if a simple, relatively inexpensive system can be proven effective and durable. For example, some researchers are exploring passing the exhaust through a particulate trap before routing it through an EGR system.[57] Passing the exhaust through the trap could potentially address a critical problem with the use of EGR, namely oil contamination and engine wear due to particulates being introduced into the combustion chamber. It may also take care of any PM increase caused by the use of EGR, which may allow EGR to be used more aggressively for NOx control (i.e., at higher rates or higher engine load conditions). Traps are likely to be more practical for use with lighter engines, which have shorter lives, and with urban bus engines used in fleets, due to special maintenance and durability considerations such as the potential need for filter cleaning or replacement.

B. Oxides of Nitrogen Control

A few years ago, lean NOx catalytic converters for vehicles were a novelty and largely impractical as a serious means of reducing NOx from diesel engine exhaust due to the difficulties of reducing NOx in the oxygen rich exhaust environment, the transient nature of engine operation, and the difficulties of introducing a reducing agent into the exhaust. The effective NOx reduction results that have been obtained with stationary sources using commercial catalysts and ammonia or urea as reductants are difficult to duplicate on mobile sources. Remarkable progress has been made recently in the area of lean NOx reduction catalysts for mobile sources that use hydrocarbons as the NOx reducing agent. The catalysts developed to date operate within narrow temperature ranges, which limits their overall effectiveness because diesel exhaust temperature fluctuates over a wide range during the transient operation of the engines. It may be possible to use multiple catalysts to cover a broader range of vehicle operation thus providing better overall NOx control. Also, catalyst manufacturers are working to develop catalysts that are effective over a broader temperature range. Finally, closed-loop electronic control of the engine may be used to narrow the variations in the exhaust to the catalyst.

The use of hydrocarbons as a reducing agent presents special challenges to the catalyst and engine manufacturers. As with other catalysts, some lean NOx catalysts also have the ability to reduce HC emissions depending on catalyst formulations and exhaust temperatures. It would be important to ensure that the hydrocarbons are being oxidized by the catalyst and not passing through, which may require careful monitoring of the timing and amount of HC being added. The systems also must be optimized to reduce the fuel economy penalties associated with their use due the critical importance of fuel economy to the trucking industry and other affected industries.

1. High temperature NOx catalyst

Until recently, the state-of-the-art lean NOx catalyst was a copper (Cu) catalyst supported on a zeolite base with hydrocarbons injected or added. The Cu-zeolite is usually active at temperatures above 350°C for both NOx and HC emission reductions.[58] NOx reductions of about 15-30 percent between 350°C and 550°C have been achieved with Cu-zeolite catalysts.[59,60]

There are some significant problems to overcome with the Cu-zeolite catalyst. The Cu-zeolite system performance degrades significantly after being exposed to very high temperatures in the presence of steam.[61] Another problem encountered over time is sintering, which reduces the surface area of the catalytically active material. Sintering is when a mass of metal particles are shaped and partially fused by temperature and pressure below the melting point. The Cu-zeolite system aged relatively quickly, making it impractical for mobile diesel sources. As recently as several years ago, lean NOx catalysts, including the Cu-zeolite, did not remain significantly active for longer than a few hours.[62,63,64] Additionally, the types of hydrocarbons that work well as a reducing agent are limited (i.e., low hydrocarbon selectivity), which translates into the need for the injection of more diesel fuel to get sizeable NOx reductions. Hydrocarbons such as propylene, ethylene, butane, methane, propane, n-hexane, kerosene, and diesel fuel have been investigated as reductants.[65,66,67] Hydrocarbons with low molecular weight and high volatility such as olefins or oxygenates have been shown to be most active for lean NOx reduction.[68] Improvements in selectivity allowing diesel fuel to be used more completely to reduce NOx would reduce the fuel economy penalty associated with the systems and may also improve efficiency.

Solving the durability and hydrocarbon selectivity problems are at the heart of world-wide research efforts. Recent studies have made strides in improving the durability of high temperature lean NOx catalysts.[69,70] New zeolite-based catalysts compare favorably with the previous Cu-zeolites in terms of activity and durability.[71] Studies using Cu-zeolite systems as recent as 1993 had achieved only about 50 hours of design durability with serious activity reduction at 125 hours.[72] The new zeolite-based catalysts retained a 25-40 percent NOx reduction activity from 425-550°C after 500 hours (equivalent to about 20,000 miles), which is only slightly less active than the same catalyst type aged 125 hours.[73]

Furthermore, in testing to determine the mode of deactivation of the new zeolite-based catalysts, tests indicated that the zeolite crystallinity after diesel aging indicated good stability of the zeolite's physical structure. Based on postmortem tests, it appears that most, if not all, of the deactivation of the diesel aged materials resulted from sulfur poisoning in the diesel exhaust (rather than the steam). Therefore it appears that using very low sulfur diesel fuel (i.e., Swedish City Diesel - 25 ppm sulfur) could extend the life of current catalysts beyond the 500 hour range.[74,75,76]

2. Low temperature NOx catalyst

Recent catalytic systems have shown high activity at lower temperatures through the use of platinum based (Pt/Al_2O_3) catalysts. These catalysts are quite active in the 200-300°C range for NOx reduction though the product is mostly N_2O (ca. 50-90 percent), a known greenhouse gas.[77] These types of catalysts can also provide HC and particulate (SOF) control. NOx reductions of 15 percent were achieved in the European light duty test cycle, along with a 35 percent PM reduction.[78,79]

The main areas of concern with the low temperature catalysts are durability, very high sulfate production, high N_2O production, and low HC selectivity. Durability of Pt based catalysts is improving, however, with one study reporting 89 percent reductive retention after 650 hours. This study also reported that with the Pt based catalyst, 45 percent NOx reduction was achieved at 210°C; furthermore, they retained 90 percent of this benefit from 192-229°C.[80]

3. NOx trap

Engelhard Corporation is working on NOx traps that could be used in addition to low or high temperature NOx catalysts.[81] The NOx trap absorbs NOx and holds it until the trap temperature exceeds a certain point, at which time the trap releases the NOx. The trap would be particularly useful for reducing NOx emitted during idle or low-speed load conditions where temperatures are less than 100°C and catalysts are not operational. The temperature at which the NOx is released varies depending on the trap material, which allows the trap to be designed for use with either a low or a high temperature catalyst.[82] One strategy for engines with a fair amount of operation at high exhaust temperatures would be to use the trap in combination with a high temperature catalyst.

IV. Developmental Technology

Researchers continue to develop many creative strategies for reducing emissions and improving performance of heavy-duty engines. This section discusses several emission control strategies that are currently being researched. These strategies are discussed separately because EPA believes that the 2004 emission standards finalized today may be met through the more conventional methods described above. However, this does not imply that the following technologies will not be feasible in the 2004 time frame. Unless otherwise stated, the following technologies could apply to diesel or gasoline engines.

A. Water Injection

Water injection may be used in much in the same way as EGR for diluting the intake charge. Water has a high heat capacity, which allows it to absorb enough of the energy in the cylinder to reduce peak combustion temperatures. Testing on a diesel engine has shown a 40 percent reduction in NOx with a water-fuel ratio of 0.5 with only a slight increase in smoke.[83] Water dilution does have significant challenges, however. Water condensation at low loads may result in rust and dilution of lubrication oil, and dissolved impurities in the water may lead to deposits in the engine. Additives would have to be added to the water to prevent freezing in cold weather. Finally, the vehicle operator may not have any incentive to keep a water reservoir filled.

B. Ceramics

Manufacturers and suppliers are researching the possibility of adding ceramic materials to the surfaces of the combustion chamber and particulate filters. Ceramic coatings may provide effective insulation, allowing the engine to retain more energy in the products of combustion. Retaining more energy in the combustion chamber increases peak combustion temperatures, resulting in decreased PM emissions and possibly increased NOx emissions. Also, a greater portion of the total energy contained in the fuel can be converted into useful work in the engine, improving the engine's fuel efficiency. When combined with other modifications such as retarded injection timing and reduced fueling rate, the use of ceramics can result in reduced NOx emissions without a loss in fuel efficiency. Expected costs for the use of ceramics would be moderate.

C. Hybrid Vehicle Designs

A hybrid vehicle uses an energy storage device as an aid to the engine. Through the use of an energy storage device in the drive train of a heavy-duty vehicle, equivalent NOx emission levels of 1-2 g/bhp-hr may be met with a 10 percent improvement in fuel economy.[84] These benefits are achieved in three ways. First, a smaller engine can be used to perform the same work. The engine would charge the storage device during low load conditions. Energy in the storage device could then be used to help the engine move the vehicle through high-load conditions. Second, the engine could be optimized for operation at steady state. Energy to and from the storage device would be used to meet the transient demands of the vehicle. Third, regenerative braking could be used to store energy normally lost during braking.

Several types of storage devices have been investigated. Energy may be stored as momentum in a high speed flywheel, as electricity in batteries, or as pressure in a hydraulic accumulator.

Flywheels may be the most promising option at this time. Battery technology has not yet developed to the point where light batteries could be developed to last throughout a heavy-duty vehicle operating life. Hydraulic accumulators are large and heavy and raise potential safety risks due to high-pressure oil lines.

D. Plasma Catalysts

Research is being conducted into plasma catalysts for heavy-duty diesel engines. Plasma catalysts use discharges of electricity, or extreme heat, to break both PM and NOx into their atomic constituents. While this area of research shows promise for the future, it may not be a viable alternative for the 2004 time frame.[85] Due to its potentially extreme effectiveness, however, EPA encourages continued work to realize viable plasma devices.

V. Fuels

The focus of this chapter has been on the technical feasibility of emission reductions from heavy-duty diesel-cycle internal combustion engines. However, we should keep in mind that there are potential benefits form changes in diesel fuel and there are alternatives to diesel fuel for heavy-duty diesel-cycle internal combustion engines. In addition, there are alternatives to internal combustion engines for heavy-duty vehicle applications. This section discusses some alternative fuels and power sources that may be used in heavy-duty engines and vehicles in the future.

A. Diesel Fuel Quality

Starting on October 1, 1993, new EPA requirements affecting highway diesel fuel quality went into effect.[86] First, the sulfur level of diesel fuel was reduced to 0.05 weight percent. In addition, diesel fuel must have either a minimum cetane of 40 or a maximum aromatics content of 35 volume percent. (CARB implemented separate requirements that apply to all diesel fuel sold in California. California's sulfur limit is the same as the federal requirement; however, California has different requirements for aromatics and cetane.) The main reason for implementing the federal diesel fuel requirements was to allow the use of technologies on new engines that would not otherwise be feasible, such as oxidation catalysts and trap oxidizers. EPA also noted that there would be small decreases in PM, HC, and CO emissions from existing heavy-duty vehicles as a result of the fuel changes.[87]

A number of test programs have examined the effects of various diesel fuel properties, including sulfur, cetane level and aromatics content, among others, on heavy-duty diesel engine emissions.[88,89,90,91] The results of these test programs show that changes in the properties of diesel fuel can have an effect on emissions. In recognition of this fact, the SOP acknowledged that changes in the composition and improvements in the quality of fuel may be needed to make the standards expected under the SOP feasible. EPA plans to work with the petroleum industry and engine manufacturers to determine if further testing is needed. Based on the results of the evaluation, EPA expects to make a decision as to whether further changes in diesel fuel quality will be necessary to comply with the low NOx and NMHC standards as part of the 1999 technology review agreed to in the SOP. If EPA determines that further fuel changes are necessary, EPA would proceed with a separate fuels rulemaking to implement such changes.

B. Alternative Fuels

Diesel and gasoline are the predominant fuels used in internal combustion engines today. However, engines have been developed and are in use that operate on alternative fuels such as natural gas or alcohol. Many of these engines can operate on more than one fuel or fuel blend. Although gaseous and alcohol fuels are not the only alternative fuels being researched, they show the most promise for the near future.

