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

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Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

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CHAPTER 1: INTRODUCTION

The Regulatory Impact Analysis (RIA) for this rule presents analysis and supporting data for the provisions EPA is reviewing or promulgating for model year 2004 and later on-highway heavy-duty diesel and otto-cycle engines and vehicles. This chapter presents a brief summary of each chapter contained in the (RIA) that follows.

I. Summary of the Regulatory Impact Analysis

A. Chapter 2—Health and Welfare Concerns

Chapter 2 provides an overview of the health and environmental effects associated with ozone, particulate matter, and other harmful pollution associated with emissions from heavy-duty engines and vehicles. Chapter 2 reviews some of EPA's key concerns at this time. The chapter also provides national NOx and VOC emissions inventories and emissions trends, with specific emphasis on the contribution from on-highway heavy-duty diesel and otto-cycle vehicles.

B. Chapter 3—Technological Feasibility of HD Diesel and Otto-cycle Standards

To achieve the standards reviewed or promulgated in this rule, heavy-duty engine manufacturers will need to consider a combination of new and existing emission control devices. Chapter 3 presents the technologies available and discusses their ability to reach the required emission levels. Chapter 3 is divided into two major sub-chapters, the first dealing with HD diesel technologies, and the second with HD otto-cycle technologies.

C. Chapter 4—Economic Impact of HD Diesel Standards

Chapter 4 presents EPA's best assessment of the economic impacts which will result from the HD diesel standards. The assessment includes EPA's estimates of the technology packages manufactures will use, as well as the costs associated with new certification and compliance requirements. Costs are estimated on a per-vehicle basis, as well as an aggregate cost to society. Chapter 4 also includes an analysis which indicates how sensitive the cost assessment is to some of EPA's best estimates.

D. Chapter 5—Economic Impact of HD Otto-cycle Standards

Chapter 5 presents EPA's best assessment of the economic impacts which will result from the HD otto-cycle engine and vehicle standards. The assessment includes EPA's estimates of the technology packages manufactures will use, as well as the costs associated with new certification and compliance requirements. Costs are estimated on a per-vehicle basis, as well as an aggregate cost to society.

E. Chapter 6—Environmental Impact of HD Diesel Standards

Chapter 6 describes the expected environmental impacts of the HD diesel engine NMHC plus NOx emissions standards described in the preamble for this rule. The modeling methodology and assumptions used to estimate nationwide NOx and VOC emission inventories (i.e., tons of pollutant per year) are described, and the estimated benefits are presented. In addition, estimates of nationwide PM inventories for HD diesel vehicles are presented.

F. Chapter 7—Environmental Impact of HD Otto-cycle Standards

Chapter 7 describes the expected environmental impacts of the exhaust and ORVR standards for heavy-duty gasoline engines and vehicles described in the previous chapters. Specifically, the chapter includes a description of how heavy-duty gasoline vehicle emission factors were developed, the per-vehicle exhaust emission reductions due to the standards over the life of heavy-duty gasoline vehicles, the estimated exhaust NOx and NMHC emission inventories from heavy-duty gasoline vehicles, and the exhaust emission benefits from the exhaust standards. The chapter also includes a description of the emission benefits from the ORVR requirements for Class 2b heavy-duty gasoline vehicles.

G. Chapter 8—Cost-effectiveness for HD Diesel and Otto-cycle Requirements

Chapter 8 presents EPA's estimated cost-effectiveness of the requirements for new heavy-duty engines, including the new standards and related requirements, OBD, useful life, allowable maintenance, in-use testing, and rebuild provisions. This analysis relies in part on cost information from Chapters 4 and 5 and emissions information from Chapters 6 and 7 to estimate the cost-effectiveness of the provisions in terms of dollars per ton of total emission reductions. Separate analyses were performed for otto-cycle engines and diesel engines. Cost-effectiveness values are presented on a per-vehicle basis using total costs and total NOx plus NMHC emission reductions over the typical lifetime of a heavy-duty vehicle, discounted at a rate of seven percent to the beginning of the vehicle's life. Analyses of the fleet cost-effectiveness for 30 model years after the new engine standards take effect are also presented.

CHAPTER 2: HEALTH AND WELFARE CONCERNS

I. Health and Welfare Concerns

A. Health and Welfare Effects from NMHC and NOx

Ground-level ozone, the main ingredient in smog, is formed by complex chemical reactions of volatile organic compounds (VOC) and nitrogen oxides (NOx) in the presence of heat and sunlight. Ozone forms readily in the lower atmosphere, usually during hot summer weather. VOCs are emitted from a variety of sources, including motor vehicles, chemical plants, refineries, factories, consumer and commercial products, and other industrial sources. VOCs also are emitted by natural sources such as vegetation. NOx is emitted largely from motor vehicles, nonroad equipment, power plants, and other sources of combustion.

The science of ozone formation, transport, and accumulation is complex. Ground-level ozone is produced and destroyed in a cyclical set of chemical reactions involving NOx, VOC, heat, and sunlight.[a] As a result, differences in NOx and VOC emissions and weather patterns contribute to daily, seasonal, and yearly differences in ozone concentrations and differences from city to city. Many of the chemical reactions that are part of the ozone-forming cycle are sensitive to temperature and sunlight. When ambient temperatures and sunlight levels remain high for several days and the air is relatively stagnant, ozone and its precursors can build up and produce more ozone than typically would occur on a single high temperature day. Further complicating matters, ozone also can be transported into an area from pollution sources found hundreds of miles upwind, resulting in elevated ozone levels even in areas with low VOC or NOx emissions.

Based on a large number of recent studies, EPA has identified several key health effects caused when people are exposed to levels of ozone found today in many areas of the country.[1, 2] Unless noted otherwise, the studies discussed in the remainder of sections I(A) and I(B) of this Chapter are from references (1) and (2), EPA Report EPA-452/R-96-007 and EPA Report EPA/600/P-93/004aF respectively. Short-term exposures (1-3 hours) to high ambient ozone concentrations have been linked to increased hospital admissions and emergency room visits for respiratory problems. For example, studies conducted in the northeastern U.S. and Canada show that ozone air pollution is associated with 10-20 percent of all of the summertime respiratory-related hospital admissions. Repeated exposure to ozone can make people more susceptible to respiratory infection and lung inflammation and can aggravate preexisting respiratory diseases, such as asthma. Exposure to ozone can cause repeated inflammation of the lung, impairment of lung defense mechanisms, and irreversible changes in lung structure, which could lead to premature aging of the

(a) Carbon monoxide also participates in the production of ozone, albeit at a much slower rate than most VOC and NOx compounds.

lungs and/or chronic respiratory illnesses such as emphysema, chronic bronchitis and chronic asthma.

Children are most at risk from ozone exposure because they typically are active outside, playing and exercising, during the summer when ozone levels are highest. For example, summer camp studies in the eastern U.S. and southeastern Canada have reported significant reductions in lung function in children who are active outdoors. Further, children are more at risk than adults from ozone exposure because their respiratory systems are still developing. Adults who are outdoors and moderately active during the summer months, such as construction workers and other outdoor workers, also are among those most at risk. These individuals, as well as people with respiratory illnesses such as asthma, especially asthmatic children, can experience reduced lung function and increased respiratory symptoms, such as chest pain and cough, when exposed to ozone during periods of moderate exertion.

Evidence also exists of a possible relationship between daily increases in ozone levels and increases in daily mortality levels. While the magnitude of this relationship is still too uncertain to allow for direct quantification, the full body of evidence indicates a likely positive relationship between ozone exposure and premature mortality.

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.[3] NOx also is a contributor to acid deposition, which can damage trees at high elevations and increases the acidity of lakes and streams, which can severely damage aquatic life. Finally, NOx emissions can contribute to increased levels of particulate matter by changing into nitric acid in the atmosphere and forming particulate nitrate.

In addition to their contribution to ozone levels, emissions of NMHC contain toxic air pollutants that may have a significant effect on the public health, as discussed below.

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.[4]

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 the 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 crop land, 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. Need for Ozone Control

A. Standards for 2004 HD Diesels Are a Key Part of State Air Pollution Control Plans

Since we published the final rule establishing the 2004 HD diesel emission standards in 1997, those states with State Implementation Plans (SIPs) have considered the projected emission reductions from these engines to be an important component of their overall SIPs. The NOx and NMHC nationwide emission reductions that will result from these standards beginning in the 2004 model year will help states to attain the ozone NAAQS. These states have incorporated the beneficial effects of the 2004 HD diesel standards into their air quality modeling and they continue to count on the emission reductions from this program to meet their air quality goals.

B. New Standards for 2005 HD Gasoline Engines and Vehicles Are Important for States in Meeting Their Air Quality Goals

Today, many states are finding it difficult to show how they can meet or maintain compliance with the current National Ambient Air Quality Standard (NAAQS) for ozone by the deadlines established in the Clean Air Act. In December, 1999, 92 million people (1990 population) lived in 32 metropolitan areas designated nonattainment under the 1-hour ozone NAAQS.[5]

There is a very clear risk that there will be elevated levels of ground-level ozone above the 1-hour NAAQS during the time period when the heavy-duty gasoline vehicle standards of this rulemaking will take effect. The reductions in oxides of nitrogen (NOx) and volatile organic compounds (VOCs) projected from the proposed new standards will benefit public health and welfare by reducing ozone levels. This assessment is based upon our recent and extensive ozone air quality modeling and analysis performed for the Tier 2/Gasoline Sulfur rulemaking, which predicts that a significant number of areas across the nation are at risk of failing to meet the 1-hour ozone NAAQS even with Tier 2 and other controls currently in place. Because ozone concentrations causing violations of the 1-hour ozone standard are well established to endanger public health and welfare, we conclude that today's new standards for 2005 and later gasoline heavy-duty vehicles are warranted.

1. Projected Air Quality Problems Remain After Tier 2/Gasoline Sulfur Program Is in Place

In conjunction with our Tier 2/Gasoline Sulfur rulemaking efforts, we performed ozone air quality modeling for nearly the entire eastern U.S. covering metropolitan areas from Texas to the Northeast, and for a western U.S. modeling domain. As a part of this modeling, we considered the air quality of these areas after the Tier 2/Gasoline Sulfur program is implemented. This modeling predicted that without further emission reductions, a significant number of areas now experiencing ozone exceedances across the nation are at risk of failing to meet the 1-hour ozone NAAQS in 2004 and beyond, even with the Tier 2/Gasoline Sulfur program and other current controls in place.

The general pattern that the ozone modeling shows is a broad reduction between 1996 and 2007 in the geographic extent of ozone concentrations above the 1-hour NAAQS, and in the frequency and severity of exceedances. In the absence of additional controls beyond those that will be achieved by current control programs -- including the Tier 2/Gasoline Sulfur program -- we expect there will be a slight decrease below 2007 ozone concentrations and frequencies of exceedances in 2030. However, the general trends and modeling results show that many of the areas we modeled may have exceedances continuously throughout the period from 2007 to 2030 without further reductions in emissions. Others may briefly attain and then return to nonattainment by 2030 or earlier. Although for practical reasons we limited our modeling of ozone concentrations to 1996, 2007, and 2030, we expect that concentrations between 2007 and 2030 will generally track the national emissions trend, showing a period of improvement after 2007 followed by a reversal of the trend and deterioration back towards the 2007 levels. Because individual areas' emissions trends differ, we expect that the air quality of individual areas will also vary from this general pattern.

We believe that there is a risk that future air quality in each of these areas would exceed the ozone standard during the time period when this rule will take effect. This belief is based on three factors: (1) recent exceedances in 1995-1997 or 1996-1998, (2) predicted exceedances in 2007 or 2030 after accounting for reductions from Tier 2 and other local or regional controls currently in place or required, and (3) our assessment of the magnitude of recent exceedances, the variability of meteorological conditions, transport from areas with later attainment dates, and other variables involved in predicting future attainment such as the potential for some areas to experience unexpectedly high economic growth rates, growth in vehicle miles traveled, varying population growth from area to area, and differences in vehicle choice.

Based on the Tier 2 modeling analyses and information from recently-submitted SIPs, we have determined that over 71 million people (1996 population) in 21 metropolitan areas are likely to be exposed to unhealthy levels of ground level ozone at some point in time between 2004 and 2030 without significant additional controls. These 21 areas are those that currently violate the 1-hour ozone NAAQS and are predicted by the best ozone modeling we have available to exceed the 1-hour ozone standard without significant new controls. This analysis accounts for the expected benefits from the Tier 2 program and other control programs already in place.[b] It does not include additional control measures that states would need to implement to meet their requirements under the recently proposed SIP findings. Table 2.1 lists these 21 areas.

(b) Air quality modeling shows that improvements in ozone levels can be expected to occur throughout the country because of the Tier 2/Gasoline Sulfur program. EPA found that the program significantly lowers the model-predicted number of exceedances of the ozone standard by one tenth in 2007, and by almost one-third in 2030 (Tier 2/Gasoline Sulfur Final RIA, Docket A-97-10, Document Number V-B-1).

Table 2.1
Twenty-one Metropolitan Areas Likely to Exceed the 1-Hour Ozone NAAQS in 2004 or Thereafter Without Additional Emission Reductions

Metropolitan Area	*1996 Population (millions)*
Baltimore-Hagerstown, MD PSMA	2.6
Barnstable-Yarmouth, MA MSA[a]	0.2
Baton Rouge, LA MSA	0.6
Beaumont-Port Arthur, TX MSA	0.4
Birmingham, AL MSA	0.9
Boston-Worcester-Lawrence, MA-NH-ME-CT CMSA[a]	5.6
Charlotte-Gastonia-Rock Hill, NC-SC MSA[a]	1.3
Dallas-Fort Worth, TX CMSA	4.6
Houma, LA MSA[a]	0.2
Houston-Galveston-Brazoria, TX CMSA	4.3
Huntington-Ashland, WV-KY-OH MSA[a]	0.3
Indianapolis, IN MSA[a]	1.5
Los Angeles-Riverside-San Bernardino CA CMSA	15.5
Louisville, KY-IN MSA	1.0
Memphis, TN-AR-MS MSA[a]	1.1
Nashville, TN MSA[a]	1.1
New York-Northern New Jersey-Long Island, NY-NJ-CT-PA CMSA	19.9
Philadelphia-Wilmington-Atlantic City, PA-NJ-DE-MD CMSA	6.0
Providence-Fall River-Warwick, RI-MA MSA[a]	1.1
Richmond-Petersburg, VA MSA[a]	0.9
St. Louis, MO-IL MSA	2.5
TOTAL POPULATION	71.5

a. The 1-hour ozone NAAQS does not currently apply, but we have proposed to re-instate it.

There are 14 additional metropolitan areas, with another 35 million people in 1996, for which the available ozone modeling and other evidence is less clear regarding the need for additional reductions. Table 2.2 lists the areas we put in this second category. Our own ozone modeling predicted these 14 areas to need further reductions to avoid exceedences during the period when the standards are effective.

Table 2.2
Fourteen Metropolitan Areas With Some Risk of Exceeding the 1-Hour Ozone Standard in 2004 or Thereafter Without Additional Emission Reductions.

Metropolitan Area	*1996 Population (millions)*
Atlanta, GA MSA	3.5
Benton Harbor, MI MSA[a]	0.2
Biloxi-Gulfport-Pascagoula, MS MSA[a]	0.3
Chicago-Gary-Kenosha, IL-IN-WI CMSA	8.6
Cincinnati-Hamilton, OH-KY-IN CMSA[c]	1.9
Cleveland-Akron, OH CMSA[a]	2.9
Detroit-Ann Arbor-Flint, MI CMSA[a]	5.3
Grand Rapids-Muskegon-Holland, MI MSA[a]	1.0
Greater Connecticut, CT-RI CMSA[b]	2.4
Milwaukee-Racine, WI CMSA	1.6
New Orleans, LA MSA[a]	0.3
Pensacola, FL MSA[a]	0.4
Tampa, FL MSA[a]	2.2
Washington, DC MSA	4.6
TOTAL POPULATION	35.3

a. The 1-hour ozone NAAQS does not currently apply, but we have proposed to re-instate it.
b. For the New London-Norwich portions of this area, the 1-hour ozone NAAQS does not currently apply, but we have proposed to re-instate it.
c. Based on more recent air quality monitoring data not considered in the Tier 2 analysis, and on ten year emissions projections, we expect to re-designate Cincinnati-Hamilton to attainment soon.

For all of these areas, recent air quality monitoring data indicate that exceedances may occur in 2007 or 2030. Eight areas have recent exceedances, but local ozone modeling and other evidence indicates attainment in 2007.[c] Based on this evidence, we have kept these areas separate from the previous set of 21 areas. However, we still consider there to be some risk of future exceedances for these eight areas.

For the other six of the 14 areas,[d] the air quality monitoring data shows current attainment but with less than a 10 percent margin below the NAAQS. This suggests that these areas may remain without exceedances for some time, but that there is still a risk of future exceedance of the NAAQS due, for example, to meteorological conditions that may be more severe in the future.

(c) Atlanta, Benton Harbor, Chicago, Cincinnati, Grand Rapids, Greater Connecticut, Milwaukee, and Washington, DC. (The Cincinnati-Hamilton area did not have exceedances in the 1996-1998 period).

(d) Biloxi, Cleveland, Detroit, New Orleans, Pensacola, and Tampa.

There is significant risk that at least some of these 35 areas will violate the NAAQS in 2004 or thereafter without additional reductions. We consider the situation in these areas to support our belief that, overall, additional reductions are needed.

2. Today's Program Will Help Areas Meet Their Attainment and Maintenance Requirements

The HD gasoline vehicle standards finalized today, and the HD diesel standards reviewed today, will help all of the areas discussed above to either meet their attainment deadlines, to maintain attainment in the future, or both. The new program will be very important to each of the areas with deadlines in 2005 and later that will require (or may require) additional emission reductions (2005 is the year that new gasoline HD vehicles will begin to enter the fleet). As Table 2.3 shows, there are 10 such areas with almost 66 million people. The following table lists these areas and their expected attainment dates:

Table 2.3
Areas with 2005, 2007, or 2010 Attainment Deadlines

Metropolitan Area	Attainment Deadline	Modeling Predictions	Population
Baltimore	2005	VOC Shortfall	2.6
Philadelphia	2005	NOx and VOC Shortfall	6.0
Greater Connecticut (Hartford and other MSAs)	2007 (requested extension)	Contingent on New York Attainment	2.4
New York City, NY-NJ-CT	2007	VOC and NOx Shortfall	19.9
Houston, TX	2007	NOx Shortfall	4.3
Chicago, IL-IN	2007	Regional modeling to analyze existence of shortfall is underway	8.6
Milwaukee, WI	2007	Regional modeling to analyze existence of shortfall is underway	1.6
Dallas, TX	2007 (requested extension)	Local modeling shows nonattainment in 2007	4.6
Beaumont-Port Arthur, TX	2007 (requested extension)	Local modeling shows nonattainment in 2007	0.4
Los Angeles (South Coast Air Basin), CA	2010	Approved SIP with commitments for unspecified additional controls	15.5
			65.9

All of the areas in Table 2.3 with 2005 or later attainment deadlines will be able to take credit in their attainment demonstrations (or in revisions to their demonstrations) for the expected reductions for the preexisting standards for HD diesel engines and for today's new standards for HD gasoline engines and vehicles. (EPA has not approved deadline extensions for Dallas and

Beaumont/Port Arthur at this time; if their requested extensions (to 2007) are approved, these areas, too, could take credit for today's program). The ability to take credit for the new HD gasoline vehicle standards will be especially important for the several areas with emission "shortfalls" (i.e., those for which we have made our proposal to approve their attainment demonstrations contingent on their adoption of new measures for further emission reductions).

In addition to helping 8 areas from Table 2.3 meet their attainment deadlines (plus Dallas and Beaumont/Port Arthur if they receive a deadline extension to 2005 or later), the new program will help these and all other areas with current or potential future ozone problems to maintain their attainment into the future. This includes at least the 37 areas we expressed concern about earlier. In effect, the emission reductions of this program will reduce the risk that these areas that today are in or approaching attainment will fall back into nonattainment as they face economic development and growth in vehicle travel.

3. The Program Will Help States Avoid More Costly Measures

In general, the task of states to reach and/or maintain attainment will be easier and the economic impact on their industries and citizens will be lighter if, as a result of today's new gasoline HD vehicle standards, they are able to forego other, less cost effective programs. Following implementation of the Regional Ozone Transport Rule, states will have already adopted emission reduction requirements for nearly all large sources of VOC and NOx for which cost-effective control technologies are known and for which they have authority to control. Those that remain in nonattainment therefore will have to consider their remaining alternatives.

Thus, the emission reductions from the standards we are finalizing today will help states that would otherwise need to seek controls for the first time from the sources that have not yet been controlled -- mostly smaller sources including area sources that are closely related to the activities of individuals and small businesses. The emission reductions from today's standards will also help states prevent or delay deeper reductions from large and small sources that have previously implemented emission controls.

C. HD Diesel and Gasoline Engines Contribute to Total NOx and VOC Emissions

HD engines and vehicles are major contributors to nationwide emissions of NOx and they are moderate contributors to nationwide emissions of VOC (estimates of a geographic area's emissions are called "emission inventories"). Table 2.4 summarizes EPA's current estimates for national NOx and VOC contributions from major mobile source categories. (See Chapter 6 for more information about how we developed these values.)

Table 2.4
2000 National NOx and VOC Emissions, (thousand short tons per year)

Emission Source	NOx	NOx %	VOC	VOC %
Light-Duty Vehicles	4,420	18%	4,098	25%
Heavy-Duty Vehicles	3,759	15%	355	2%
Nonroad Engines and Vehicles	5,343	22%	2,485	15%
Other (Stationary Point and Area Sources)	10,656	44%	9,567	58%
Total Nationwide Emissions	24,178		16,505	

Table 2.4 indicates that HD gasoline and diesel vehicles currently represent about 15 percent of national NOx emissions and two percent of national VOC emissions. Moreover, the local heavy-duty vehicle NOx contributions are higher than the national average in many important urban areas. Table 2.5 shows projections of local contributions to NOx from HD vehicles in 2007 in several metropolitan areas with ozone concerns. In each of these cases, the local contributions of NOx are greater than the projected national contribution -- in several cases, significantly higher.

Table 2.5
2007 Heavy-Duty Vehicle Contribution to Urban NOx Inventories

Metropolitan Statistical Area	Contribution to Total NOx	Contribution to Mobile Source NOx
National	*12%*	*23%*
Atlanta	18%	28%
Dallas	17%	21%
Charlotte	15%	27%
Washington	15%	29%
Los Angeles	15%	19%
New York	14%	23%
Philadelphia	13%	23%
Cleveland	13%	23%

Chapters 6 and 7 of this RIA also present updated emission inventory modeling for HD vehicles in future years. The results show that without additional HD NOx control beyond the 1998 standards, national NOx emissions from HD vehicles would decline for the next few years but that this trend would reverse around 2006. After that, without additional emission controls, NOx emissions from the HD vehicle fleet would again increase as a result of future growth in the HD vehicle market. A similar trend is seen for national NMHC emissions from HD vehicles -- we project that NMHC emissions will decrease until around 2009, after which growth in numbers of vehicles will offset emission reductions and NMHC emissions from HD vehicles will increase.[e]

III. Particulate Matter

A. Current and Future Compliance with the PM_{10} NAAQS

Compliance with the current PM_{10} standard continues to be a problem. This section reviews our most recent analyses regarding PM_{10} air quality, discussed in detail in the Regulatory Impact Analysis for the Tier 2/Gasoline Sulfur final rule.[6] The most recent PM_{10} monitoring data indicates that 15 counties designated PM_{10} nonattainment counties, with a population of 8.6 million in 1996, violated the PM_{10} NAAQS in the period 1996-1998. The areas that are violating do so because of exceedances of the 24-hour PM_{10} NAAQS. No areas had monitored violations of the annual standard in this period. Table 2.6 lists these 15 counties. The table also indicates the classification for each area, the status of our review of the SIPs, and population for each area in 1996.

(e) The emission inventory modeling we performed for this rule includes the excess emissions that occurred as a result of certain HD diesel engines manufactured between 1988 and 1998. These engines were at issue in the "consent decrees" involving certain HD diesel engine manufacturers, as discussed in Section I.C. of the preamble for this final rule.

Table 2.6
PM_{10} Nonattainment Areas Violating the PM_{10} NAAQS in 1996-1998

Area	Classification	SIP Approved?	1996 Population (millions)
Clark Co., NV	Serious	No	0.93
El Paso, TX	Moderate	Yes	0.67
Gila, AZ	Moderate	No	0.05
Imperial Co., CA	Moderate	No	0.14
Inyo Co., CA	Moderate	No	0.02
Kern Co., CA	Serious	No	0.62
Mono Co., CA	Moderate	No	0.01
Kings Co., CA	Serious	No	0.11
Maricopa Co., AZ	Serious	No	2.61
Power Co., ID	Moderate	No	0.01
Riverside Co., CA	Serious	No	1.41
San Bernardino Co., CA	Serious	No	1.59
Santa Cruz Co., AZ	Moderate	No	0.04
Tulare Co., CA	Serious	No	0.35
Walla Walla Co., WA	Moderate	Yes	0.05
		TOTAL POPULATION	8.61

Using a PM_{10} modeling approach conducted for the Tier 2 rulemaking, we have concluded that the 8 areas shown in Table 2.7 have a high risk of failing to attain and maintain the PM_{10} NAAQS without further emission reductions. These areas have a population of nearly 8 million. Included in the group are the counties that are part of the Los Angeles, Phoenix, and Las Vegas metropolitan areas, where traffic from heavy-duty vehicles is substantial. These 8 areas would clearly benefit from the reduction in emissions which would occur from the new standards for heavy-duty vehicles.

Table 2.7
Areas With High Risk of Failing To Attain and Maintain the PM_{10} NAAQS Without Further Emission Reductions

Area	1996 Population (millions)
Clark Co., NV	0.93
Imperial Co., CA	0.14
Kern Co., CA	0.62
Kings Co., CA	0.11
Maricopa Co., AZ	2.61
Riverside Co., CA	1.41
San Bernardino Co., CA	1.59
Tulare Co., CA	0.35
TOTAL POPULATION	7.76

Table 2.7 is limited to designated PM_{10} nonattainment areas which both had monitored violations of the PM_{10} NAAQS in 1996-1998 and are predicted to be in nonattainment in 2030 in our PM_{10} air quality modeling. This gives us high confidence that these areas require further emission reductions to attain and maintain, but does not fully consider the possibility that there are other areas which are now meeting the PM_{10} NAAQS which have at least a significant probability of requiring further reductions to continue to maintain it.

In our Tier 2 analysis, we created a second category of areas with a risk of failing to attain the PM_{10} NAAQS in the future that did not rise to the level of risk attributed to those areas listed in Table 2.7. The Tier 2 air quality modeling predicted that even considering the emission reductions from the Tier 2/Gasoline Sulfur program and other controls already in place, there would be violations in 2030 of the annual average PM_{10} NAAQS in five additional counties. We chose these five counties because they registered, in either 1997 or 1998, single-year annual average monitored PM_{10} levels of at least 90 percent of the NAAQS, but did not exceed the formal definition of the NAAQS over the three-year period ending in 1998. Table 2.8 shows these areas. They have a combined population of almost 17 million, and a broad geographic spread.

Table 2.8
Five areas with a significant risk of failing to maintain the PM_{10} NAAQS without further reductions in emissions

Area	1996 Population (millions)
New York Co., NY	1.33
Cuyahoga Co., OH	1.39
Harris, Co., TX	3.10
San Diego Co., CA	2.67
Los Angeles Co., CA	8.11
TOTAL POPULATION	16.6

Unlike the situation for ozone, for which precursor emissions are generally declining over the next 10 years or so before beginning to increase, we estimate that emissions of PM_{10} will rise steadily unless new controls are implemented. The small margin of attainment which these areas currently enjoy will likely erode; the PM air quality modeling suggests that it will be reversed. We therefore consider these areas to each individually have a significant risk of failing to maintain the NAAQS without further emission reductions. There is a substantial risk that at least some of them would fail to maintain attainment without further emission reductions. The emission reductions from the new standards for heavy-duty vehicles will help to keep them in attainment.

B. HD Diesel and Gasoline Engines Contribute to Secondary Formation of Particulate Matter

Because we are not changing the particulate matter emission standards for HD vehicles in this rule, the effect of this rule on PM results primarily from reductions in NOx emissions and in turn reductions in the secondary formation of nitrate particles in the atmosphere. Most available modeling of PM emissions, however, focuses only on direct (primary) emissions of PM.

We have not attempted to quantify the contribution of HD vehicles to the secondary nitrate particles formed from the large NOx emissions of these vehicles in this final rule. We are convinced that this contribution is substantial, especially in regions of the country where ammonia levels in the air are relatively high (NOx reacts with ammonia to form ammonium nitrate particles). Similarly, we believe that the very significant NOx reductions from HD diesel and gasoline vehicles that will result from the 2004 standards will also result in important reductions in the HD contribution to nitrate PM.

IV. Air Toxics from HD Engines and Vehicles

In addition to contributing to the health and welfare problems associated with exceedances of the National Ambient Air Quality Standards for ozone and PM_{10}, emissions from HD diesel and gasoline vehicles include a number of air pollutants that increase the risk of cancer or have other negative health effects. These air pollutants include benzene, formaldehyde, acetaldehyde, 1,3-butadiene, and diesel particulate matter. For several of these pollutants, motor vehicle emissions are believed to account for a significant proportion of total nation-wide emissions. All of these compounds are products of combustion; benzene is also found in non-exhaust emissions from gasoline-fueled vehicles. The reductions in hydrocarbon emissions from HD vehicles resulting from today's program will further reduce the potential cancer risk and other health risks from these air toxics (other than diesel PM) because many of these pollutants are themselves VOCs.

Diesel engine particulate matter is also a potential concern because of its possible carcinogenic and mutagenic effects on people. However, because today's program does not include more stringent standards for emissions of diesel PM, this action will not make a large difference in any health effects from direct diesel PM.

We are addressing the issues raised by air toxics from motor vehicles and their fuels in a separate rulemaking that we recently proposed and was signed by the Administrator on July 14, 2000 under section 202(l)(2) of the Act. That rulemaking process will address the emissions of hazardous air pollutants from motor vehicles and fuels, and the appropriate level of control of hazardous air pollutants from these sources.

Chapter 2 References

1. U.S. EPA, 1996, Review of National Ambient Air Quality Standards for Ozone, Assessment of Scientific and Technical Information, OAQPS Staff Paper, EPA-452/R-96-007.

2. U.S. EPA, 1996, Air Quality Criteria for Ozone and Related Photochemical Oxidants, EPA/600/P-93/004aF.

3. Vitousek, Pert M., John Aber, Robert W. Howarth, Gene E. Likens, et al. 1997. Human Alteration of the Global Nitrogen Cycle: Causes and Consequences. *Issues in Ecology*. Published by Ecological Society of America, Number 1, Spring 1997.

4. U.S. EPA, 1996, Air Quality Criteria for Particulate Matter, EPA/600/P-95/001aF.

5. Memorandum to the Docket, Drew Kodjak, EPA, January 12, 2000 (found in the docket for this rule as well). Information on ozone nonattainment areas and population as of December 13, 1999.