1. Gaseous fuels

Several manufacturers are already producing compressed natural gas (CNG) and/or liquified natural gas (LNG) heavy-duty engines for applications that traditionally called for diesel engines. Detroit Diesel Corporation makes the DDC Series 50G, which is already being commercially used in approximately 200 vehicles, mainly urban buses. The Series 50G is now being testing in other heavy-duty vehicle applications. It has recently been installed in a Kenworth tractor for testing, as well as in refuse packers in California and York City.[92]

About 600 gaseous-fueled Cummins L-10 engines have been sold in 44 different locations in the United States. They are used mainly in urban buses (Spokane, Wa. has logged 2 million miles on L-10 buses; Sacramento, California has 100 L-10s used in buses). Many of the L-10s run on CNG. Cummins has recently installed ten of their new L-11 LNG engines in United Postal Service and Overnight Express tractors for on-the-road testing. These engines currently rate at about 330 hp with 900 to 1000 ft-lbs torque. Cummins also has a new, undesignated LNG engine in the greater than 400 bhp range being tested in two refuse packers in Santa Barbara.[93]

Hercules makes two natural gas engines with displacements of 3.7L and 5.6L. The 5.6L, which is a turbocharged aftercooled engine, is suitable for heavy-duty vehicle applications. Over 400 of these engines have been sold, mostly to urban bus and school bus manufacturers.[94]

One study was performed on a 220 hp natural gas engine using the 13-mode ECE R49 steady-state test.[95] This engine was equipped with a three-way catalyst and an electronically controlled carburettor. Over the steady-state test, emission results of 0.07g/bhp-hr HC, 0.15 g/bhp-hr CO, 0.75 g/bhp-hr NOx, 0.04 g/bhp-hr PM were reported. During a transient "real bus cycle," HC, CO, and NOx were considerably higher. This was probably due to an exhaust mixture that was too lean for peak catalytic conversion efficiency. The authors stated that this could be overcome with an optimization of the mixture formation system's dynamic characteristics.

As can be seen, a variety of heavy-duty natural gas engines are already commercially available in many different load configurations. Emission levels from gaseous fueled engines are typically around 2.0 g/bhp-hr NOx and 0.01 g/bhp-hr PM. Because hydrocarbon emissions from natural gas vehicles are primarily methane, reactive hydrocarbon levels in the exhaust are very low. Further development is expected to further reduce NOx and PM emissions from these engines.

2. Alcohols

The purpose of this section is to present alcohols as another alternative for reducing emissions from mobile sources. The brief discussion below is only a glimpse of the technological issues that alcohols raise. More complete studies can be found in the reference section of this chapter.

For many years, alcohols have been known as potential transportation fuels. This interest has resurfaced recently due to the advantages that alcohols offer in terms of reduced pollution and increased efficiency. In addition, the desire to lessen dependency on oil imports has also helped facilitate technological and economical research on this subject. Some of the technological problems mentioned below with using alcohol fuels can be overcome with proper design optimization and materials selection. Today ethanol is added in small amounts (10 percent ethanol, 90 percent gasoline) in 7.5 percent of the gasoline used in the U.S. Methanol, however, is used simply as a gasoline blending agent. Table 4-3 shows some of the important chemical properties for gasoline, diesel, ethanol and methanol; and it helps understand the advantages and disadvantages discussed below.[96]

Table 4-3
Fuel Properties

Fuel	Heating Value [MJ/kg]	Reid Vap. Pres. 100°F [psi]	Stoichiometric A/F ratio	Octane (research)
Gasoline	43.5	7-13	14.6	91-100
No. 2 Diesel	43	0.04	14.6	N/A
Ethanol	27	2.5	9	111
Methanol	20.1	4.6	6.4	112

a. Ethanol

Most of the ethanol produced in the U.S. comes from the wet or dry-milling of corn. Ethanol has a high octane number, which, in addition to helping to reduce knocking, allows the use of higher compression ratios and results in higher thermal efficiencies. Its lower vapor pressure, when compared to gasoline, helps produce less evaporative emissions (may not be true for all ethanol-gasoline blends), but increases cold starting difficulties. Environmentally, neat ethanol has some advantages over gasoline. Emission studies have reported an insignificant production of benzene and carcinogenic substances such as 1,3 butadiene and polycyclic organic matter (POM). Furthermore, carbon dioxide production, in grams per mile, can be reduced as much as 22 percent by using 100 percent ethanol.[97] The combustion of ethanol occurs at smaller air-to-fuel ratios, which, combined with lower flame temperature, helps reduce NOx and CO. However, the use of higher compression ratios could negate these benefits by increasing these emissions. Although aldehyde formation is always a concern when using alcohol fuels, the formation of formaldehyde in ethanol-fueled engines is not as high as in methanol-fueled engines. However, acetaldehyde formation is a concern from ethanol-fueled vehicles prior to the catalyst being heated to its operating temperature.

Some technological difficulties need to be addressed before ethanol can be used efficiently as a transportation fuel. First, because it has just 67 percent the energy content of gasoline, ethanol gives less miles per gallon than both gasoline and diesel fuels. In addition, cold starting can be specially difficult in compression-ignition engines due to ethanol's low cetane number.[98]

Currently, the best example of wide use of ethanol is in Brazil, where 60 percent of the vehicles use a 78 percent gasoline, 22 percent ethanol blend; and the other 40 percent uses a neat thanol blend (95 percent ethanol, 5 percent water).[99] In the U.S. ethanol blends (85 percent ethanol, 15 percent gasoline) are scarcely available in the upper Midwest, Washington, D.C., and California. Today about 400 vehicles fueled with these blends are used.[100]

b. Methanol

Methanol is another alcohol used as an alternative fuel. Methanol's high octane number, like ethanol's, would allow engineers to design an engine with a higher compression ratio and thus greater efficiency. Methanol does not produce significant amounts of air toxics when compared to gasoline-fueled vehicles, but CO_2 and HC can be much higher than diesel fuels. The use of methanol fuel could help reduce NOx and PM emissions, as evidenced by recent studies.[101]

Methanol does have some technical difficulties. Aldehyde formation is a concern because of the relatively high levels of formaldehyde found during the combustion of methanol. Other problems with using methanol are its low heating value, its invisible flame and toxicity. Methanol fuel contains less energy per unit mass than ethanol, gasoline and diesel.[102] However this disadvantage can be reversed by designing a smaller and lighter engine, with a higher compression ratio, with similar efficiency and capable of providing more miles per gallon. During combustion methanol gives off an invisible flame that can be a major safety issue; but it can be solved by using additives that will make the flame visible or through the use fire-suppression equipment. Also, corrosion-resistant materials are necessary in the fuel system design.

Presently, methanol fueled vehicles are available in the U.S. Two car manufacturers are offering flexible-fueled vehicles capable of using a variety of methanol blends (up to 85 percent methanol, 15 percent gasoline). Moreover, one heavy-duty diesel engine manufacturer has made available a model capable of using 100 percent methanol fuel.[103]

C. Alternative Power Sources

Vehicles that produce essentially no ground level exhaust and evaporative emissions during operation are known as Zero Emission Vehicles (ZEV). Although the internal combustion engine is presently the most practical power source for a heavy-duty vehicle, it cannot meet zero emissions.

Two ZEV designs that have been investigated for heavy-duty applications are vehicles powered by electric batteries and by fuel cells. ZEVs have emissions associated with their power source (i.e. power station for electric vehicle); however, these emissions may be generally lower than an internal combustion engine for the same work and are often produced outside of urban areas.

1. Electric vehicles

Another possible power source for heavy-duty vehicles is the electric vehicle concept. Electric vehicles use rechargeable batteries to drive an electric motor that powers the vehicle. Power normally lost to braking is usually collected, and routed back to the battery, by using a generator load to slow the vehicle. Although many types of batteries are being developed, only lead-acid and nickel-cadmium (Ni-Cd) batteries are commercially available at this time. Nickel-iron (Ni-Fe) batteries should be available in the near term. A lead-acid battery is capable of about 500 charges (one per day) with a peak power output 180 W/kg, an energy density of 36 W-hr/kg, and a cost of under $150/kW-hr. The Advanced Battery Consortium is targeting a battery design capable of operating 50-100,000 miles with a peak power output of 150-300 kW, an energy density of 100-200 W-hr/kg, and a cost of $100-150/kW-hr.[104] The main limitations on electric vehicles are the high costs and weight and the short lives of today's battery designs.

Several programs are underway to bring electric vehicles to the market. To help combat the severe pollution problem in Mexico City, one university is developing a 30-person shuttle bus design that will operate wholly on batteries.[105] In California, several electric buses are already in use. These buses were developed under a program started in 1992 by the Federal Transit Administration. Even when power plant emissions are considered in southern California, these vehicles are 90 to 97 percent cleaner than diesel-fueled buses and 50 percent cleaner than alternative-fueled buses. In this case, most of the electricity is generated from natural gas or hydro-electric power plants. Energy consumption costs for electric buses are estimated at 5 to 6 cents a mile, which is much lower than the estimated 10 to 12 cents a mile for diesel-fueled buses.[106]

2. Fuel cells

A fuel cell is a power plant that consumes hydrogen through a reaction with air and converts the chemical energy directly to electrical energy. Hydrogen can be carried on-board the vehicle or derived from other fuels such as natural gas, alcohols, or other hydrocarbon fuels. Because fuel cells are not subject to the heat loss inefficiencies associated with internal combustion engines, they are about twice as energy efficient as internal combustion engines. Fuel cells remove energy from the fuel without chemical combustion; therefore, they are much cleaner than internal combustion engines. In addition, fuel cell systems are relatively quiet power plants because they have only a few moving parts.[107]

The capability of a fuel cell to provide the sole source of electric power for a ZEV bus was demonstrated in 1993. This system used a proton exchange membrane and was fueled with compressed hydrogen gas. Hydrogen was used in the fuel cell because it is the only fuel that can be used in a fuel cell with zero emissions. (Hydrogen burned in an internal combustion engine would still produce some NOx).[108] Even with a fuel cell powered by methanol, CO and NOx emissions are on the order of 30 times lower than the 1998 Federal emission standards. For a methanol fueled application, a reformer reacts methanol with water to produce hydrogen. The hydrogen is used for the anode in a phosphoric acid fuel cell.[109]

VI. Conclusion

This chapter identifies technologies that can be used to achieve at least 2.4 g/bhp-hr NMHC plus NOx levels by 2004 from heavy-duty diesel engines while still meeting the applicable PM standard of 0.1 g/bhp-hr (0.05 g/bhp-hr for urban buses). Currently, CO levels are well below 1998 Federal emission standards and are expected to remain so even as HC and NOx levels are lowered.

For heavy-duty diesel engines, emission control technologies such as exhaust gas recirculation, advanced fuel injection, and charge air pressure and temperature control have been shown to be capable of reducing NMHC plus NOx to 2.4 g/bhp-hr. At this time, PM levels increase above 0.1 g/bhp-hr at these low NMHC and NOx calibrations. However, PM may be brought back to 1998 levels through the continued use of aftertreatment or through further advances in currently developed technology. Aftertreatment devices are being developed for both PM and NOx reduction. Manufacturers are expected to use some combination of engine and aftertreatment controls to meet the 2.4 g/bhp-hr NMHC plus NOx level without increasing PM emissions.

The following chapter distinguishes between primary and secondary technologies for diesel engines. Primary technologies are those control technologies that EPA believes manufacturers will use specifically to meet the requirements of this rule. Secondary technologies are those that either would be used in the future for reasons other than emission control or are not predicted to be the most cost-effective strategies. Primary technologies include hot and cold EGR, combustion optimization, and fuel injection improvements. Fuel injection improvements have benefits that go beyond control of NOx emissions, but can be considered a primary technology to the extent that they are used to comply with the emission standards finalized today. A partial list of secondary technologies follows: decreased fuel consumption, variable geometry turbocharger, converting to four valves per cylinder, variable valve timing, oxidation catalyst improvements, and lean NOx catalysts.

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CHAPTER 5: ECONOMIC IMPACT

I. Lead Time and R&D

In previous rules to set heavy-duty engine emission standards, EPA has typically allowed engine manufacturers about four years of preproduction lead time. This four-year lead time, the period called for in the Clean Air Act, has given manufacturers sufficient opportunity to complete the research, development, retooling, and certification efforts necessary to comply with promulgated emission standards. The requirements for the 2004 model year do not follow this pattern. The Statement of Principles and the Advance Notice of Proposed Rulemaking gave the engine manufacturers a good idea of the level of the emission standards and other related requirements a full eight years before 2004. This relatively long lead time has significant positive implications for the economic impact of the new requirements. As discussed in Chapter 4, diesel engine manufacturers are expected to meet the proposed requirement using a combination of control strategies and techniques aimed at reducing NOx and HC in-cylinder, rather than relying on the development of aftertreatment technologies. This approach requires a significant amount of up-front R&D effort to develop and evaluate the various fuel and air control strategies and techniques, which could potentially help reduce emissions. Eight years of lead time provides enough time to plan and conduct a comprehensive, efficient, and orderly R&D program including basic research on the fuel and air control strategies and techniques under consideration and the application of the fruits of these efforts to the individual engine models. This lead time allows for the efficient application of this technology while maintaining (if not improving) engine durability and fuel consumption characteristics. Thus, as will be discussed below, R&D is a significant factor in developing and optimizing the engine control approaches; toward this end, EPA has identified significant resources for R&D as part of the overall cost of control.

Changes to heavy-duty engine emission standards for the 1998 model year provide an intermediate step toward compliance with the 2004 model year standards. All 1998 model year heavy-duty vehicles must meet a 4 g/bhp-hr NOx standard. Some fleet vehicles must meet a 3.8 g/bhp-hr NOx + NMHC standard beginning the same year. To comply with these standards, manufacturers may implement some design improvements needed for the 2004 model year engines. Complying with these intermediate standards gives manufacturers a milestone for making these improvements and provides them the opportunity to get information on in-use operating characteristics of the selected technologies at that stage in their development. The learning from this early deployment of emission control technologies can in turn be factored into the development process for further refinement to comply with 2004 model year standards. A difficulty in estimating the cost of complying with these standards lies in the uncertainty in precisely defining a baseline package of emission control technology for meeting the 1998 model year standards.

II. Methodology

Using the technical information in Chapter 4, EPA identified packages of technologies that diesel engine manufacturers could use to meet the emission standards. To assist EPA in this economic analysis, ICF, Incorporated and Acurex Environmental Corporation conducted a study of the potential costs of a wide variety of technologies. While the following analysis projects a relatively uniform emission control strategy for designing the different categories of engines, this should not suggest that a single combination of technologies will be used by all manufacturers. In fact, depending on basic engine emission characteristics, EPA expects that control technology packages will gradually be fine-tuned to each application. Furthermore, EPA expects manufacturers to use averaging, banking, and trading programs as a means to deploy varying degrees of emission control technologies on different engines. EPA nevertheless believes that the projections presented here provide a cost estimate representative of the different approaches manufacturers may ultimately take.

Costs of control include variable costs (for incremental hardware costs, assembly costs, and associated markups) and fixed costs (for tooling, R&D, and certification). Variable costs are marked up at a rate of 29 percent to account for manufacturers' overhead and profit.[1] For technologies sold by a supplier to the engine manufacturers, an additional 29 percent markup is included for the supplier's overhead and profit. Fixed costs for R&D would be incurred over the seven-year period from 1996 through 2002, while tooling and certification costs are incurred one year ahead of initial production. Fixed costs are increased by seven percent for every year before the start of production to reflect the time value of money, and are then recovered with a five-year amortization at the same rate. The analysis also includes consideration of lifetime operating costs where applicable.

Projected costs were derived for four service classes of heavy-duty diesel vehicles, as depicted in Table 5-1. The cost for each technology applied to urban buses is the same as the cost of that technology when applied to heavy heavy-duty vehicles, unless otherwise specified.

III. Technologies for Meeting the 2004 Standards

The following discussion provides a description and estimated costs for those technologies EPA projects will be needed to comply with the new emission standards. It is difficult to make a distinction between technologies needed to reduce NOx emissions for compliance with 2004 model year standards and those technologies that offer other benefits for improved fuel economy and engine performance or for better control of HC or particulate emissions. EPA believes that without 2004 model year standards, manufacturers would continue research on and eventually deploy many technological upgrades to improve engine performance or more cost-effectively control emissions.

Table 5-1
Service Classes of Heavy-Duty Vehicles

Service Class	Vehicle Class	GVWR (lbs.)
Light	2B - 5	8,500 - 19,500
Medium	6 - 7	19,501 - 33,000
Heavy	8	33,001 +
Urban Bus	—	—

Accordingly, EPA believes that a small set of technologies represent the primary changes manufacturers must make to meet the 2004 model year standards. Other technologies applied to heavy-duty engines, before or after implementation of new emission standards, will make smaller contributions to controlling NOx or HC emissions and are therefore considered secondary improvements for this analysis. In this category are design changes such as improved oil control, variable-geometry turbochargers, optimized catalyst designs, and variable-valve timing. Lean NOx catalysts are also considered secondary technologies in this analysis, not because NOx control is an incidental benefit, but because it appears unlikely that they will be part of 2004 model year technology packages. Modifications to fuel injection systems will also continue independently of new standards, though some further development with a focus on reducing NOx or HC emissions would be evaluated. While a few engines must reduce HC emission levels, EPA expects the combination of technologies selected for meeting NOx and particulate emission standards to be sufficient for adequate control of HC emissions.

The technology packages include two sets of projections. First, the baseline technology packages represent a projection of the strategies expected from manufacturers to meet the 1998 emission standards and to improve their engine designs generally. Specification of these technologies is based on an observation of current trends in heavy-duty engine technology and a set of technical judgments about the most likely control steps needed to meet the 1998 model year emission standards.

Second, several technological improvements are projected for complying with the proposed 2004 model year emission standards. Selecting this package of technologies requires extensive engineering judgment. The fact that manufacturers have nearly a full decade before implementation of the proposed standards ensures that the technologies used to comply with the proposed emission standards will develop significantly before reaching production. This ongoing development will lead to reduced costs in three ways. First, research will lead to enhanced effectiveness for individual technologies, allowing manufacturers to use simpler packages of emission control technologies than we would predict given the current state of development. Similarly, the continuing effort to improve the emission control technologies will include innovations that allow lower-cost production. Finally, manufacturers will focus research efforts on any potential drawbacks, such as increased fuel consumption or maintenance costs, attempting to minimize or overcome any negative effects.

Cost estimates based on these projected technology packages would increase the cost of engines in the 2004 model year. Costs in subsequent years would be reduced by several factors. After manufacturers certify engines to meet new emission standards, they will continue to pursue innovations that reduce the cost of compliance, either by improving the effectiveness of control technologies, or by reducing the cost of manufacturing and assembling the hardware. Also, current research activities include development of several technologies not included in this analysis. Further improvement of some of these longer range technologies may ultimately provide the opportunity to meet emission standards at a lower overall cost. EPA has attempted to quantify the cost savings associated with this ongoing development, as described in Section V below.

The baseline control technologies projected for engines meeting 1998 emission standards include technologies that contribute directly to lower NOx emissions and a variety of engine improvements with only secondary benefits for NOx control. The baseline scenario includes full utilization of electronic controls and unit injectors. Except for urban bus engines, one-third to one-half of diesel engines are expected to include unit injectors designed to operate independently of engine speed; one example of such an injector is the Hydraulically-activated, Electronically-controlled Unit Injector (HEUI), which is currently manufactured for several Caterpillar and Navistar engine models. Also, all the engine models will likely have some basic manipulation of the fuel injection profile (for "rate shaping"). Variable-geometry turbochargers are expected for several engine lines as manufacturers aim for better performance and fuel economy. Light and medium heavy-duty engines may be modified to further reduce the contribution of lubricating oil to particulate emissions. Manufacturers may also pursue variable-valve timing or upgrade to four valves per cylinder for improved engine performance.

A combination of primary technology upgrades are anticipated for the 2004 model year. Achieving very low NOx emissions will require basic research on reducing in-cylinder NOx and HC. Modifications to basic engine design features can improve intake air characteristics and distribution during combustion. Manufacturers are also expected to use upgraded electronics and advanced fuel-injection techniques and hardware to modify various fuel injection parameters for higher pressure, further rate shaping, and some split injection. EPA also expects that many engines will incorporate a moderate degree of cooled exhaust gas recirculation. The costs of these individual technologies are considered in the following paragraphs and summarized in Tables 5-2. The costs of secondary improvements are also discussed, but are not included in the calculation of total vehicle costs, since it is not expected that these will be needed for compliance with the proposed emission standards.

Tables 5-2
2004 Model Year Cost Estimates

Light Heavy-Duty Diesel Vehicles

Item	Fraction	Fixed Cost	Variable Cost	Operating Cost
Cooled EGR	100%	63	140	7
Combustion Optimization	100%	20	0	0
Improved fuel injection	25%	2	31	0
Certification	100%	2	0	0
Total	—	87	170	7

Medium Heavy-Duty Diesel Vehicles

Item	Fraction	Fixed Cost	Variable Cost	Operating Cost
Cooled EGR	100%	119	154	62
Combustion optimization	100%	50	0	0
Improved fuel injection	50%	9	58	0
Certification	100%	7	0	0
Total	—	185	212	62

Heavy Heavy-Duty Diesel Vehicles

Item	Fraction	Fixed Cost	Variable Cost	Operating Cost
Cooled EGR	100%	119	216	131
Combustion optimization	100%	50	0	0
Improved fuel injection	50%	9	115	0
Certification	100%	8	0	0
Total	—	186	281	131

Tables 5-2, continued

Urban Buses

Item	Fraction	Fixed Cost	Variable Cost	Operating Cost
Cooled EGR	100%	119	174	127
Combustion optimization	100%	50	0	0
Improved fuel injection	50%	6	49	0
Certification	100%	8	0	0
Total	—	183	223	127

A. Primary Technologies

The following discussion presents the projected costs of the primary technological improvements expected for complying with the proposed emission standards, first for fixed costs, then for hardware and operating costs of the individual technologies.

The cost analysis anticipates an extensive ongoing research program to develop these technologies. For the cost analysis, R&D expenditures total nearly $40 million per year over a seven-year period beginning in 1996. These costs are discounted at a seven percent rate to reflect the time value of money. R&D costs account for over 90 percent of the total fixed costs per engine detailed in Tables 5-2.

Retooling is another fixed cost factored into the analysis. The net present value in 1995 of the expected retooling costs is about $25 million. Retooling costs will be incurred about one year before initial production and are discounted accordingly.

Manufacturers will also incur costs for certifying the range of engine families to the proposed emission standards. EPA previously developed a detailed methodology for calculating certification costs.[2] Adjusting those figures to account for inflation results in an estimated certification cost of $230,000 per engine family. Because certification costs will be incurred on average one year before the beginning of production, the calculated cost is increased by seven percent. The calculated certification costs for heavy-duty diesel engines can be rounded up to $23 million. Distributing those costs across the different engine categories, amortizing the costs over five years, and dividing by the number of projected 2004 model year sales for each category results in per-engine costs between $2 and $8 for each category of heavy-duty diesel vehicles.

1. Exhaust gas recirculation

Exhaust gas recirculation (EGR) may represent the biggest area of technology development enabling manufacturers to achieve the targeted NOx emission levels. Unlike the other technological developments, which are largely evolutionary, introduction of EGR would be a step change in the design of heavy-duty diesel engines. While much research remains to optimize EGR systems for maximum NOx-control effectiveness with minimum negative impacts on performance and durability, current developments show great promise for substantial emission-control improvements with EGR systems.

Manufacturers have several design options for developing a system for exhaust gas recirculation (EGR). Current designs seem to be moving toward cooled EGR systems with varying levels of recirculation, ranging from roughly 50 percent of intake air volume at idle to 5 percent or less near peak power. Recirculation rates during intermediate speed and load operation will be carefully tailored to consider the needs for engine performance and emission control. With the low level of engine-out particulate matter, this degree of recirculation will not require filtration of the recirculated exhaust gases. EGR cooling is expected to come from a heat exchanger that relies on the engine coolant coming out of the engine to draw heat from the recirculated exhaust gases. Engine designs will likely route exhaust gases into the engine's air intake downstream of the turbocharger inlet. Pressure pulses in the exhaust may be sufficient to force the exhaust gases into the intake manifold, though simple devices such as a venturi or a flow-restricting orifice may serve to improve the pressure differential across the EGR valve. For maximum control, a pump could be installed to enable varying flow rates in any operating conditions. Development of any of these types of EGR depend on electronics to control the airflow through the EGR valve. Though a variety of design choices are yet to be decided, the basic system design seems to be getting clearer; this analysis presents the estimated cost for this EGR system.

The cost to manufacturers of adding the hardware for a cooled EGR system ranges from $140 to $220 per engine. Factoring in the fixed costs and the appropriate markups results in an increased purchase price of $203, $273, $335, and $293 for light, medium, and heavy heavy-duty diesel vehicles, and urban buses, respectively.

2. Combustion optimization

Manufacturers can make a variety of changes to the basic engine design that do not require additional components. Programming the engine's electronic controls, optimizing intake air characteristics and distribution, and making changes to piston bowl shape, the compression ratio, and the injection timing strategy add little or no variable cost, but require significant expenses for R&D and retooling. Total costs for these improvements are estimated at $5 million per engine line. For the different classes of vehicles, this translates to an incremental cost between $20 and $50 per engine.

3. Fuel System Upgrades

Manufacturers are expected to improve their fuel injection systems by increasing fuel injection pressure, improving spray patterns, and adding rate shaping or split injection capability; however, much of this improvement is expected to occur independently of 2004 model year emission standards.

For cam-driven electronic unit injection systems, the expected fuel system improvements will require stronger and better performing fuel injectors and solenoids. Advanced systems such as Caterpillar's Hydraulically-Activated Electronically-controlled Unit Injection (HEUI) technology require various reinforcements and better high-pressure oil pumps and solenoid valves. Common rail injection systems are similar enough to HEUI designs that the cost estimate would mirror that for HEUI systems.