6. Regulatory Impact Analysis for the Tier 2/Gasoline Sulfur final rule, available in Docket A-97-10 (document number V-B-1) and through the Office of Transportation and Air Quality Tier 2 web page at www.epa.gov/otaq/tr2home.htm.

CHAPTER 3: TECHNOLOGICAL FEASIBILITY OF HD DIESEL AND OTTO-CYCLE STANDARDS

I. Overview

This chapter provides a technical discussion on emission related control technologies for lower emissions from HD diesel and otto-cycle engines and vehicles. The chapter is divided into two sub-chapters, the first dedicated to diesel controls, the second to otto-cycle controls. In addition, the final section discusses on-board diagnostics for HD, both diesel and otto-cycle.

II. Diesel Engine Technologies

A. HD Diesel Technology Overview

This sub-chapter presents an assessment of emission control strategies that EPA expects will be available for diesel engine manufacturers to use to meet the emission standards contained in this final rule. In addition, we present a review of the technologies examined which provided the basis on which we reviewed the HD 2004 NMHC+NOx standards which were established in 1997. To meet the 1998 emissions standards for heavy-duty diesel engines, manufacturers have implemented high-pressure fuel injection systems with retarded injection strategies, waste-gated turbo-chargers, air-to-air after-coolers, advanced combustion chamber designs, and electronic controls. EPA expects that incremental improvements will occur with respect to these strategies, but EPA does not expect that improvements in these strategies alone will achieve the levels required by the new standards. To meet these levels, EPA expects that, in addition to the aforementioned strategies, manufacturers will utilize exhaust gas re-circulation (EGR), fuel injection rate shaping, and possibly exhaust after-treatment. It is important to note that each of these technologies should be able to achieve emission reductions over a broad range of in-use operating conditions. Of these, EGR is expected to achieve most of the necessary reductions. As is discussed in more detail below, EGR has been shown to reduce NOx emissions by up to 90 percent under laboratory conditions. Because these future emission control strategies will rely on electronic controls for adequate performance, EPA expects that the best available on-board diagnostics will be implemented to ensure that these strategies remain effective in-use. Furthermore, although changes in diesel fuel composition might be required to enable certain emerging aftertreatment technologies, no change in diesel fuel composition will be required to meet the new standards. In addition, the current status of technologies which EPA does not believe will be necessary for the requirements contained in this final rule, but which could provide additional emission reductions beyond the final rule requirements are discussed (these technologies include NOx absorber catalysts, urea-based SCR systems, and PM traps).

This sub-chapter is divided into five sections: EGR, fuel injection rate shaping, exhaust after-treatment, fuel composition, and new test cycles. Several sections also discuss strategy-enabling technologies such as variable geometry turbo-chargers (VGT) for driving EGR, or common rail fuel systems for performing fuel injection rate shaping.

The RIA for the 1997 HD rulemaking contains additional information regarding the effectiveness of several of the technologies discussed here, primarily cooled EGR systems. The conclusions in the 1997 rulemaking regarding the effectiveness of cooled EGR for the reduction of NOx emissions from HD diesel engines continue to be relevant, but the analysis which led EPA to the conclusion that cooled EGR would be the principle technology for meeting the standards will not be repeated here. The reader should refer to Chapter 4 of the 1997 RIA for additional discussion of EGR systems beyond what is covered in this RIA. In addition, a discussion of the potential incremental improvements from control strategies already being used to meet the 1998 standards can be found in the RIA of the 1997 final rule.

B. Exhaust Gas Re-circulation (EGR)

EGR is the re-circulation of exhaust gas from a point in an engine's exhaust system to a point in its intake system. EGR is used to decrease nitric oxide (NO) emissions, the primary species in diesel oxides of nitrogen (NOx). EGR dilutes intake air with combustion products, namely carbon dioxide (CO_2) and water vapor. These diluents decrease the adiabatic stoichiometric flame temperature for a given mass of fuel and oxygen burned.[1] This decrease in temperature exponentially decreases the oxidation rate of dissociated nitrogen (N) to nitric oxide (NO).[2] EGR also decreases the overall mole fraction of oxygen, which proportionally decreases the oxidation rate of N to NO.[3] Finally, the specific heats of CO_2 (above 532˚ K) and water vapor are greater than that of air; therefore they absorb more heat per increase in temperature than air, thus lowering the peak temperature for a given release of heat. This last effect on NO formation, however, is small compared to the first two.[4]

EGR is very effective at decreasing NOx. Laboratory studies have shown that EGR can reduce NOx emissions by up to 90 percent at light load and up to 60 percent at full load near rated speed.[5] These studies and others have shown similar reductions at other speeds and loads.[6] However, because EGR decreases the overall rate of combustion in the cylinder, EGR tends to increase particulate matter (PM) emissions and brake specific fuel consumption (BSFC). Furthermore, if EGR is not cooled before it is introduced to the intake system, it will reduce the density of the intake charge, and thus decrease the volumetric efficiency of the engine, which will decrease maximum power and increase BSFC. Hot EGR also offsets EGR's beneficial effect on combustion temperature because hot EGR increases the initial temperature of the air charge. Finally, EGR without additional boost air decreases the excess air ratio. This can result in incomplete combustion during some modes of operation and an increase in PM emissions. Through proper EGR system design, however, researchers have demonstrated that these undesirable effects of EGR can be minimized so that the 2004 emission standards can be met.[7]

From a design perspective, there have been several challenges to EGR's feasibility, all of which have been addressed. First, a sufficient positive pressure difference must exist between the point in the exhaust system where the exhaust gas is extracted and the point in the intake system where it is introduced. Second, under most conditions, EGR should be cooled for best performance, which raises corrosion, fouling and design issues. Third, the rate of EGR must be controlled accurately, and the control system must respond quickly to changes in engine operation.[8]

The positive pressure difference required to drive EGR may be achieved a number of ways. Extracting the exhaust gas downstream of the exhaust turbine and introducing it to the inlet of the intake compressor is called Low-Pressure-Loop (LPL) EGR. LPL EGR possesses the advantage of having a sufficient pressure differential to drive EGR over a wide engine operating range, but LPL EGR may cause durability problems with the intake compressor and after-cooler.[9,10] However, through confidential discussions with engine manufacturers, EPA has learned that some manufacturers may have overcome these durability issues at least for light and medium heavy-duty engine applications.

Another way of performing EGR is by extracting the exhaust gas from the exhaust manifold and routing it to the intake manifold. This minimizes the durability issues associated with the LPL method by introducing the EGR after the compressor and after-cooler. This is called High-Pressure-Loop (HPL) EGR. HPL EGR short-circuits the compressor and after-cooler, but the required pressure differential is difficult to achieve at high load, and particularly in heavy-duty engine applications.[11] To improve the pressure differential to enable HPL EGR, researchers have investigated enabling technologies such as exhaust back-pressure valves, variable geometry turbo-chargers (VGTs), and full-flow and bypass intake venturis. In three different studies investigators positioned exhaust back-pressure valves downstream of the exhaust turbine to drive HPL EGR. Researchers reported significant NOx reductions, but the turbo-chargers extracted less energy in these configurations, and the re-circulated exhaust displaced fresh air without any increase in charge air pressure.[12] Unacceptable increases in PM and BSFC resulted due to decreased excess air ratios.[13,14,15]

Two recent studies concluded that turbo-charger nozzle geometry must vary in order to drive EGR without unacceptable decreases in excess air ratios,[16, 17] and a third study investigated the application of a by-pass venturi to draw exhaust gas into the intake system.[18] A variable geometry turbocharger (VGT) is a turbocharger that has adjustable turbine inlet nozzle vanes. Closing these vanes decreases the nozzle area, whereby exhaust back pressure is increased to drive EGR, while simultaneously, the turbine and compressor work are increased, as well as the compressor pressure ratio. VGTs have been demonstrated to drive EGR without significantly decreasing excess air ratios. In fact, under some operating conditions researchers achieved simultaneous decreases in NOx, PM and BSFC by driving HPL EGR with a VGT.[19] One study combined a VGT with a full-flow EGR venturi that was positioned within the intake system just upstream of the intake manifold. On a 12 liter 315 kW heavy-duty diesel, the venturi increased EGR suction pressure by up to 20 kPa with an intake pressure recovery of 60% downstream of the venturi.[20] Because the venturi restricted airflow, it caused decreased excess air ratios which resulted in increased PM and BSFC. However, the venturi can significantly extend the range of EGR flow, and it might improve the durability of a VGT by allowing the VGT to operate at lower back pressures and temperatures.[21] Another variation of the venturi concept that does not employ a VGT is the bypass venturi. In this system EGR is introduced into a venturi positioned in an intake duct that flows parallel to another intake duct in which there is a controllable butterfly valve. By closing the butterfly valve in the one duct, more intake flow is forced through the venturi's duct, which causes more EGR to be drawn into the intake flow.[22] Results from this configuration indicated that about 30% reductions in NOx were achievable with no significant increase in BSFC or PM over a wide range of operating conditions. Further decreases in NOx were achievable with some increase in PM and only a slight increase in BSFC.[23]

Another important enabling technology for EGR is effective and durable EGR coolers. As mentioned previously, cooled EGR is desirable under most operating conditions to maximize volumetric efficiency and to lower intake charge temperatures. Studies have indicated that the issues concerning EGR coolers - namely, corrosion, fouling, and compact design - have been resolved.

Corrosion is an issue because current on-highway diesel fuel contains up to 0.04% fuel sulfur (S) by weight, which forms corrosive sulfuric acid (H_2SO_4) in diesel exhaust. During combustion S is oxidized 97-99%[24] to sulfur dioxide (SO_2) and trace amounts of sulfate (SO_3). SO_3 also forms in the exhaust manifold as equilibrium thermodynamics begin to favor its formation below ~730 C. Reaction kinetics limit SO_3's formation rate, however.[25] In diesel exhaust SO_3 immediately reacts with water vapor to form aqueous sulfuric acid (~73% H_2SO_4 by wt.),[26] and this acid begins to condense from about 80 to 145 C ,[27,28] depending upon engine operating conditions. Although the acid's concentration is strong, the acid at this point only accounts for ~0.5% of the fuel sulfur. However, once the exhaust cools below the water vapor dew point (~30 to 80 C), SO_2, which accounts for nearly all of the fuel sulfur, will begin to react significantly with condensed water to form H_2SO_4.[29] For this reason, EPA expects that EGR coolers will utilize engine coolant, which is thermostatically controlled typically between 80-90 C. This will help to prevent EGR cooling below the exhaust's water vapor dew point. Because ~0.5% of the <0.04% S in the fuel may condense as strong sulfuric acid and because additional H_2SO_4 may form during cold engine operating conditions (start-up, idle, cool-down, winter conditions), stainless steels with special corrosion resistance to sulfuric acid have been selected to resolve the corrosion issue.[30,31]

EGR cooler fouling can be minimized if the cross-sectional area of the exhaust channel can be designed sufficiently large. This is generally problematic because this design leads to a large EGR cooler. However, one heat exchanger manufacturer has implemented a heat exchanger channel design that simultaneously minimizes fouling while increasing heat transfer, thereby reducing the EGR cooler size. The design implements winglets that are vortex-generators arranged in pairs in the gas channel. They are opened in a V-shaped configuration in the direction of flow.[32] These winglets increase turbulence, which increases heat transfer by reducing the thermal boundary layer in the channel. They also decrease fouling by forcing particles and vapors back toward the center of the tube. This stable, turbulent action counters thermophoretic deposition, condensation, and diffusion due to a concentration gradient.[33] Experimental results indicate that cooler fouling stabilized after 100 hrs, and that in the end, fouling decreased cooler efficiency by only 15%.

Controlling EGR flow rate is a crucial aspect for successful EGR system design. EPA expects manufacturers to make full use of an engine's electronic control system to measure parameters that should be used to control EGR rate. Many of these parameters, such as engine speed, fuel rate, manifold pressures, temperatures and flow rates, are already being measured. EPA expects individual manufacturers to match their control parameters to their unique EGR systems. Sufficient control for transient response may be achieved by a number of methods. As mentioned above, some researchers have demonstrated the use of VGTs and bypass venturis with continuously variable valves in the intake system to achieve EGR control. For transient response, however, quick and temporary EGR shut-off seems to be the best method for maintaining adequate torque response without a sharp increase in transient PM emissions.[34] For this reason EPA expects that EGR systems will have valves positioned in the EGR loop to achieve fast response for transient engine operation.[35,36,37] Durable EGR valves have been demonstrated by various manufacturers.[38] One valve manufacturer indicated that their EGR valve design will incorporate a fast acting (<50 ms) electrically actuated rotary solenoid, which operates an airfoil-shaped valve plate. The manufacturer expects to have the valve in production within the 2002 time frame. [39]

Because researchers and manufacturers have demonstrated that EGR strategy can result in significant NOx reductions without unacceptable effects on PM emissions, BSFC, or performance, and because manufacturers have demonstrated enabling technologies such as VGTs, venturis, EGR coolers, and control valves for complete EGR system implementation, EPA expects EGR to be a primary strategy for achieving the emission standards in this rule.

C. Fuel Injection Rate-shaping

Another key emission control strategy that EPA expects heavy-duty diesel engine manufacturers to use to meet the new emission standards is fuel injection rate shaping. Fuel injection rate shaping refers to precisely controlling the rate of fuel injected into the cylinder on a crank-angle by crank-angle resolution. Specific rate-shaping methods include pilot injection where a pilot quantity of fuel, typically less than 2% of the total fuel charge,[40] is injected at some crank angle before the main injection event. Split fuel injection refers to splitting, more or less evenly, the main injection into two or more separate injections. Other methods include ramping the main injection event so that it resembles a triangular profile, rather than a square-shaped profile. Effective injection rate-shaping systems modulate the fuel injection timing, pressure, rate, and duration independent of engine speed and load. This characteristic of the fuel system implies that it is mechanically de-coupled from the engine. Timing is then achieved, presumably, by electronic control.

Injection rate shaping has been shown to simultaneously reduce NOx by 20 percent and PM by 50 percent under some conditions.[41] It has also been shown to reduce BSFC by up to 10 percent without increasing NOx emissions.[42] However, it can also lead to increases in smoke emissions and may not be as effective on low-NOx engines equipped with EGR.

Fuel injection rate shaping is used to control the rate of combustion within the cylinder. By controlling the combustion rate, the rate of pressure and temperature rise is controlled. Therefore, rate shaping controls NOx formation by one of the same mechanisms as EGR; it is used to lower peak combustion temperatures. Rate shaping can affect the time and temperature at which combustion ends, therefore, it can also lower PM emissions by enhancing the mechanisms of in-cylinder soot oxidation.[43]

Several manufacturers and fuel system suppliers have demonstrated fuel injection systems that can achieve effective rate shaping. The three most common systems are the common rail; the mechanically actuated electronically controlled unit injector (MEUI); and the hydraulically actuated, electronically controlled unit injector (HEUI). The common rail system consists of a high-pressure (~25,000 psi.) fuel pump that pressurizes a pressure-regulated fuel header, or rail, that is connected to each fuel injector. The fuel injectors are actuated by individual electronically controlled solenoids.[44,45] A variation of the common rail system eliminates the individual solenoids by utilizing a distributor sub-system.[46,47] The MEUI system has low-pressure fuel (~ 60 psi.)[48] delivered to its injectors. The MEUI injectors pressurize the fuel when an overhead cam actuates them. By passing the pressurized fuel via an electronically controlled spill-valve controls the injection rate.[49] The HEUI system is similar except that a high-pressure hydraulic/accumulator system is used to pressurize the fuel. One advantage of the HEUI system over the MEUI is that it is not limited in injection timing, pressure or rate by a cam lobe profile. However, a HEUI system tends to have lower peak injection pressures versus a MEUI; 25,000 psi vs. 30,000 psi.[50] Other rate shaping systems may utilize spool valve acceleration and fuel-hammering in the injection line, fuel tube geometry, or dual springs at the injector needle to perform rate shaping.[51,52]

Several studies have suggested rate-shaping methods to achieve emissions benefits. Researchers have reported decreased NOx and PM emissions at intermediate speeds and loads by optimizing reduced-rate pilot injection with a high-pressure main injection,[53,54,55] and one report suggested a fuel injection strategy at high loads. At intermediate loads, burnt pilot fuel is used as a torch to decrease ignition delay of the main injection event. This lowers peak flame temperatures and, thus, NOx formation. At high loads the ignition delay is not as significant, but a very early pilot event (>20° before top-dead center) can be used to distribute low-temperature burnt gas in the cylinder, similar to EGR. This method can be optimized to decrease NOx, PM, and BSFC simultaneously.[56] Other reports have suggested ramped main injection at high loads and high speeds to decrease NOx, square main injection at peak torque to decrease PM, and split injection at idle to decrease volatile PM (i.e. white smoke).[57]

EPA expects manufacturers to utilize fuel injection rate shaping in combination with EGR and 1998 engine technologies to meet the new emission standards. EPA believes that the fuel injection rate shaping strategy is technologically feasible because fuel injection rate shaping is used to a limited extent today to meet 1998 emissions standards and has been shown in testing to be reliable and effective.[58]

D. Exhaust After-treatment

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 finalizing 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. An extensive description of aftertreatment technologies was presented in the 1997 rulemaking package for the 2004 standards, including the final Regulatory Impact Analysis document. The reader is directed to the final RIA from the 1997 rulemaking for a discussion of aftertreatment technologies as of the 1997 time frame. The following discussion will include information which has become available since the 1997 rulemaking, and will not repeat what was in that final RIA.

1. Particulate Matter Control

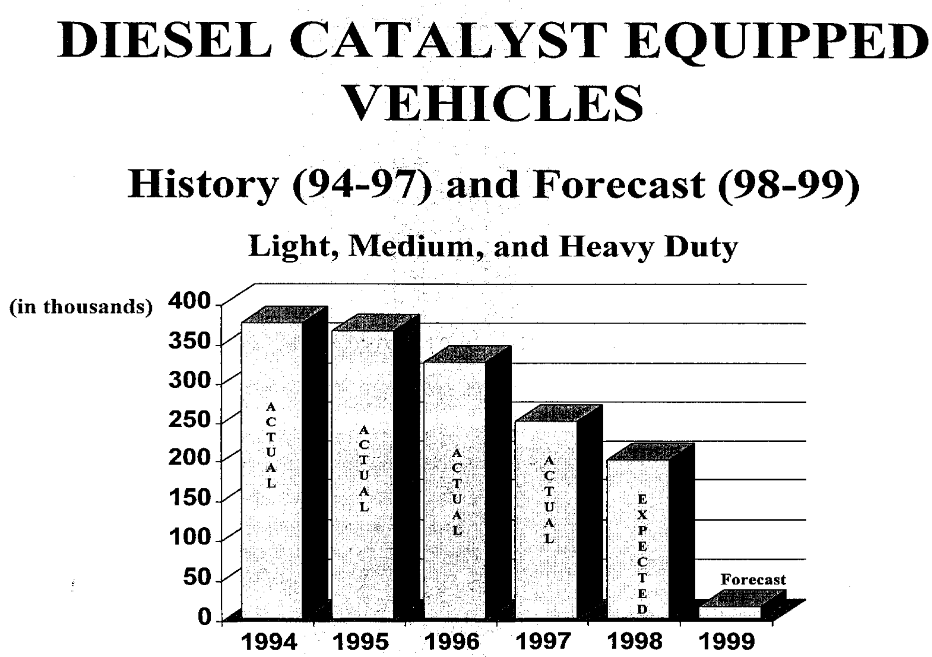
Two aftertreatment technologies have received the most attention for particulate control, the flow-through oxidation catalyst and the particulate trap. The oxidation catalyst provides relatively moderate overall PM reductions by oxidizing a portion of the particulate as the exhaust passes through it. 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 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. However, research on traps has been on-going, and some recent iterations look promising.

(a) Diesel Oxidation Catalysts

As mentioned above, engine manufacturers have started to use diesel oxidation catalysts (DOC) 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 HDDE’s). 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. Recent sales data on oxidation catalyst for HD from the Manufacturers of Emission Control Association shows a continual decrease in the number of DOC’s being sold in the U.S. (See Figure 3-1 below).

Figure 3-1 - U.S. Sales Figures for HD Oxidation Catalysts



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.[59] 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.[60] 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 diesel fuel. 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.[61] 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.[62] 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. Recent published reports show that for modern HD diesel engines, palladium based oxidation catalysts can achieve an approximate 30% reduction in PM under steady-state (European 13-mode) operation using current U.S. diesel fuel, and these formulations show good durability.[63]

A recent test program sponsored by the Manufacturers of Emission Controls (MECA), included the testing of several oxidation catalysts on a modern HD diesel engine certified to the 1998 U.S. HD standards. The results of this report showed up to a 29% reduction in PM over the transient FTP, and PM reductions ranging between 0 and 67% on a series of 13 steady-state modes, with one high load mode showing a slight (15%) increase in PM due to sulfate formation, these results were all using a typical D2 diesel fuel used in the U.S. today (sulfur content approx. 350ppm)[64]. This project also reported an additional 13 percent reduction in PM from the use of low sulfur diesel fuel (54ppm).

Oxidation catalyst development and use is likely to continue. 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.

(b) 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 back pressure on the engine. 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 which 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. The 1997 RIA discusses both active and passive trap regeneration, however, the most promising areas of improvement since that time have been in the area of passive systems, and only those systems will be discussed here.

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. The catalyst will oxidize sulfur and Johnson-Matthey is requiring the use of fuel with a sulfur level much lower than EPA specifications. One recent study utilizing this type of trap reported large reductions in both mass based PM and HC on a modern, direct injection, turbo-charged, intercooled, 6.8 liter HD engine, but the system requires ultra-low sulfur fuel, less than 10ppm.[65]

As discussed in the 1997 RIA, several companies have explored the use of fuel additives which assist in the regeneration process by lowering the PM ignition temperature. For example, fuel additives including a cerium-oxide additive has been developed by Rhodia Chimie (formerly Rhone-Poulenc) and a copper-oxide additive has been developed by Lubrizol Corporation.

A recent test program sponsored by the Manufacturers of Emission Controls Association (MECA), included the testing of two PM filter technologies tested in a laboratory on a modern HD diesel engine certified to the 1998 U.S. HD standards.[66] One filter employed a catalytic coating applied directly to the filter element (system A), the second filter technology utilizes a catalyst element placed directly upstream of the filter element (system B). System A was tested on D-2 diesel fuel with current sulfur levels (368ppm), while System B requires low sulfur fuel, and was tested with a low sulfur (54ppm) diesel fuel. System A was tested over the transient U.S. FTP, System B was tested on both the U.S. FTP, as well as a series of 13 steady-state modes. Table 3-1 contains a summary of the FTP results.

Table 3-1
PM trap testing results from MECA test program, U.S. HD FTP test cycle

	Engine Baseline (g/bhp-hr)	**Results w/ trap system installed (g/bhp-hr)**
System A - tested w/ fuel sulfur level = 368ppm	0.073	0.022
System B - tested w/ fuel sulfur level = 54ppm	~ 0.06	0.008

Emission results on the 13-steady-state test cycle from the low sulfur fuel with System B showed reductions ranging between approximately 20 and 70 percent, with the exception of one high power mode, where PM increased approximately 30 percent. These emission results indicate that PM traps applied to a 1998 technology HD diesel engine can provide large reductions in PM with current fuel sulfur levels, and even lower PM levels may be achievable with the use of low sulfur fuel. Durability information was not collected in this test program.

Catalyst materials bring down the temperatures needed for PM 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. 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, but these back-up systems would likely be expensive.

Filter development is also focused on reducing the amount of exhaust back pressure 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. If traps begin to play a larger role as an emission control technology, improvements to engine oil (e.g. use of ashless oils) may increase the amount of time a trap can perform before ash build-up becomes a maintenance issue.

In the long term, traps may be among the mix of technologies considered by engine manufacturers in meeting future standards, if a durable system with consistent regeneration and a reasonable cost becomes available. Issues such as regeneration, ash accumulation, and sulfur tolerance have yet to be resolved by the 2004 time frame.

2. Oxides of Nitrogen Control

The 1997 RIA contains a description of the major developments in NOx control aftertreatment devices which have been investigated in recent years, including lean-NOx high temperature and low temperature catalysts, NOx absorber catalysts, and urea-based SCR systems. Additional development work has occurred in all of these areas since the finalization of the 1997 rulemaking. The discussion below will not repeat what was contained in the final RIA for the 1997 rule, however, much of that information continues to be relevant and the reader should refer to the final RIA for the 1997 rule for additional information.

In general, the issues associated with lean NOx catalysts, NOx absorber catalysts, and urea-based SCR systems are similar today as they were in 1997. These three systems continue to be the focus of intensive research because of the benefits they may someday offer. The technical difficulties discussed in 1997 continue to exist, though some progress has been made.

Lean NOx catalysts continue to offer limited NOx reduction capability when considered across the entire temperature operating range encountered by HD diesel engines, while peak reduction capabilities may approach 60 percent under limited operating range, overall reductions on the U.S. HD FTP continue to be modest, between 20 and 30 percent. Lean NOx absorber catalysts have shown a potential for much higher levels of NOx reduction, perhaps as high as 80 or 90 percent. However, at today's on-highway diesel fuel sulfur levels, catalysts activity can be severely impacted in a matter of hours. Urea-based SCR systems have shown the potential for high levels of NOx reduction from diesel engines, however, the technical issues such as urea refueling, tampering, and ammonium slip remain to be solved. Finally, if the above issues can be solved for these aftertreatment technologies, issues such as in-use durability, fuel economy impact, cost, and and cost-effectiveness will also need to be examined.

The discussion below on each of these technologies discusses in more detail some of the promise offered by NOx aftertreatment.

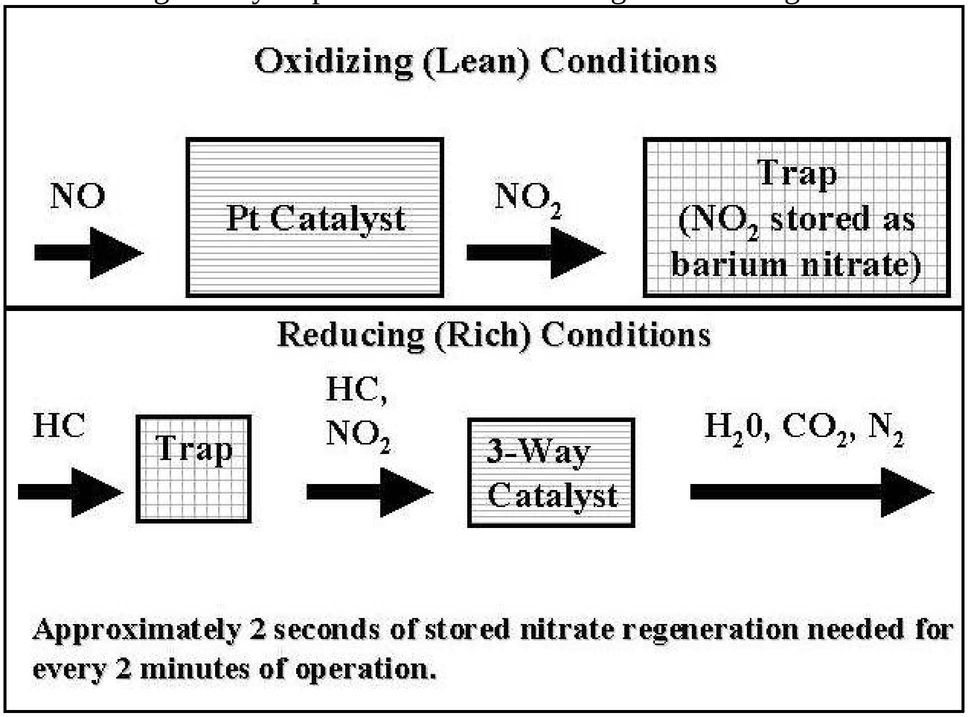
(a) NOx Storage Catalysts

NOx storage catalysts (also referred to as NOx absorber catalysts) are probably the best example of a diesel emissions control capable of large reductions (>25%) reductions in NOx emissions, but only if diesel fuel sulfur levels are considerably reduced. A generalized schematic of their operation is included in Figure 3-2. This catalyst system employs a high-platinum (Pt) content catalyst for oxidation of nitric oxide (NO) to nitrogen dioxide (NO_2)[f]. The NO_2 is then stored, using one of a number of barium compounds, as barium nitrate. For approximately two-second durations every two minutes, diesel fuel is either sprayed into the exhaust, or fuel is injected into the cylinder after combustion to provide the necessary hydrocarbons to remove the NOx from the storage components. The NOx is then reduced over a standard three-way catalytic converter. The average NOx reduction potential for this technology over the light-duty Federal Test Procedure (FTP) is 50 to 75%, with a fuel consumption penalty of approximately 3 to 5%.[67] Figure 3-3 compares the NOx reducing capabilities of a NOx storage catalyst system to two other lean-NOx catalyst systems (one of which is sulfur tolerant).

Unfortunately, the chemistry for sulfate storage in such systems is similar to the desired nitrate storage. Sulfur dioxide from combustion of fuel sulfur compounds is oxidized to SO_3 by the platinum catalyst, and stored as barium sulfate. Purging sulfate from the storage components requires significantly longer periods of fuel-rich conditions and significantly higher temperatures (600 to 700 °C). The extended periods of high exhaust temperatures necessary for sulfate purging from the storage components of the catalyst would be difficult to achieve, even for many heavy duty diesel applications. Extended high temperature operation would also have a detrimental impact on the useful life of the NOx storage components of the system. Creation of the necessary fuel-rich environment would pose a significant fuel consumption penalty, and would increase PM and hydrocarbon emissions levels.

(f) In the absence of an oxidation catalyst, total oxides of nitrogen (NOx) in diesel exhaust is primarily NO (typically >80%) with lesser amounts of NO_2.

Figure 3-3
NOx-storage catalyst operation under oxidizing and reducing conditions.



Without sulfate purging, fuel sulfur levels of 350 ppm result in near complete deactivation of NOx storage within 20 hours of operation. NOx storage catalysts are clearly not a viable NOx exhaust aftertreatment control at current diesel fuel sulfur levels. Diesel engines employing NOx storage catalyst systems will probably be limited to the use of diesel fuels with less than 30 to 50 ppm sulfur[68]. Even at such fairly low sulfur levels, additional development of catalyst components that reduce sulfur poisoning of the NOx storage components and less frequent, lower temperature sulfate purging cycles may still be needed.

(b) Lean-NOx Catalysts

Various types of active (requiring a post-combustion fuel injection event) and passive (no post-injection) lean-NOx catalysts are in production or are under investigation for reduction of NOx emissions in lean exhaust environments such as those present in diesel exhaust. Lean-NOx catalysts typically reduce NOx efficiently over a fairly narrow range of catalyst temperatures. There are both "high" and "low" temperature varieties of lean-NOx catalysts. Low temperature, platinum-based lean-NOx catalysts using zeolites for support, catalyst promotion, and adsorption of NOx and HC, would be typical of a lean-NOx catalyst technology for light-duty diesel vehicles with catalyst temperatures primarily in the 200 to 300 °C range. High-temperature lean-NOx catalyst formulations are under investigation primarily for highly-loaded, heavy-duty diesel engine applications. High-temperature lean-NOx catalysts are primarily base metal catalysts that are only effective at exhaust temperatures exceeding 300 °C.