Incremental costs for this set of fuel injector improvements are roughly proportional to the number of cylinders in an engine. Light heavy-duty vehicles, typically equipped with eight-cylinder engines, have an estimated total cost of about $130 per engine, which is an average for the different hardware configurations. Medium and heavy heavy-duty vehicles, with six-cylinder engines, would have a cost between $130 and $150 per engine. Urban buses, currently equipped with four-cylinder engines, have the lowest estimated total cost of about $110.

4. Technology package costs

The estimated incremental costs of these primary technologies depend on several judgments about which technologies will be used. For example, identifying the degree of EGR flow that will be needed to meet emission standards is difficult. If manufacturers need a higher EGR flows than estimated here, hardware costs will increase, more R&D time will be required, and there will be a greater potential for increased operating expenses for fuel consumption and maintenance.

EPA believes it is not appropriate to assign the full cost of fuel system upgrades to the proposed emission standards. Much of the anticipated improvements will come independently of the 2004 model year standards and any remaining system improvements for 2004 and later model year vehicles will provide benefits beyond lower NOx emissions. In an effort to properly assess the cost of the fuel system upgrades, EPA estimates for light heavy-duty vehicles that 25 percent of the fuel system cost increase should be allocated to the proposed standards. For all other engines, half the fuel system cost increase is attributed to the proposed standards. The lower estimate for light heavy-duty vehicles reflects the lower sensitivity of these engines to fuel economy concerns, i.e., manufacturers will likely resort to less costly hardware improvements that may result in small increases in fuel consumption.

The resulting calculation of total incremental cost for the set of primary technologies, summarized in Tables 5-2, shows the expected increase in purchase price due to the proposed emission standards. Projected cost increases are $258, $397, $467, and $406 for light, medium, and heavy heavy-duty vehicles, and urban buses, respectively.

To test the sensitivity of these estimates, EPA calculated the cost increase assuming that heavy heavy-duty vehicles would need high-flow EGR systems. This would increase hardware costs by about $80 (retail price equivalent) and operating costs by about $800 (net present value at the point of sale). The affect of increasing fuel consumption, in this case by 1 percent, is clearly great enough that manufacturers would seek alternative engineering solutions to comply with emission standards to minimize the cost impacts.

B. Operating Costs

EGR has the potential, if not developed and implemented properly, to increase operating costs, either by increasing fuel consumption or requiring additional maintenance to avoid accelerated engine or component wear. While it is possible to develop scenarios and estimate the impact on operating costs of current diesel EGR concepts, this is of minimal value due to the expected continuing development of these technologies. One major focus of the R&D conducted over the next seven years will be to resolve potential operating cost impacts related to the use of EGR; thus the current state of the technology is not representative of what is expected for 2004. Furthermore, for the degree of cooled EGR expected for the proposed 2004 model year standards, even current data shows very little impact on operating costs. EPA has nevertheless assessed the potential for increased operating costs, as described below, first for EGR-related maintenance, then for fuel economy.

While engine-out particulate emissions are dramatically lower than only a few years ago, recirculating even a small amount of particulate matter through an engine introduces a concern for engine durability. To prevent wear, manufacturers might specify more frequent oil change intervals or a greater oil sump volume to accommodate any effects of acidity or particulate agglomeration in the oil. However, EPA expects manufacturers to make a great effort to minimize any potential new maintenance burden for the end user. Alternatively, changing fuel or oil formulations may be the most cost-effective way to reduce the potential for particulate-related wear. EPA therefore believes that manufacturers will be able to keep engine costs lowest by investing in research to address these concerns—an expenditure of $10 million to $15 million industry-wide, or about $25 per engine when amortized over the fleet, should provide sufficient development potential to prevent durability problems in a way that is transparent to the user. To include the affect of improved materials resulting from the R&D effort, the analysis incorporates a 2 percent increase in the cost of engine oil. The increased expense of oil changes over the lifetime of vehicles ranges from $10 to $50 per engine (net present value at the point of sale).

In addition, EPA has included a cost for preventive maintenance, at the time of rebuild, to ensure that EGR systems will not malfunction. EPA data show that nearly all engines from heavy heavy-duty vehicles and 65 percent of those from medium heavy-duty vehicles are rebuilt.[3] Rebuilding engines from light heavy-duty vehicles is rare. EPA estimates that engine rebuild occurs at 240,000 miles for medium heavy-duty vehicles, at 500,000 miles for heavy heavy-duty vehicles, and at 300,000 miles for urban buses. These mileage figures represent an approximate average across the various applications within each service class, which experience widely differing mileage accumulation rates. For example, garbage trucks have much different operating characteristics than line-haul trucks. According to the MOBILE model, these mileage figures translate into a rebuild in the eleventh year for both truck categories and in the ninth year for urban buses. EPA expects that rebuild procedures for EGR systems will include solvent cleaning of the EGR tubing and replacement of the electronic control valve. Removal, cleaning, and replacement of the tubing are estimated to take 30 minutes at a $65 per hour labor rate. Replacing the control valve on an aftermarket basis is expected to cost three times the manufacturers' long-term direct cost, or $65 and $95 for medium and heavy heavy-duty vehicles, respectively. Calculated in terms of net present value at the point of sale, the net effect of EGR servicing comes to about $50 for medium heavy-duty vehicles and $100 for heavy heavy-duty vehicles and urban buses.

With respect to fuel economy, several secondary technologies described below may lead to cost savings, while EGR has the potential to incur a fuel economy penalty. As with potential new maintenance cost burdens, EPA believes manufacturers will focus their research efforts on overcoming any negative impact on fuel economy caused by EGR. In any case, it is not clear at this stage of development that the set of changes resulting from the proposed emission standards will have any net negative impact on fuel economy; additional fuel costs are therefore not included in the cost analysis.

While EPA believes that sufficient R&D and the use of cooled EGR will address operating cost concerns, one can determine the sensitivity of this position by assessing the potential burden associated with increased operating costs. Acurex estimated the burden of increasing the oil sump volume by ten percent to address maintenance concerns with EGR. Oil sump volumes currently range from 4 gallons for light heavy-duty diesel vehicles to 11 gallons for heavy heavy-duty vehicles, so the cost impact varies greatly by vehicle category. Calculating a cost at each oil change as vehicles accumulate mileage and discounting the life-cycle costs to the point of sale results in a cost estimate of $25, $55, $145, and $95 for light, medium, and heavy heavy-duty vehicles, and urban buses, respectively.

The cost sensitivity to potential increases in fuel consumption is even more dependent on vehicle category because of the widely differing mileage accumulation rates for different vehicles. For each one percent increase in fuel consumption, Acurex has estimated that life-cycle costs, calculated as a net present value at the point of sale, are $85, $210, and $720 for light, medium, and heavy heavy-duty vehicles, respectively.

C. Secondary Technologies

The set of secondary technologies is divided into two categories. Technologies in the first category have a minor role in controlling NOx emissions, contributing primarily to engine power, fuel efficiency, or more cost-effective control of particulate emissions. Most of these technologies would be incorporated for reasons unrelated to the proposed emission standards, but it is possible that the emission benefits would be a consideration in designing 2004 model year engines. In the second category are those emission-control technologies that are under development for controlling NOx emissions, but may not be ready by the 2004 model year. EPA's analysis is based on the view that the primary technologies described above will be sufficient to meet the proposed standards.

Meeting the proposed NOx + NMHC standard will increase the challenge to control particulate emissions. Manufacturers might use several different technologies to maintain control of particulate emissions; however, EPA believes that the fuel system improvements described above will be sufficient to prevent any potential increase in particulate emissions. In fact, manufacturers are attempting to lessen the cost of meeting current particulate emission standards over the next several years by decreasing their reliance on catalysts. This underscores EPA's belief that 2004 model year engines could control particulate emissions without major technological innovation. The following paragraphs provide cost estimates for several secondary technology developments.

Manufacturers are expected to reduce the contribution of lubricating oil to engine-out particulate emissions for light and medium heavy-duty engines. Heavy heavy-duty engines already have very little oil-related particulate emissions. Hardware costs for improved piston rings and valve guide seals are estimated at $2.50 per cylinder. R&D and retooling costs are expected to approach $1.2 million per engine line. The resulting costs, with appropriate markups, come to $35 per engine.

For several years research has focused on improving turbocharger designs to reduce response time and increase compressor efficiency. One such design, the variable-geometry turbocharger, is more complex than existing turbochargers, but offers two primary operating enhancements: boost pressure is maintained over a wider range of engine operation and response time is reduced. These improvements contribute to lower exhaust emissions and provide control of airflow needed for engines with EGR. Variable-geometry turbochargers require more parts and more assembly time, resulting in a variable cost to manufacturers ranging from about $200 to $300 per engine. Fixed costs for R&D and retooling are estimated at $3.5 million per engine line. Combining the costs with the appropriate markups results in costs of $271, $349, and $436 for light, medium, and heavy heavy-duty engines, respectively, for those engines that switch to variable-geometry turbochargers.

Oxidation catalysts are currently in widespread use in light and medium heavy-duty engines. Acurex developed cost estimates for a next generation of catalysts that may be used in the future to meet emission standards. Projected catalyst upgrades involve variations of catalyst and washcoat materials. The projected increase in retail-price-equivalent costs for the new catalysts are $125 and $165 for light and medium heavy-duty engines, respectively. For urban buses, the new catalysts are estimated to cost $185 more than current models.

Lean NOx catalyst technology is currently the focus of extensive research. Reducing NOx from diesel exhaust is difficult because of the abundance of oxygen in the exhaust stream. Lean NOx catalysts, when coupled with oxidation catalysts, would provide effective aftertreatment for particulate, HC, and CO in addition to reduced NOx emissions. The principle drawback of lean NOx catalysts is their dependence on a reductant for reaction with the NOx molecules. The most likely reductant is diesel fuel, based on its ready availability more than its effectiveness with the catalyst. Diverting fuel to a lean NOx catalyst can be done most easily by injecting fuel into one or more cylinders at the end of a combustion event. Supplying diesel fuel as a reductant carries with it a fuel penalty, though some smaller fuel efficiency gains may be possible through injection timing or removal of other technologies that would otherwise be needed to control NOx emissions. Calculated fuel penalties include an estimated net penalty of four percent. For light heavy-duty vehicles, purchase price is estimated to increase by nearly $900 for lean NOx catalysts, with a discounted lifetime fuel cost of about $350. For medium heavy-duty vehicles, purchase price would increase approximately $1,200 with fuel costs of $900. Heavy heavy-duty vehicles would have costs of about $1,900 and $3,000 for purchase price and fuel costs, respectively.

IV. Summary of Costs

The per-vehicle cost figures presented above are used in Chapter 7 to calculate the cost-effectiveness of the program by comparing to emission reductions over the lifetime of each vehicle category for those engines covered by the new standards. Included in that calculation are the following modifications for later model year production.

First, manufacturers recover their initial fixed costs for tooling, R&D, and certification over a five-year period. Fixed costs are therefore applied only to the first five model years of production.

The second modification is related to the effects of the manufacturing learning curve. This is a well documented and accepted phenomenon dating back to the 1930s. The general concept is that unit costs decrease as cumulative production increases. Learning curves are often characterized in terms of a progress ratio, where each doubling in cumulative production leads to a reduction in unit cost to a percentage "p" of its former value (referred to as a "p cycle"). The organizational learning which brings about a reduction in total cost is caused by improvements in several areas. Areas involving direct labor and material are usually the source of the greatest savings. These include, but are not limited to, a reduction in the number or complexity of component parts, improved component production, improved assembly speed and processes, reduced error rates, and improved manufacturing process. These all result in higher overall production, less scrappage of materials and products, and better overall quality.

Companies and industry sectors learn differently. In a 1984 publication, Dutton and Thomas reviewed the progress ratios for 108 manufactured items from 22 separate field studies representing a variety of products and services.[4] As shown in Figure 5-1, of the 108 progress ratios observed, 8 were less than 70 percent, 39 were in the range of 71 to 80 percent, 54 were in the range of 81 to 90 percent, and 7 were above 90 percent. The average progress ratio for the whole data set falls between 81 and 82 percent. The lowest progress ratio of 55 percent shows the biggest improvement, representing a remarkable 45 percent reduction in costs with every doubling of production volume. At the other extreme, except for one company that saw *increasing* costs as production continued, every study showed cost savings of at least 5 percent for every doubling of production volume. This data supports the commonly used p value of 80 percent, i.e., each doubling of cumulative production reduces the former cost level by 20 percent. As each successive p cycle takes longer to complete, production proficiency generally reaches a relatively stable plateau, beyond which increased production does not necessarily lead to markedly decreased costs.

Figure 5-1

EPA applied a p value of 20 percent beginning in 2004 in this analysis. That is, the variable costs were reduced by 20 percent for each doubling of cumulative production. However, to avoid overly optimistic projections, EPA included several additional constraints. Using one year as the base unit of production, the first doubling would occur at the start of the 2006 model year and the second doubling at the start of the 2008 model year. To be conservative, EPA incorporated the second doubling at the start of the 2009 model year. Recognizing that the learning curve effect may not continue indefinitely with ongoing production, EPA used only two p cycles.