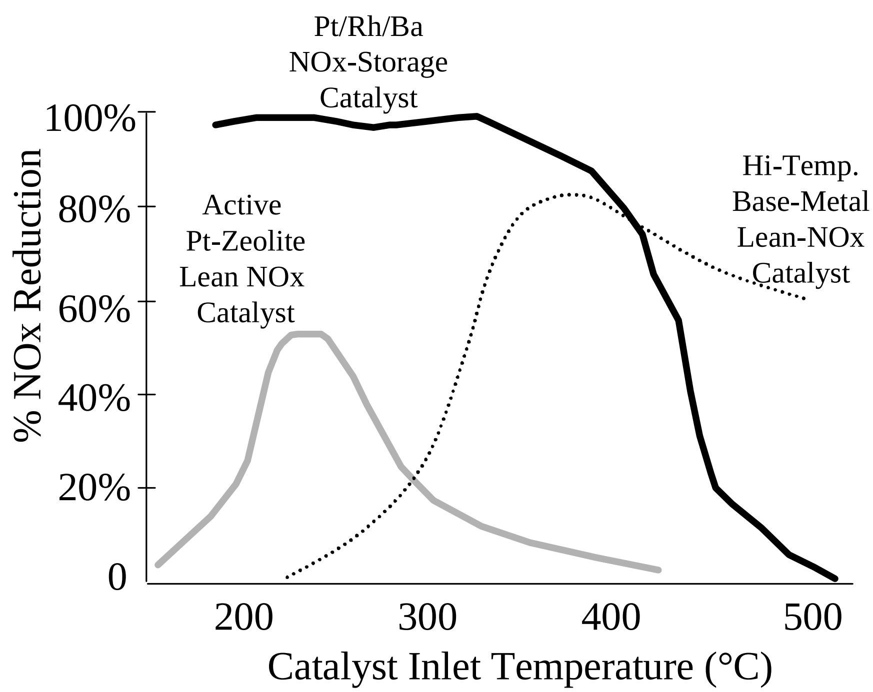
A number of new common rail fuel injection systems are capable of injecting fuel after combustion to provide additional hydrocarbons for use as a NOx reductant with active lean-NOx catalysts. One example is the introduction of an active lean-NOx catalyst system for a European light-duty diesel application[69]. Although active Pt-zeolite catalyst systems have higher NOx removal efficiencies than similar passive catalyst systems, NOx removal efficiencies are still only in the range of 15 to 35 % on average, and significantly below that of NOx storage catalyst systems (Figure 3-3). It is more likely that low-temperature systems like the Pt-zeolite lean-NOx catalyst systems will be used for incremental NOx reduction for light-duty applications in combination with other technologies, such as cooled EGR.

An approximately 25% reduction in catalyst NOx efficiency due to adsorption of sulfur compounds has been reported after 40,000 miles of roadway aging in a light-duty application at a nominal 500 ppm fuel sulfur limit[70]. Sulfate PM emissions (primarily sulfuric acid), rather than sulfur poisoning, will probably be a more pressing issue with respect to fuel sulfur content[g]. Conversion efficiencies for fuel sulfur to sulfuric acid of up to 20% are possible with Pt-zeolite lean-NOx catalysts[71].

High-temperature base metal catalysts reduce NOx emissions by up to 30 % over the heavy-duty FTP cycle. One such catalyst is the Cu ZSM5 catalyst[72]. Similar to low temperature systems, they may be used for incremental NOx reduction in combination with cooled EGR for heavy-duty diesel engine applications, however, in-use durability issues remain. It is not clear whether or not long term exposure to SO_2 poses a significant problem for this technology.

(g) Direct PM emissions from diesel engines primarily consist of 3 constituents: elemental carbon (soot), organics, and sulfates.

Figure 3-3: A comparison of the NOx reduction efficiency over a range of temperature conditions for the sulfur-intolerant NOx storage catalyst system (system for lean Gasoline Direct Injection engine application shown[73]), the more sulfur-tolerant, active Pt-zeolite catalyst system and a high-temperature base-metal (Cu-ZSM5) catalyst system.[74] Although peak NOx reductions efficiencies for various types of non-storage lean-NOx catalysts (similar to the Pt-Zeolite catalyst shown here) approach 50-60%, average reductions are 15 to 30% over various light- and heavy-duty vehicle and engine certification cycles.



(c) Selective Catalytic Reduction

Selective catalytic reduction (SCR) for NOx control is currently available for stationary diesel engines, and prototype systems have been developed for mobile light- and heavy-diesel applications. SCR uses ammonia as a reducing agent for NOx over a catalyst composed of precious metals, base metals, and zeolites. The ammonia is supplied by introducing a urea/water mixture into the exhaust upstream of the catalyst. The urea/water mixture is typically stored in a separate tank that must be periodically replenished. NOx reductions of 70% to 90% are possible using such systems.[75] These systems appear to be tolerant of current U.S. on-highway diesel fuel sulfur levels.

Control of the quantity of urea injection into the exhaust, particularly during transient operation, is an important issue with SCR systems. Injection of too large of a quantity of urea leads to a condition of "ammonia slip", whereby excess ammonia formation can lead to both direct ammonia emissions and oxidation of ammonia to produce (rather than reduce) NOx. There are also a number of potential hurdles to overcome with respect to a major emission control system that requires frequent replenishing in order to function. This raises issues related to supply, quality control, tampering, and the possibility of running the urea tank dry. There is currently no wide-spread distribution system in the U.S. for supplying the necessary water/urea mixtures for diesel vehicles and trucks.

E. Diesel Fuel Composition

1. Introduction

The purpose of this section is to assess the current understanding of the role diesel fuel quality plays in the ability of diesel engines to meet the emission standards in this rule. The effects of fuel formulation on exhaust emission formation as well as engine durability are examined.

It has long been realized that diesel engine technology alone is not the only mechanism to lower emissions, diesel fuel quality also plays an important role in emission formation as well as engine performance. In addition, diesel fuel quality can play a role in the effectiveness of certain emission control technologies, and in some cases can be considered a technology enabler, i.e., some emission control devices may not function because of certain diesel fuel properties, such as sulfur content.

In EPA's 1997 final rulemaking for the 2004 standards, we stated that we believed the 2004 standards were technologically feasible thru diesel engine technology modifications alone, without changes to diesel fuel quality (see 62 Federal Register, 54700, Oct. 21, 1997). However, we also stated that this issue would be revisited in the 1999 technology review rulemaking, "EPA will evaluate in light of any new information whether diesel fuel improvements are needed for the standards to be appropriate for 2004" (see 62 Federal Register, 54700, Oct. 21, 1997). In section 2 below we review the new information which has become available since the 1997 rulemaking thru a study performed by the Heavy-duty Engine Working Group and durability information supplied by manufacturers. Section 3 below addresses issues regarding the effect of diesel fuel sulfur levels on emission control system and engine durability for the technology neccessary for HD diesel engines to comply with the standards in this rule.

2. Heavy-duty Engine Working Group

(a) Background

In anticipation of the need for new information regarding the influence of diesel fuel quality on future emission technologies and achievable levels, in December of 1995 a new Working Group called the Heavy-duty Engine Working Group (HDEWG) was formed under the Mobile Source Technical Advisory Subcommittee of the Clean Air Act Advisory Committee. The HDEWG consists of approximately 30 members, including representatives from EPA, heavy-duty engine OEMs, the oil industry, state air quality agencies, private consultants and members of academic institutions. The HDEWG formed a steering committee which consisted of representatives from EPA, Cummins, Caterpillar, Navistar, Ford, British Petroleum, Equilon, Mobil Oil, Phillips, the Engine Manufacturers Association, the American Petroleum Institute, and the National Petroleum Refinery Association. The HDEWG set as their research objective to contribute to EPA's 1999 technology review of emission standards for model year 2004 heavy-duty diesel engines by assessing relative merits of achieving 2.5 g/bhp-hr HC+NOx level either through engine system modifications alone, or a combination of engine system and fuel modifications.

The HDEWG established a three phase process in order to meet their objective. In Phase 1, the goal was to determine whether the combined effects of diesel fuel properties on exhaust emissions of "black box", advanced prototype engines being developed by engine manufacturers were large enough to warrant a Phase 2. "Black box" engines are advanced engines being designed by engine manufacturers to meet the 2004 standards, but the details of each black box engine would not be shared with the HDEWG. In addition, the HDEWG agreed to use one "transparent" engine at an independent test facility, Southwest Research Institute (SwRI). During Phase 1, testing was to be performed on the transparent engine at SwRI, as well as the black box engines at manufacturers own testing facilities, to determine if the transparent engine was representative of the black box engines with respect to diesel fuel effects on NOx emissions.

Phase 2 of the program, which would occur upon successful completion of Phase 1, would be used to test a range of relevant fuel properties on the transparent engine at SwRI, in order to determine the effects of those fuel properties on emissions. Finally, Phase 3 of the test program would determine whether or not the results seen during Phase 2 on the transparent engine was in fact representative of black box engines, i.e., advanced prototype engines being developed by engine manufacturers to meet the 2004 standards. Phase 3 would be performed at engine manufacturer's laboratories using a subset of the fuel matrix from Phase 2.

(b) Phase 1 of the HDEWG Test Program

The Phase 1 test program consisted of two test phases; first, testing on three fuels by engine manufacturers at their facilities of “black box” engines, i.e., advanced prototype engines being designed to meet the 2004 HC+NOx standard, and second, testing on the same three fuels at SwRI of the transparent engine. The purpose of Phase 1 was to determine first, whether or not changes in relevant fuel properties had an important effect on NOx emissions for the black box engines which would justify continuing to Phase 2, and second, whether or not the transparent engine behaved similarly to the black box engines, and, thus, could be used for Phase 2 testing. Two reports are available in the docket for this rulemaking which contain detailed information on the Phase 1 portion of the program, the following discussion will summarize the results of Phase 1, the reader should see the detailed reports for more in depth information.[76,77] Table 3-2 describes the three fuel formulations used for Phase 1 testing.

Table 3-2:
Diesel Fuel Formulations used for Phase 1 Testing by the Heavy-duty Engine Working Group

Fuel Property	Baseline Fuel	Baseline Fuel w/ Cetane Enhancer	Naturally High Cetane, Low Aromatic Fuel
Density kg/m^3	856	856	823
Cetane Number	45.9	52.4	56.9
Monoaromatics %	26.6	26.2	15.5
Polyaromatics %	9.1	8.9	4.5
Total Aromatics %	35.7	35.1	20

It should be noted that the HDEWG’s primary focus was on the effects of diesel fuel properties on HC and NOx emissions, not on PM emissions, and therefore fuel sulfur level was not investigated. A significant amount of data exists on the effects of diesel fuel sulfur on engine emissions, and in fact this data was summarized recently in an SAE paper published by members of the HDEWG which will be summarized below. Based on the existing data on recent model year HD engines, diesel fuel sulfur level does have a statistically significant effect on PM emissions, but no statistically significant effect on HC, CO, or NOx emissions (on engines with no aftertreatment). For this reason, and because of the focus on HC and NOx emissions, as well as the limitations of the SwRI transparent engine discussed below, the HDEWG did not include fuel sulfur level as a variable in Phase 1, 2 or 3 of their test program, nor were PM emissions measured in Phase 1 or 2.

Engine manufacturers tested the three fuels shown in Table 3-2 on a total of six black box engines. In addition, SwRI tested the transparent engine on the same three fuels. The test cycle used by SwRI was the so-called AVL 8-mode test. This steady-state test cycle, with associated weighting factors, has been shown in the past to correlate very well with NOx emissions measured over the U.S. FTP. The transparent engine is representative of a modern, heavy-heavy duty diesel engine which could be certified to 1998 U.S. emission standards in it’s baseline condition. SwRI calibrated the transparent engine on the baseline test fuel to a 2.7g/hp-hr HC+NOx level utilizing a prototype low-pressure loop cooled EGR system, this was followed by testing on the two non-baseline fuels. The cooled EGR system developed by SwRI was not capable of transient operation, and while the AVL 8-mode does adequately predict transient U.S. FTP NOx, it does not accurately predict PM emissions, therefore, PM emissions were not measured. Table 3-3 below summarizes the results of the Phase 1 testing program.

Table 3-3:
Summary of HDEWG Phase 1 Test Results

	% Change in NOx Emissions	
Test Engines	**Naturally High Cetane, Low Aromatic Fuel vs. Baseline Fuel**	**Baseline Fuel w/ Cetane Enhancer vs. Baseline Fuel**
Six Black Box Engines	7.6 percent decrease	2.4 percent increase
SwRI Transparent Engine	7.0 percent decrease	3.4 percent increase

The HDEWG concluded the following from the Phase 1 test results; the transparent engine at SwRI responds to fuel property changes similarly to the black box engines and therefore the transparent engine is appropriate for the Phase 2 test program, and the magnitude of the fuel effects on NOx emissions for the transparent engine and the black box engines was significant enough to warrant the continuation of the program into the Phase 2 testing.

In addition to the test program portion of Phase 1, several members of the HDEWG performed an extensive literature review of existing data on the effects of diesel fuel formulation on emissions. The result of this work was recently published by Society of Automotive Engineers, paper number 982649, "Fuel Quality Impact On Heavy-Duty Diesel Emissions:- A Literature Review." This paper reviewed publically available data which looked at the following fuel properties; sulfur, cetane number, total aromatics, polyaromatics, density, volatility (back-end volatility as determined by T90/T95) and oxygenates. This paper reviewed published results which include test data measured from both the U.S. HD transient FTP, as well as the European steady-state 13-mode ECE R49 test cycle. The literature search included engines of various levels of emission control technology, in general the engines were designed to meet U.S. 1991 through 1998 standards, or European 1993 through 1996 emission limits. The authors divided the available engines into two groups; "low emission emitting engines" and "high emission emitting engines." Low emission engines were those engines with NOx emissions between approximately 3.5 and 5 g/hp-hr, and PM emissions approximately between .05 and .2 g/hp-hr. High emission engines were those engines with NOx emissions between approximately 5.5 and 8 g/hp-hr, and PM emissions approximately between .4 and .5 g/hp-hr. The paper offers an excellent overview of available information, and the details of the paper will not be restated here. A summary of the effects which were found on the "low emission emitting engines" is summarized in Table 3-4 below.

Table 3-4:
Summary of Diesel Fuel Properties on Recent Model Year Heavy-duty Diesel Emissions from "low emission emitting engines" from SAE paper 982649

Fuel Modification	HC	CO	NOx	PM
Reduced Sulfur	no effect	no effect	no effect	large effect for moving from .3% to .05%, minimal effect for reducing S from 0.05%
Increase Cetane	no effect	no effect	small decrease in NOx	no effect
Reduce Total Aromatics	no effect	no effect	small decrease in NOx	no effect
Reduce Density	large increase in HC	small increase in CO	small decrease in NOx	no effect
Reduce Polyaromatics	small decrease in HC	no effect	small decrease in NOx	no effect
Reduce T90/T95	very small increase in HC	very small increase in CO	very small decrease in NOx	no effect

The authors noted that there was very little information available on the effect of increasing oxygenates, and any conclusions would be very tentative, therefore, the summary of oxygenates is not included here. It should be noted that the term "low emission emitting engines" employed by the authors is well above the 2.5g/hp-hr HC+NOx level.

Based on the results of the Phase 1 results for "black box" engines, the "transparent" engine, and the literature review of available data, the HDEWG agreed to proceed to Phase 2.

(c) Phase 2 of the HDEWG Test Program

The purpose of the Phase 2 component of the test program was to test a range of relevant fuel properties on the transparent engine at SwRI in order to determine the effects of various fuel properties on emissions. All testing during Phase 2 of the test program was done at SwRI on the transparent engine. The parameters investigated and the results of the Phase 2 testing are summarized in this section. A document containing detailed information on the Phase 2 test program is available in the docket for this rulemaking, the following discussion will summarize the relevant results of Phase 2, the reader should see the detailed report for more in depth information.[78]

Based on the results of the Phase 1 testing, as well as the literature review performed under Phase 1, the HDEWG selected four fuel properties for investigation under Phase 2: density, cetane (natural and "boosted"[h]), monoaromatic content and polyaromatic content. As mentioned previously, fuel sulfur level was not investigated. A test matrix was designed to decouple these fuel properties from each other, in addition, fuel blends were added to the matrix to evaluate density effects as a function of engine injection timing and a direct comparison of natural and boosted cetane number. The design matrix included two levels of density, monoaromatic hydrocarbons, polyaromatic hydrocarbons, and three levels of cetane. The final matrix included eighteen test fuels, with density varying from 830 to 860 kg/m^3, cetane numbers from 42 to 48 to 53, monoaromatic content from 10 to 25 percent, and polyaromatic content from 2.5 to 10 percent. For all emission testing, the AVL 8-mode test was utilized, and all emission tests were performed at least in duplicate. In addition to the fuel property effects, the effects of injection timing and EGR were evaluated. The SwRI prototype, low-pressure loop, cooled EGR system was manually controlled to set EGR rates in order to approach an AVL 8-mode composite NOx level of 2.5g/hp-hr.

The large quantity of test data generated by the test program was evaluated using statistical techniques in order to develop exhaust emission and fuel consumption prediction models based on the four fuel properties. All properties were evaluated using a significance level of 5 percent. The HDEWG examined the dependence of emissions and fuel consumption on the four parameters (density, cetane, monoaromatic content and polyaromatic content).

The following tables summarize the most important results of the Phase 2 test program. Table 3-5 summarizes the effects of individual fuel properties on predicted NOx, HC, and HC+NOx emissions. Table 3-6 summarizes the combined effects of fuel properties on predicted NOx, HC, and HC+NOx emissions. Table 3-6 contains a summary of percent changes in predicted results for two fuels, a blend representative of current U.S. diesel fuel (based on national fuel surveys for 1994 and 1995, except for polyaromatic content, which was estimated by the HDEWG), and a "clean" diesel fuel, i.e., a fuel low in density, high in cetane, and low in both monoaromatics and polyaromatics.

(h) Boosted cetane is achieved by the addition of a fuel additive, in this case ethylhexyl nitrate

Table 3-5:
Effects of Individual Fuel Properties on Predicted Emissions from Phase 2 Testing of the Heavy-duty Engine Working Group Project (Reference values for NOx, HC, and HC+NOx of 2.57 g/hp-hr, 0.13 g/bhp-hr, and 2.7 g/bhp-hr respectively were used. Negative percentages represent a decrease in emissions with the corresponding decrease in fuel property)

Pollutant	**Density 860 → 830 kg/m^3**	**Cetane Number 52 → 42**	**Monoaromatics 25 → 10 %**	**Polyaromatics 10 →2.5 %**
% NOx Change @ 2.57 g/bhp-hr	-4.8	-1.3	-3.8	-2.2
% HC Change @ 0.13 g/bhp-hr	Not Significant	14.3	-7.8	-9.2
% HC+NOx Change @ 2.70 g/bhp-hr	-4.3	Not Significant	-4.3	-2.3

Table 3-6:
Combined Effects Fuel Properties on Predicted Emissions from Phase 2 Testing of the Heavy-duty Engine Working Group Project (Reference values for NOx, HC, and HC+NOx of 2.57 g/hp-hr, 0.13 g/bhp-hr, and 2.7 g/bhp-hr respectively were used. Negative percentages represent a decrease in emissions)

	Fuel Property				**Predicted Emission Change**		
	Density kg/m^3	Cetane Number	Mono-aromatics %	Poly-aromatic s %	% Change in NOx vs. “Light” at 2.57g/bhp-hr level	% Change in HC vs. “Light” at 0.13 g/bhp-hr level	% Change in HC+NOx vs. “Light” at 2.70g/bhp-hr level
Average U.S. Diesel Fuel	845	45	25	9			
“Light”, High Cetane, Low Aromatic Fuel	830	52	10	2.5	-7.2	-25.8	-8.4

The test data was also analyzed to look at the effect of the prototype low pressure loop, cooled EGR system on measured emissions and on measured fuel consumption (not predicted).

Duplicate emission tests performed on each of seven test fuels with the EGR system on and off were examined. The results indicated EGR had a strong, statistically significant effect on NOx emissions, no effect on HC emissions, and a strong effect on HC+NOx emissions. The EGR system used reduced NOx emissions between 35.9 and 37.2 percent, and HC+NOx emissions by 34.2 to 35.3percent. The EGR system had no statistically significant impact on brake-specific fuel consumption.

(d) Phase 3 of the HDEWG Test Program

Phase 3 of the test program has not been completed. The purpose of the Phase 3 program will be to determine whether or not the Phase 2 results seen on the transparent engine are representative of "black box" engines, i.e., advanced, prototype HD diesels being developed by manufacturers to meet the 2004 standards. The Phase 3 testing will occur at individual engine manufacturers facilities, and will utilize full U.S. FTP transient emission testing, and will include PM measurement. The Phase 3 program is scheduled to be competed in mid-1999.

(e) EPA Assessment of HDEWG Data

The most significant data for this rulemaking activity generated up to this point in time by the HDEWG is presented in Tables 3-5 and 3-6. The data in Table 3-5 indicates that for engines utilizing advanced fuel injection and a cooled EGR system operating at emissions levels near the 2004 standards, the effects of relatively large changes in individual fuel properties is statistically significant but rather small, and for cetane number not statistically significant. A large decrease in fuel density (from 860 to 830 kg/m^3) or in monoaromatic content (from 25 to 10 percent) is predicted to result in a 4.3 percent decrease in HC+NOx emissions, and a large decrease in polyaromatics content (from 10 to 2.5 percent) is predicted to result in a 2.3 percent decrease in HC+NOx emissions.

The data in Table 3-6 indicates the potential impacts on HC+NOx emissions from the combined effects of significantly changing diesel fuel formulation from today's currently available U.S. on-highway diesel fuel. The results predict that a combined, relatively large decrease in density, large increase in cetane, and large decrease in both monoaromatic content and polyaromatic content would result in a 8.4 percent decrease in HC+NOx emissions.

3. Fuel Sulfur Impact on Engine Durability

(a) Condensate Issues

Cooled EGR poses several design issues, one of those being corrosion from EGR condensate. This condensate is composed of two major components, water and sulfuric acid. The water is a normal byproduct of combustion and the sulfuric acid (H_2SO_4) is formed primarily from sulfur in the fuel. The rate of acid condensation is proportional to the concentration of sulfur in the fuel. Current on-highway requirements limit diesel fuel sulfur to 500 ppm or less. Manufacturers have proposed at least 30 ppm maximum sulfur fuel to minimize sulfur induced corrosion.

The EGR cooler, intake plumbing, intake manifold, cylinder kit (piston rings and cylinder liner), and engine oil will be exposed to this condensate. The EGR cooler will be the most critical component from a corrosion standpoint. It will be cooling raw exhaust, which is more likely to condense than the diluted exhaust found in the engine intake system. Corrosion of the EGR system and intake charge plumbing can lead to contamination of the intake charge. Particles from the walls of the intake plumbing can be released by the corrosion process and carried by the intake charge into the cylinders. Once there, the particles act to abrasively wear the cylinder kit causing loss of oil control. Corrosion induced pitting on the cylinder liner from the sulfuric acid entrained in the EGR could also be an issue.

The engine oil will also be impacted by the fuel sulfur and EGR. The sulfuric acid can get into the engine oil via the blow-by or via deposition on the cylinder liner. The result will be accelerated depletion of the oil PH control package.

(b) Corrosion Resistance

Most of the EGR induced corrosion issues will be dealt with through careful material and bonding process selection. Stainless steels with higher nickel or cobalt content may be necessary to provide the required EGR cooler life.[79] Bonding methods used in the construction of these coolers are also available to reduce corrosion. Along with corrosion resistant materials, the EGR can also be controlled to minimize condensation under adverse conditions, such as cold start. This attention to material selection and the level of EGR cooling will minimize the condensation impact on engine durability.

Engine oil reformulation studies have already begun to set a new standard for engines with cooled EGR. Improved TBN control additive packages will be part of this standard along with increased oil soot tolerance capability. These improvements should allow the oil to perform at least as well as current (non-EGR) oils.

F. Performance of Projected Emission Control Technologies over Typical In-Use Conditions

The technologies discussed in this chapter, cooled EGR, advanced fuel injection systems with rate shaping, and variable-nozzle turbochargers, combined with electronic control systems, are all applicable for in-use operation, under both steady-state and transient operation. The Agency expects that this technology package can achieve the emission reductions necessary to comply with the 2004 standards under a large variety of operating conditions, not simply the test cycle contained in the Federal transient FTP. Many of the published reports in the past several years have looked at the application of these technologies not only under transient operation, but also under steady-state test cycle conditions. Some of these reports included data for the steady-state cycles used in Japan and Europe, which are similar to the EPA cycle for the steady-state MAEL requirements. As indicated in Table 3-7, NOx and PM performance in these steady-state conditions are at or near the standards in this rulemaking. In addition, the test results included in the 1997 RIA indicate NOx and PM performance at or near the standards using both transient and steady-state tests. The Agency sees no reason why the technologies discussed previously would not function sufficiently well under a wide range of operating conditions, and thus we expect them to be designed to provide comparable levels of emission control under a wide range of operating conditions in the timeframe require by this rule. As discussed previously, cooled EGR alone has been demonstrated under laboratory conditions to provide NOx reductions up to 90 percent at light load conditions and up to 60 percent near rated speed. These conclusions are fully consistent with the expectation in the 1997 rulemaking.

Following the October 29, 1999 Federal Register publication of the proposal for this final rule the Agency met with a number of HD diesel engine manufacturers to discuss the supplemental test procedure requirements. During this time we received a substantial amount of confidential business information from a number of HD diesel manufacturers who are designing engines to comply with the NTE requirements under the 1998 HD diesel consent decrees. We have summarized this information into a memorandum which is available for review in the public docket for this rule.[80] This memorandum shows that a number of manufacturers have made significant progress towards meeting the 2007 supplemental requirements. The principle issue which manufacturers are now in the process of addressing is the ability to drive and control cooled EGR under high load conditions for highly rated versions of their engines. Manufacturers have encountered a number of technical issues, depending on the engine design path they have chosen. Some manufacturers are encountering the physical limitations of current turbocharger designs, while others are addressing complex control strategies which in some cases push the limits of currently available sensors and actuators. Engine manufacturers are at different stages of product development for achieving NTE limits. Based on the information provided to the Agency, those manufacturers who have progressed the furthest have narrowed the remaining technical issues substantially. These manufacturers have narrowed the focus of their efforts to the ability to drive and control EGR for the highly rated versions of their engines while maintaining engine performance, under the high load regions of the NTE, and only under ambient conditions of high temperature and/or high altitude. The Agency also spoke with a major turbocharger manufacturer regarding the performance capabilities of turbocharger in the 2004 time frame and beyond.[81] Based on the emission capabilities of the emission control technologies previously discussed in this RIA (cooled EGR, advanced turbomachinery, and advanced fuel injection systems), the information the Agency has received from manufacturers, and the summary of the confidential information provided by a number of engine manufacturers, the Agency concludes the supplemental test procedure requirements (NTE and SSS) are technically feasible by 2007.

For these reasons, EPA believes the primary technologies discussed in this chapter will provide the necessary NMHC+NOx and PM control on the existing transient FTP by 2004, as well as the supplemental test cycles, procedures and associated standards contained in this rule for 2007. Thus, we do not expect these requirements to impose new hardware burdens. Manufacturers are expected to only need to conduct additional emission testing and perform recabilbration of their engines to comply with these requirements.

G. Summary and Conclusions regarding HD Diesel Technologies

The Regulatory Impact Analysis document for the 1997 HD diesel FRM documents EPA's analysis which lead to the conclusion that the Agency believed the 2004 HD NOx+NMHC standards were technologically feasible. This RIA contains EPA's reassessment of the technological feasibility of these standards, including a discussion of the role diesel fuel quality plays in the appropriateness of the standards. Table 3-7 summarizes the emission performance results of several studies that were recently conducted on heavy-duty diesel engines, and which have been discussed earlier in this chapter. In the technological feasibility chapter of the 1997 RIA for this rule, a similar table is presented for results up to 1997.

Table 3-7:
Summary of recently published data on 2004 capable control strategies

Technology	Test Cycle	NOx	PM	BSFC
VGT turbocharged, aftercooled, 4-valve/cyl, high-pressure fuel injection, HPL cooled EGR, with full-flow venturi mixer[82]	ECE R49 13-mode	2.24 g/hp-hr	0.08 g/hp-hr	No significant change
VGT turbocharged, aftercooled, high-pressure electronic fuel injection, HPL cooled EGR, with full-flow venturi mixer[83]	ECE R49 13-mode	1.80 g/hp-hr	0.08 g/hp-hr	2.3% inc. from no EGR
VGT turbocharged, aftercooled, HPL cooled EGR[84]	Japanese 13-mode	22% dec. from no EGR & VGT	No significant change	1.5% dec. from no EGR & VGT
waste-gate turbocharged, air-air aftercooled, 4 valve/cyl, MEUI fuel injection, HPL cooled EGR with partial flow venturi mixer[85]	Euro-3 ESC	3.24 g/hp-hr	0.06 g/hp-hr	No significant change
same as above, including reference	Euro-3 ESC	2.33 g/hp-hr	0.08 g/hp-hr	0.9% inc. from no EGR
same as above, including reference	Euro-3 ESC	1.83 g/hp-hr	0.15 g/hp-hr	2.4% inc. from no EGR

These results and the results indicated in the 1997 RIA show the types of emission values which can be achieved from the combination of cooled EGR, advanced electronic controls, advanced turbo-chargers, and high-pressure fuel injection systems with rate shaping capabilities. The results above indicate that current technology can achieve NOx and PM results at or near the 2004 standards. Results referenced in the 1997 RIA include a study showing HC + NOx levels of 2.54 g/bhp-hr on the current transient cycle FTP. Based on the tests that have been conducted in the past few years, EPA projects that manufacturers will continue to optimize fuel injection and EGR strategies in the lead time available to them , and will be able to meet the NMHC+NOx emission standards in this rule, while continuing to meet the PM standard, with little or no brake specific fuel consumption penalty. Also, as discussed previously, the Agency has placed information into this rulemaking record summaries of information and discussion with engine manufacturers and component suppliers regarding the feasibility of the 2007 supplemental requirements. This information shows manufacturers have made substantial progress towards meeting the supplemental requirements (NTE and supplemental steady-state requirements). Considering the remaining technical issues, the potential solution to these issues, and the significant lead time (more than six years), the Agency concludes the supplemental requirements contained in this final rule will be feasible by model year 2007.

III. HD Otto-cycle Engine & Vehicle Technologies

The purpose of this sub-chapter is to further expand upon the technical discussion that was presented in the preamble. HD otto-cycle vehicle and engine exhaust emissions can be reduced by a number of technologies, but the most potential for improvement exists in reductions to base engine-out emissions, improvement in air-fuel ratio control, better fuel delivery and atomization, and continued advances in exhaust aftertreatment.

The following descriptions provide an overview of the latest technologies capable of reducing exhaust emissions. The descriptions will also discuss the state of development and current production usage of the various technologies. It is important to point out that the use of all of the following technologies is not required to further reduce emissions. The choices and combinations of technologies will depend on several factors, such as current engine-out emission levels, effectiveness of existing emission control systems, and individual manufacturer preferences. With the exception of a few technologies, many of these technologies are used in some heavy-duty and light-duty vehicles already in production.

EPA used a number of references for the following discussion. EPA consulted an Energy and Environmental Analysis, Inc. (EEA), study evaluating emission control technologies for light-duty vehicles and light-duty trucks.[86] EPA used as references, the State of California Air Resources Board (CARB) staff reports on “Low-Emission Vehicle and Zero-Emission Vehicle Program Review,” and “LEVII” published in November 1996 and September 1998 respectively.[87,88] EPA also used as a reference information from the Manufacturers of Emission Controls Association (MECA) and vehicle manufacturers.

While the EEA report focused on light-duty vehicles, the emissions controls for heavy-duty vehicles would be very similar. Often technologies are first introduced on light-duty vehicles and then later applied to heavier vehicles as needed. For example, most heavy-duty vehicles and engines are now equipped with sequential fuel injection, three way catalyst systems with closed loop control, and EGR. The CARB medium-duty vehicle program applies to vehicles up to 14,000 pounds

GVWR and includes LEV and ULEV standards. For heavy-duty vehicles and engine specifically, EPA contracted Arcadis Geraghty and Miller to review technologies and perform cost analyses for the standards that were proposed in the NPRM for this rulemaking.[89]

A. Base Engine Improvements

There are several design techniques that can be used for reducing engine-out emissions, especially for HC and NOx. The main causes of excessive engine-out emissions are unburned HCs and high combustion temperatures for NOx. Methods for reducing engine-out HC emissions include the reduction of crevice volumes in the combustion chamber, reducing the combustion of lubricating oil in the combustion chamber and developing leak-free exhaust systems. Leak-free exhaust systems are listed under base engine improvements because any modifications or changes made to the exhaust manifold can directly affect the design of the base engine. Base engine control strategies for reducing NOx include the use of "fast burn" combustion chamber designs, multiple valves with variable-valve timing, and exhaust gas recirculation.

1. Combustion Chamber Design

Unburned fuel can be trapped momentarily in crevice volumes (i.e., the space between the piston and cylinder wall) before being subsequently released. Since trapped and re-released fuel can increase engine-out HC, the reduction of crevice volumes is beneficial to emission performance. One way to reduce crevice volumes is to design pistons with reduced top "land heights" (distance between the top of the piston and the first piston ring). The reduction of crevice volume is especially preferable for vehicles with larger displacement engines, since they typically produce greater levels of engine-out HC than smaller displacement engines.

Another cause of excess engine-out HC emissions is the combustion of lubricating oil that leaks into the combustion chamber, since heavier hydrocarbons in oil do not oxidize as readily as those in gasoline. Oil in the combustion chamber can also trap gaseous HC from the fuel and release it later unburned. In addition, some components in lubricating oil can poison the catalyst and reduce its effectiveness. To reduce oil consumption, vehicle manufacturers will tighten tolerances and improve surface finishes for cylinders and pistons, improve piston ring design and material, and improve exhaust valve stem seals to prevent excessive leakage of lubricating oil into the combustion chamber.

As discussed above, engine-out NOx emissions result from high combustion temperatures. Therefore, the main control strategies for reducing engine-out NOx are designed to lower combustion temperature. The most promising techniques for reducing combustion temperatures, and thus engine-out NOx emissions, are the combination of increasing the rate of combustion, reducing spark advance, and adding a diluent to the air-fuel mixture, typically via exhaust gas recirculation (EGR). The rate of combustion can be increased by using "fast burn" combustion chamber designs. A fast burn combustion rate provides improved thermal efficiency and a greater tolerance for dilution from EGR resulting in better fuel economy and lower NOx emissions. There are numerous ways to design a fast burn combustion chamber. However, the most common approach is to induce turbulence into the combustion chamber which increases the surface area of the flame front and thereby increases the rate of combustion, and to locate the spark plug in the center of the combustion chamber. Locating the spark plug in the center of the combustion chamber promotes more thorough combustion and allows the ignition timing to be retarded, decreasing the dwell time of hot gases in the combustion chamber and reducing NOx formation. Many engine designs induce turbulence into the combustion chamber by increasing the velocity of the incoming air-fuel mixture and having it enter the chamber in a swirling motion (known as “swirl”).

2. Improved EGR Design

One of the most effective means of reducing engine-out NOx emissions is exhaust gas recirculation. By recirculating spent exhaust gases into the combustion chamber, the overall air-fuel mixture is diluted, lowering peak combustion temperatures and reducing NOx. As discussed above, the use of high swirl, high turbulence combustion chambers can allow the amount of EGR to be increased from current levels of 15 to 17 percent to levels possibly as high as 20 to 25[i] percent, resulting in a 15 to 20 percent reduction in engine-out NOx emissions.

Many EGR systems in today’s vehicles utilize a control valve that requires vacuum from the intake manifold to regulate EGR flow. Under part-throttle operation where EGR is needed, engine vacuum is sufficient to open the valve. However, during throttle applications near or at wide-open throttle, engine vacuum is too low to open the EGR valve. While EGR operation only during part-throttle driving conditions has been sufficient to control NOx emissions for most vehicles in the past, more stringent NOx standards and emphasis on controlling off-cycle emission levels may require more precise EGR control and additional EGR during heavy throttle operation to reduce NOx emissions. Many manufacturers now use electronic EGR in place of mechanical back-pressure designs. By using electronic solenoids to open and close the EGR valve, the flow of EGR can be more precisely controlled.

While most manufacturers agree that electronic EGR gives more precise control of EGR flow rate, not all manufacturers are using it. Numerous LEV vehicles certified for the 1998 model year still use mechanical EGR systems, and in some cases, no EGR at all. Nonetheless, the use of EGR remains a very important tool in reducing engine-out NOx emissions, whether mechanical or electronic.

3. Multiple Valves and Variable-Valve Timing

Conventional engines have two valves per cylinder, one for intake of the air-fuel mixture and the other for exhaust of the combusted mixture. The duration and lift (distance the valve head is

(i) Some manufacturers have stated that EGR impacts the ability to control net air-fuel ratios tightly due to dynamic changes in exhaust back pressure and temperature, and that the advantages of increasing EGR flow rates are lost partly in losses in air-fuel ratio control even with electronic control of EGR. Higher EGR flow rates can be tolerated by modern engines with more advanced combustion chambers, but EGR cooling may be necessary to achieve higher EGR flow rates within acceptable detonation limits without significant loss of air-fuel control.

pushed away from its seat) of valve openings is constant regardless of engine speed. As engine speed increases, the aerodynamic resistance to pumping air in and out of the cylinder for intake and exhaust also increases. By doubling the number of intake and exhaust valves, pumping losses are reduced, improving the volumetric efficiency and useful power output.

In addition to gains in breathing, the multiple-valve (typically 4-valve) design allows the spark plug to be positioned closer to the center of the combustion chamber (as discussed above) which decreases the distance the flame must travel inside the chamber. In addition, the two streams of incoming gas can be used to achieve greater mixing of air and fuel, further increasing combustion efficiency which lowers engine-out HC emissions.

Even greater improvements to combustion efficiency can be realized by using valve timing and lift control to take advantage of the 4-valve configuration. Conventional engines utilize fixed-valve timing and lift across all engine speeds. Typically the valve timing is set at a level that is a compromise between low speed torque and high engine speed horsepower. At light engine loads it would be desirable to close the intake valve earlier to reduce pumping losses. Variable valve timing can enhance both low speed torque and high speed horsepower with no necessary compromise between the two. Variable valve timing can allow for increased swirl and intake charge velocity, especially during low load operating conditions where sufficient swirl and turbulence tend to be lacking. By providing a strong swirl formation in the combustion chamber, the air-fuel mixture can mix sufficiently, resulting in a faster, more complete combustion, even under lean air-fuel conditions, thereby reducing emissions. Variable valve technology by itself may have somewhat limited effect on reducing emissions. Several vehicle manufacturers estimate emission reductions of 3%-10% for both, NMHC and NOx, but reductions could be increased when variable valve timing is combined with optimized spark plug location and additional EGR.

Multi-valve engines already exist in numerous federal and California certified vehicles and are projected by CARB to become even more common. CARB also projects that in order to meet LEV and ULEV standards, more vehicles will have to make improvements to the induction system, including the use of variable valve timing.

4. Leak-Free Exhaust System

Leaks in the exhaust system can result in increased emissions, but not necessarily from emissions escaping from the exhaust leak to the atmosphere. With an exhaust system leak, ambient air is typically sucked into the exhaust system by the pressure difference created by the flowing exhaust gases inside the exhaust pipe. The air that is sucked into the exhaust system is unmetered and, therefore, unaccounted for in the fuel system's closed-loop feedback control, resulting in erratic and/or overly rich fuel control. This results in increased emission levels and potentially poor drive ability. In addition, an air leak can cause an oxidation environment to exist in a three-way catalyst at low speeds that would hamper reduction of NOx and lead to increased NOx emissions.

Some vehicles currently use leak-free exhaust systems today. These systems consist of an improved exhaust manifold/exhaust pipe interface plus a corrosion-free flexible coupling inserted between the exhaust manifold flange and the catalyst to reduce stress and the tendency for leakage to occur at the joint. In addition, improvements to the welding process for catalytic converter canning could ensure less air leakage into the converter and provide reduced emissions. CARB and MECA project that vehicle manufacturers will continue to incorporate leak-free exhaust systems as emission standards become more stringent.

5. Improvements in Air-Fuel Ratio Control

Modern three-way catalysts require the air-fuel ratio (A/F) to be as close to stoichiometric operation (the amount of air and fuel just sufficient for nearly complete combustion) as possible. This is because three-way catalysts simultaneously oxidize HC and CO, and reduce NOx. Since HC and CO are oxidized during A/F operation slightly lean of stoichiometry, while NOx is reduced during operation slightly rich of stoichiometry, there exists a very small A/F window of operation around stoichiometry where catalyst conversion efficiency is maximized for all three pollutants (i.e., less than 1% deviation in A/F or roughly $\pm$ 0.15). Contemporary vehicles have been able to maintain stoichiometric, or very close to it, operation by using closed-loop feedback fuel control systems. At the heart of these systems has been a single heated exhaust gas oxygen (HEGO) sensor. The HEGO sensor continuously switches between rich and lean readings. By maintaining an equal number of rich readings with lean readings over a given period, the fuel control system is able to maintain stoichiometry. While this fuel control system is capable of maintaining the A/F with the required accuracy under steady-state operating conditions, the system accuracy is challenged during transient operation where rapidly changing throttle conditions occur. Also, as the sensor ages, its accuracy decreases.

(a) Dual Oxygen Sensors

Many vehicle manufacturers have placed a second HEGO sensor(s) downstream of one or more catalysts in the exhaust system as a method for monitoring the catalyst effectiveness of the federally and California mandated on-board diagnostic (OBD II) system. In addition to monitoring the effectiveness of the catalyst, the downstream sensors can also be used to monitor the primary control sensor and adjust for deterioration, thereby maintaining precise A/F control at higher mileages. Should the front primary HEGO sensor, which operates in a higher temperature environment, begin to exhibit slow response or drift from its calibration point, the secondary downstream sensor can be relied upon for modifying the fuel system controls to compensate for the aging effects. By placing the second sensor further downstream from the hot engine exhaust, where it is also less susceptible to poisoning, the rear sensor is less susceptible to aging over the life of the vehicle. As a result, the use of a dual oxygen sensor fuel control system can ensure more robust and precise fuel control, resulting in lower emissions.

Currently, all vehicle manufacturers use a dual oxygen sensor system for monitoring the catalyst as part of the OBD II system. As discussed above, most manufacturers also utilize the secondary HEGO sensor for trim (i.e., adjustments to) of the fuel control system. It is anticipated that all manufacturers will soon use the secondary sensor for fuel trim.

(b) Universal Oxygen Sensors

The universal exhaust gas oxygen (UEGO) sensor, also called a "linear oxygen sensor", could replace conventional HEGO sensors. Conventional HEGO sensors only determine if an engine's A/F is richer or leaner than stoichiometric, providing no indication of what the magnitude of the A/F actually is. In contrast, UEGO's are capable of recognizing both the direction and magnitude of A/F transients since the voltage output of the UEGO is "proportional" with changing A/F (i.e., each voltage value corresponds to a certain A/F). Therefore, proportional A/F control is possible with the use of UEGO sensors, facilitating faster response of the fuel feedback control system and tighter control of A/F.

Although some manufacturers are currently using UEGO sensors, discussions with various manufacturers suggest that some manufacturers are of mixed opinion as to the future applicability of UEGO sensors. Because of their high cost, manufacturers claim that it may be cheaper to improve HEGO technology rather than utilize UEGO sensors. An example of this is the use of a "planar" design for HEGO sensors. Planar HEGO sensors (also known as "fast light-off" HEGO sensors) have a thimble design that is considerably lighter than conventional designs. The main benefits are shorter heat-up time and faster sensor response.

(c) Individual Cylinder A/F Control

Another method for tightening fuel control is to control the A/F in each individual cylinder. Current fuel control systems control the A/F for the entire engine or a bank of cylinders. By controlling A/F for the entire engine or a bank of cylinders, any necessary adjustments made to fuel delivery for the engine are applied to all cylinders simultaneously, regardless of whether all cylinders need the that amount of fuel delivered. For example, there is usually some deviation in A/F between cylinders. If a particular cylinder is rich, but the "bulk" A/F indication for the engine is lean, the fuel control system will simultaneously increase the amount of fuel delivered to all of the cylinders, including the rich cylinder. Thus, the rich cylinder becomes even richer having a potentially negative effect on the net A/F.

Individual cylinder A/F control helps diminish variation among individual cylinders. This is accomplished by modeling the behavior of the exhaust gases in the exhaust manifold and using sophisticated software algorithms to predict individual cylinder A/F. Individual cylinder A/F control requires use of an UEGO sensor in lieu of the traditional HEGO sensor, and requires a more powerful engine control computer.

(d) Adaptive Fuel Control Systems

The fuel control systems of virtually all current vehicles incorporate a feature known as "adaptive memory" or "adaptive block learn." Adaptive fuel control systems automatically adjust the amount of fuel delivered to compensate for component tolerances, component wear, varying environmental conditions, varying fuel compositions, etc., to more closely maintain proper fuel control under various operating conditions.

For most fuel control systems in use today, the adaption process affects only steady-state operation conditions (i.e., constant or slowly changing throttle conditions). Because transient operating conditions have always provided a challenge to maintaining precise fuel control, the use of adaptive fuel control for transient operation would be extremely valuable. Accurate fuel control during transient driving conditions has traditionally been difficult because of inaccuracies in predicting the air and fuel flow under rapidly changing throttle conditions. Air and fuel dynamics within the intake manifold (fuel evaporation and air flow behavior), and the time delay between measurement of air flow and the injection of the calculated fuel mass, result in temporarily lean A/F during transient operation. Variation in fuel properties, particularly distillation characteristics, also increases the difficulty in predicting A/F during transients. These can all lead to poor drive ability and an increase in NOx emissions.

6. Electronic Throttle Control Systems

As mentioned above, the time delay between the air mass measurement and the calculated fuel delivery presents one of the primary difficulties in maintaining accurate fuel control and good drive ability during transient driving conditions. With the conventional mechanical throttle system (a metal linkage connected from the accelerator pedal to the throttle blade in the throttle body), quick throttle openings can result in a lean A/F spike in the combustion chamber. Although algorithms can be developed to model air and fuel flow dynamics to compensate for these time delay effects, the use of an electronic throttle control system, known as “drive-by-wire” or “throttle-by-wire,” may better synchronize the air and fuel flow to achieve proper fueling during transients (e.g., the driver moves the throttle, but the fuel delivery is momentarily delayed to match the inertial lag of the increased airflow).

While this technology is currently used in several vehicle models, it is considered expensive and those vehicles equipped with the feature are expensive higher end vehicles. Because of its high cost, it is not anticipated that drive-by-wire technology will become commonplace in the near future.

B. Improvements in Fuel Atomization

In addition to maintaining a stoichiometric A/F ratio, it is also important that a homogeneous air-fuel mixture be delivered at the proper time and that the mixture is finely atomized to provide the best combustion characteristics and lowest emissions. Poorly prepared air-fuel mixtures, especially after a cold start and during the warm-up phase of the engine, result in significantly higher emissions of unburned HC since combustion of the mixture is less complete. By providing better fuel atomization, more efficient combustion can be attained, which should aid in improving fuel economy and reducing emissions. Sequential multi-point fuel injection and air-assisted fuel injectors are examples of the most promising technologies available for improving fuel atomization.

1. Sequential Multi-Point

Typically, conventional multi-point fuel injection systems inject fuel into the intake manifold by injector pairs. This means that rather than injecting fuel into each individual cylinder, a pair of injectors (or even a whole bank of injectors) fires simultaneously into several cylinders. Since only one of the cylinders is actually ready for fuel at the moment of injection, the other cylinder(s) gets too much or too little fuel. With this less than optimum fuel injection timing, fuel puddling and intake manifold wall wetting can occur, both of which can hinder complete combustion. Sequential injection, on the other hand, delivers a more precise amount of fuel that is required by each cylinder to each cylinder at the appropriate time. Because of the emission reductions and other performance benefits "timed" fuel injection offers, sequential fuel injection systems are very common on today's vehicles and are expected to be incorporated in all vehicles soon.

2. Air-Assisted Fuel Injectors

Another method to further homogenize the air-fuel mixture is through the use of air-assisted fuel injection. By injecting high pressure air into the fuel injector, and subsequently, the fuel spray, greater atomization of the fuel droplets can occur. Since achieving good fuel atomization is difficult when the air flow into the engine is low, air-assisted fuel injection can be particularly beneficial in reducing emissions at low engine speeds. In addition, industry studies have shown that the short burst of additional fuel needed for responsive, smooth transient maneuvers can be reduced significantly with air-assisted fuel injection due to a decrease in wall wetting in the intake manifold.

C. Improvements to Exhaust Aftertreatment Systems

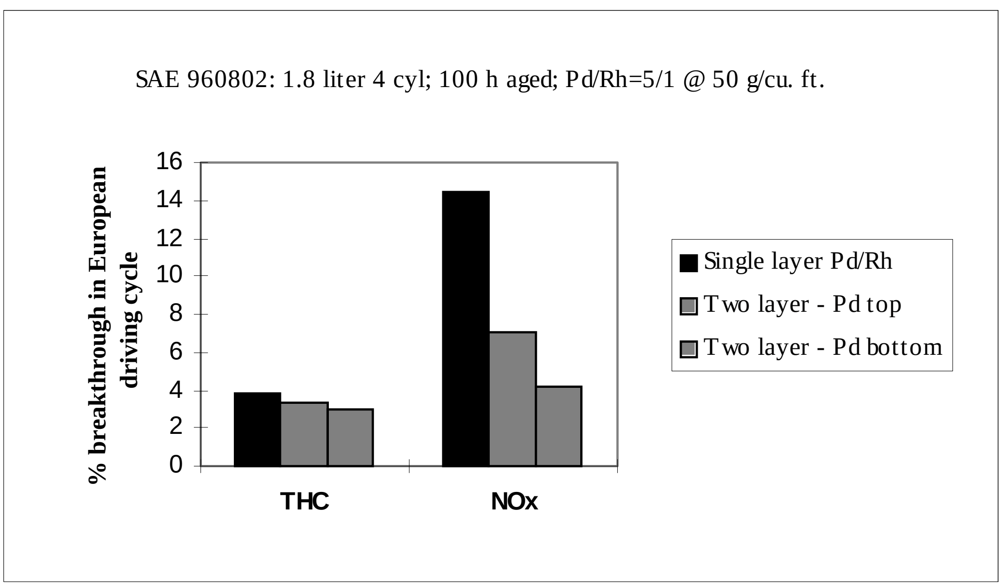
Over the last five years or so, there have been tremendous advancements in exhaust aftertreatment systems. Catalyst manufacturers are progressively moving to palladium (Pd) as the main precious metal in automotive catalyst applications. Improvements to catalyst thermal stability and washcoat technologies, the design of higher cell densities, and the use of two-layer washcoat applications are just some of the advancements made to catalyst technology. There has also been much development in HC and NOx absorber technology. The advancements to exhaust aftertreatment systems are probably the single most important area of emission control development.

1. Catalysts

As previously mentioned, significant changes in catalyst formulation, size and design have been made in recent years and additional advances in these areas are still possible. Palladium (Pd) is likely to continue as the precious metal of choice for close-coupled applications and will start to see more use in underfloor applications. Palladium catalysts, however, are less resistant to poisoning by oil-and fuel-based additives than conventional platinum/rhodium (Pt/Rh) catalysts. Based on current certification trends and information from vehicle manufacturers and catalyst suppliers, it is expected that Pd-only and Pd/Rh catalysts will be used in the close-coupled locations while conventional or tri-metal (Pd/Pt/Rh) catalysts will continue to be used in underfloor applications. Some manufacturers have suggested that they will use Pd/Rh in lieu of tri-metal or conventional Pt/Rh catalysts for underfloor applications. As palladium technology continues to improve, it may be possible for a single close-coupled catalyst to replace both catalysts. If fact, at least one vehicle manufacturer currently uses a single Pd-only catalyst for one of their models. According to MECA, new Pd-based catalysts are now capable of withstanding exposure to temperatures as high as 1100°C and, as a result, can be moved very close to the exhaust manifold to enhance catalyst light-off performance.

In addition to reliance on Pd and tri-metal applications, catalyst manufacturers have developed "multi-layered" washcoat technologies. Automotive catalysts consist of a cylindrical or oval shaped substrate, typically made of ceramic or metal. The substrate is made up of hundreds of very small, but long cells configured in a shape similar to a honey-comb. The substrate is coated with a substance containing precious metals, rare earth metals, and base-metal oxides, that is known as the catalyst washcoat. Typical washcoat formulations consist of precious metals which either oxidize or reduce pollutants, base-metal oxides, such as alumina, which provide the surface area support for the precious metals to adhere to, and base components (rare earth metals) such as lanthanum, ceria, and zirconia, which act as promoters, stabilizers, and encourage storage and reduction of oxygen. Conventional catalysts have had a single layer of washcoat and precious metals applied to the catalyst substrate. Multi-layered washcoats use a combination of washcoat and precious metals on different layers. The washcoat can be applied to the substrate such that one layer can be applied on top of another. The use of multi-layered washcoat technology allows precious metals that have adverse reactions together to be separated such that catalyst durability and emission reduction performance are significantly enhanced. For example, Pd and Rh can have adverse reactions when combined together in a single washcoat formulation. A multi-layer washcoat architecture that uses Pd and Rh could have the Pd on the bottom layer and the Rh on the top layer or vice versa. Figure 3-4 illustrates the impact coating architecture (multi-layered washcoat technology) can have on emission performance.

Figure 3-4. Impact of Coating Architecture on HC and NOx Emissions



Manufacturers have also been developing catalysts with substrates which utilize thinner walls in order to design higher cell density, low thermal mass catalysts for close-coupled applications (improves mass transfer at high engine loads and increase catalyst surface area). The greater the number of cells there are the more surface area that exists for washcoat components and precious metals to adhere to, resulting in more precious metal sites available for oxidizing and reducing pollutants. Cell densities of 600 cells per square inch (cpsi) have already been commercialized, and research on 900 cpsi catalysts has been progressing. Typical cell densities for conventional catalysts are 400 cpsi.

The largest source for HC continues to be from cold start operation where the combination of rich A/F operation and the ineffectiveness of a still relatively cool catalyst result in excess HC emissions. One of the most effective strategies for controlling cold start HC emissions is to reduce the time it takes to increase the operating temperature of the catalyst immediately following engine start-up. The effectiveness or efficiency of the catalyst increases as the catalyst temperature increases. One common strategy is to move the catalyst closer to the exhaust manifold where the exhaust temperature is greater (e.g., a close-coupled catalyst). In addition to locating the catalyst closer to the engine, retarding the spark timing, which causes combustion to occur late in the power stroke allowing more heat to escape into the exhaust manifold during the exhaust stroke, increased idle speed. Increased idle speed leads to a greater amount of combustion per unit time and thus to a greater quantity of heat for heating the exhaust manifold, headpipe, and catalyst. Another strategy is to use an electrically-heated catalyst (EHC). The EHC consists of a small electrically heated catalyst placed directly in front of a conventional catalyst. Both substrates are located in a single can or container. The EHC is powered by the alternator, or solely from the vehicle's battery, or from a combination of the alternator and battery. The EHC is capable of heating up almost immediately, assisting the catalyst that directly follows it to also heat up and obtain light-off temperature (e.g., the catalyst temperature where catalyst efficiency is 50 percent) quickly. Manufacturers have indicated that EHC's will probably only be necessary for a limited number of LEV/ULEV engine families, mostly larger displacement V-8's where cold start emissions are difficult to control.

2. Adsorbers/Traps

Other potential exhaust aftertreatment systems that are used in conjunction with a catalyst or catalysts, are the HC and NOx adsorbers/traps. Hydrocarbon adsorbers are designed to trap HC while the catalyst is cold and unable to sufficiently convert the HC. They accomplish this by utilizing an adsorbing material which holds onto the HC. Once the catalyst is warmed up, the trapped HC are released from the adsorption material and directed to the fully functioning downstream three-way catalyst. There are three principal methods for incorporating the adsorber into the exhaust system. The first is to coat the adsorber directly on the catalyst substrate. The advantage is that there are no changes to the exhaust system required, but the desorption process cannot be easily controlled and usually occurs before the catalyst has reached light-off temperature. The second method locates the adsorber in another exhaust pipe parallel with the main exhaust pipe, but in front of the catalyst and includes a series of valves that route the exhaust through the adsorber in the first few seconds after cold start, switching exhaust flow through the catalyst thereafter. Under this system, mechanisms to purge the trap are also required. The third method places the trap at the end of the exhaust system, in another exhaust pipe parallel to the muffler, because of the low thermal tolerance of adsorber material. Again a purging mechanism is required to purge the adsorbed HC back into the catalyst, but adsorber overheating is avoided.

NOx adsorbers have been researched, but according to MECA, are generally recognized as a control for NOx resulting from reduced EGR. They are typically used for lean-burn applications and are not applicable to engines that attempt to maintain stoichiometry all the time.

3. Secondary Air Injection

Secondary injection of air into exhaust ports after cold start (e.g., the first 40-60 seconds) when the engine is operating rich, coupled with spark retard, can promote combustion of unburned HC and CO in the exhaust manifold and increase the warm-up rate of the catalyst. By means of an electrical pump, secondary air is injected into the exhaust system, preferably in close proximity of the exhaust valve. Together with the oxygen of the secondary air and the hot exhaust components of HC and CO, an advanced reaction ahead of the catalyst can bring about an efficient increase in the exhaust temperature which helps the catalyst to heat up quicker. The exothermic reaction that occurs is dependent on several parameters (secondary air mass, location of secondary air injection, engine A/F ratio, engine air mass, ignition timing, manifold and headpipe construction, etc.), and ensuring reproducibility of functions demands detailed individual application for each vehicle or engine design.

4. Insulated or Dual Wall Exhaust System

Insulating the exhaust system is another method of furnishing heat to the catalyst to decrease light-off time. Similar to close-coupled catalysts, the principle behind insulating the exhaust system is to conserve heat generated in the engine for aiding the catalyst warm-up. Through the use of laminated thin-wall exhaust pipes, less heat will be lost in the exhaust system, enabling quicker catalyst light-off.

D. Improvements in Engine Calibration Techniques

Of all the technologies discussed above, one of the most important emission control strategies is not hardware-related. Rather, it's the software and, more specifically, the algorithms and calibrations contained within the software that are used in the power-train control module (PCM) which control how the various engine and emission control components and systems operate. Advancements in software along with refinements to existing algorithms and calibrations can have a major impact in reducing emissions. Confidential discussions between manufacturers and EPA suggest that manufacturers believe emissions can be further reduced by improving and updating their calibration techniques. As computer technology and software continues to advance, so does the ability of the automotive engineer to use these advancements in ways to better optimize the emission control systems. For example, as processors become faster, it is possible to perform calculations quicker, thus allowing for faster response times for things such as fuel and spark control. As the PCM becomes more powerful with greater memory capability, algorithms can become more sophisticated. Manufacturers have found that as computer processors, engine control sensors and actuators, and computer software become more advanced, and, in conjunction with their growing experience with developing calibrations, as time passes, their calibration skills will continue to become more refined and robust, resulting in even lower emissions.

Manufacturers have suggested to EPA that perhaps the single most effective method for controlling NOx emissions will be tighter A/F control which could be accomplished with advancements in calibration techniques without necessarily having to use advanced technologies, such as UEGO sensors. Manufacturers have found ways to improve calibration strategies such that meeting federal cold CO requirements, as well as, complying with LEV standards, have not required the use of advanced hardware, such as EHCs or adsorbers.

Since emission control calibrations are typically confidential, it is difficult to predict what advancements will occur in the future, but it is clear that improved calibration techniques and strategies are a very important and viable method for further reducing emissions.

E. Advanced Technology

Thus far, the technology assessment has focused on conventional emission control technology for vehicles with gasoline-powered spark ignition engines. There are a number of advanced technologies in the near horizon that may be capable even further reductions in emissions. Examples of such technologies are fuel cells, electric vehicles, and hybrid vehicles.

Fuel cell technology converts such fuels as methanol, natural gas, and gasoline into electrical energy without generating the pollutants associated with internal-combustion engines. A fuel cell is made of a thin plastic film sandwiched between two plates. Hydrogen fuel and oxygen from the air are electrically combined in the fuel cell to produce electricity. Typically, the only by-products are heat and water vapor. A fuel cell coupled with an electrically powered drive-train is essentially a quite, zero-emissions vehicle.

Electric vehicles use electric motors to power the wheels. The electric motors are powered by packs of batteries stored underneath the vehicle. These vehicles use many newer technologies, such as advanced charging and regenerating systems as well as vehicle structural design. Battery technology, which has been the major technical limitation to date, has been and will be the focus of much developmental work. Improved nickel-metal hydride and lithium ion batteries are two of the battery types being analyzed for use in electric vehicles produced in the near future.

Hybrid vehicles are typically powered by a combination of two powertrain systems. There is usually a low or zero emitting main powertrain system (e.g., battery-powered electric motors) that powers the vehicle during steady-state operation, when power demands are low. When more power is required to accelerate or drive up a hill, an axillary powertrain, usually a small displacement internal combustion engine is used. The engine may be diesel-powered, or some derivative thereof, or an alternative-fuel powered spark ignition engine that is low emitting. Because the engine used is small and low polluting, and the majority of operation uses the non-engine powertrain, hybrid vehicles have the potential to be very low emitting vehicles.

F. Technologies In-use On Current Otto-cycle HD Engines

Otto-cycle engine manufacturers are producing heavy-duty engines equipped with substantial emission controls. Table 3-8 provides a list of some key technologies currently being used for HD engine emissions control. Manufacturers have introduced improved systems as they have introduced new or revised engine models. These systems can provide very good emissions control and many engines are being certified to levels of less than half the current standards. Many of the technologies have been carried over from light-duty applications.

Table 3-8:
Key Technologies for Current Engines

Sequential Fuel Injection/electronic control
3 way catalyst
pre and post catalyst heated exhaust gas oxygen sensors
Electronic EGR
Secondary air injection
Improved electronic control modules

Improving fuel injection has been proven to be an effective and durable strategy for controlling emissions and reducing fuel consumption from gasoline engines. Improved fuel injection will result in better fuel atomization and a more homogeneous charge with less cylinder-to-cylinder and cycle-to-cycle variation of the air-fuel ratio. These engine performance benefits will increase as technology advances allow fuel to be injected with better atomization. Increased atomization of fuel promotes more rapid evaporation by increasing the surface area to mass ratio of the injected fuel. This results in a more homogeneous charge to the combustion chamber and more complete combustion. Currently, sequential multi-port fuel injection (SFI) is used in most, if not all, applications because of its proven effectiveness.