EPA believes the use of the learning curve is appropriate to consider in assessing the cost impact of heavy-duty engine emission controls. The learning curve applies to new technology, new manufacturing operations, new parts, and new assembly operations. Heavy-duty diesel engines do not use EGR of any type today (hot, cooled, or cooled and filtered), nor is widespread use expected before 2004. This is therefore a new technology for heavy-duty diesel engines and will involve new manufacturing operations, new parts, and new assembly operations. Since this will be a new and unique product, EPA believes this is an optimal situation for the learning curve concept to apply. Opportunities to reduce unit labor and material costs and increase productivity (as discussed above) will be great. EPA believes a similar opportunity exists for fuel systems on heavy-duty diesel engines. While all diesel engines have high-pressure fuel injection systems, the changes envisioned for common rail and unit injection systems require fundamental redesign of system hardware. These new parts and new assemblies will involve new manufacturing operations. As manufacturers gain experience with these new systems, comparable learning is expected to occur with respect to unit labor and material costs. These changes require manufacturers to start new production procedures, which, over time, will be improved with experience.

Table 5-4 lists the projected schedule of costs over time for each category of heavy-duty diesel vehicles. The estimated long-term cost savings would reduce the impact on the total cost of heavy-duty vehicles by about half.

To demonstrate the sensitivity of the projected learning curves on total costs, Table 5-5 compares the estimated incremental purchase price over time using p values of 0.70 and 0.90 (or 30 and 10 percent savings with every doubling of production, respectively) instead of 0.80. Focusing on heavy heavy-duty vehicles as an example, the incremental variable cost is projected to decrease from $210 in the first year to $134 for 2009 and later model years using the standard p value of 0.80. With p values of 0.70 and 0.90, the long-term variable cost is projected to be $103 or $170, respectively. With the less aggressive learning scenario (p = 0.90), the learning curve yields total cost savings of $40, compared to a $76 reduction with the standard p value (p = 0.80). For comparison, the more aggressive learning (p = 0.70) would result in a $97 reduction in variable costs. Thus, the various approaches to quantifying learning curves result in projected incremental costs that are noticeably different, but these differences do not have a significant impact on EPA's overall characterization of the cost of complying with the new emission standards.[5]

Characterizing these estimated costs in the context of their fraction of the total purchase price and life-cycle operating costs is helpful in gauging the economic impact of the proposed standards. Table 5-6 presents the baseline costs for each vehicle category, as developed by ICF.

V. Aggregate Costs to Society

The above analysis develops per-vehicle cost estimates for each vehicle class. With current data for the size and characteristics of the heavy-duty vehicle fleet and projections for the future, these costs can be translated into a total cost to the nation for the proposed emission standards in any year. The result of this analysis is a projected total cost starting at $242 million in 2004. Per-vehicle cost savings over time reduce projected costs to a minimum value of $123 million in 2009, after which the growth in truck population leads to an increase to $180 million in 2020. Total costs for these years are presented by vehicle class in Table 5-7.

Fixed costs, including R&D, retooling, and certification costs, are summed across the industry. Costs are amortized equally over five years at a seven percent discount rate. Industry-wide then, an estimated $310 million of total fixed costs would be recovered at the rate of about $75 million per year for the first five years of production.

Variable costs are computed as a product of one full year of heavy-duty vehicle sales and the cost increase for assembly time and new hardware. Based on data submitted by engine manufacturers, EPA estimates 1995 sales to be 280,000, 140,000, and 220,000 for light, medium, and heavy heavy-duty diesel vehicles (including urban buses). These numbers are projected to grow at an annual rate of two percent of the base year (without compounding) through 2020. Total variable costs in 2004 are estimated at $164 million. Variable cost projections for 2020 show a small decrease, indicating that the decrease in per-engine variable costs over time counters the projected population growth.

The incremental cost associated with oil changes is incorporated on an annual basis for each vehicle category. Incremental costs related to rebuild are not include in 2004 or 2009, since the first rebuilds would be expected after 2009. In 2020, incremental rebuild costs are applied to the vehicles that would be rebuilt in that year. Maintenance costs are projected to reach nearly $30 million by 2020.

Table 5-4
Projected Long-Term Diesel Engine/Vehicle Costs
(net present value at point of sale in 1995 dollars)

Vehicle Class	Model Year	Change	Purchase Price	Life-cycle Operating Cost
Light heavy-duty	2004	—	258	7
	2006	20 percent learning curve applied to variable costs	224	7
	2009	Fixed costs expire; 20 percent learning curve applied to variable costs	109	7
Medium heavy-duty	2004	—	397	62
	2006	20 percent learning curve applied to variable costs	355	62
	2009	Fixed costs expire; 20 percent learning curve applied to variable costs	136	62
Heavy heavy-duty	2004	—	467	131
	2006	20 percent learning curve applied to variable costs	411	131
	2009	Fixed costs expire; 20 percent learning curve applied to variable costs	180	131
Urban Bus	2004	—	406	127
	2006	20 percent learning curve applied to variable costs	361	127
	2009	Fixed costs expire; 20 percent learning curve applied to variable costs	143	127

Table 5-5
Sensitivity of Learning Curves on Incremental Purchase Price

Vehicle Class	Incremental Purchase Price by Model Year						
	2004	2006			2009		
		p=0.7	p=0.8	p=0.9	p=0.7	p=0.8	p=0.9
Light heavy-duty	$258	$207	$224	$241	$83	$109	$138
Medium heavy-duty	$397	$333	$355	$376	$104	$136	$172
Heavy heavy-duty	$467	$383	$411	$439	$138	$180	$228
Urban Bus	$406	$339	$361	$384	$109	$143	$180

Table 5-6
Baseline Costs for Heavy-Duty Engines and Vehicles

Vehicle Class	Engine Cost	Vehicle Cost	Operating Costs
Light heavy-duty	$7,800	$22,504	$12,450
Medium heavy-duty	$12,400	$46,132	$31,242
Heavy heavy-duty	$21,700	$96,490	$108,027
Urban Bus	$22,000	$224,000	$437,153

Table 5-7
Estimated Annual Costs for Improved Heavy-Duty Vehicles

Year	Category	Cost Elements (millions of dollars)			
		Fixed	Variable	Operation	Total
2004	Light heavy-duty	14	56	0.3	71
	Medium heavy-duty	28	35	0.2	64
	Heavy heavy-duty	33	73	1.1	107
	Total Annual Cost	**76**	**164**	**1.6**	**242**
2009	Light heavy-duty	0	39	2	41
	Medium heavy-duty	0	24	1	26
	Heavy heavy-duty	0	51	6	56
	Total Annual Cost	**0**	**114**	**9**	**123**
2020	Light heavy-duty	0	46	4	49
	Medium heavy-duty	0	28	10	38
	Heavy heavy-duty	0	59	34	93
	Total Annual Cost	**0**	**134**	**47**	**180**

CHAPTER 5 References

1."Update of EPA's Motor Vehicle Emission Control Equipment Retail Price Equivalent (RPE) Calculation Formula," Jack Faucett Associates, Report No. JACKFAU-85-322-3, September 1985.

2.Draft Regulatory Impact Analysis and Oxides of Nitrogen Pollutant Specific Study, p. 3-29 ff., October 1984.

3."Heavy Duty Engine Rebuilding Practices," Draft EPA Report by Karl Simon and Tom Stricker, March 21, 1995.

4.J.M Dutton and A. Thomas, *Academy of Management Review*, Rev. 9, 235, 1984.

5.ICF memo re. engine/operating costs.

CHAPTER 6: ENVIRONMENTAL IMPACT

This chapter describes the expected environmental impacts of the NMHC plus NOx emission standards described in the previous chapters. Specifically, this chapter includes an estimated total nationwide NOx and VOC emission inventory for 1990, heavy-duty diesel vehicle NOx and NMHC inventory projections for future years (with and without additional control), estimates of the impacts of the standards on typical vehicles over their lifetime, and a discussion of the environmental effects of the emission reductions.[g]

While the standards are combined NMHC plus NOx standards, it was necessary to consider the NMHC and NOx emission impacts separately. Given the technologies that are expected to be used for complying with the standards, as described in Chapters 4 and 5, it is reasonable to model the fleet-average impact of the new standards as being equivalent to a 2.0 g/bhp-hr NOx standard and a 0.4 g/bhp-hr NMHC standard. This is because the application of these technologies to heavy-duty engines would be expected to lead to very large reductions in NOx emissions for all engine families, and small NMHC emission reductions for some engine families. It should be emphasized, however, that this is only an analytical approach; manufacturers are actually expected to optimize each engine family uniquely with respect to the combined standards, balancing the sometimes competing effects of NMHC and NOx control technologies. Thus individual engine families may have emission levels different from the fleet-average emissions used in this analysis.

I. Total Nationwide Emissions

A. Current Inventories

Total nationwide emissions of NOx and VOC were estimated in the 1994 EPA Trends Report.[1] The purpose of including these inventories here is to show the relative importance of heavy-duty sources. The highway emissions were estimated using EPA's emission factor model MOBILE5a, and information from the Federal Highway Administration's Highway Performance Monitoring System and the 1980 U.S. census. More information about the methodologies used to estimate the mobile source emissions, as well as the other emissions, can be found in the Trends Report. The

[g]Three terms are used in this chapter to describe organic emissions: "total hydrocarbons", volatile organic compounds", and "nonmethane hydrocarbons". The term "total hydrocarbons" (THC or HC) refers to the organic emissions from an engine as measured by the test procedures of 40 CFR 86. The term "volatile organic compounds" (VOC) refers to organic emissions excluding compounds that have negligible photochemical reactivity, primarily, methane and ethane. (For a more precise definition of VOC, see 40 CFR 51.100.) The term "nonmethane hydrocarbons" refers to the difference obtained by subtracting methane from total hydrocarbons. Since the ethane content of emissions is very small from diesel engines, organic emissions measured as NMHC are approximately the same as when measured as VOC.

national NOx and VOC emission inventories are summarized in Table 6-1. These data indicate that emissions from "current" heavy-duty diesel vehicles account for about 10 percent of total NOx emissions and only 1.3 percent of total VOC emissions.

Table 6-1
1990 National NOx and VOC Emissions
(thousand short tons per year)

Emission Source	NOx	VOC
Light-Duty Vehicles	4,821	6,068
Heavy-Duty Diesel Vehicles	2,332	316
Heavy-Duty Gasoline Vehicles	335	470
Nonroad	2,843	2,120
Other	12,861	15,302
Total Nationwide Emissions	23,192	24,276

B. NOx Emission Projections and Impacts

A detailed analysis of NOx emissions was prepared for EPA by E.H. Pechan and Associates using the same methodologies as were used in the Trends Report.[2] This analysis projected future emissions with and without new emission standards for heavy-duty vehicles and addressed the geographic distribution of the emissions. It differed from the 1994 Trends Report in that it incorporated the effects of the 1994 standards for large nonroad compression-ignition engines, and that it projected emissions to the year 2020, instead of 2010. The annual growth rates assumed for highway sources came from the MOBILE4.1 Fuel Consumption Model, while the annual growth rates for other sources were held constant for the years 2010 through 2020. A more detailed description of this analysis can be found in the docket.[3]

The future NOx emissions of heavy-duty vehicles were projected by Pechan using MOBILE5a, which takes into account the 4.0 g/bhp-hr NOx standard going into effect in 1998, as well as all existing standards. The effects of this rulemaking were modeled by assuming that the effect of the combined standards was equivalent to that of 2.0 g/bhp-hr NOx-only standards. This was projected using MOBILE5a by replacing the basic emission rate (BER) equations[h] for 2004 and

[h]BER equations describe emissions as a function of vehicle mileage, for properly maintained nontampered vehicles, at specific standard conditions. The equations are in the form of zero-mile level (ZML) plus the product of a deterioration rate (DR) and mileage(M):

later heavy-duty vehicles, as shown in Table 6-2. The Pechan projections of NOx emissions from heavy-duty diesel vehicles, with and without the new standards, are summarized in Table 6-3.

Table 6-2
Pechan's Basic Emission Rate Equations
for NOx from 2004 and Later Heavy-Duty Diesel Engines

	Zero-Mile Level g/bhp-hr	Deterioration Rate g/bhp-hr per 10,000 miles
MOBILE5a Default	3.19	0.000
Modified	1.84	0.000

Table 6-3
Pechan's Estimated National NOx Emissions
from Heavy-Duty Diesel Vehicles (thousand short tons per year)

Year	Without New Standards	With New Standards
2005	1,707	1,627
2010	1,728	1,346
2015	1,860	1,251
2020	2,026	1,253

EPA now believes, however, that the default NOx equations for 1991 and later diesel engines apply a safety margin below the certification emission standards that is too large. The correct equations should have zero-mile levels of 4.60 g/bhp-hr (instead of 4.00) for 1991 and later model year engines, which are subject to a 5.0 g/bhp-hr standard; 1998 and later model year engines, which are subject to a 4.0 g/bhp-hr standard, should have zero-mile levels of 3.68 g/bhp-hr (instead of 3.19). This is reflected in Table 6-4.