One of the most effective means of reducing engine-out NOx emissions is exhaust gas recirculation (EGR). By recirculating spent exhaust gases into the combustion chamber, the overall air-fuel mixture is diluted, lowering peak combustion temperatures and reducing NOx. Exhaust gas recirculation is currently used on heavy-duty gasoline engines as a NOx control strategy. Many manufacturers now use electronic EGR in place of mechanical back-pressure designs. By using electronic solenoids to open and close the EGR valve, the flow of EGR can be more precisely controlled.

EPA believes that the most promising overall emission control strategy for heavy-duty gasoline engines is the combination of a three-way catalyst and closed loop electronic control of the air-fuel ratio. Control of the air-fuel ratio is important because the three-way catalyst is only effective if the air-fuel ratio is at a narrow band near stoichiometry. For example, for an 80 percent conversion efficiency of HC, CO, and NOx with a typical three-way catalyst, the air-fuel ratio must be maintained within a fraction of one percent of stoichiometry. During transient operation, this minimal variation cannot be maintained with open-loop control. For closed-loop control, the air-fuel ratio in the exhaust is measured by an oxygen sensor and used in a feedback loop. The throttle position, fuel injection, and spark timing can then be adjusted for given operating conditions to result in the proper air-fuel ratio in the exhaust. Most if not all engines have been equipped with close loop controls. Some engines have been equipped catalysts that are achieving catalyst efficiencies in excess of 90 percent. This is one key reason engine and vehicle certification levels are very low. In addition, electronic control can be used to adjust the air-fuel ratio and spark timing to adapt to lower engine temperatures, therefore controlling HC emissions during cold start operation.

All HD engines are equipped with three-way catalysts. Engine may be equipped with a variety of different catalyst sizes and configurations. Manufacturers choose catalysts to fit their needs for particular vehicles. Typically, federal vehicle catalyst systems are a single converter or two converters in series or in parallel. A converter is constructed of a substrate, washcoat, and catalytic material. The substrate may be metallic or ceramic with a flow-through design similar to a honeycomb. A high surface area coating, or washcoat, is used to provide a suitable surface for the catalytic material. Under high temperatures, the catalytic material will increase the rate of chemical reaction of the exhaust gas constituents. Catalyst systems on HD vehicles tend to be large with fairly low precious metal loading. Catalyst volumes are typically 80 to 90 percent of engine volumes. Precious metal loadings are in the range of 1 to 4 grams per liter (g/l).

Significant changes in catalyst formulation have been made in recent years and additional advances in these areas are still possible. Platinum, Palladium and Rhodium (Pt, Pd, and Rh) are the precious metals typically used in catalysts. Historically, platinum has been widely used. Today, palladium is being used much more widely due to its ability to withstand very high exhaust temperatures. In fact, some HD vehicles currently are equipped with palladium-only catalysts. Other catalysts contain all three metals or contain both palladium and rhodium. Some manufacturers have suggested that they will use Pd/Rh in lieu of tri-metal or conventional Pt/Rh catalysts for underfloor applications. Improvements in substrate and washcoat materials and technology have also significantly improved catalyst performance.

Tables 3-9 and 3-10 provide certification results from either the 1998 or 1999 model year for various engines and vehicles. The engine data is from EPA certification data and the vehicle data comes from California Medium-duty Vehicle certification data. California vehicles were certified to the Tier 1 standards. The table provide and indication of the emissions levels that have been achieved through the application of these technologies.

Table 3-9:
1998 or 1999 Model Year Certification Data (g/mile)

Manufacturer	Model	Engine size	GVWR	NOx (120k)	HC (120k)
Chrysler	Ram 3500 Cab Chassis	8.0	11,000	0.6 0.9	0.23 0.24
	Ram 3500 Cab Chassis	8.0	11,000	0.7 0.9	0.24
	Ram 3500 Cab Chassis	8.0	11,000	0.9	0.24
	Ram 2500 Pickup	8.0	8,800	0.5	0.19 0.21
	Ram 3500 Pickup	8.0	10,500	0.5	0.19 0.21
Ford	F250/F350	5.4	8,800- 9,700	0.209 0.212	0.301 0.314
	F250/F350 Dual rear wheel	6.8	8,800- 11,000	0.273	0.263
	E250 Econoline	5.4	8,550	0.289, 0.446	0.295 0.300
	E350	5.4	9,100	0.278 0.654	0.263 0.283
	E250 Strip Chassis	4.2	8,550	0.161	0.111
	E350	6.8	9,400	0.299	0.270
	E350	6.8	9,300	0.308	0.296
	E350	6.8	9,300	0.364	0.276
	F250/F350	5.4	8,800- 9,700	0.209 0.212	0.301 0.314
	F250/F350 Dual rear wheel	6.8	8,800- 11,000	0.273	0.263
GM	K2500 Suburban	5.7	8,600	0.6	0.22
	K2500 Pickup	5.7	8,600	0.6	0.2
	K3500 Pickup	5.7	10,000	0.6	0.27
	K3500 Pickup	7.4	10,000	0.5	0.16
	C/K2500 4WD Pickup	6.0	8,600	0.4 0.5	0.14 0.12
	C/K2500 2WD Pickup	6.0	8,600	0.3	0.13
	C/K2500, 3500, Suburban,	6.0	8,600-	0.5	0.15

Table 3-10:
1998/1999 Model Year Engine Certification Data (g/bhp-hr)

Manufacturer	Engine size	NOx	HC
Chrysler	5.9	3.8	0.4
	8.0	1.2	0.2
Ford	5.4	0.4	0.1
	6.8	0.1	0.1
	6.8	0.4	0.1
GM	4.3	1.1	0.3
	5.7	1.2	0.1
	5.7	1.7	0.2
	6.0	0.4	0.1
	7.4	2.3	0.3
	7.4	0.7	0.4

G. Chassis-based standards

EPA is extending the California LEV standards nationwide. California began requiring some vehicles to meet LEV standards in 1998 and the phase-in will be complete in 2001. We have based our technological feasibility assessment and technology projections primarily on the mix of technologies being used to achieve California LEV emissions levels. Cold start emissions contribute to a larger portion of the emissions measured over the chassis-based test procedure compared to the engine-based test procedure. This will likely influence some of the technology choices manufacturers make in response to the chassis-based standards.

Of the anticipated changes, enhancements to the catalyst systems are expected to be most critical. Catalyst configurations are likely to continue to vary widely among the manufacturers because manufacturers must design the catalyst configurations to fit the vehicles. One potential change is that manufacturers may move the catalyst closer to the engine (close-coupled) or may place a small catalyst close to the engine followed by a larger underfloor catalyst. These designs provide lower cold start emissions because the catalyst is closer to the engine and warms up more quickly.

Typically, the catalyst systems used in HD applications have a large total volume but with lower precious metal content per liter compared to light-duty catalyst systems. For 2004, we are projecting an increase in overall precious metal loading of about 50 percent for a catalyst loading of between 4 to 5 g/l. We are not expecting significant increases in total catalyst volume. The trend toward increased use of Pd and Rh is also expected to continue. Close-coupled catalysts would likely be Pd only.

Calibration changes will also be important. The engine and catalyst systems must be calibrated to optimize the performance of the systems as a whole. Post catalyst oxygen sensors will allow further air fuel control. Manufacturers are moving to more powerful computer systems and EPA expects this trend to continue. Other technologies such as insulated exhaust systems may also be used in some cases to reduce cold start emissions.

As shown in Table 3-9, HD vehicles in California have typically been certified with full life emissions levels in the 0.3 - 0.5 g/mile range for NOx and the 0.1 - 0.3 g/mile range for NMOG. These levels are well within the LEV standards and provide manufacturers with head room or compliance cushion. We expect manufacturers would equip vehicles with very similar technologies to meet our new standards.

H. Engine-based Standards

As shown in Table 3-10, a few engine families are currently certified with NOx emissions levels close to the current standards. Many others are certified with emissions levels of less than half the standard. Manufacturers have begun to apply advanced system designs to their heavy-duty applications. Some newer engine families have been certified with emissions levels of 0.5 g/bhp-hr combined NOx plus NMHC. These engines and systems feature precise air/fuel control and catalyst designs comparable to the catalyst systems being used in LEV applications. Based on industry input, we believe that manufacturers will continue the process of replacing their old engine families with advanced engines over the next several years. New and more advanced engines are being introduced, and we anticipate that they will be capable of achieving our new standards.

Catalyst systems with increased precious metal loading will be the critical hardware change for meeting the standards being finalized in this rule. Catalyst system volumes and precious metal loading are likely to be similar to the systems discussed above for the chassis-based standards. Engines used in vehicles above 14,000 pounds may have more rigorous duty cycles which may lead to some catalyst enhancements. A small increase in precious metal loading over that used in chassis-based systems may be needed to ensure the thermal durability of the system. Palladium and palladium/rhodium catalyst formulations are expected. There is likely to be less use of close coupled systems compared with chassis-based certifications because of durability concerns. Also, there is less emphasis on cold start emissions with the engine test than with the chassis test. Advanced washcoats including layering may also be used to enhance durability.

Optimizing and calibrating the catalyst and engine systems as a whole will also be important in achieving the levels required by the standards. Precise air/fuel control is critical to meeting these standards. Increased use of air injection to control cold start emissions may occur, especially to reduce NMHC emissions during cold start operation. Also, improved EGR systems and retarded spark timing may be needed to reduce engine out NOx emissions levels.

Manufacturers have noted on several occasions that they target emissions certification levels of about half the standard. Manufacturers noted that they maintain this cushion between the standard and their certification level in part due to the potential for in-use deterioration of catalysts and oxygen sensors beyond that captured during the certification process. Catalysts experience wide variations in exhaust temperature due to the wide and varied usage of vehicles in the field. Some vehicles may experience more severe in-use operation than is represented by the durability testing conducted for engine certification. Manufacturers have argued that EPA should not set new standards based on certification data because certification levels do not account for severe in-use deterioration. Taking manufacturer practices into account, EPA would expect that engines certified in the 0.5 g/bhp-hr NOx plus NMHC range would meet a 1.0 g/bhp-hr standard.

Catalyst system durability is a key issue in the feasibility of the standards. Historically, catalysts have deteriorated when exposed to very high temperatures and this has long been a concern for heavy-duty work vehicles. Manufacturers have often taken steps to protect catalysts by ensuring exhaust temperatures remain in an acceptable range. Catalyst technologies in use currently are much improved over the catalysts used only a few years ago. The improvements have come with the use of palladium, which has superior thermal stability, and through much improved washcoat technology. The use of rhodium with palladium will also enhance performance of the catalyst. The catalysts have been shown to withstand temperatures typically experienced in HD applications. Manufacturers also continue to limit exhaust temperature extremes not only to protect catalyst systems but also to protect the engine. EPA requirements allow manufacturers to take necessary steps to protect engine and emission control systems from high temperatures.

In addition to general comments noted above regarding the need for compliance cushion, manufacturers presented EPA with an analysis of the otto-cycle engine emissions standards for 2004. The analysis assumed:

- NOx catalyst efficiency of 90.9 percent at the end of the engine's useful life;
- An engine-out NOx level of 12 g/bhp-hr;
- A cushion of .3 g/bhp-hr for engine variability and a safety margin of 20 percent of the standard;
- Tailpipe NMHC levels of 15 percent of the NOx level (.26 g/bhp-hr).

Based on these assumptions, manufacturers recommended a 2.0 g/bhp-hr NMHC plus NOx standard.[j] Manufacturers noted that a catalyst efficiency of about 97 percent would be needed to meet a 1.0 g/bhp-hr standard and that their assessments of post-2000 catalysts indicate worst case performance well below this level. The manufacturers' recommended 2.0 g/bhp-hr standard seems to indicate that compliance cushions greater than half the standard are needed.

(j) 12.0 g engine out x.091 for catalyst efficiency + 0.65 for compliance cushion = 1.74 g NOx. The difference between 2.0g and 1.74 g is reserved for NMHC emissions.)

Manufacturers state that their catalyst assumptions represented catalyst deterioration based on worst case vehicle operation (highly loaded operation, high exhaust temperatures). Details of the catalyst were not available except that manufacturers stated that the catalyst represented post-2000 catalyst technology. Due to the lack of detail, it is difficult to evaluate the assumption. However, EPA believes that this assumption is somewhat conservative given the recent developments in catalyst technology, the lead time available, and methods available to protect catalysts under worst case vehicle operation.

Engine-out NOx levels are also critical to the analysis. In their analysis, manufacturers assumed engine-out NOx levels of 12 g/bhp-hr, based on manufacturer development data for one engine. EPA does not believe that the engine-out NOx level of 12 g/bhp-hr is a reasonable or representative assumption. Other available data indicates that several engines have engine-out NOx emissions well below this level in the 6 to 10 g/bhp-hr range. Also, a previous assessment of engine standards presented to EPA by one manufacturer assumed much lower engine-out NOx levels.[k] EPA does not believe that the current standards have encouraged manufacturers to place a high priority on engine-out emissions levels. For recent engines, catalysts have provided the majority of needed emissions control.

EPA also further considered the engine variability factor of 0.3 g/bhp-hr built into the manufacturers analysis. The analysis as presented assumes a 12 g/bhp-hr engine-out NOx level. Manufacturer data for the developmental engine suggests that 12 g/bhp-hr is the worst case engine-out level anticipated (the actual highest test point recorded was 12.65). It appears to EPA that manufacturers double counted engine variability by using the worst case engine data and an engine variability factor. Using engine-out NOx levels of 12 g in the analysis but without the engine variability factor yields a NOx + NMHC level of 1.6 g/bhp-hr. Without including a safety margin, which may be appropriate considering the analysis is already based on worst case engine and catalyst assumptions, the level would be 1.3 g/bhp-hr. To reach the 1.0 g/bhp-hr level with this engine and a 20 percent safety margin, a catalyst efficiency of 94 percent would be needed. The catalyst efficiency would need to be 93 percent if the 20 percent safety margin were not included in the analysis.

EPA believes that the standards will require manufacturers to focus some effort on engine-out emissions control and that engine-out NOx levels in the 6 to 8 g/bhp-hr are reasonably achievable. Some engines are already in this range. For other engines, some recalibration of engine systems including the EGR system and perhaps some modest hardware changes to those systems would be necessary. EGR plays a key role in reducing engine-out NOx and system redesign may allow more effective use of this technology.

When coupled with a catalyst with worst case efficiencies in the 91 to 93 percent range, these engines could achieve the standards. Of course with higher catalyst efficiencies, manufacturers

(k) The details of this analysis are considered Confidential Business Information.

would not have to achieve lower NOx engine-out levels. Catalyst efficiencies of about 93 percent would allow manufacturers to maintain compliance margins in the range of 25 and 45 percent of the standard. EPA believes these margins are sufficient considering the analysis is also based on worst case catalyst efficiencies.

To help address phase in concerns that could arise for manufacturers, EPA is finalizing a modified ABT program for engines. The averaging, banking, and trading (ABT) program can be an important tool for manufacturers in implementing a new standard. The program allows manufacturers to comply with the more stringent standards by introducing emissions controls over a longer period of time, as opposed to during a single model year. Manufacturers plan their product introductions well in advance. With ABT, manufacturers can better manage their product lines so that the new standards don't interrupt their product introduction plans. Also, the program also allows manufacturers to focus on higher sales volume vehicles first and use credits for low sales volume vehicles. EPA believes manufacturers have significant opportunity to earn credits in the pre-2004 time frame.

Considering all of these factors, EPA believes that the 1.0 g/bhp-hr NOx plus NMHC standard is the appropriate standard for HD otto-cycle engines in the 2004 time frame. Certification levels of 0.5 g/bhp-hr NOx plus NMHC have been achieved on recently introduced engines of various sizes. EPA believes that the standard provides sufficient opportunity for manufacturers to maintain a compliance margin. As manufacturers continue with normal product plans between now and 2004, improved engines will continue to replace older models. The ABT program is available for manufacturers who have not completely changed over to new engine models by 2004. ABT provides manufacturers with the opportunity to earn credits prior to 2004 and use the credits to continue to offer older engine models that have not yet been redesigned or retired by 2004.

IV. On-board Diagnostics for HD Diesel and Otto-cycle Engines

To meet customer demands, manufacturers of heavy-duty engines currently use on-board diagnostics (OBD) to electronically monitor engine parameters to ensure proper engine performance and to assist in malfunction diagnostics and repair[90]. Because EPA expects manufacturers to implement electronically controlled emission control strategies such as EGR and fuel injection rate shaping, EPA is promulgating OBD requirements for heavy-duty engines used in vehicles up to 14,000 pounds, gross vehicle weight (GVW) to ensure that emission-control components meet certain performance standards. These requirements are intended to ensure that emission-control components remain effective in-use. The California Air Resources Board (CARB) has already implemented similar requirements.

EPA believes that the new requirements are already technologically feasible. All classes of HD vehicles currently employee some form of on-board diagnostics for performance purposes, and many of these systems are highly sophisticated. In addition, HD vehicles up to 14,000 pounds already have to meet regulatory OBD requirements in California. Finally, federal and California emission driven OBD regulatory requirements have been in place for Otto-cycle and diesel light-duty vehicles for a number of years. The technology necessary to perform OBD of HD vehicles is available today. The new emission control technologies employed in 2004 will also lend themselves easily to OBD. For example, LD vehicle manufacturers have been monitoring EGR systems for OBD for a number of years.

As discussed previously, EPA does not expect diesel engine manufacturers to utilize aftertreatment devices in order to achieve the 2004 HD standards, or the 2007 supplemental requirements. However, in the past engine manufacturers have used diesel oxidation to provide typically a 20 to 30 % reduction in PM on some light- and medium-heavy duty engine families. For these diesel oxidation catalysts, a complete failure of the catalysts would not result in an exceedance of the 1.5 times the standard threshold, therefore monitoring of catalyst performance would not be a requirement. For PM traps and lean NOx catalysts, neither technology is anticipated for the 2004 model year. However, in the event a manufacturer did employee either of these types of aftertreatment devices, EPA believes a back-pressure sensor would be feasible to monitor a PM trap for a complete failure of the trap, and either a chemical sensor (such as the oxygen sensors used for gasoline 3-way catalysts) or potentially a temperature sensor could be used to monitor the performance of a lean NOx catalyst.

The final rule requires that PM traps whose failure would result in an exceedance of 1.5 times the PM standard must be monitored. However, the rule does not require that the monitor detect an exceedance of 1.5 times the standard threshold. Rather, the requirement is to detect a complete failure of the device. We define complete failure as a sudden drop in exhaust back-pressure below that of a clean or unloaded trap under monitoring conditions specified by the manufacturer. Current pressure monitoring sensors are clearly capable of performing this detection.

Direct emission measurement has been identified as an important technology to achieve diesel engine closed-loop feedback control and to achieve after-treatment OBD. Researchers already have achieved promising results on a compact NOx sensor that is capable of measuring real-time NOx within 10% accuracy of laboratory-grade instruments under a wide range of operating conditions, including the temperature, pressure, and oxygen concentration typical of diesel engine exhaust. This breakthrough technology could be used for closed-loop control, and, because it can accurately measure NOx in the 100 ppm range, it would enable monitoring of NOx aftertreatment technologies.[91,92] The most recent of these papers (Kato et. al., 1999) provides an in depth discussion the accuracy, repeatability, and durability of an on-board NOx sensor, as well strategies for using the sensor for closed loop control and OBD monitoring of an active lean NOx absorber.

The federal requirements for OBD, as they exist today, require manufacturers to monitor emission related powertrain components, OBD does not monitor actual regulated pollutant emissions. It is possible that in the future the on-board measurement of actual emission performance may become feasible. EPA is following the development of a number of emerging on-board emission measurement technologies which may lend themselves to regulatory requirements in the future. These technologies include in-cylinder measurement devices, on-board PM measurement devices, and predictive emission measurement systems such as neural networks. Crank-angle resolved pressure and/or temperature measurements would allow for NOx emission prediction, based on the current understanding of NOx formation.[93] Piezo-electric and infrared pressure sensing technologies are currently used to measure crank-angle resolved in-cylinder pressure. Based on recent advances in sensor durability,[94,95] EPA expects that future advances could allow their use on-board. Lastly, neural networks have recently demonstrated a technique for accurately predicting emissions based solely on currently measured engine parameters. One study has shown excellent correlation between predicted NOx and PM measurement with respect to actual emissions measurements.[96]

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CHAPTER 4: ECONOMIC IMPACT OF HD DIESEL STANDARDS

I. Methodology

EPA previously analyzed the costs of the 2004 FTP heavy-duty diesel standards for the 1997 FRM. That economic analysis was based on a study conducted by ICF Incorporated and Acurex Environmental Corporation, which analyzed the potential costs of a wide variety of technologies.[1] This current analysis is generally a re-analysis of those previous analyses (unless noted otherwise), but also addresses new requirements such as the NTE requirements. The reader should refer to the previous analyses for additional information and background. In the previous analyses, all costs were described in terms of 1995 dollars. Where these costs were used in this analysis, they were adjusted upward by 9.3 percent to be equivalent to 1999 dollars. This adjustment was based on the Consumer Price Index. (Note: This adjustment was not made in the Draft RIA.) As was done in the proposal, EPA is projecting costs assuming that testing will be completed in time for the 2004 model year, even though the supplemental requirements are being finalized for the 2007 model year. We believe that many manufacturers will choose (as a convenience) to incorporate the minor calibration changes necessary to comply with these requirements during the 2004 model year, rather than to modify their 2004 designs for the 2007 model year. Since this assumption means that manufacturers would incur the testing costs three years earlier than required, it results in a slight increase in the net present value of the costs.

While the following analysis is based on a relatively uniform emission control strategy for designing the different categories of engines, this is not intended to suggest that a single combination of technologies will actually 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.[2] For technologies sold by a supplier to the engine manufacturers, an additional 29 percent markup is included for the supplier's overhead and profit. Estimated variable costs for new technologies (i.e., EGR and VGT) include a ten percent markup to account for increased warranty costs. Fixed costs for R&D are assumed to be incurred over the seven-year period from 1996 through 2002, tooling and certification costs are assumed to be 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. This total preproduction cost is then amortized at the same rate over a five-year period during which the manufacturer would be able to recoup the fixed costs. The analysis also includes consideration of lifetime operating costs where applicable. Projected costs were derived for three service classes of heavy-duty diesel vehicles, as depicted in Table 4-1.

In some cases, EPA expects that there may be significant overlap 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. In the absence of future standards, manufacturers would have continued research on and eventually deploy many technological upgrades to improve engine performance or more cost-effectively control emissions. Specifically, this is most appropriate for the application of VGT and improved fuel injection technologies, as is discussed in Sections A(3) and A(4) of this chapter. For those cases, EPA is assuming that only a fraction of the fixed and variable costs are attributable to emission control.

Table 4-1:
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 +

II. Technologies for Meeting the New 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. EPA believes that a small set of technologies represent the primary changes manufacturers must make to meet the standards in this rule. Other technologies applied to heavy-duty engines, before or after implementation of new emission standards, will make smaller secondary 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, 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 analysis includes an analysis of the baseline technology being used by manufacturers to meet the 1998 emission standards and future technologies that will be used to improve engine designs through model year 2003. Specification of the future technologies is based on an observation of current trends in heavy-duty engine technology. The baseline control technologies being assumed for engines meeting 1998 emission standards in 2003 include technologies that contribute directly to lower NOx emissions and a variety of engine improvements with only secondary benefits for NOx control. The assumed 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. Another example is the newer, more advanced, Next Generation Electronic Unit Injector (NGEUI) developed by Caterpillar. Also, these engine models are assumed to 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, and potentially for additional braking capacity. 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. While EPA is not assuming EGR to be included among the baseline technologies, EPA recognizes that some manufacturers may actually incorporate EGR into future engines to offset fuel consumption increases associated with the 1998 NOx standard (due to injection timing retard). For example, DDC recently announced the introduction of their new Series 50 heavy-duty bus and truck engine, which is being equipped with EGR and VGT in the 2000 model year.[3] DDC specifically noted, in its announcement, that this was being done as an alternative to retarded injection timing in order to minimize fuel consumption. Thus, this assumption, that 100 percent of the cost of adding EGR is attributable to compliance with the standards in this rule, is conservative and actual compliance costs for the these standards may be significantly lower than is estimated here.

Compliance costs for 2004 and later model year engines are based on an assumed combination of primary technology upgrades. 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 all engines will incorporate cooled exhaust gas recirculation and many will incorporate variable geometry turbochargers. The costs of these individual technologies are considered in the following paragraphs and summarized in Table 4-2. The costs of secondary improvements are not included in this analysis since they are not expected to be needed for compliance with these emission standards. The reader is referred to the RIA for the June 2, 2000 NPRM that proposed new standards for the 2007 model year (Docket A-99-06) for more information regarding the potential costs of these secondary technologies. In that NPRM, EPA projected that many of these technologies would be available for the 2007 model year.

Table 4-2
2004 Model Year Cost Estimates

Light Heavy-Duty Diesel Vehicles (Dollars per Engine)

Item	Fixed Cost	Variable Cost	Operating Cost	Fraction of Cost For Emissions*
Cooled EGR (high-flow)	42	215	8	100%
Combustion optimization	22	0	0	100%
Improved fuel injection	9	135	0	50%
Variable geometry turbochargers	15	188	0	50%
Onboard diagnostics	1	0	0	100%
Emission map testing	2	0	0	100%
Certification	2	0	0	100%

* Costs listed in the table are the full costs for adding each of the technologies. However, because both fuel injection improvements and variable geometry turbochargers provide performance benefits not related to emissions control, and because these technologies may be in use prior to 2004, only fractions of the full costs are used for the cost-effectiveness analysis.

Medium Heavy-Duty Diesel Vehicles (Dollars per Engine)

Item	Fixed Cost	Variable Cost	Operating Cost	Fraction of Cost For Emissions*
Cooled EGR (high-flow)	103	242	49	100%
Combustion optimization	55	0	0	100%
Improved fuel injection	20	127	0	50%
Variable geometry turbochargers	35	248	0	50%
Onboard diagnostics	0	0	0	100%
Emission map testing	5	0	0	100%
Certification	2	0	0	100%

* Costs listed in the table are the full costs for adding each of the technologies. However, because both fuel injection improvements and variable geometry turbochargers provide performance benefits not related to emissions control, and because these technologies may be in use prior to 2004, only fractions of the full costs are used for the cost-effectiveness analysis.

Heavy Heavy-Duty Diesel Vehicles (Dollars per Engine)

Item	Fixed Cost	Variable Cost	Operating Cost	Fraction of Cost For Emissions*
Cooled EGR (high-flow)	103	336	104	100%
Combustion optimization	55	0	0	100%
Improved fuel injection	20	140	0	50%
Variable geometry turbochargers	35	338	0	50%
Onboard diagnostics	0	0	0	100%
Emission map testing	5	0	0	100%
Certification	9	0	0	100%

* Costs listed in the table are the full costs for adding each of the technologies. However, because both fuel injection improvements and variable geometry turbochargers provide performance benefits not related to emissions control, and because these technologies may be in use prior to 2004, only fractions of the full costs are used for the cost-effectiveness analysis.

A. Primary Technologies

The following discussion presents the projected costs of the primary technological improvements expected for complying with the new 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. While most of this R&D will be needed to develop new technologies for reducing emissions, some will be needed to verify emission performance for compliance with the supplemental standards and OBD requirements. R&D costs account for over 90 percent of the total fixed costs per engine detailed in Table 4-2. Retooling is another fixed cost factored into the analysis. 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 emission standards. EPA previously developed a detailed methodology for calculating certification costs.[4] Adjusting those figures to convert them to 1999 dollars (using the Consumer Price Index) results in an estimated certification cost of $250,000 per engine family. This estimate, which is used here, is the same estimate that was used in the 1997 analysis (after being adjusted to 1999 dollars). This is because EPA believes that the new supplemental steady-state certification requirement will not significantly affect certification costs. Certification costs will be incurred on average one year before the beginning of production, so the calculated cost is increased by seven percent. 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 $9 for each category of heavy-duty diesel vehicles.

1. Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is projected to be the most important area of technology development that will enable manufacturers to achieve the targeted NOx emission levels. Unlike most other technological developments, which are largely further optimization of the baseline technologies discussed in Chapter 3.II.A, introduction of EGR would be a step change in the design of heavy-duty diesel engines. The technological challenges facing the manufacturers in developing EGR for diesel engines are described in Chapter 3.II.B. While some 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.

According to the Acurex cost report, the typical cost to manufacturers of adding the hardware for a high-flow cooled EGR system is estimated to range from \$140 to \$220 (in 1995 dollars) per engine depending on the service class. Factoring in the fixed costs, the appropriate markups, and inflation results in an increased purchase price of \$257, \$345, and \$439 for light, medium, and heavy heavy-duty diesel vehicles, 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. According to the Acurex cost report, total costs for these improvements would be \$5 million per engine line. For the different classes of vehicles, this translates to an incremental cost between \$22 and \$55 per engine.

3. Improved Fuel Injection

Manufacturers are expected to improve their fuel injection systems by increasing fuel injection pressure, improving spray patterns, and adding rate shaping and split injection capability; however, much of this improvement is expected to occur independently of the new emission standards.[5,6,7,8,9,10] 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 HEUI or NGEUI 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. EPA calculated typical costs for these improvements using the information contained in the Acurex report. Light heavy-duty vehicles, typically equipped with eight-cylinder engines, have an estimated total cost of $144 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 $147 and $160 per engine. These cost estimates are based on the cost estimates in the Acurex cost report, assuming that half of light and medium heavy-duty engines, and that two-thirds of heavy heavy-duty engines will have cam-driven unit injectors (and that the remainder will have common rail, HEUI, or similar systems), and by adjusting to 1999 dollars. For this analysis EPA is assuming that 50 percent of the costs for these improvements are attributable to emission control. This is because EPA believes that manufacturers would make these improvements for many of their engines, even in the absence of these emission standards, to reduce fuel consumption and improve engine performance.[11]

4. Variable Geometry Turbochargers

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 as high as $200 to $300 per engine according to the Acurex cost report. However, EPA has become aware of new simpler designs for VGT systems that are expected to be less expensive than the systems considered by Acurex. Thus EPA has revised the Acurex estimate by reducing assembly costs by 70 percent, and eliminating the actuator costs.[12] The revised estimates of the variable cost increase to manufacturers for VGT (relative to current technology turbochargers) range from $90 to $150. Fixed costs for R&D and retooling were estimated at about $3.5 million per engine line. Combining the costs with the appropriate markups, and adjusting for inflation results in costs of $203, $283, and $373 for light, medium and heavy heavy-duty engines, respectively. For this analysis, however, 50 percent of these costs are assumed to be attributable to emission control. As with the expected fuel injection improvements, EPA believes that manufacturers would make these improvements for many of their engines, even in the absence of these emission standards, to reduce fuel consumption and improve engine performance.[3] An EPA technical memo to the docket for this rulemaking contains additional discussion of the Agency's 50 percent cost estimate for both improved electronic fuel injection, including a cost sensitivity analysis detailing what impact this estimate has on the standards cost-effectiveness.[11] This cost sensitivity is also summarized in Table 8-13 of Chapter 8, Section IV of this RIA.

5. Onboard Diagnostics

Manufacturers are not expected to make significant hardware modifications in response to the OBD requirements for vehicles at or under 14,000 pounds. This is because, even without the OBD regulations, manufacturers would monitor emission control components to ensure proper engine performance. In fact, manufacturers already use onboard monitors for fuel injectors for current engines. However, manufacturers are expected to incur additional costs for emission testing of representative engine configurations in various malfunction modes. Based on EPA's engineering judgement, we estimate this testing will add $1 to the fixed costs for light heavy-duty engines, but will not affect variable or operating costs. Even though only those light heavy-duty engines for vehicles at or under 14,000 pounds would be subject to the OBD requirements, EPA is applying this cost to all light heavy-duty engines for this analysis. (Note: the Draft RIA analysis estimated this cost to be $3 using an incorrect amortization calculation.)

6. Engine Map Testing

While manufacturers are not expected to make significant hardware modifications in response to the new supplemental standards, they are expected to conduct extensive steady-state and transient cycle emission testing (i.e., testing at speeds and loads represented by the new supplemental test cycles) as part of their R&D efforts. This will add $2, $5, and $5 to the fixed costs for light, medium, and heavy heavy-duty engines, respectively, but will not affect variable or operating costs. (Note: the Draft RIA analysis estimated this cost to be $9, $23, and $23 using an incorrect amortization calculation.)

7. Total Technology Package Costs

The estimated incremental costs of these primary technologies depend on several judgements about which technologies will be used. For example, predicting precisely how much these technologies will impact engine-out PM emissions is difficult. If engine-out PM emissions are increased, then manufacturers may need to increase the use of aftertreatment. This increases hardware costs and there would be a greater potential for increased operating expenses.

EPA believes it is not appropriate to assign the full cost of fuel system upgrades or the addition of VGT to the new emission standards. As is discussed in Sections A.3 and A.4 of this chapter, much of the anticipated improvements will come independently of the new standards and any remaining system improvements for 2004 and later model year vehicles will provide benefits beyond lower NOx emissions. The resulting calculation of total incremental cost for the set of primary technologies, summarized in Table 4-2, shows the expected increase in purchase price due to the new emission standards. Projected cost increases are $485, $657 and $803 for light, medium, and heavy and heavy-duty vehicles, respectively for the 2004 model year.

B. Operating Costs

EPA has assessed the potential for increased operating costs, as described below, first for EGR-related maintenance, then for fuel economy. 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 several 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.

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 originally proposed in the 1996 NPRM that manufacturers would be able to keep engine costs lowest by investing $10 million to $15 million industry-wide in research to address these concerns (about $25 per engine when amortized over the fleet). This estimate was based on EPA's engineering judgement and prior experience. Although manufacturers have had two opportunities to provide information in their public comments, they have not provided any information that allow the Agency to improve this estimate. Therefore, we continue to believe that it is the best available estimate of the cost of addressing this issue. 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 $8 to $33 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.[13] 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. As mentioned in the Acurex report, rebuild procedures for EGR systems will likely 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 $71 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 $73 and $105 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 $55 for medium heavy-duty vehicles and $71 for heavy heavy-duty vehicles and urban buses.

While EPA believes that sufficient R&D and the use of cooled EGR will address other operating cost concerns, the Acurex report includes a cost estimate for increasing oil sump volumes by 10 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. By calculating a cost at each oil change as vehicles accumulate mileage and discounting the life-cycle costs to the point of sale, Acurex estimated that the cost of increasing oil sump volumes by 10 percent would cost $25, $55, and $145 for light, medium, and heavy heavy-duty vehicles, respectively (in 1995 dollars). These cost are presented here only for informational purposes, and are not included in the cost-effectiveness analysis.

As is discussed in Chapter 3, while EGR has the potential to incur a fuel economy penalty, it will probably be more than offset by improvements in fuel injection and the use of VGT. In fact, EPA believes that the combined effect of these three technologies may decrease fuel consumption by as much as 1.5 percent. EPA estimated the cost savings for each one percent decrease in fuel consumption, based on a diesel fuel cost of $1.00 per gallon. Calculated as a net present value at the point of sale, these estimates are $102, $178, and $891 for light, medium, and heavy heavy-duty vehicles, respectively. This sensitivity with respect to changes in fuel consumption varies so much by vehicle category because of the widely differing mileage accumulation rates for different vehicle categories. As discussed in section IV of Chapter 8, we have also performed a sensitivity analysis to estimate the impact on costs if this rulemaking resulted in an increase in fuel consumption for HD diesel engines. Table 8-11 estimates the impact on the per-vehicle cost increase for a one percent increase in fuel consumption, and Table 8-12 estimates the increase in per-vehicle cost-effectiveness for a one percent increase in fuel consumption.

C. Secondary Technologies

In the 1997 FRM, EPA analyzed the potential costs of secondary technologies (i.e., those technologies that may potentially be available, but that EPA was projecting would not be used by manufacturers to comply with the 2004 standards). EPA is not revising this analysis of secondary technologies for this technology review rulemaking. The reader is referred to the RIA for the 1997 FRM for more information regarding this analysis. However, new cost information has been recently presented to the Agency which will be presented here.

As discussed in Chapter 3, the Manufacturers of Emission Control Associations (MECA) has recently undertaken a test program at Southwest Research Institute to evaluate the emission benefit potential of several aftertreatment devices. Specifically, MECA members provided to SwRI a number of diesel oxidation catalysts (DOC), particulate traps, and urea-based selective catalytic reduction systems (SCR). As discussed in Chapter 4, DOC's have been used in the past for some light- and medium-heavy duty engine families in order to comply with the 0.1 g/bhp-hr PM standard which began in 1994, and for urban buses to comply with the 0.05 g/bhp-hr PM standard. It is likely some number of engine families would continue to rely on DOC's for modest PM reductions. As discussed in Chapter 3, technical issues remain to be solved before PM traps or SCR systems could be considered feasible for wide spread us in the U.S. HD diesel market, and we believe it is unlikely manufacturers will use either of these technologies in 2004. However, it appears that these technologies could be available for the 2007 model year.

III. Summary of Costs

The per-vehicle cost figures presented above are used in Chapter 9 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.[14,15] The average progress ratio for the whole data was slightly higher than 80 percent, which 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. In their article, Dutton and Thomas emphasize the importance of understanding the dynamics underlying learning processes.

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 currently do not use EGR of any type today (hot, cooled, or cooled and filtered). 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 4-4 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.

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 standards. Table 4-5 presents the baseline costs for each vehicle category, as developed by ICF.

IV. 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 emission standards in any year. 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. The result of this analysis is a projected total cost starting at $479 million in 2004. Per-vehicle cost savings over time reduce projected costs to a minimum value of $248 million in 2009, after which the growth in truck population leads to an increase to $325 million in 2020. Total costs for these years are presented by vehicle class in Table 4-6.

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 be over $44 million per year by 2020.

Table 4-4
Projected Long-Term Diesel Engine/Vehicle Costs
(net present value at point of sale in 1999 dollars)

Vehicle Class	Model Year	Change	Purchase Price	Life-cycle Operating Cost (NPV)
Light heavy-duty	2004	—	485	8
	2006	20 percent learning curve applied to variable costs	410	8
	2009	Fixed costs expire; 20 percent learning curve applied to variable costs	241	8
Medium heavy-duty	2004	—	657	49
	2006	20 percent learning curve applied to variable costs	571	49
	2009	Fixed costs expire; 20 percent learning curve applied to variable costs	275	49
Heavy heavy-duty	2004	—	803	104
	2006	20 percent learning curve applied to variable costs	688	104
	2009	Fixed costs expire; 20 percent learning curve applied to variable costs	368	104

Table 4-5
Baseline Costs for Heavy-Duty Engines and Vehicles (1995 dollars)

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 4-6
Estimated Annual Costs for Improved Heavy-Duty Vehicles

Year	Category	Cost Elements (millions of 1999 dollars)			
		Fixed	Variable	Operation	Total
2004	Light heavy-duty	36	125	0.3	161
	Medium heavy-duty	38	71	0.3	109
	Heavy heavy-duty	59	149	1.2	210
	Total Annual Cost	**133**	**344**	**1.7**	**479**
2009	Light heavy-duty	0	86	1.6	88
	Medium heavy-duty	0	49	1.3	50
	Heavy heavy-duty	0	104	6.0	110
	Total Annual Cost	**0**	**239**	**8.9**	**248**
2020	Light heavy-duty	0	101	3.4	105
	Medium heavy-duty	0	58	9.3	67
	Heavy heavy-duty	0	121	32	153
	Total Annual Cost	**0**	**280**	**45**	**325**

Chapter 4 References

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CHAPTER 5: ECONOMIC IMPACTS OF HD OTTO-CYCLE STANDARDS

This chapter contains an analysis of the economic impacts of the new emission standards for heavy-duty Otto-cycle vehicles and engines. First, a brief outline of the methodology used to estimate the economic impacts is presented, followed by a summary of the technology packages that are expected to be used to meet the standards. Next, the projected costs of the individual technologies is presented, along with a discussion of fixed costs such as research and development (R&D), tooling and certification costs. Following the discussion of the individual costs components is a summary of the projected per-vehicle cost of the new regulations. Finally, an analysis of the aggregate cost to society of the regulations is presented. The costs presented here are in 1999 dollars.

I. Methodology for Estimating Costs

Using the information on emission reduction technology presented in Chapter 4, we identified packages of technologies that would be likely to be used by the manufacturers to comply with the emission standards. These technology packages are those which are being implemented to meet California's low emission vehicle (LEV) standards. To identify the required technologies and to quantify the costs of most of these technologies, we relied on the contracted study of heavy-duty gasoline vehicle technology conducted by Arcadis Geraghty & Miller (hereafter referred to as the Arcadis report).[1] Information in the Arcadis report regarding technology costs and current nationwide vehicle and California LEV technologies (including such things as catalyst sizes and loadings, as well as estimates of the percentages of vehicles that will require certain technologies) were obtained though a series of confidential discussions with vehicle and engine manufacturers, catalyst and equipment suppliers, and other relevant entities. Costs for onboard refueling vapor recovery (ORVR) equipment were taken from the final Regulatory Impact Analysis for ORVR controls and updated for purposes of this analysis, and are not from the Arcadis report.[2]

The costs of meeting the emission standards include both variable costs (incremental hardware costs, assembly costs, and associated markups) and fixed costs (tooling, R&D, and certification costs). Variable costs are marked up at a rate of 29 percent to account for manufacturers' overhead and profit.[3] For a technology which is sold by a supplier to the vehicle or engine manufacturer an additional 29 percent markup is included to cover the suppliers' overhead and profit. The exception to this is for precious metals. Vehicle manufacturers typically provide catalyst suppliers with precious metals for use in the catalysts the suppliers manufacture. Thus, the additional 29 percent supplier markup is not applied to the cost of precious metals. Fixed costs were 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.

II. Technology Packages for Compliance with the Regulations

The various technologies that could be used to comply with the regulations were discussed in the previous chapter on technological feasibility. We expect that the technology mixes being used to meet the California LEV standards fairly accurately represent those that will be used to comply with the federal standards beginning with the 2005 model year. Thus, in developing costs for the associated technologies we looked at the current technology used on HDVs and compared that to the technologies being used to meet the LEV standards in California. Table 5-1 shows both the current baseline and expected technologies for complete vehicles. Table 5-2 shows the current baseline and expected technologies for the engine-based standards. The information contained in these tables comes form the Arcadis report and is derived from conversations with the vehicle manufacturers concerning their estimated configurations to be used to meet the new standards. These tables only show the technologies which are expected to change in some way from their current design or be applied to different percentages of the fleet than they are currently. Technologies which are currently being widely used on these vehicles such as sequential multi-port fuel injection and EGR, while important to meeting the standards, are not expected to be fundamentally changed in their design, or be utilized in different percentages of the fleet than they currently are. Thus, while such technologies will continue to be used on these vehicles, they are not included in these tables. However, in some cases the cost of optimizing such technologies is included in the cost estimates and are discussed in the following section.

Table 5-1
Current and Expected Technology Packages for Complete Vehicle Standards

Technology	Baseline Federal	Estimated 2005
Catalysts[1]	60% single underfloor 40% dual underfloor	13% single underfloor 50% dual underfloor 37% dual close-coupled and dual underfloor
Oxygen sensors	70% dual heated 10% triple heated 20% four heated	13% dual heated 87% four heated
ECM	50% 32 bit computers 50% 16 bit computers	100% 32 bit computers
Adaptive learning	0%	80%
Individual cylinder A/F control	0%	10%
Leak free exhaust	90%	100%
Insulated exhaust	0%	40%
Secondary air injection	20%	30%
ORVR	0%	100%[2]

1. In addition to the change in catalyst configurations shown, we expect that catalyst washcoat and precious metal compositions and loadings will change.
2. ORVR only applies to complete vehicles 10,000 lbs GVWR and under, and is phased in, with 100% application to those vehicles in 2006.

Table 5-2
Current and Expected Technology Packages for Engine-based Standards

Technology	Baseline Federal	Estimated 2005
Catalysts[1]	60% single underfloor 40% dual underfloor	13% single underfloor 87% dual underfloor
Oxygen sensors[2]	70% dual heated 10% triple heated 20% four heated	13% triple heated 87% four heated
ECM	50% 32 bit computers 50% 16 bit computers	100% 32 bit computers
Improved fuel control	50%	100%
Secondary air injection	20%	50%

1. In addition to the change in catalyst configurations shown, we expect that catalyst washcoat and precious metal compositions and loadings will change.
2. OBD only applies to HDGEs under 14,000 lbs GVWR (approximately 60 percent of HDGEs).

III. Technology Costs

The following sections outline in detail the costs of new technologies and the costs of improvements to existing technologies we expect will be used to comply with the standards.

A. Improved Catalysts

Improvements in catalyst systems fall into two broad categories: changes in catalyst system configuration and changes in the catalyst precious metal and washcoat compositions and loadings. In addition estimating costs for these improvements, we estimated the costs of substrates and packaging (cans) for the improved catalysts.

1. Changes in Catalyst Configurations

Currently, all non-California Otto-cycle HDVs either have single or dual underfloor catalyst configurations. Under the single underfloor catalyst system the exhaust from both banks of engine cylinders "Y" into a single catalyst. With the dual underfloor catalyst system each bank of engine cylinders exhaust into their own catalyst. Currently 60 percent of vehicles utilize the single catalyst approach with the remaining 40 percent utilizing the dual catalyst approach. We expect that the usage of the single floor catalyst system will drop to 13 percent as a result of the new standards, and usage of the dual catalyst system will drop to 50 percent. We expect that the remaining 37 percent of vehicles will utilize dual underfloor catalysts in conjunction with dual close-coupled catalysts. The costs of the single underfloor catalyst and the dual underfloor catalysts were analyzed for both the baseline (i.e., current) scenario and for enhanced versions used in compliance with the standards.

The cost dual underfloor/dual close-coupled catalyst system was only analyzed in an enhanced configuration for use in compliance with the standards since there are currently no close-coupled systems in wide use outside of California. Since the required catalyst size tend to be a function of engine size, we analyzed catalysts for two engine sizes, standard and large. For purposes of developing an average per-vehicle cost we weighted the costs of the two catalyst systems assuming that 75 percent of HDVs would be representative of the standard engine size and that the remaining 25 percent would be representative of the large engine size.

2. Changes in Precious Metals

The catalyst enhancements referred to in the previous paragraph consist of changes in the catalyst precious metal and washcoat compositions and loadings. Vehicle catalysts have typically used some combination of platinum (Pt), palladium (Pd) and rhodium (Rh). These precious metals account for a significant portion of the catalyst cost. Historically, a Pt/Rh combination has been used, although Pd has been used in much greater quantities (up to 100 percent). Pd is more thermally stable than Pt and Rh and is therefore a good choice for applications which see a high degree of thermal loading, such as close-coupled catalysts. Currently, federally-certified HDVs typically have a precious metal mix of 6.7 grams (g) Pd for each g of Rh, with no Pt. This is generally applied at loading of 2 grams per liter (g/L) of total catalyst substrate volume. However, Pd usage is going up.

We used a 10/1 ratio of Pd to Rh as it baseline assumption. Currently, enhanced underfloor catalysts being used in California are loaded at 3 to 6 g/L of substrate volume at a Pd/Rh ratio of 10 to 1. Close-coupled catalysts are typically 100 percent Pd loaded at 5 to 8 g/L of substrate volume. Current federally-certified HDVs tend to have rather large catalysts with fairly low precious metal loadings. Thus, we expect that no increase in catalyst volume will be required to comply with the standards. Rather, the improvements will center on the precious metals and washcoats, as well as the movement toward increased use of close-coupled catalysts. In cases where close-coupled catalysts will be utilized, we are assuming that total catalyst volume will remain unchanged, and that the size of the underfloor catalysts will be reduced from the baseline size by the volume of the close-coupled catalysts. We are assuming that, on average, the new standards will be met using a Pd/Rh combination in a 10 to 1 ratio and at a loading of 4 g/L for underfloor catalysts. For close-coupled catalysts we assumed that 100 percent Pd will be used at a loading of 6.25 g/L.

Precious metal prices have shown some volatility in recent years. In order to smooth out this volatility, as well as insure an uninterrupted supply of precious metals, vehicle manufacturers typically buy precious metals in bulk and supply them to the catalyst manufacturers. It is for this reason that the 29 percent supplier markup that we are applying to products supplied to the manufacturers by component suppliers is not being applied to the cost of precious metals. We chose to use the same precious metal spot prices (i.e., short-term, or daily, prices) for the purposes of this analysis that we recently used in support of the Tier 2 emission standards for light-duty vehicles, light-duty trucks, and medium-duty passenger vehicles. These are $868 per troy ounce for Rh and $390 per troy ounce for Pd. We believe that the spot prices used in the Tier 2 rulemaking are appropriate here for two reasons. First, the manufacturers affected by today's regulations also produce vehicles which must comply with the Tier 2 regulations. Second, today's regulations and the Tier 2 regulations take effect in the same time frame.

3. Changes in Washcoat

In addition to the changes to precious metals just discussed, we expect that the new standards will also result in changes to the catalyst washcoat compositions and loadings. Current washcoats are typically a combination of a cerium oxide blend (ceria) and aluminum oxide (alumina). Current ratios of these tow components range from 75 percent ceria/25 percent alumina to 100 percent alumina. We assumed a 70/30 ceria to alumina ratio to represent the current baseline configuration. Of the two common washcoat components, ceria is more thermally stable and, thus, is expected in higher concentrations in close-coupled catalysts. The We assumed that a slightly higher ceria concentration (75/25 ratio of ceria to alumina) will be used in compliance with the vehicle-based standards and that an even higher ceria concentration (80/20 ratio of ceria to alumina) will be used in compliance with the engine-based standards.

Current washcoat loadings range from 160 to 220 g/L of catalyst substrate volume. For simplicity we assumed an average loading of 190 g/L for the baseline configuration, and that this loading would remain unchanged for compliance with the vehicle-based standards. For compliance with the engine-based standards, we assumed that the washcoat loading will increase to 220 g/L. In addition, we expect that a new technique of layering the washcoat and precious metals will be employed for compliance with the engine-based standards. Currently, the precious metals and washcoat are applied to the catalyst substrate in a single slurry. Under the layering approach there is a separate slurry for each precious metal, with the second slurry being applied after the first dries. This process allows for more reaction surface area, resulting in a more efficient catalyst. Table 5-3 provides a summary of the precious metal and washcoat compositions and loadings for the current baseline vehicle, as well as those expected to be used in compliance with the vehicle-based and engine-based standards.

Table 5-3
Current and Projected Catalyst Precious Metal and Washcoat Compositions and Loadings

	Baseline	Vehicle-based	Engine-based
Precious Metals	Pd/Rh = 10/1 Loading = 2.1 g/L	Pd/Rh = 10/1 Loading = 4.0 g/L[1]	Pd/Rh = 10/1 Loading = 4.5 g/L
Washcoat	30%Alumina/ 70% Ceria Loading = 190 g/L	25% Alumina/ 75% Ceria Loading = 190 g/L	20% Alumina/ 80% Ceria Loading = 220 g/L

1. For close-coupled catalysts we assumed 100 Percent Pd at a loading of 6.25 g/L.

4. Substrates

The substrate that the precious metals and washcoat are affixed to are typically ceramic substrates of 400 cells per inch. Increasing efforts are going into developing metallic substrates, which offer better temperature and vibration stability, as well as requiring less precious metal loading to achieve the same emission benefits. However, information from catalyst suppliers suggested that the increased costs of the metal substrates will tend to cancel out any savings in precious metal costs, as discussed in the Arcadis report.. Thus, we assumed that the current ceramic substrate would continue to be used in compliance with the standards. Based on cost data obtained from catalyst substrate suppliers, the following linear relationship

$$C = \$4.67V + \$1.50$$

where:

C = cost to the vehicle manufacturer from the substrate supplier
V = substrate volume in liters

was developed in the Arcadis report and is accurate for ceramic substrates sized from 0.5 L to 4 L. Generally, catalyst substrates for HDVs are manufactured in bricks no larger than 2.5 L, with a catalyst of greater than 2.5 L being comprised of more than one brick.

5. Packaging

The final cost component of the catalyst system is the can. The catalyst substrate is typically packaged in a can made of 409 stainless steel and around 0.12 centimeters thick (18 gauge). The cost of the can is a very small portion of the overall catalyst cost.

The following tables (Tables 5-4, 5-5 and 5-6) show our estimates of the total catalyst system cost for each of the three configurations previously discussed, and for the current, baseline formulation as well as the formulations projected to be used to comply with the vehicle-based and engine-based requirements. No baseline costs are shown in Table 5-6 (dual underfloor plus dual close-couple catalyst system) because these systems are not currently in wide use on federally-certified vehicles. These tables show the estimated costs rounded to the nearest dollar.

Table 5-4
Estimated Catalyst Costs of Single Underfloor Catalyst System

	Baseline		Projected Vehicle-based Standards		Projected Engine-based Standards	
Engine Size	Standard	Large	Standard	Large	Standard	Large
Catalyst Volume (L)	4.8	5.8	4.8	5.8	4.8	5.8
Substrate	$26	$31	$26	$31	$26	$31
Washcoat	$19	$22	$19	$22	$23	$27
Precious Metals	$141	$170	$268	$324	$302	$365
Can	$5	$5	$5	$5	$5	$5
Total Material Cost	$191	$228	$318	$382	$356	$428
Labor	$4	$4	$4	$4	$6	$6
Labor Overhead @40%	$1	$1	$1	$2	$2	$2
Supplier Markup @29%[1]	$16	$18	$16	$19	$18	$21
Manufacturer Cost	$212	$251	$339	$407	$382	$457

[1] The supplier markup is not applied to the cost of the precious metals because the precious metals are supplied by the vehicle manufacturer.

Table 5-5
Estimated Catalyst Costs of Dual Underfloor Catalyst System

	Baseline		Projected Vehicle-based Standards		Projected Engine-based Standards	
Engine Size	Standard	Large	Standard	Large	Standard	Large
Catalyst Volume (L)	4.8	5.8	4.8	5.8	4.8	5.8
Substrate	$26	$31	$26	$31	$26	$31
Washcoat	$19	$22	$19	$22	$23	$27
Precious Metals	$141	$170	$268	$324	$302	$365
Can	$5	$6	$5	$6	$5	$6
Total Material Cost	$191	$229	$318	$383	$356	$429
Labor	$5	$6	$7	$8	$11	$12
Labor Overhead @40%	$2	$2	$3	$3	$4	$5
Supplier Markup @29%[1]	$17	$19	$17	$20	$20	$23
Manufacturer Cost	$215	$256	$345	$414	$391	$469

[1] The supplier markup is not applied to the cost of the precious metals because the precious metals are supplied by the vehicle manufacturer.

Table 5-6
Estimated Catalyst Costs of Dual Underfloor Plus Dual Close-coupled Catalyst System

	Projected Vehicle-based Standards	
Engine Size	Standard	Large
Catalyst Volume (L)	4.8	5.8
Substrate	$29	$34
Washcoat	$20	$24
Precious Metals	$314	$370
Can	$6	$7
Total Material Cost	$369	$435
Labor	$15	$16
Labor Overhead @40%	$6	$6
Supplier Markup @29%[1]	$22	$25
Manufacturer Cost	$412	$482

[1] The supplier markup is not applied to the cost of the precious metals because the precious metals are supplied by the vehicle manufacturer.

B. Exhaust Gas Recirculation (EGR)

Electronically controlled EGR is currently used on about 85 percent of non-California Otto-cycle HDVs. Those manufacturers that do not currently employ EGR on their federally certified vehicles are not expected to utilize it to comply with the standards. Thus, the percentage of the fleet with EGR is not expected to change as a result of the standards. However, some improvements to flow control are expected to be made to those EGR systems that are currently being used, primarily to comply with the new OBD requirements. In addition to minor changes in control algorithms, we expect minor changes to the EGR valve and gasket, as well as the EGR flow sensor. These changes are expected to cost from $5 to $12 per vehicle. For simplicity we assumed that the EGR improvements will cost $7 per EGR-equipped vehicle for the purposes of this analysis.

C. Secondary Air Injection

The hardware cost for vehicles which utilize secondary air injection to reduce HC and CO is expected to be about $67 per vehicle. We expect that the usage rate of secondary air injection will rise from its current use on about 20 percent of Otto-cycle HDVs to about 30 percent as a result of the standards.

D. On-board Diagnostics

On-board diagnostics systems are currently required in California (OBD II). Although not required federally, many non-California HDVs do have some form of OBD system. This is primarily for ease of manufacturing. On lines where vehicles are being assembled for both the California and non-California markets it is often easier to simply install the California hardware on all vehicles rather than install different parts on vehicles depending on their destination. This is especially true of parts such as electronic control modules, some form of which needs to be installed regardless of the vehicle's destination. It is less true of hardware needed specifically for the California market that is not required outside of California, such as additional oxygen sensors for catalyst monitoring. Thus, the changes required to implement OBD nationwide are not extensive. The main cost components associated with adopting OBD nationwide are as follows:

- Oxygen sensors/catalyst efficiency monitoring
- Evaporative emissions purge and leak
- Electronic control module improvements
- Manifold vapor pressure sensor improvements

Each of these OBD cost components is discussed in the following sections. A National OBD program is only being applied to HDGVs weighing 14,000 lbs GVWR or less. Thus, only 60 percent of HDGVs certified according to the engine-based program would be required to comply with the OBD requirements. This is reflected in the cost summary table later in this chapter.

1. Oxygen Sensors/Catalyst Efficiency Monitoring

The OBD requirements, as well as the expected changes in catalyst configuration, will result in changes in the number and placement of oxygen sensors in the exhaust system. Oxygen sensors in non-California are typically only placed before the catalyst and used for closed loop air/fuel ratio control. Compliance with the OBD requirements will require the use of oxygen sensors both before and after the catalysts, to be used to monitor catalyst efficiency in addition to controlling air/fuel ratio.

Heated oxygen sensors are used for both California and non-California vehicles. We also expect them to be used in compliance with the standards. Heated oxygen sensors have an average manufacturer's cost of $10 to $15. Thus, for simplicity we used a manufacturer's cost of $13 for each sensor for this analysis.

Oxygen sensors are currently required downstream of the catalyst only on California vehicles. However, many non-California vehicles are equipped with downstream sensors as a way of reducing part complexity when they are manufactured on the same production line as vehicles destined for California. Of non-California vehicles, one-sixth of single underfloor catalyst vehicles and half of dual underfloor catalyst vehicles have downstream oxygen sensors. However, the OBD requirements (as well as the expected changes in catalyst configurations) will result in 80 percent of HDGEs subject to the OBD requirements needing an average of two additional oxygen sensors.

2. Evaporative Emissions Purge and Leak

The OBD provisions include a requirement for evaporative emissions control system purge and leak detection. The most common method of performing these functions is to close off the vent solenoid, use manifold vacuum to purge vapors from the evaporative control system, close the vapor management valve and monitor the system vacuum using a fuel tank pressure transducer. Any change in the vacuum over time indicates a leak with the rate of vacuum loss related to the size of the leak.

The additional costs associated with this system include those for the canister vent solenoid, the fuel tank pressure transducer, tubing and wiring, and programming of the electronic control module. The manufacturer costs are $11 for the canister vent solenoid and $16 for the fuel tank pressure transducer. Wiring and labor bring the average unit cost of this system to around $31.

3. Electronic Control Module Improvements

Although almost all vehicles use 16 bit electronic control modules (ECMs), there is a gradual change toward 32 bit processors on California vehicles. We expect that many non-California vehicles will have 32 bit processors as well in order to reduce parts complexity. Thus, we assumed that, as a baseline, 50 percent of non-California vehicles will be equipped with 32 bit processors prior to 2005. We expect that all vehicles will be equipped with 32 bit processors in order to comply with the standards. We expect that this move to 32 bit processors will result in a $21 increase over the baseline vehicle. However, the need for 32 bit processors is only partly driven by the OBD requirements. The lower emission limits will also result in a move to more powerful ECMs. Thus, we are assigning half of the incremental cost of the improved ECM to the OBD requirements and the other half to the exhaust emission standard requirements for all covered vehicles. For engines we are assigning half of the ECM cost to OBD for engines under 14,000 lb GVWR (about 60 percent of Otto-cycle HDEs) and none of the ECM cost to OBD for those over 14,000 lb GVWR.

4. Manifold Vapor Pressure Sensor Improvements

We expect that the OBD requirements will result in improved exhaust gas recirculation (EGR) flow control. This will require improvements to the manifold vapor pressure sensor at a cost of $6 per EGR-equipped vehicle.

E. Exhaust Systems

We expect that insulated exhaust systems will be used in close-coupled catalyst-equipped vehicles in order to improve catalyst light-off time. We estimate that such systems will cost $42 per vehicle. Since we project that 40 percent of chassis-based vehicles will use close-coupled catalysts, the cost per vehicle on average will be $17.

F. Electronic Control Module

The projected improvements to electronic control modules (ECMs) were discussed in the earlier section on OBD systems. As was discussed there, half of the cost of the ECM improvements will be a result of the OBD requirements and half will be a result of the lower exhaust emission standards for vehicles and those engines subject to the OBD requirements.1 Thus, we project that ECM improvements due to the increased stringency of the exhaust emission standards will result in a $11 per vehicle increase for vehicles, and engine subject to the OBD requirements. For those engines over 14,000 lb GVWR (which are not subject to the OBD requirements) we are assigning the entire $21 cost of the ECM improvements to the emission standards.

G. Onboard Refueling Vapor Recovery

We estimated the costs for onboard refueling vapor recovery (ORVR) equipment by updating the estimates of ORVR technology cost that were developed in the Regulatory Impact Analysis for the original ORVR regulations, as referenced at the beginning of this chapter. While we did not ultimately adopt ORVR requirements for any heavy-duty vehicles in the original rulemaking, we did estimate the cost of such controls separately for both light heavy-duty vehicles (8,501 through 14,000 lbs. GVWR) and heavy heavy-duty vehicles (14,001 lbs. GVWR and greater). For this analysis we assumed that the technology required to meet the standards has not changed since the original ORVR analysis was done, and that the nature of the light heavy-duty fleet (in terms of percentage of vehicles with one versus two fuel tanks, etc.) also has not changed. Despite specific requests for comment on these assumptions in the proposal, we received no comments disputing them. Thus, we simply took the cost estimates for light heavy-duty vehicles from the original analysis and adjusted them to account for inflation. EPA believes this is reasonable because the vehicles we are applying ORVR requirements to in this action (complete vehicles from 8,501 through 10,000 lbs. GVWR) are a subset of the light heavy-duty vehicle class analyzed for the original rulemaking. The original per-vehicle cost estimates (in 1992 dollars) were $6.29 for variable cost and $2.60 for fixed cost. Using the Consumer Price Index to account for inflation, these costs were adjusted (to 1999 dollars) to $7.50 for variable cost and $3.00 for fixed cost.