BER = ZML + DR×M.

Table 6-4
Basic Emission Rate Equations for
2004 and Later Heavy-Duty Diesel Engines

	Zero-Mile Level g/bhp-hr	Deterioration Rate g/bhp-hr per 10,000 miles
Without New Standard	3.68	0.000
With New Standard	1.84	0.000

It should be noted that each of these BER equations predict that emissions at the end of the useful life would be at least 5 percent below the applicable standard. This is because manufacturers include a compliance cushion in the design of their engines to account for production variability, which results in the average end-of-useful life emissions for an engine being below the level of the standard to which it was certified. The NOx inventories were corrected by multiplying the Pechan estimates for total emissions diesel vehicles by the ratios of the fleet-average NOx emission factors predicted by MOBILE5a with and without the revised BER equations. For example, for the year 2020, the MOBILE5a emission factors for heavy-duty diesel vehicles, without the new standard, were 7.57 g/mi and 6.56 g/mi, with and without the corrections, respectively. Thus, the Pechan estimate (2,026,000 tons per year) was multiplied by 7.57/6.56 (1.154) to give 2,338,000 tons per year. The effects of these revisions on the emission inventories are shown in Table 6-5.

Table 6-5
Revised Estimate of National NOx Emissions
from Heavy-Duty Diesel Vehicles (thousand short tons per year)

Year	Uncorrected Emissions Without New Standard	Corrected Emissions Without New Standard	Uncorrected Emissions With New Standard	Corrected Emissions With New Standard	Emission Reduction From New Standard
2005	1,707	1,922	1,627	1,816	106
2010	1,728	1,980	1,346	1,462	518
2015	1,860	2,146	1,251	1,314	832
2020	2,026	2,338	1,253	1,272	1,066

Figure 6-1 shows corrected projections of total NOx emissions, with and without the new engine controls for the entire nation. The emissions are projected to decline over the next several years, due to implementation of stricter controls, but then begin to increase due to growth in the number of vehicles and other sources, unless there are additional controls. By the year 2020, without these additional controls, total national NOx emissions are projected to exceed current levels. Figure 6-2 shows the corrected projections of mobile source emissions by category. The estimates of the total NOx reductions are shown in Table 6-6.

Table 6-6
Estimated National NOx Emission Reductions
from 2004 Model Year Heavy-Duty Diesel Vehicles
(thousand short tons per year)

Year	Emission Reductions
2005	106
2010	518
2015	832
2020	1,066

C. NMHC Emission Projections and Impacts

Estimates of the impact of the new standards on NMHC emissions are described below.[i] For this analysis, it was assumed that the effect of the combined standards was equivalent to 0.4 g/bhp-hr NMHC-only standards. Emissions were modeled using MOBILE5a with modified BER equations for NMHC emissions. It was necessary to modify the BER equations to account for recent certification emission data, which show that NMHC emissions are lower than predicted by the MOBILE5a default equations. It should be noted that the analysis of the NMHC emission impacts is limited to a large extent by the difficulty in projecting what the NMHC emissions from heavy-duty engines will be in the future in the absence of new standards. This difficulty arises because NMHC emission levels from heavy-duty engines are largely the incidental result of a variety of other engine design constraints, and thus are highly variable. As is described below, the fact that total HC emissions from current engines are so far below the applicable HC standards, and that they vary among different engine families by more than an order of magnitude, is evidence of the incidental nature of HC emission reductions.

[i]Heavy-duty engines do not currently have applicable NMHC standards, so the discussion in this section focuses on total hydrocarbon emissions.

Figures 6-1 goes here

Figures 6-2 goes here

Figure 6-3 shows the distribution of HC emission levels among 1994 certification diesel engine families. Only one of the 90 engine families has HC emissions that are even close to the level of the standard, and more than 90 percent of the engine families have HC emissions of 0.5 g/bhp-hr or less. (For this analysis, it is assumed that NMHC emissions from diesel engines are approximately 95 percent of total HC emissions.) Much of the reason for this is that the tight particulate standards already in place have forced manufacturers to improve combustion conditions in their engines or add catalytic aftertreatment, and both of these also reduce HC emissions; though the magnitude of the effect varies by technology and by engine. On the other hand, the use of control strategies that reduce NOx emissions often leads to increases in HC emissions. Thus, as manufacturers modify their engine designs to improve fuel economy and to comply with the lower 1998 NOx standard, HC emissions will undoubtedly change. However, determining how these emissions will change would require detailed knowledge of each manufacturer's optimization strategy. Even if the effect of these future changes could be determined, changes in the numbers of engines produced for each engine family will also change by 2004, and it would not be possible to properly weight the emissions from those engines. The average HC emissions for engines sold in the year 2004 could increase either because of increases in the emission levels of some of the engine families, or because of a market shift to engine families with higher emission levels and away from engines families with lower emission levels.

Figure 6-3

If it is assumed that the NMHC emission levels and market share for each engine family in 2004 will be the same as they were in 1994, then the net effect of a 0.4 g/bhp-hr NMHC emission standard would be very small for diesel engines. Those engines with NMHC emissions currently greater than 0.4 g/bhp-hr represented about ten percent of the sales in 1994. The reduction that would result if all of these engines certified at 0.4 g/bhp-hr NMHC would be about nine percent, based on 1994 sales data. If none of the engines families that have NMHC emissions at or below 0.4 g/bhp-hr had increases in NMHC emissions, then the total emission reduction would be the same. However, it is probable that NMHC emission would increase for some of those engine families as a result of the changes made to lower NOx emissions; thus, it is possible that there may be an even larger reduction in average NMHC emissions as a result of this action.

The potential impact of these NMHC reductions (9 percent for diesel engines) on nationwide emissions was modeled using MOBILE5a with modified BER equations for NMHC emissions, as shown in Table 6-7. The baseline emissions (without new standard) were based on the 1994 certification data. It was assumed that there is no deterioration, and that the zero-mile level was equal to the sales weighted average certification emission level. The control-case emissions were determined by reducing the zero-mile levels and deterioration rates by nine percent. The estimates of vehicle miles traveled were based on the Pechan estimates. The results are shown in Table 6-8. This approach would lead to much lower projections of VOC emissions than those predicted by the Trends Report, because the Trends Report analysis used the MOBILE5a default BER equations for HC emissions, which predict significantly higher emissions than those used here.

Table 6-7
Basic Emission Rate Equations for
HC Emissions from Heavy-Duty Diesel Engines

	Zero-Mile Level g/bhp-hr	Deterioration Rate g/bhp-hr per 10,000 miles
Without New Standard	0.283	0.000
With New Standard	0.257	0.000

Table 6-8
Estimated National NMHC Emission Reductions
for 2004 Model Year Heavy-Duty Diesel Engines
(thousand short tons per year)

Year	Emission Reductions
2004	1.5
2005	2.2
2006	2.9
2007	3.9
2008	4.7
2009	5.6
2010	6.8
2011	7.7
2012	8.9
2013	10.0
2014	11.0
2015	12.1
2016	13.0
2017	13.9
2018	14.8
2019	15.7
2020	16.4

II. Per-Vehicle Emission Impacts

In addition to the fleet analysis described above, EPA estimated the per-vehicle NOx and NMHC emission reductions due to the new standards over the life of average heavy-duty diesel vehicles. The per-vehicle reductions were predicted for the three different categories of heavy-duty diesel vehicles covered by the new engine standards. The resulting lifetime emission reductions are used in Chapter 7 for determining the per-vehicle cost-effectiveness of the new standards.

To calculate the per-vehicle emission reductions, two pieces of information are needed: vehicle-specific emission factors (in grams per mile) and yearly mileage accumulation rates over the life of an average heavy-duty diesel vehicle. The following section presents the information used in calculating the per-vehicle NOx and NMHC emission reductions over the life of average heavy-duty diesel vehicles as well as the estimated per-vehicle NOx and NMHC emission reductions.

A. Per-Vehicle Emission Factors

Sections II.B and II.C of this chapter present the per-vehicle NOx and NMHC zero-mile emission level and deterioration rates, respectively, assumed in modeling the nationwide emission inventories. Both sections present the assumptions for vehicles complying with the new standards and for vehicles designed in the absence of tighter 2004 standards (i.e., subject to the standards in effect immediately prior to the 2004 model year). The emission reduction due to the new standards is the difference between the two numbers. Estimated brake-specific, zero-mile emission reductions are 1.84 g/bhp-hr for NOx and 0.026 g/bhp-hr for NMHC.

To estimate emissions on a gram-per-mile basis, EPA multiplies the brake-specific emission levels (g/bhp-hr) by "conversion factors." For this analysis, EPA used conversion factors for specific vehicle classes, as derived from the information contained in the EPA technical report, "Heavy-Duty Vehicle Emission Conversion Factors II" (EPA-AA-SDSB-89-01, October 1988). To estimate the conversion factors for the various heavy-duty diesel vehicle categories, EPA weighted the individual class conversion factors by the sales estimates contained in the report noted above using the information presented for model year 2000 and later. Table 6-9 contains the resulting conversion factors for the different categories of heavy-duty diesel vehicles presented in this analysis.

Table 6-9
Conversion Factors for Heavy-Duty Diesel Vehicles

Vehicle Category	Conversion Factor (bhp-hr/mi)
Light HD	0.919
Medium HD	2.07
Heavy HD	3.10

Table 6-10 presents the estimated zero-mile level emission reductions due to the new standards based on the conversion factors listed above.

Table 6-10
Difference in Emission Levels
Due to the New Standards for Heavy-duty Diesel Engines

Vehicle	Zero Mile Level Reduction (g/mi)	
	NOx	NMHC
Light HD	1.69	0.024
Medium HD	3.81	0.054
Heavy HD	5.70	0.081

B. Per-Vehicle Average Mileage Accumulation Rates

Table 6-11 contains the MOBILE5 mileage accumulation rates used in this analysis to predict the mileage accumulation rates for average heavy-duty vehicles over a 30-year period.

The mileage accumulation rates contained in Table 6-11 represent the number of miles a heavy-duty diesel vehicle would drive in a given year assuming the vehicle had not been scrapped (i.e., removed from the fleet) for some reason. In order to estimate the per-vehicle average mileage accumulation rates for the average vehicle in the fleet it is necessary to factor in the effect of scrappage. MOBILE5 contains information on the registration distribution of heavy-duty diesel vehicles by model year, but it does not include explicit scrappage rates. An attempt was made to determine the scrappage rates that would provide the same registration distribution contained in MOBILE5. However, because the MOBILE5 registration distributions are based on a snapshot of the 1990 fleet and therefore include the effects of sales swings in the heavy-duty vehicle market, EPA was unable to develop scrappage rates that would reproduce the registration distribution contained in MOBILE5. For this reason, EPA used the registration distributions contained in the EMFAC7F model developed by the California Air Resource Board to predict the scrappage rates for heavy-duty diesel vehicles. The registration distributions contained in the EMFAC7F model represent an average registration distribution and do not include the impact of year to year sales swings. Table 6-12 contains the resulting survival rates for heavy-duty diesel vehicles used in this analysis. For a given vehicle age, the numbers contained in Table 6-12 represent the fraction of the original number of vehicles sold that are still in existence at that point in time.

Table 6-13 contains the average annual mileage accumulation rates for heavy-duty diesel vehicles factoring in the effect of scrappage. The average life totals contained at the bottom of Table 6-13 represent the number of miles an average heavy-duty diesel vehicle accumulates over a 30-year life.

Based on the average life totals contained in Table 6-13, EPA determined the number of years it would take for vehicles to accumulate that level of mileage based on the mileage accumulation rates in Table 6-11 (i.e., rates that do not factor in scrappage). Table 6-14 contains the years it takes for a heavy-duty diesel vehicle to accumulate the average lifetime mileage.

Table 6-11
MOBILE5 Mileage Accumulation Rates by Vehicle Category

Vehicle Age	HDDVs		
	Light	Medium	Heavy
1	22,517	26,081	62,176
2	20,009	25,204	58,663
3	17,779	24,357	55,348
4	15,798	23,538	52,220
5	14,038	22,746	49,269
6	11,474	21,982	46,485
7	11,084	21,243	43,858
8	9,849	20,528	41,380
9	8,752	19,838	39,042
10	7,777	19,171	36,836
11	6,910	18,527	34,754
12	6,140	17,904	32,790
13	5,456	17,302	30,937
14	4,848	16,720	29,189
15	4,308	16,158	27,540
16	3,828	15,614	25,983
17	3,402	15,089	24,515
18	3,023	14,582	23,130
19	2,686	14,092	21,823
20	2,387	13,618	20,590
21	2,121	13,160	19,426
22	1,884	12,718	18,328
23	1,675	12,290	17,293
24	1,488	11,877	16,315
25	1,322	11,478	15,393
26	1,322	11,478	15,393
27	1,322	11,478	15,393
28	1,322	11,478	15,393
29	1,322	11,478	15,393
30	1,322	11,478	15,393
Total	198,165	503,207	920,248

Table 6-12
Estimated Vehicle Survival Rates

Vehicle Age	Registration Distribution
1	1.000
2	1.000
3	0.909
4	0.851
5	0.827
6	0.827
7	0.827
8	0.788
9	0.749
10	0.668
11	0.598
12	0.540
13	0.466
14	0.417
15	0.395
16	0.387
17	0.363
18	0.339
19	0.315
20	0.304
21	0.278
22	0.251
23	0.238
24	0.238
25	0.213
26	0.177
27	0.142
28	0.106
29	0.071
30	0.035

Table 6-13
Average Mileage Accumulation Rates
by Vehicle Category (Factoring in Scrappage)

Vehicle Age	HD Diesel		
	Light	Medium	Heavy
1	22,517	26,081	62,176
2	20,009	25,204	58,663
3	16,157	22,135	50,299
4	13,437	20,020	44,415
5	11,607	18,807	40,736
6	10,314	18,176	38,437
7	9,164	17,563	36,260
8	7,764	16,182	32,620
9	6,551	14,849	29,223
10	5,195	12,807	24,608
11	4,134	11,084	20,793
12	3,314	9,664	17,700
13	2,541	8,058	14,407
14	2,022	6,974	12,174
15	1,702	6,384	10,881
16	1,480	6,038	10,048
17	1,236	5,484	8,910
18	1,026	4,949	7,850
19	845	4,432	6,864
20	726	4,140	6,260
21	589	3,655	5,395
22	472	3,187	4,593
23	399	2,930	4,123
24	355	2,832	3,890
25	281	2,444	3,277
26	235	2,036	2,731
27	188	1,629	2,185
28	141	1,222	1,639
29	94	815	1,092
30	47	407	546
Avg. Life-time miles	145,000	280,000	560,000

Table 6-14
Heavy-Duty Vehicle Average Lifetimes (years)

Light HD	Medium HD	Heavy HD
10	13	12

C.	Estimated Per-Vehicle Average Lifetime Emission Reductions

Table 6-15 contains the per-vehicle average lifetime NOx and NMHC emission reductions, both discounted (at a rate of three percent) and undiscounted, for the various categories of heavy-duty diesel vehicles. The numbers are based on the emission reductions contained in Table 6-10 and the annual mileage accumulation rates contained in Table 6-11 summed over the number of years it takes to achieve the average lifetime total mileage.

Table 6-15
Per-Vehicle Average Lifetime Emission Reductions
Due to the New Standards for Heavy-Duty Diesel Engines

Vehicle Category	Undiscounted Reductions (lbs.)		Discounted Reductions (lbs.)	
	NOx	NMHC	NOx	NMHC
Light HD	540	10	480	10
Medium HD	2,350	30	2,000	30
Heavy HD	7,040	100	6,120	90

III. Environmental Impacts of Emission Reductions

A. Ozone Impacts

The effect of the reduced NOx emissions on ozone concentrations is expected to vary geographically. In general, when fully phased-in, the effect of this action in most nonattainment areas should be a reduction in ozone concentrations on the order of a few percent. It should be noted, however, that the potential exists for a few localized areas to actually experience slight increases in ozone concentrations as a result of NOx emission reductions. The effect of the NMHC reductions on ozone concentrations will be positive, though relatively small.

B. Particulate Impacts

The new emission standards should not affect particulate emissions from heavy-duty engines, since they do not change the particulate standard. However, the NOx reductions described above are expected to provide reductions in the concentrations of secondary nitrate particulates. As described in Chapter 2, NOx can react with ammonia in the atmosphere to form ammonium nitrate particulates, especially when ambient sulfur levels are relatively low.

EPA contracted with Systems Applications International (SAI) to investigate the formation of secondary nitrate particulates in the United States.[4] SAI used a combination of ambient concentration data and computer modeling that simulates atmospheric conditions to estimate the conversion of NOx to PM nitrate. For the purpose of modeling, the continental 48 states were divided into nine regions, and rural areas were distinguished from urban areas. The model was designed to perform the equilibrium calculation to estimate particulate nitrate formation for different regions, seasons, and times of day and then was calibrated using ambient data.

Ambient data was collected from 72 ozone, 64 NOx, and 14 NOMC monitoring sites for use in the oxidation calculations. Data was also collected from 45 nitrate/NOx monitoring sites for use in the equilibrium calculations. SAI admitted that, in a number of regions, the available data from monitoring sites was limited and stated that more data would improve confidence in the results from these regions. However, EPA has reviewed the SAI report and its associated uncertainty analysis and believes that is the best estimate of atmospheric NOx to PM nitrate conversion rates available today.

The results from the SAI report state that the fraction of NOx converted to nitrates (g/g) ranges from 0.01 in the northeast to 0.07 in southern California. Based on the vehicle miles traveled in the various regions, the average fraction of NOx converted to nitrates is approximately 0.04. This value changes slightly from year-to-year due to the effects of ozone and SOx projections on the calculations for future years. The effects of the conversion fraction on future PM reductions is shown in Table 6-16.

Table 6-16
Estimated Equivalent National Particulate Emission Reductions
from 2004 Model Year Heavy-Duty Engines (thousand short tons per year)

Year	Total NOx Emission Reductions	Equivalent Particulate Emission Reductions
2005	106	5
2010	518	22
2015	832	35
2020	1,066	44

C. Other Impacts of Emission Reductions

The expected reductions in NOx emissions should also positively effect visibility, acid deposition, and estuary eutrophication. As noted in Chapter 2, both NO_2 and nitrate particulates are optically active, and in some urban areas, NO_2 and nitrate particulates can be responsible for 20 to 40 percent of the visible light extinction. The effect of this action on visibility should be small but potentially significant, given that it is expected to reduce overall NOx emissions by several percent. For example, the new engine controls are expected to result in about five percent less total NOx in the year 2020, and therefore would be expected to decrease haze by about one percent in an area where NO_2 and nitrate particulates cause 20 percent of the haze.

The new standards are also expected to provide benefits with respect to acid deposition. The 1.2 million ton per year reduction in NOx emissions expected in 2020 as a result of this action is greater than the 400,000 ton per year reduction expected from Phase I of the Agency's acid rain NOx control rule (59 FR 13538, March 22, 1994), which was considered to be a significant step toward controlling the ecological damage caused by acid deposition. It is not clear, however, that reducing emissions of NOx from ground-level sources such as heavy-duty vehicles is truly equivalent to reducing NOx emissions from elevated smokestacks, since NOx emitted higher into the atmosphere is likely to travel further downwind, undergoing additional reactions before deposition. Nevertheless, it is clear that there will be some significant reduction in the adverse effects of acid deposition as a result of this rule.

This action should also lead to a reduction in the nitrogen loading of estuaries. This is significant since high nitrogen loadings can lead to eutrophication of the estuary, which causes disruption in the ecological balance. The effect should be most significant in areas heavily affected by atmospheric NOx emissions. One such estuary is Chesapeake Bay, where as much as 40 percent of the nitrogen loading may be caused by atmospheric deposition.

IV. Summary

The projected total NOx and NMHC emission reductions expected as a result of this action are shown in Figure 6-4. NOx reductions are projected to exceed 1.2 million tons per year in 2020, which would be a five percent reduction in the total NOx inventory. NMHC reductions are projected to be much smaller, about 25,000 tons per year in 2020, which would be much less than one percent of the national NMHC (or VOC) inventory. These emission reductions are expected to contribute very significantly towards reducing and controlling ambient ozone levels in the future, counteracting the expected effects of new sources and growth in vehicle miles traveled. The new controls would also result in benefits with respect to nitrate particulates, visibility, acid deposition, and estuarine eutrophication.

Figure 6-4 goes here

CHAPTER 6 References

1. “National Air Pollutant Emission Trends, 1900-1993", EPA-454/R-94-027.

2. Inventory Development Summary Report From E.H. Pechan and Associates, Draft, August 1995, EPA Docket A-95-27, # II-A-11.

3. Inventory Development Summary Report from E.H. Pechan and Associates, Docket A-95-27, # II-A-11.

4.   “Benefits of Mobile Source NOx Related Particulate Matter Reductions,” Systems Applications International, EPA Contract No. 68-C5-0010, WAN 1-8, October 1996.

CHAPTER 7: COST-EFFECTIVENESS

This chapter assesses the cost-effectiveness of the requirements being finalized for new heavy-duty diesel engines, including the new standards, useful life, allowable maintenance and rebuild provisions. This analysis relies in part on cost information from Chapter 5 and emissions information from Chapter 6 to estimate the cost-effectiveness of the provisions in terms of dollars per ton of total emission reductions. This chapter also examines the sensitivity of the cost-effectiveness numbers for the provisions under varying assumptions regarding fuel economy impacts and maintenance costs, and different assumptions regarding the cost of technologies likely to be used to comply with the standards being finalized. Finally, the chapter compares the cost-effectiveness of the new provisions with the cost-effectiveness of other NOx control strategies from previous EPA rules.

The analysis presented in this chapter is performed for heavy-duty diesel vehicles (including a breakout for individual heavy-duty diesel categories). The analysis is performed on a per-vehicle basis and examines total costs and total NOx plus NMHC emission reductions over the typical lifetime of a heavy-duty diesel vehicle, discounted at a rate of three percent to the beginning of the vehicle's life. An analysis of the fleet cost-effectiveness for 30 model years after the new engine standards take effect is also presented.

The cost-effectiveness of the provisions is analyzed under two different cost-effectiveness scenarios. The first scenario presents the nationwide cost-effectiveness in which the net present value (NPV) of the total life-cycle costs is divided by the discounted lifetime NOx plus NMHC emission benefits. The second scenario presents a regional ozone control strategy cost-effectiveness in which the net present value of the total life-cycle costs is divided by the discounted lifetime NOx plus NMHC emission benefits after adjusting for the fraction of emissions that occur in the regions that are expected to impact ozone levels in ozone nonattainment areas. Air quality modeling indicates that these regions include all of the states that border on the Mississippi River, all of the states east of the Mississippi River, Texas, California, and any remaining ozone nonattainment areas west of the Mississippi River not already included. Based on the emission modeling performed in support of the environmental impacts analysis presented in Chapter 6, it was estimated that approximately 87 percent of the nationwide NOx and VOC emissions from heavy-duty vehicles occur in these regions. (See also Chapter 2 for additional discussion of this regional approach.) Therefore, for the regional ozone control strategy cost-effectiveness calculations, the per-vehicle NOx plus NMHC emission reductions were multiplied by a factor of 0.87 (i.e., reduced by 13 percent) to account for the impact that the new engine standards will have on ozone levels in ozone nonattainment areas.

The following section describes the cost-effectiveness of the new engine NOx and NMHC standards for the various categories of heavy-duty diesel vehicles noted above. As discussed in Chapter 5, the estimated cost of complying with the provisions varies depending on the model year under consideration. Therefore, the following section presents the per-vehicle cost-effectiveness results for the different model years during which the costs are expected to change. Just as the emission standard combines NOx and NMHC emissions, the cost-effectiveness of adopting the new standard is calculated by dividing the combined NOx and NMHC emission reductions into the cost of compliance.

Also presented is the fleet cost-effectiveness over the first 30 model years after the new engine standards take effect (i.e., model years 2004 through 2033). These cost-effectiveness numbers are calculated by weighting the various model year per-vehicle cost-effectiveness results by the fraction of the total 30 model year sales they represent. The sales for the different categories of heavy-duty diesel engines that would be covered by the rule based on the 1995 model year were determined using production information provided by manufacturers to EPA and were assumed to grow at a linear rate of two percent from the 1995 levels. Table 7-1 contains the numbers used in the cost-effectiveness analysis of 1995 model year heavy-duty diesel engines affected by the new emission standards.

Table 7-1
1995 Model Year Production of Affected Heavy-Duty Diesel Engines

Light HD	Medium HD	Heavy HD
280,000	140,000	220,000

A copy of the spreadsheets prepared for this cost-effectiveness analysis has been placed in the public docket for this rulemaking. The reader is directed to the spreadsheets for a complete version of the cost-effectiveness calculations.