In addition to variable and fixed costs, ORVR also has an associated operating cost benefit, which takes into account both a the fuel economy penalty of the added weight of the hardware and the much larger fuel economy benefit that comes from recovering refueling vapors and using them in the engine. In the analysis for the original ORVR regulations this operating cost was estimated to be a $5.50 per-vehicle lifetime credit for light heavy-duty vehicles. The credit was conservatively calculated assuming that Stage II refueling vapor recovery controls would not be discontinued. Since the value of this credit is entirely dependent on the price of gasoline, it was not updated to account for inflation because the price of gasoline has not generally risen with inflation. Although gasoline prices have risen significantly in recent months, it is too early to tell whether this is a long term trend. Thus, a lifetime operating credit of $5.50 per vehicle is used in this analysis. Using the recent higher gasoline prices would have resulted in a higher per vehicle credit.

IV. Fixed Costs

The fixed costs are broken into four main components: research and development, tooling, certification, and in-use testing. Of these four, only certification and in-use testing costs apply to vehicle-based certifications. In-use testing costs do not apply to engine-based certifications. These costs are discussed individually in the following sections.

A. R&D and Tooling Costs

The vehicle-based standards will essentially require the application of California LEV technology to HDVs nationally. Since this technology has already been developed and is being implemented and the tooling is in place to make California vehicles on the same assembly lines as non-California vehicles, there are no R&D or tooling costs associated with the vehicle-based requirements. However, in the case of the engine-based standards, we expect that some R&D and new tooling will be required. We believe that, on average, R&D costs for a single engine family will be about $3 million, and that tooling costs will be about $75 thousand per engine family. Assuming that annual sales per engine family average 25 thousand units and that these costs are recovered over a five year period, we estimate that the R&D and tooling costs will be $34 per engine for the first five years of the program.

B. Certification Costs

We relied on a previous analysis for estimating certification costs.[4] Updating those costs for inflation using the Consumer Price Index results in an estimated certification cost of $252,750 per engine family. Certification costs will be incurred on average one year before the start of production. Thus, this cost is increased by seven percent. Summing the costs separately for engine families certified to the chassis-based and engine-based and amortizing them over five years results in projected per-vehicle certification costs of $1 for chassis-based configurations and $6 for engine-based configurations.

C. In-use Testing Costs

Using cost information developed in support of our CAP 2000 regulations, we project that the in-use testing requirement will cost $1 per vehicle. We used the cost from the CAP 2000 rulemaking of $4,600 per test. We used the Consumer Price Index to inflate this cost from 1998 to 1999 dollars Assuming seven engine families and ten tests per engine family, total in-use testing costs would be $334,000. Using assumed complete heavy-duty vehicle sales of just under 300,000 in 2005 yields a per vehicle in-use testing cost of just over $1. This cost will be incurred indefinitely for each year of production, rather than being recovered over five years as with the other fixed costs. In other words, while other fixed costs such as tooling and R&D are incurred only once and then recovered over a five year period, the in-use testing costs are incurred every year.

V. Summary of Costs

Table 5-7 contains a summary of per-vehicle costs associated with the new standards for Otto-cycle heavy-duty vehicles and engines. The various hardware cost components include the manufacturers' 29 percent markup. These costs are presented as incremental cost increases from the cost of current vehicle emission control systems.

Table 5-7
Summary of Incremental Costs to Meet the Otto-cycle Vehicle Emission Standards

	Chassis-based Standards	Engine-based Standards
Catalyst	$163	$187
On-board Diagnostics	$68	$41
ORVR	$8	--
Other Emissions Hardware	$41	$28
Total Hardware	**$280**	**$256**
Fixed Costs	$5	$40
Operating Costs (ORVR)	-$6	--
Total Incremental Cost	**$279**	**$296**

VI. Aggregate Cost to Society

In addition to the per vehicle costs just described, we also calculated the aggregate cost to society. This was done by combining the per vehicle costs with assumed future sales of HDVs. The sales for the different categories of heavy-duty Otto-cycle vehicles and 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. The results of this analysis are summarized in Table 5-8. The recovery of fixed costs results in slightly reduced costs beginning in 2010, after which costs begin to rise in accordance with projected increased sales. The aggregate costs represent a combined estimate of the fixed costs as they are allocated over the first five years of sales (with the exception of fixed costs for in-use testing, which continue indefinitely), variable costs assessed at the point of sale, and operating costs (primarily in the form of fuel cost savings) for ORVR-equipped vehicles (calculated to net present value and applied at the point of sale).

Table 5-8
Aggregate Cost to Society of the Heavy-duty Otto-cycle Requirements

Year	Cost ($million)
2005	$110
2006	$117
2007	$124
2008	$126
2009	$129
2010	$124
2011	$126
2012	$128
2013	$131
2014	$133
2015	$135
2016	$137
2017	$139
2018	$141
2019	$144
2020	$146
2021	$148
2022	$150
2023	$152
2024	$154

Chapter 5 References

1.“Cost Estimates for Heavy-duty Gasoline Vehicles,” Arcadis Geraghty & Miller, Final Report, September 30, 1998.

2. “Final Regulatory Impact Analysis: Refueling Emission Regulations for Light Duty Vehicles and Trucks and Heavy Duty Vehicles,” U.S. EPA, January, 1994.

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

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

CHAPTER 6: ENVIRONMENTAL IMPACT OF HD DIESEL STANDARDS

I. Introduction

This chapter describes the expected environmental impacts of the new heavy-duty diesel engine NMHC plus NOx emissions standards described in the preamble. Specifically, this chapter includes an estimated nationwide NOx, VOC, and PM_{10} inventory for 2000, heavy-duty diesel engine NOx, NMHC, and PM 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 emissions reductions.[l]

While the new standards are combined NMHC plus NOx levels, we consider the NMHC and NOx emissions impacts separately. Given the technologies we expect manufacturers to use on heavy-duty diesel engines to comply with the new standards, we model the fleet-average impact of the combined standard as being equivalent to a 2.3 g/bhp-hr NOx standard and a 0.2 g/bhp-hr NMHC standard. We base these emission factors on the judgement that manufacturers will find it easier to design for low NMHC to give them more flexibility for their NOx calibrations. This is consistent with statements made in informal discussions with engine manufacturers.

We emphasize, however, that this is only an analytical approach; we expect that manufacturers will optimize each family uniquely with respect to the combined standards, balancing the sometimes competing effects on NMHC and NOx control technologies. Thus individual engine families may have emission levels different from the fleet-average emissions we use in this analysis. It is also important to note that we are modeling the environmental impacts of the supplemental testing requirements beginning in calendar year 2004, because we believe that manufacturers will design most, if not all, of their engine models to comply with these requirements in model year 2004. This assumption, which is consistent with the assumptions made for the economic analysis in Chapter 4, should not significantly affect the results of the cost-effectiveness analysis in Chapter 8.

The inventory analysis described below builds on the inventory analysis in the Regulatory Impact Analysis associated with the 1997 Final Rulemaking for heavy-duty diesel engines (HDDE).[1] However, we use recent studies to improve our understanding of the emissions impact of mobile sources. We discuss these studies and their effects on the calculated HDDE emissions inventories in this chapter.

(l) Three terms are used in this chapter to describe organic emissions: “total hydrocarbons” (THC or HC), volatile organic compounds”(VOC), and “nonmethane hydrocarbons” (NMHC). THC refers to the organic emissions from an engine as measured by the test procedures of 40 CFR 86. VOC refers to organic emissions excluding compounds that have negligible photochemical reactivity, primarily methane and ethane (see 40 CFR 51.100). NMHC 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.

II. Description of Calculation Method

In modeling emissions from heavy-duty diesel engines, our intent is to be consistent with the upcoming MOBILE6 model. MOBILE6 is the upcoming version of the MOBILE model that we historically use to develop calendar year specific emission factors for on-highway vehicles. However, it does not have the capability to analyze all of the scenarios needed to support the rulemaking. Consequently, we developed a spreadsheet model which provides consistent results with the MOBILE model, and has the needed capability.

A. General Equation

We divide HDDEs into four distinctive classes for the purpose of inventory calculations. Table 6-1 presents these classes which have different characteristics due to the difference in their size and use. Later in this chapter, we discuss some of these differences as they apply to emission modeling. Our standards apply throughout an engine's regulatory useful life. Therefore, emissions may be cleaner earlier in an engine's life and dirtier later in its life due to deterioration. We use regulatory useful life in our modeling as the point in the engine's life at which the engine just meets the emissions standards with an assumed compliance margin.

Table 6-1
HDDE Classes and Regulatory Useful Life

Class	Description*	Regulatory Useful Life**
Light HDDE	8,501-19,500 lbs. GVWR	110,000 mi /10 yrs
Medium HDDE	19,501-33,000 lbs. GVWR	185,000 mi /10 yrs
Heavy HDDE	> 33,000 lbs. GVWR	435,000 mi /10 yrs / 22,000 hrs
Urban Bus	characterized by application	435,000 mi /10 yrs / 22,000 hrs

* GVWR refers to gross vehicle weight rating; "urban bus" does not generally include school buses or inter-city buses.
** Whichever occurs first; for the purposes of these calculations, we use 290,000 miles for urban buses.

For our calculations, emissions from HDDEs are primarily a function of per-engine emission factors, in-use deterioration, and vehicle miles traveled. Equation 1 presents the basic calculation we use to determine emissions from HDDEs in short tons per year. Following this section, we supply more detail on the components of this equation.

$$Tons_{\mathrm{CY}} = (454 \text{ x } 2000)^{-1} \text{ x } \sum_{class} \left\{ VMT \text{ x } CF \text{ x } \sum_{MY/age} \left[(ZML_{\mathrm{MY}} + DET_{\mathrm{MY/\,age}}) \text{x } TF_{\mathrm{age}} \right] \right\} \quad (1)$$

where:

$Tons_{CY}$ - emissions for a given calendar year expressed in short tons
class - LHDDE, MHDDE, HHDDE, and urban bus
VMT- total vehicle miles traveled in a given calendar year by class
CF - conversion factor from g/bhp-hr to g/mi by class
MY/age - distribution of vehicles in a calendar year by vehicle age
ZML_{MY} - zero-mile emission level in g/bhp-hr for a given model year engine
$DET_{MY/age}$ - emissions deterioration as a function of model year and vehicle age
TF_{age} - travel fraction of vehicles from each model year in a given calendar year
$(454 \times 2000)^{-1}$ - conversion from grams to short tons

B. Conversion Factors

Our engine standards are in terms of grams of pollutant per work performed. We use these units because we believe they best characterize emissions for an engine-based emission standard. However, we use vehicle miles traveled (VMT) to characterize heavy-duty engine operation in our emission inventory calculations. We believe that we can more accurately determine VMT for HDDVs than we can determine the work performed by HDDEs.

To apply VMT to our emissions calculations, we need emission factors in terms of grams per mile. Therefore, in our calculations, we convert the g/bhp-hr figures to g/mi. Because large engines typically perform more work in a mile of travel than small engines, we use separate conversion factors (CF) for each class of HDDEs. These numbers are reported in units of bhp-hr/mi and are based on work performed for MOBILE6[2]. The conversion factor is a function of fuel density, brake specific fuel consumption and fuel economy. Table 6-2 presents the CFs we use for 1996 and later model year engines. For older engines, the CFs may vary, some higher and others lower than the values in Table 6-2.

Table 6-2
Conversion Factors for HDDEs (bhp-hr/mi)

LHDDE	MHDDE	HHDDE	Urban Bus
1.23	2.25	2.97	4.68

C. Vehicle Miles Traveled

To determine the tons of emissions in a given calendar year we need to know the total VMT for that calendar year and the travel fraction of each model year of engines. The travel fraction is important because engines produced before and after a new standard goes into effect will have different emission levels.

Total Miles

To determine the tons of emissions in a given calendar year we need to know the total VMT for that calendar year and the travel fraction of each model year of engines. The travel fraction is important because engines produced before and after a new standard goes into effect will have different emission levels.

To calculate nationwide emissions from HDDEs, we multiply the total VMT by the emission factors for HDDEs. For this analysis, we base the nationwide annual VMT on Federal Highway Administration estimates of annual VMT by highway category and vehicle type. We extrapolate the VMT estimates out to 2030 using linear growth at approximately 3 percent for all classes of heavy duty diesel vehicles.

We also split this VMT by MOBILE class and fuel type. To split the VMT by class and fuel type, we use information on engine registrations by class and per-vehicle operation in miles per year collected for use in MOBILE6.[3] We use the products of the vehicle registrations and per-vehicle operation to determine the VMT fractions. Table 6-3 presents the resulting breakdown of VMT by class.

Table 6-3
Total VMT by Class for Heavy Duty Diesel Vehicles [million miles]

Calendar Year	LHDDV	MHDDV	HHDDV	Urban Bus
2000	41,158	37,013	143,974	2,753
2005	48,475	43,593	169,355	3,242
2010	55,713	50,102	194,643	3,726
2015	63,550	57,149	222,022	4,250
2020	71,386	64,197	249,401	4,774
2030	87,060	78,292	304,160	5,823

These HDDE VMT estimates are higher than those used in our proposal for 2004 heavy-duty engine standards due to the use of new and updated MOBILE6 estimates of the fraction of total VMT that is heavy-duty and the fraction of heavy-duty VMT that is diesel (see Chapter 6 of the draft RIA for a discussion of the VMT estimates used in the proposal, available in EPA Air Docket A-98-32, docket item III-B-01). The predominant changes were to increase VMT estimates of light heavy-duty vehicles and the diesel fraction of heavy-duty vehicles, both of which are consistent with recent trends. The net result is that if the MOBILE values [4] are used to calculate diesel fuel consumption, they agree very well with Federal Highway Administration estimates.[5,6] This gives us added confidence that these new estimates are accurate.

Travel Fraction

Travel fraction refers to the percentage of total miles driven in a given calendar year coming from each surviving model year of vehicles. In determining the travel fraction of vehicles by age, we considered both the survival rates of HDDVs and the average annual mileage accumulation rates by age. The survival rates give us the distribution of the number of vehicles of each model year in a given calendar year. HDDEs are operated less as they age; therefore, we consider the miles traveled by age when determining our travel fraction. We use the age distributions and VMT by age rates developed for MOBILE6.[7] Table 6-4 presents survival distribution and mileage accumulation rates by age.

Table 6-4
Survival Distribution of HDDEs by Age

Vehicle Age	Survival Distributions				Mileage Accumulation Rates			
	Light	Medium	Heavy	Bus	Light	Medium	Heavy	Bus
1	0.740	0.535	0.535	0.500	28,951	36,493	113,208	45,171
2	1.000	1.000	1.000	1.000	26,479	33,203	102,211	43,731
3	0.932	0.935	0.935	1.000	24,226	30,221	92,288	42,337
4	0.870	0.875	0.875	1.000	22,173	27,519	83,332	40,987
5	0.811	0.818	0.818	1.000	20,301	25,069	75,250	39,681
6	0.756	0.765	0.765	1.000	18,593	22,849	67,954	38,416
7	0.705	0.715	0.715	1.000	17,035	20,836	61,369	37,191
8	0.657	0.669	0.669	1.000	15,613	19,012	55,424	36,005
9	0.613	0.626	0.626	1.000	14,314	17,359	50,059	34,857
10	0.572	0.585	0.585	0.999	13,128	15,861	45,214	33,746
11	0.533	0.547	0.547	0.996	12,043	14,502	40,840	32,670
12	0.497	0.512	0.512	0.989	11,052	13,271	36,892	31,629
13	0.464	0.478	0.478	0.970	10,146	12,155	33,327	30,620
14	0.432	0.447	0.447	0.925	9,317	11,145	30,107	29,644
15	0.403	0.418	0.418	0.832	8,558	10,228	27,200	28,699
16	0.376	0.391	0.391	0.662	7,864	9,397	24,575	27,784
17	0.351	0.366	0.366	0.413	7,227	8,644	22,204	26,898
18	0.327	0.342	0.342	0.197	6,645	7,962	20,063	26,041
19	0.305	0.320	0.320	0.161	6,111	7,342	18,129	25,211
20	0.284	0.299	0.299	0.132	5,622	6,782	16,382	24,407
21	0.265	0.280	0.280	0.108	5,173	6,274	14,804	23,629
22	0.247	0.262	0.262	0.089	4,762	5,814	13,379	22,875
23	0.231	0.245	0.245	0.072	4,384	5,396	12,091	22,146
24	0.215	0.229	0.229	0.059	4,038	5,017	10,928	21,440
25	0.207	0.218	0.218	0.065	3,720	4,674	9,877	20,757
26	0.194	0.204	0.204	0.033	3,427	4,363	8,928	20,095
27	0.177	0.191	0.191	0.033	3,159	4,082	8,069	19,454
28	0.167	0.179	0.179	0.033	2,913	3,826	7,294	18,834
29	0.153	0.165	0.165	0.016	2,686	3,595	6,595	18,234
30	0.119	0.151	0.151	0.016	2,477	3,385	5,962	17,652

To calculate the annual VMT by age for an average HDDV, we multiply the vehicle survival distribution by the vehicle mileage accumulation by age. To get the travel fraction, we divide the annual VMT by the total average lifetime miles. Table 6-5 presents the annual VMT by age for an average HDDV and the total average lifetime miles.

Table 6-5
Average Annual VMT by Age for HDDVs

Vehicle Age	LHDDE	MHDDE	HHDDE	Urban Bus
1	21,426	19,511	60,517	22,579
2	26,479	33,203	102,211	43,731
3	22,591	28,263	86,321	42,337
4	19,281	24,067	72,905	40,987
5	16,461	20,503	61,577	39,681
6	14,059	17,476	52,011	38,416
7	12,011	14,904	43,934	37,191
8	10,265	12,718	37,113	35,995
9	8,776	10,859	31,353	34,847
10	7,505	9,279	26,487	33,707
11	6,421	7,934	22,378	32,547
12	5,495	6,790	18,908	31,273
13	4,704	5,816	15,976	29,692
14	4,028	4,987	13,499	27,427
15	3,450	4,280	11,407	23,876
16	2,957	3,678	9,640	18,381
17	2,534	3,164	8,147	11,115
18	2,173	2,725	6,885	5,136
19	1,863	2,350	5,819	4,070
20	1,598	2,030	4,918	3,228
21	1,372	1,756	4,157	2,559
22	1,177	1,522	3,514	2,028
23	1,011	1,321	2,971	1,605
24	868	1,149	2,511	1,275
25	771	1,020	2,177	1,353
26	664	892	1,845	655
27	559	730	1,445	634
28	485	684	1,306	614
29	411	593	1,090	297
30	294	512	903	288
Total	**201,689**	**244,716**	**713,926**	**567,521**

III. Total Nationwide Inventories

This section looks at 2000 emission inventories of NOx, NMHC and PM from HDDEs as well as projected inventories for NOx and NMHC. We present our projected baseline and controlled emissions inventories in addition to our anticipated benefits.

A. Current Inventories

The 1997 Trends Report estimates total nationwide emissions of NOx, VOC, and PM. 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 emissions factor models MOBILE5a (NOx and NMHC) and PART5 (PM) and information from the Federal Highway Administration's 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.

Due to recent information, we adjust the HDV NOx and VOC estimates to reflect the changes described above and those described in the next chapter. In addition, we modify the nonroad inventories to be consistent with recently finalized rules for land-based nonroad diesel engines[8] and for marine diesel engines.[9] Light duty vehicle estimates reflect emission inventory estimates projected in the recent Tier 2 rule[10] with a small adjustment in light-duty VMT due to the updated total VMT splits by class (see section II.C).

The national NOx, VOC, and PM_{10} inventories for HDVs are summarized in Table 6-6. These data indicate that emissions from "current" heavy-duty diesel vehicles account for about 17 percent of total NOx emissions and 1.7 percent of total VOC emissions. The PM numbers presented in this table represent total vehicle emissions, which includes brake wear, and exhaust. Excluding fugitive dust and wind erosion, HDDVs account for about 1.0 percent of total PM emissions. The PM data presented in Table 6-6 is for informational purposes, this rule does not establish new PM standards for HD vehicles.

Table 6-6
2000 National NOx, VOC, and PM Emissions
(thousand short tons per year)

Emission Source	NOx	VOC	PM_{10}
Light-Duty Vehicles	4,005	3,965	96
Heavy-Duty Diesel Vehicles	4,181	282	131
Heavy-Duty Gasoline Vehicles	298	241	8
Nonroad	5,343	2,485	642
Other	10,656	9,567	8,206
Total Nationwide Emissions	24,485	16,540	9,044

B. NOx Emission Projections and Impacts

We calculate NOx emissions using the same methodology as was used for the 1997 RIA. However, this analysis uses new conversion factors, scrappage rates, and vehicle miles traveled as described above. Baseline EFs and DFs for 1988 to 2003 model year engines are based on a report which considered certification data from 1988 to the present.[11] These emission factors were developed for use with MOBILE6. For earlier years, we continue to use the EFs and DFs in MOBILE5b. As discussed in the introduction to this chapter, we modified the controlled emission factor for NOx.

For both the baseline and controlled EFs, we assume a compliance margin of 8%. We base this compliance margin on historical certification data showing past practices. In other words, we assume that the manufacturers will conservatively design their engines to be 8% below the standards. Therefore, for a NOx standard of 2.3 g/bhp-hr, we use a level of 2.12 g/bhp-hr for the deteriorated emission level at the regulatory useful life of the engine. Table 6-7 presents baseline and controlled EFs and DFs for HDDEs. For the purposes of the HDDE inventory calculations, EF refers to the emission factor at the end of the regulatory useful life.

Table 6-7
NOx Emission Factors and Deterioration Rates for
2004 and Later Heavy-Duty Diesel Engines

	Zero-Mile Level [g/bhp-hr]				DR [g/bhp-hr per 10,000 miles]			
	LHDDE	MHDDE	HHDDE	Urban Bus	LHDDE	MHDDE	HHDDE	Urban Bus
Baseline	3.26	3.69	3.68	3.90	0.001	0.001	0.003	0.000
Controlled	2.10	2.10	1.99	2.21	0.001	0.001	0.003	0.000

In our current analysis of HDDE emissions, we may underestimate emissions due to engine deterioration in-use. We believe, that current modeling only represents properly maintained engines but may not be representative of in-use malmaintenance or tampering. One study[12] shows much larger deterioration rates for HDDEs. However, in the time frame of this rule, we have not been able to fully consider this study or assess other relevant information. In our future modeling efforts, we intend to strengthen this part of our analysis.

The EFs and DFs in Table 6-7 above do not account for excess emissions from engines, produced in the past, that operate with higher NOx in-use than on the certification test cycle which were at issue in the 1998 consent decree between EPA and a number of HDDE manufacturers. Although it does not affect the emissions benefits from this rule, we add excess emissions to our annual NOx projections for some HDDE engines built in the 1988 through 1998 model years to accurately represent the entire HDDE inventory over time. We use the excess emissions inventory developed by the EPA's Office of Enforcement and Compliance Assurance.[13]

Figure 6-1 shows our national projections of total NOx emissions with and without the new engine controls. The new standards should result in about a 43% reduction in NOx from new engines. Table 6-8 presents these projections with the estimated NOx benefits for selected years.

Figure 6-1: Projected National Exhaust NOx Emissions from HDDEs

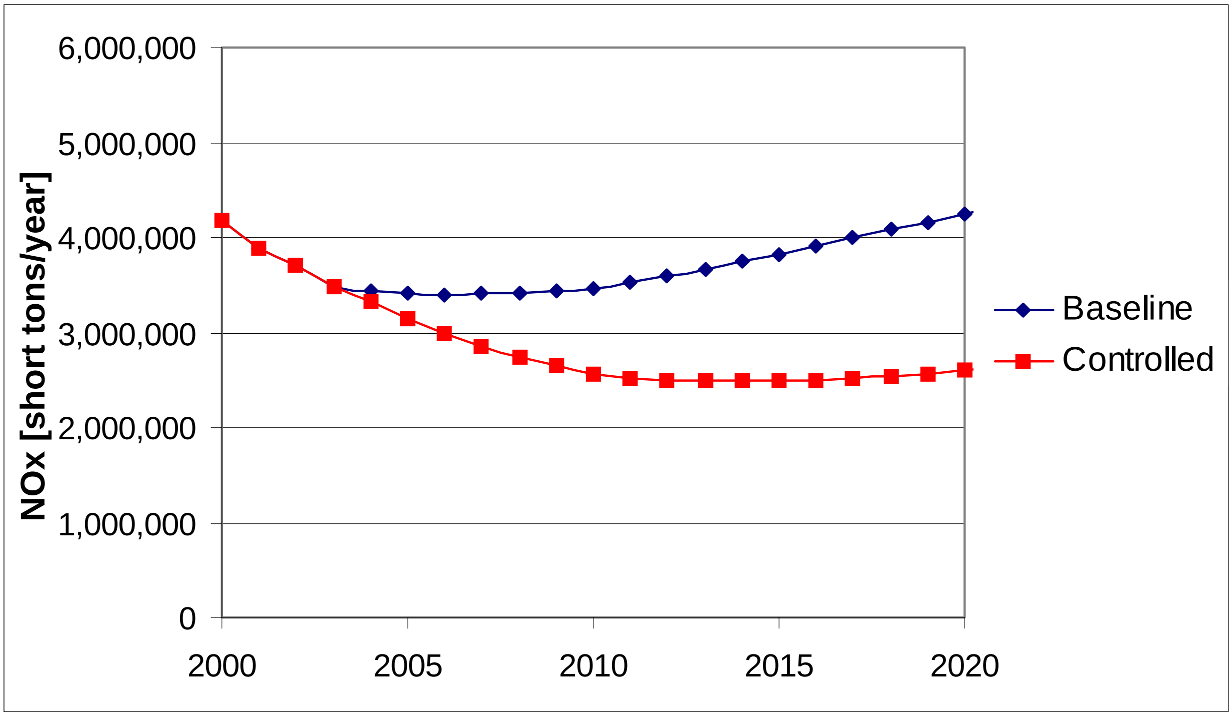


Table 6-8
Estimated National NOx Emissions and Benefits from HDDEs
(thousand short tons per year)

Calendar Year	Baseline	Controlled	Benefit
2005	3,410	3,150	266
2010	3,470	2,570	900
2015	3,830	2,490	1,340
2020	4,250	2,600	1,650
2030	5,130	3,000	2,130

C. NMHC Emission Projections and Impacts

Estimates of the impact of the new standards on NMHC emissions are described below. Heavy-duty engines do not currently have applicable NMHC standards, so the discussion in this section focuses on total hydrocarbons. For this analysis, we assume that the effect of the combined standards is equivalent to 0.2 g/bhp-hr NMHC-only standards. Emissions are modeled using the same methodology as in the 1997 RIA with the updates described earlier.

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 diesel 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. Although the current HC standard is much higher than the baseline HC emission factors in our calculations, the actual certification levels for HDDEs have shown historically low HC emissions compared to the standards.

Baseline EFs and DFs for 1988 to 2003 model year engines are based on a report which considered certification data from 1988 to the present.[14] These emission factors were developed for use in MOBILE6. For earlier model years, we rely on the EFs and DFs in MOBILE5b. Table 6-9 presents the baseline and controlled emission factors and deterioration rates. As with NOx, we assume a compliance margin of 8 percent.

Table 6-9
NMHC Emission Factors and Deterioration Rates for
2004 and Later Heavy-Duty Diesel Engines

	Zero-Mile Level [g/bhp-hr]				DR [g/bhp-hr per 10,000 miles]	
	LHDDE	MHDDE	HHDDE	Urban Bus	HDDE	Urban Bus
Baseline	0.26	0.31	0.22	0.08	0.001	0.000
Controlled	0.17	0.17	0.14	0.08	0.001	0.000

Figure 6-2 shows our national projections of total NMHC emissions with and without the new engine controls. The new standards should result in about a 32% reduction in NMHC from new engines. Table 6-10 presents these projections with the estimated NMHC benefits for selected years.

Figure 6-2: Projected National Exhaust NMHC Emissions from HDDEs

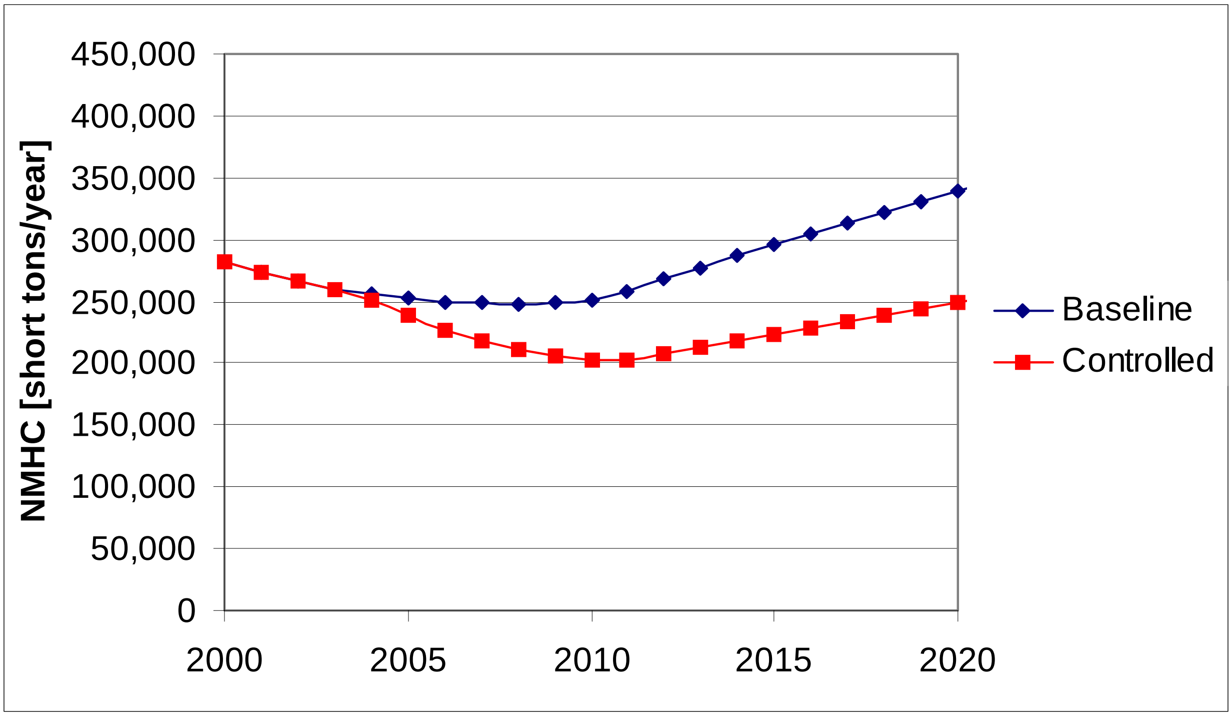


Table 6-10
Estimated National NMHC Emissions and New Benefits from HDDEs
(thousand short tons per year)

Calendar Year	Baseline	Controlled	Benefit
2005	253	238	14
2010	251	202	49
2015	296	223	73
2020	339	249	90
2030	409	292	117

IV. Per Vehicle Emission Impacts

Using the emissions factors and lifetime vehicle miles traveled described above, lifetime emissions can be calculated for individual heavy-duty diesel vehicles. Table 6-11 presents the lifetime benefits associated with this new control program on a per-vehicle basis. Because emissions reductions are considered to be more valuable in the present than in the future, we present these benefits both with and without a seven percent discount on the value of emissions reductions.