I. Cost-Effectiveness of the NOx and NMHC Emission Standards

Tables 7-2, 7-3, and 7-4 contain the total net present value costs based on the information presented in Chapter 5, the lifetime emission reductions as presented in Chapter 6, and the resulting cost-effectiveness values for the two cost-effectiveness scenarios described earlier for light-, medium-, and heavy-heavy duty diesel vehicles, respectively. Tables 7-2, 7-3 and 7-4 also contain the fleet cost-effectiveness covering the first 30 model years after the new engine standards take effect (i.e., model years 2004 through 2033).

Table 7-2
Cost-Effectiveness for Light Heavy-Duty Diesel Vehicles

Model Year Grouping	Total NPV Costs per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton)	
		NOx	NMHC	Nationwide Scenario	Regional Strategy Scenario
2004-05	$265	0.242	0.003	$1100	$1200
2006-08	$231			$900	$1100
2009+	$117			$500	$500
30 Year Fleet	—	—	—	$600	$700

Table 7-3
Cost-Effectiveness for Medium Heavy-Duty Diesel Vehicles

Model Year Grouping	Total NPV Costs per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton)	
		NOx	NMHC	Nationwide Scenario	Regional Strategy Scenario
2004-05	$459	1.002	0.014	$500	$500
2006-08	$417			$400	$500
2009+	$198			$200	$200
30 Year Fleet	—	—	—	$200	$300

Table 7-4
Cost-Effectiveness for Heavy Heavy-Duty Diesel Vehicles

Model Year Grouping	Total NPV Costs per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton)	
		NOx	NMHC	Nationwide Scenario	Regional Strategy Scenario
2004-05	$598	3.059	0.043	$200	$200
2006-08	$542			$200	$200
2009+	$311			$100	$100
30 Year Fleet	—	—	—	$100	$100

Table 7-5 contains the total net present value costs, the lifetime emission reductions, and the resulting cost-effectiveness values for all heavy-duty diesel vehicles for the two cost-effectiveness scenarios described earlier. In determining the cost-effectiveness for all heavy-duty diesel vehicles, the cost and emission reductions for all heavy-duty diesel vehicles were determined by weighting the corresponding light, medium, and heavy heavy-duty diesel vehicle results by the respective sales estimates for each year.

Table 7-5
Cost-Effectiveness for All Heavy-Duty Diesel Vehicles

Model Year Grouping	Total Average NPV Costs per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton)	
		NOx	NMHC	Nationwide Scenario	Regional Strategy Scenario
2004-05	$422	1.377	0.019	$300	$300
2006-08	$379			$300	$300
2009+	$202			$100	$200
30 Year Fleet	—	—	—	$200	$200

In addition to the primary benefit of reducing ozone within and transported into urban ozone nonattainment areas, the NOx reductions from the new engine standards are expected to have secondary benefits as well. These secondary benefits include impacts with respect to human mortality, human morbidity, agricultural yields, visibility, soiling (due to secondary particulate), and ecosystems (e.g., through the reduced effects of acid deposition and eutrophication). In order to estimate the monetary value of these secondary benefits to society, ICF Incorporated prepared a study summarizing the results of a variety of studies that examined the value of ozone control on the secondary benefits highlighted above.[5] Table 7-6 contains a summary of the results of the ICF report. The total value of all the secondary benefits is estimated to $967 per metric ton of NOx reduction. It should be noted that the cost-effectiveness analysis presented in this chapter does not assign any value to these secondary benefits. They are presented in this chapter for informational purposes only.

Table 7-6
Summary of Estimated Monetized Benefits per Ton

Benefit Category	Point Estimate of Benefits per Metric Ton of NOx Reduction
Human Mortality	$343
Human Morbidity	$11
Agricultural Yields	$316
Soiling	$19
Ecosystems	$18
Visibility	$260

II. Cost-Effectiveness Sensitivity Analyses

The following section presents an analysis of the sensitivity of the cost-effectiveness results for heavy-duty diesel vehicles to different assumptions regarding the impact of the new standards on fuel economy and maintenance costs. Based on the substantial lead time available and the R&D expected, EPA is not projecting losses in fuel economy, engine durability, or increased maintenance. Even if such impacts were to occur for a few engines, they would be short-term in nature. Nonetheless, it is of value to examine the sensitivity of the cost-effectiveness estimates to potential short-term changes. The sensitivity of the estimated heavy-duty diesel vehicle cost-effectiveness results to different projections regarding the cost of technologies that will be needed to comply with the new standards is also examined.

A. Sensitivity to Fuel Economy Penalty

Table 7-7 contains the discounted per-vehicle lifetime cost associated with a ½ percent fuel economy penalty calculated over the typical lifetime of heavy-duty diesel vehicles. As discussed above, it is projected that any fuel economy penalty would be short-term. For this analysis, the fuel economy penalty was assumed to apply for the first five model years (i.e., 2004 through 2008) only.

Table 7-7
Discounted Per-Vehicle Lifetime Operating Costs
Associated with a ½ Percent Fuel Economy Penalty

Light HD	Medium HD	Heavy HD	All Heavy-Duty
$52	$133	$450	$207

To calculate the cost-effectiveness of the new standards with the fuel economy penalty, the fuel economy penalty costs in Table 7-7 were added to the per-vehicle costs (contained in Table 7-5) and then divided by the emission reductions (as presented in Table 7-5). Table 7-8 contains the resulting discounted per-vehicle cost-effectiveness numbers.

Table 7-8
Cost-Effectiveness for All Heavy-Duty Diesel Vehicles
Assuming an Average ½ Percent Fuel Economy Penalty

Model Year Grouping	Total NPV Costs per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton)	
		NOx	NMHC	Nationwide Scenario	Regional Strategy Scenario
2004-05	$629	1.377	0.019	$400	$500
2006-08	$585			$400	$500
2009+	$202			$100	$200
30 Year Fleet	—	—	—	$200	$200

Comparing the 30-year fleet cost-effectiveness results in Table 7-8 with those presented in Table 7-5, it can be seen that a fuel economy penalty of 0.5 percent has only a slight impact on the cost-effectiveness results.

B. Sensitivity to Increased Maintenance Costs

As described in Chapter 5, it is possible that there may be greater maintenance costs associated with exhaust gas recirculation (EGR), such as increased oil capacity and therefore increased oil change costs. Table 7-9 contains the discounted per-vehicle lifetime cost associated with increased oil capacity assuming that 25 percent of vehicles would have their oil capacity increased by 10 percent. (The remaining 75 percent of vehicles continue to have slightly increased oil change costs for the reasons described in Chapter 5.)

Table 7-9
Discounted Per-Vehicle Lifetime Maintenance
Costs Associated with Increased Oil Capacity

Light HD	Medium HD	Heavy HD	All Heavy-Duty
$9	$14	$36	$19

To calculate the cost-effectiveness of the new standards with the increased maintenance costs, the increased maintenance costs in Table 7-9 were added to the per-vehicle costs (contained in Table 7-5) and then divided by the emission reductions (as presented in Table 7-5). Table 7-10 contains the resulting discounted per-vehicle cost-effectiveness numbers.

Comparing the 30 year fleet cost-effectiveness results in Table 7-10 with the results presented in Table 7-5, it can be seen that the increased maintenance cost has almost no effect on cost-effectiveness.

C. Sensitivity to the Cost of Projected Compliance Technologies

As described in Chapter 5, there is some uncertainty regarding the exact mix of technologies that will be used to comply with the new standards. For this analysis, EPA did not attempt to project different technology mixes than those contained in Chapter 5. However, to determine the sensitivity of these cost effectiveness projections to potentially higher cost estimates that could be associated with different technology projections, EPA assumed a first year incremental per-engine cost of $100 for all categories of heavy-duty diesel vehicles above those established in Chapter 5 (and summarized in Table 7-5). Table 7-11 contains the resulting discounted per-vehicle cost-effectiveness numbers assuming the higher technology costs.

Table 7-10
Cost-Effectiveness for All Heavy-Duty Diesel Vehicles
Assuming Increased Oil Capacity on 25 Percent of Vehicles

Model Year Grouping	Total NPV Costs per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton)	
		NOx	NMHC	Nationwide Scenario	Regional Strategy Scenario
2004-05	$441	1.377	0.019	$300	$400
2006-08	$398			$300	$300
2009+	$221			$200	$200
30 Year Fleet	—	—	—	$200	$200

Table 7-11
Cost-Effectiveness for All Heavy-Duty Diesel Vehicles
Assuming Incrementally Higher Technology Costs

Model Year Grouping	Total NPV Costs per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton)	
		NOx	NMHC	Nationwide Scenario	Regional Strategy Scenario
2004-05	$522	1.377	0.019	$400	$400
2006-08	$459			$300	$400
2009+	$266			$200	$200
30 Year Fleet	—	—	—	$200	$300

Comparing the 30 year fleet cost-effectiveness results in Table 7-11 with those presented in Table 7-5, it can be seen that higher technology costs leads to slightly higher cost-effectiveness results.

III. Comparison of Cost-Effectiveness with Other NOx Control Strategies

In an effort to evaluate the cost-effectiveness of the new standards, EPA has summarized the cost-effectiveness results for two other recent EPA mobile source rulemakings that required reductions in NOx emissions, the primary focus of the new standards. Table 7-12 summarizes the cost-effectiveness results from the heavy-duty vehicle portion of the Clean Fuel Fleet Vehicle Program and Phase II of the Reformulated Gasoline Program.

Table 7-12
Summary of Cost-Effectiveness Results for Recent EPA Programs

EPA Final Rule	Pollutants Considered in Calculations	Cost-Effectiveness ($/ton)
Clean Fuel Fleet Vehicle Program (Heavy-duty)	NOx	$1,300-1,500
Reformulated Gasoline—Phase II	NOx	$5,000

A comparison of the cost-effectiveness numbers in Table 7-12 with the cost-effectiveness results presented throughout this chapter shows that the cost-effectiveness of the new engine standards are more favorable than the cost-effectiveness of these recent EPA mobile source programs that addressed NOx emissions.

Chapter 7 References

Appendix to the Regulatory Impact Analysis

Table A-1 contains the year by year fleetwide costs and NOx emission reductions associated with the new engine standards for the twenty year period from 2004 to 2023. (The numbers presented in Table A-1 are not discounted.)

Table A-1
Costs and NOx Benefits of the New HDDE Standard

Calendar Year	Fleetwide Costs	Fleetwide NOx Reductions (tons)
2004	$241,500,000	53,000
2005	$246,000,000	106,000
2006	$216,300,000	188,400
2007	$219,900,000	270,800
2008	$223,300,000	353,200
2009	$122,600,000	435,600
2010	$125,600,000	518,000
2011	$128,500,000	580,800
2012	$131,400,000	643,600
2013	$134,000,000	706,400
2014	$163,100,000	769,200
2015	$166,000,000	832,000
2016	$169,000,000	878,800
2017	$171,900,000	925,600
2018	$174,700,000	972,400
2019	$177,600,000	1,019,200
2020	$180,400,000	1,066,000
2021	$183,200,000	1,112,800
2022	$186,000,000	1,159,600
2023	$188,800,000	1,206,400

Table A-2 contains the discounted year by year fleetwide costs and NOx emission reductions associated with the new engine standards for the twenty year period from 2004 to 2023. The year by year results were discounted to 2004 and a discount rate of seven percent was assumed for the analysis.

Table A-2

Discounted Costs and NOx Benefits of the New HDDE Standard

Calendar Year	Discounted Fleetwide Costs	Discounted Fleetwide NOx Reductions (tons)
2004	$241,500,000	53,000
2005	$229,900,000	99,100
2006	$188,900,000	164,600
2007	$179,500,000	221,100
2008	$170,400,000	269,500
2009	$87,400,000	310,600
2010	$83,700,000	345,200
2011	$80,000,000	361,700
2012	$76,500,000	374,600
2013	$72,900,000	384,200
2014	$82,900,000	391,000
2015	$78,900,000	395,300
2016	$75,100,000	390,200
2017	$71,300,000	384,100
2018	$67,800,000	377,100
2019	$64,400,000	369,400
2020	$61,100,000	361,100
2021	$58,000,000	352,300
2022	$55,000,000	343,100
2023	$52,200,000	333,600

Summing the discounted annual costs and discounted NOx reductions over the 20 year period yields a 20-year fleetwide cost of $2.1 billion and a 20-year NOx reduction of 6.3 million tons. The resulting 20-year annualized fleetwide costs and NOx reductions are $196 million per year and 593,000 tons per year, respectively. The complete analysis of the 20-year costs and emission benefits of the new standards has been included in the memo to the docket describing the cost-effectiveness analysis of the new standards.

5. "Benefits of Reducing Mobile Source NOx Emissions," prepared by ICF Incorporated for Office of Mobile Sources, U.S. EPA, Draft Final, September 30, 1996.