Table 6-11
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
LHDDV	634	49	423	33
MHDDV	1,930	170	1,270	112
HHDDV	7,890	374	5,308	251
Urban Bus	9,887	—	5,848	—

V. Environmental Impacts of Emission Reductions

A. Ozone Impacts

We expect the effect of the reduced NOx on ozone concentrations 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. Air Toxics

The term "hydrocarbons" includes many different molecules. Speciation of the hydrocarbons would show that many of the molecules are those which are considered to be air toxics including benzene, formaldehyde, acetaldehyde, and 1,3-butadiene. Speciated hydrocarbon data was collected for heavy-duty diesel engines.[15,16,17,18] According to this data, hydrocarbons from a HDDV include approximately 1.1 percent benzene, 7.8 percent formaldehyde, 2.9 percent acetaldehyde, and 0.6 percent 1,3-butadiene. Table 6-12 shows the estimated air toxics reductions associated with the hydrocarbon reductions in this rule.

Table 6-12
Estimated Annual Air Toxics Reductions [short tons]

Year	Benzene	Formaldehyde	Acetaldehyde	1,3-Butadiene
2005	159	1,130	419	87
2010	541	3,840	1,430	295
2015	799	5,670	2,110	436
2020	990	7,020	2,610	540

C. Other Impacts of Emission Reductions

The discussion in this section was contained in the RIA from the 1997 rulemaking for HD diesel standards which established the 2004 HDDE NMHC+NOx standard, and the estimates contained here were not re-analyzed for the affirmation of these standards contained in this rulemaking activity. The expected reductions in NOx emissions should also positively affect visibility, acid deposition, and estuary eutrophication. 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, given that it is expected to reduce overall NOx emissions by several percent. For example, we expect the new engine controls 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 where NO_2 and nitrate particulates cause 20 percent of the haze.

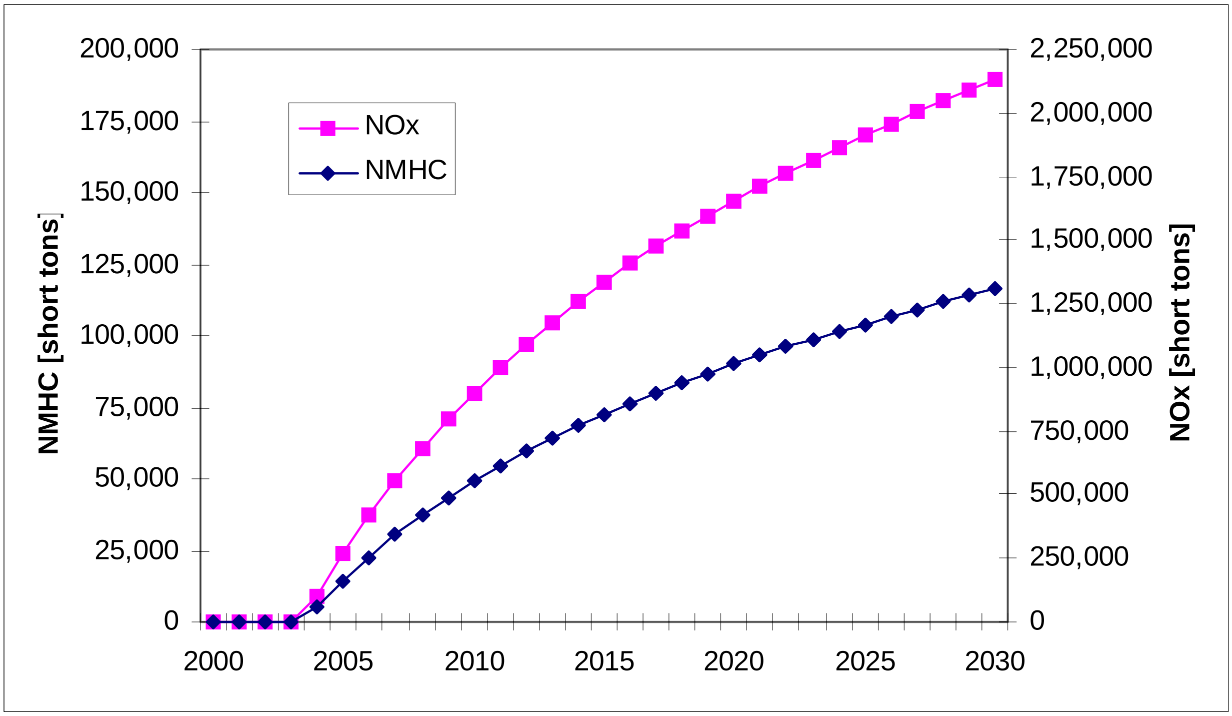
We also expect the new standards to provide benefits with respect to acid deposition. The 1.7 million ton per year reduction expected in 2020 as a result of this action is greater than the 400,000 ton per year reduction expected from Phase I of the Agency's acid rain NOx control rule (59 FR 13538, March 22, 1995), 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. In any case, 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.

VI. Summary

The projected total NOx and NMHC emission reductions as a result of this action are shown in Figure 6-4. NOx reductions are projected to be about 1.7 million tons per year in 2020. NMHC reductions are projected to be much smaller, about 90,000 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 the vehicle miles traveled. The new controls would also result in benefits with respect to visibility, acid deposition, and estuary eutrophication.

Figure 6-4: Projected Benefits of Control for NOx and NMHC



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CHAPTER 7: ENVIRONMENTAL IMPACT OF THE HD OTTO-CYCLE STANDARDS

I. Introduction

This chapter describes the expected environmental impacts of the new exhaust and ORVR standards for heavy-duty gasoline engines and vehicles described in the previous chapters. Specifically, this chapter includes a description of how heavy-duty gasoline vehicle emission factors were developed, the per-vehicle exhaust emission reductions due to the new standards over the life of heavy-duty gasoline vehicles, the estimated exhaust NOx and NMHC emission inventories from heavy-duty gasoline vehicles, and the exhaust emission benefits from the new exhaust standards. Last of all, the chapter concludes with a description of the emission benefits from the new ORVR requirements for Class 2b heavy-duty gasoline vehicles.

In evaluating the environmental impact of today's heavy-duty gasoline engine and vehicle standards for 2005 and later, we developed estimates of exhaust NOx and NMHC emissions from HDGVs (excluding California) both with and without the effect of the standards. The analysis performed to estimate the emission reductions from HD gasoline vehicles and engines in this final rule is identical to the analysis performed for the Agency's recently announced proposal to reduce emissions from HD gasoline engines in the 2007 time frame (published on June 2, 2000 (65 FR 35430)). This analysis is different than the analysis we performed for the proposed rulemaking. In the proposal we used the EPA MOBILE5 emission model, with in-use adjustment factors developed specifically for the proposal. As discussed in the RIA, the draft MOBILE6 emission rates for HD gasoline engines and vehicles have been completed, so we use those emission rates in this final rule. Because MOBILE6 is not complete, we used the updated emission rates from MOBILE6 in MOBILE5 for our analysis. The EPA report in which these emission rates are reported has gone through an external stakeholder review.[m] For this final rule we use zero-mile and deterioration rates for 1988 and later model year HD gasoline exhaust emissions developed for the draft MOBILE6 emission model. The impact of this change on this final rule, as compared to the proposal, was to decrease the estimated in-use emission rates, for both the baseline and controlled scenarios, for 1998 and later model year HD gasoline engines. Full details of the environmental impact analysis can be found in Chapter 7 of the RIA. The following paragraphs summarize the key results.

II. Exhaust NOx and NMHC Emission Factors

A. Baseline Emission Rates (Zero-Mile Levels and Deterioration Rates)

To determine the impact of the standards, we first estimate the emission levels of vehicles currently in the fleet and then estimate the emission levels of vehicles that will meet the new

(m) "Update of Heavy-Duty Emission Levels (Model Years 1988-2004+) for Use in MOBILE6", EPA document EPA-420-R-99-010.

standards. For the emission rates of engines currently in the fleet, we use the recently updated zero-mile level and deterioration rates for 1988 and later model years that were developed for the upcoming MOBILE6 model.[1] (For pre-1988 model year heavy-duty gasoline vehicles, we use the standard MOBILE5 emission rates.) Because MOBILE6 is not yet complete, we perform our emissions calculations by running MOBILE5 with the updated emission rates. Table 7-1 presents the zero-mile level in grams per brake horsepower-hour (g/bhp-hr) and the deterioration rate in g/bhp-hr per 10,000 miles for 1988 and later model year heavy-duty gasoline engines.

Table 7-1
Baseline Exhaust Emission Rates for 1988 and later Model Year
Heavy-Duty Gasoline Engines

Model Year	Zero-Mile Level g/bhp-hr		Deterioration Rate g/bhp-hr per 10,000 miles	
	NOx	NMHC	NOx	NMHC
1988-1989	4.96	0.62	0.044	0.023
1991	3.61	0.35	0.026	0.023
1991-1997	3.24	0.33	0.038	0.021
1998-2004	2.59	0.33	0.038	0.021

B. Conversion Factors

Up until this rulemaking, we expressed the emission standards for heavy-duty gasoline engines in units of g/bhp-hr. To convert the emissions of engines certified to g/bhp-hr standards to g/mi levels, we multiply the g/bhp-hr levels by a conversion factor that is expressed in units of bhp-hr/mi. The conversion factor is a function of fuel density, brake specific fuel consumption and fuel economy. We recently updated the conversion factors for heavy-duty engines.[2] Table 7-2 contains the conversion factors assumed in this analysis for heavy-duty gasoline engines.

Table 7-2
Conversion Factors for Heavy-Duty Gasoline Engines (bhp-hr/mi)

Class 2b	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8a
1.096	1.150	1.134	1.324	1.311	1.446	1.540

C. Control Emission Rates (Zero-Mile Levels and Deterioration Rates)

Using the 120,000 mile useful life for heavy-duty gasoline engines, we estimate that a typical 1998 and later model year heavy-duty gasoline engine would emit NOx at roughly 3.0 g/bhp-hr, or

75 percent of the level of the standard of 4.0 g/bhp-hr. This is based on current and historical certification data for heavy-duty Otto-cycle engines, which shows manufacturers have relied on a large compliance margin when certifying, as well as statements from the engine manufacturers indicating they attempt to target certification levels as low as one-half the emission standard (see the discussion in Chapter 3(III)(H) for additional discussion of the manufacturers statements on certification levels). Assuming manufacturers maintain the same amount of cushion below the standard, we estimate the end of useful life level emissions levels associated with the new standards. From these reduced levels, we determine the corresponding zero-mile levels and deterioration rates assuming the ratio of the zero-mile level emissions to the deterioration rate (for 1998 engines) stays the same as shown in Table 7-1. Table 7-3 presents the resulting controlled zero-mile levels and deterioration rates for the three classes of heavy-duty gasoline engines and vehicles used in this analysis (i.e., Class 2b complete vehicles, Class 3 complete vehicles, and incomplete HDGVs).

Table 7-3
Estimated Controlled Exhaust Emission Rates for 2005 and later Model Year
Heavy-Duty Gasoline Engines and Vehicles

Vehicle Category	Zero-Mile Level grams per mile (g/mi)		Deterioration Rate g/mi per 10,000 miles	
	NOx	NMHC	NOx	NMHC
Class 2b Completes	0.574	0.119	0.008	0.008
Class 3 Completes	0.638	0.140	0.009	0.009
Incomplete HDGVs	0.674	0.117	0.009	0.007

D. Emission Rate Adjustments

In the Draft RIA for the NPRM, we adjusted the emission rates in an attempt to quantify increases in in-use emissions due to fuel that differs from the test fuel, to driving that differs from the test cycle, fuel that differs from the test fuel, and to account for "high emitters" in the fleet (engines that have much higher emissions than certification due to emission control failure). However, we remove these adjustments from the final analysis.

MOBILE5 includes adjustment factors for HDGVs to account for in-use fuel with different properties than certification test fuel. However, this adjustment is primarily driven by higher sulfur levels seen in-use. Due to the recent Tier 2 standards for light-duty vehicles which included low sulfur fuel requirements, this adjustment is no longer needed once the low sulfur fuel goes into effect in 2004. Therefore we t urn off this fuel adjustment for 2004 and later calendar years. As a result, the projected emission reductions from HDGVs, which begin in 2005, are not affected by this adjustment.

MOBILE5 includes speed correction factors which adjust the emission rates relative to the average speeds above and below the average speed of the federal test procedure. These adjustments consider the type of operation that is typically seen at these various average speeds such as stop-and-go driving at low average speeds. However, these correction factors are not specifically designed to account for off-cycle effects such as control strategies that are designed to the test procedure that may not work as well off the test procedure. We plan to work with stakeholders to explore augmenting our existing test procedures to address off-cycle concerns. If appropriate we will develop a regulatory proposal to address this issue. For this reason we do not include a further adjustment for in-use operation in our final analysis.

MOBILE5 does not include high-emitter adjustments for HDGVs. In addition, no high-emitter adjustments have been developed for the upcoming MOBILE6 model. Our NPRM analysis used high-emitter adjustments that were based on information collected on light-duty vehicles and may not represent heavy-duty vehicle emissions. For the final analysis we believe it is appropriate to be consistent with the upcoming MOBILE6 model. In the future, we intend to look into this issue further.

III. Per-Vehicle Exhaust NOx and NMHC Emission Reductions

To determine the cost-effectiveness of the new standards, we estimate the per-vehicle emissions and emission reduction over the lifetime of typical heavy-duty gasoline vehicles. The following sections presents the per-vehicle emission reduction analysis for three sub-categories of heavy-duty gasoline vehicles (Class 2b completes, Class 3 completes, and incomplete HDGVs).

A. Per Vehicle Emission Rates

To estimate the per-vehicle lifetime emission reduction from the new standards, we first estimated the emission rates of pre-control engines (i.e., model year 1998-2003 model years) and controlled engines (i.e., model year 2004 and later). Table 7-4 presents the zero-mile levels and deterioration rates that we use in our analysis. This is the same as Tables 7-1 and 7-3, except that the baseline rates are broken out by class and expressed in units of g/mi using the conversion factors in Table 7-2.

Table 7-4
Final Exhaust Emission Rates for Pre-control and Controlled
Heavy-Duty Gasoline Engines and Vehicles

Vehicle Category	Model Year Grouping	Zero-Mile Level, grams per mile (g/mi)		Deterioration Rate g/mi per 10,000 miles	
		NOx	NMHC	NOx	NMHC
Class 2b Completes	1998-2004	2.839	0.362	0.042	0.023
	2005+	0.574	0.119	0.008	0.008
Class 3 Completes	1998-2004	2.979	0.380	0.044	0.024
	2005+	0.638	0.140	0.009	0.009
Incomplete HDGVs	1998-2004	3.435	0.438	0.050	0.028
	2005+	0.674	0.117	0.009	0.007

B. Mileage Accumulation and Scrappage Rates

Table 7-5 presents the HDGV mileage accumulation rates and scrappage rates used in this analysis. The mileage accumulation rates come from our recently updated rates for heavy-duty gasoline vehicles developed for the MOBILE6 emissions model.[3] We took the scrappage rates from a National Highway Traffic Safety Administration (NHTSA) study. These scrappage rates are based on light-duty truck (LDT) scrappage rates.[4] (The scrappage rate represents the fraction of engines still in the fleet at a given age.) The NHTSA study did not include information on HDGVs. We believe the LDT scrappage rates would be similar to those for most HDGVs since three-quarters of all HDGV sales are in the Class 2b truck category, which is the weight category just above the LDT cutoff of Class 2a trucks.

Table 7-5
Annual Mileage Accumulation, Scrappage, and Composite Mileage Accumulation Rates for Heavy-duty Gasoline Vehicles

Age	Class 2b/3 Annual Mileage	Class 4+ Annual Mileage	Scrappage Rate
1	19,977	21,394	0.998
2	18,779	19,692	0.995
3	17,654	18,125	0.989
4	16,596	16,683	0.980
5	15,601	15,356	0.967
6	14,666	14,134	0.949
7	13,787	13,010	0.924
8	12,961	11,975	0894
9	12,184	11,022	0.857
10	11,454	10,145	0.816
11	10,768	9,338	0.795
12	10,122	8,595	0.734
13	9,516	7,911	0.669
14	8,946	7,282	0.604
15	8,409	6,703	0.539
16	7,905	6,169	0.476
17	7,432	5,679	0.418
18	6,986	5,227	0.364
19	6,568	4,811	0.315
20	6,174	4,428	0.271
21	5,804	4,076	0.232
22	5,456	3,752	0.198
23	5,129	3,453	0.169
24	4,822	3,178	0.143
25+	4,533	2,926	0.648

Table 7-6 contains the annual mileage accumulation rates for typical Class 2b/3 vehicles and typical incomplete vehicles factoring the effect of scrappage. (For the incomplete vehicles, We sales-weight the mileage accumulation rates for Class 2b/3 and Class 4+ vehicles in Table 7-8 based on sales data on incomplete vehicles submitted by manufacturers to EPA.)

Table 7-6
Annual Mileage Accumulation Rates (Factoring in Scrappage)
for Typical Heavy-duty Gasoline Vehicles

Age	Class 2b/3 Complete Vehicle Annual Mileage	Incomplete Vehicle Annual Mileage
1	19,937	20,524
2	18,685	19,062
3	17,460	17,653
4	16,264	16,299
5	15,086	14,988
6	13,918	13,709
7	12,739	12,441
8	11,587	11,221
9	10,442	10,028
10	9,346	8,903
11	8,561	8,089
12	7,430	6,964
13	6,366	5,921
14	5,403	4,986
15	4,532	4,151
16	3,763	3,420
17	3,107	2,802
18	2,543	2,277
19	2,069	1,839
20	1,673	1,477
21	1,347	1,180
22	1,080	940
23	867	749
24	690	592
25+	2,937	2,505
Lifetime Mileage	197,832	192,722

C. Per-vehicle Lifetime Emissions and Emission Reductions

Table 7-7 presents the NOx and NMHC emissions from typical heavy-duty gasoline vehicles over the life of the vehicle. We determine these levels by combining the emission rate information contained in Table 7-7 with the mileage accumulation rate information contained in Table 7-9.

Table 7-7
Lifetime NOx and NMHC Emissions from Heavy-duty Gasoline Vehicles

Vehicle Category	Model Year Grouping	Undiscounted, Lifetime Emissions, tons	
		NOx	NMHC
Class 2b Completes	1998-2004	0.71	0.13
	2005+	0.14	0.04
Class 3 Completes	1998-2004	0.74	0.13
	2005+	0.15	0.04
Incomplete HDGVs	1998-2004	0.83	0.83
	2005+	0.16	0.16

Table 7-8 presents the expected per vehicle NOx and NMHC emission benefits for heavy-duty gasoline vehicles from the new exhaust emission standards, both undiscounted and discounted (at a rate of seven percent). In addition to the three subclasses of heavy-duty gasoline vehicles, Table 7-8 also contains the reductions for all HDGVs calculated on a sales-weighted basis from the three individual categories.

Table 7-8
Per Vehicle Exhaust Emission Reductions
from the Heavy-duty Gasoline Engine and Vehicle Standards

Vehicle Category	Undiscounted Lifetime Emission Reductions, tons		Discounted Lifetime Emission Reductions, tons	
	NOx	NMHC	NOx	NMHC
Class 2b Completes	0.57	0.09	0.38	0.05
Class 3 Completes	0.60	0.10	0.40	0.06
Incomplete HDGVs	0.67	0.11	0.45	0.07
All HDGVs	0.60	0.09	0.40	0.06

IV. HDGV Exhaust Inventory and Reductions

To estimate the exhaust NOx and NMHC inventories from heavy-duty gasoline vehicles, we calculate the average emissions of all heavy-duty gasoline vehicles in the fleet for a variety of years.

To estimate the fleet average emissions for heavy-duty gasoline vehicles, we ran the MOBILE5b emissions model with the updated information on emission levels and vehicle usage characteristics as described in Sections II and III of this chapter. We multiply these resulting fleet average emission levels by the estimated fleetwide vehicle miles traveled (VMT) for heavy-duty gasoline vehicles for the corresponding year to yield the exhaust emission inventories.

We use the same methodology as described in Chapter 6 for HDDEs to determine the annual VMT. We use Federal Highway Administration estimates of total VMT then use information collected for MOBILE6 to split by class and fuel type. We exclude miles traveled by medium-duty passenger vehicles because they are covered by the Tier 2 FRM for light-duty vehicles.

Table 7-9 presents the exhaust NOx and NMHC fleet average emissions, VMT, and inventories from heavy-duty gasoline vehicles both without the new standards and with the new standards taking effect in the 2004 model year. The inventories presented in Table 7-9 represent nationwide inventories excluding California. California is excluded to simplify this analysis since they are claiming reductions from their own emission program for these engines. A more detailed description of the inventory development has been placed in the docket for this rulemaking.[5]

Table 7-9
Fleetwide Exhaust NOx and NMHC Emission Factors, Vehicle Miles Traveled, and Inventories from Heavy-duty Gasoline Vehicles (49-state analysis)

Pollutant	Calendar Year	49-state VMT (10^{10} miles)	Heavy-duty Gasoline Vehicle Fleet Emission Levels			
			without new standards		with the new standards	
			g/mi	10^3 short tons	g/mi	10^3 short tons
NOx	2000	6.68	4.05	298	4.05	298
	2005	7.83	3.65	315	3.50	302
	2010	9.03	3.47	345	2.18	217
	2015	10.27	3.34	378	1.46	165
	2020	11.52	3.31	420	1.12	142
	2030	14.01	3.29	507	0.83	127
NMHC	2000	6.68	1.70	125	1.70	125
	2005	7.83	1.06	91	1.04	90
	2010	9.03	0.74	73	0.59	59
	2015	10.27	0.66	75	0.43	49
	2020	11.52	0.66	84	0.38	48
	2030	14.01	0.66	102	0.34	52

Table 7-10 contains the estimated exhaust NOx and NMHC emission reductions due to the new standards for heavy-duty gasoline vehicles. As noted above, the reductions are for the entire

United States excluding California. Figures 7-1 and 7-2 present the heavy-duty gasoline vehicle exhaust NOx and NMHC inventories, respectively.

Table 7-10
49-State Exhaust Emission Reductions due to the Standards
for Heavy-duty Gasoline Engines and Vehicles

Calendar Year	Emission Benefits (thousand short tons) NOx	NMHC
2005	13	1
2010	128	14
2015	213	26
2020	278	35
2030	380	50

Figure 7-1: Projected 49-State Exhaust NOx Emissions from HDGVs

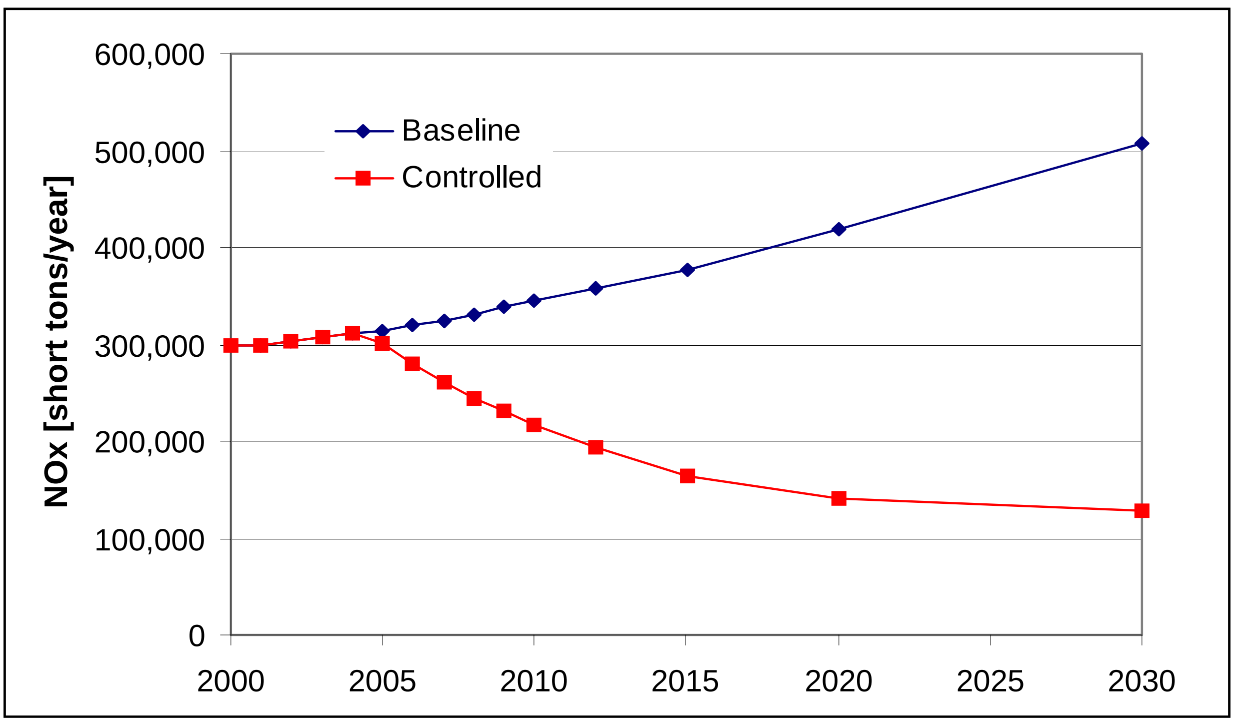
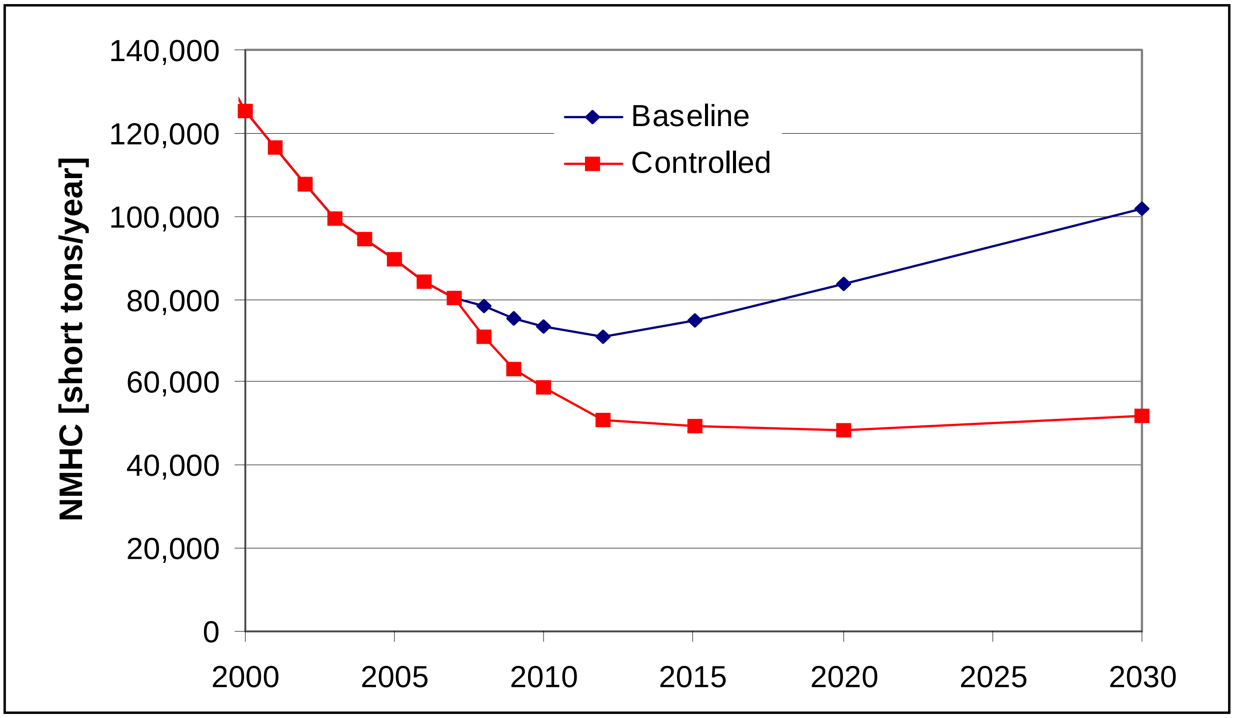


Figure 7-2: Projected 49-State Exhaust NMHC Emissions from HDGVs



V. ORVR Benefits

Along with the new exhaust standards, we are requiring ORVR regulations for Class 2b heavy-duty gasoline vehicles. Back in the early 1990s, we proposed, but never finalized, ORVR requirements for heavy-duty gasoline vehicles.[6] For this analysis, we rely on the earlier analysis to estimate the HC benefits of ORVR requirements.

Because many areas of the country have Stage II vapor recovery[n] on fuel pumps at the gas station, we developed an estimate of the HC benefits that were attributable to the ORVR equipment. For this analysis, we assume that Stage II will remain in place in the areas that currently have Stage II controls even after the ORVR requirements for light-duty vehicles and trucks have finished taking effect. This assumption lowers the benefits attributable to the ORVR requirements and likely results in a conservative estimate of benefits and cost-effectiveness as well.

Table 7-11 presents the assumptions we use in estimating the per-vehicle HC emission benefits attributable to the new ORVR requirements for Class 2b heavy-duty gasoline vehicles and the estimated benefits. The gram per gallon (g/gal) refueling HC emission benefit is taken from

(n) Stage II vapor recovery systems on fuel pumps use hoods over the refueling nozzle to collect vapor from vehicles during refueling.

Table 4.10 of the above mentioned rulemaking. The gallon/mile (gal/mi) Class 2b fuel consumption value is taken from the MOBILE6 Conversion Factor report referenced earlier. We determined the benefits over the lifetime mileage accumulation of a typical Class 2b heavy-duty gasoline vehicle as specified in Table 7-6 of this chapter on both an undiscounted basis and a discounted basis (at a rate of seven percent).

Table 7-11
Determination of Per-Vehicle Hydrocarbon Benefits from the ORVR Requirements for Class 2b Heavy-duty Gasoline Vehicles

Refueling Hydrocarbon Emission Benefit Rate	2.42 g/gal
Class 2b Heavy-duty Gasoline Vehicle Fuel Consumption	0.0987 gal/mi
Lifetime Undiscounted Emission Benefit	0.052 tons
Lifetime Discounted Emission Benefit	0.033 tons

Chapter 7 References

1. “Update of Heavy-Duty Emission Levels (Model Years 1988- 2004+) for Use in MOBILE6,” EPA Report No. EPA420-R-99-010, Christian Lindhjem and Tracie Jackson, U.S EPA, OMS, AMD, April 1999.

2. “Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6,” prepared by Arcadis for EPA, May 1998.

3. “Update of Fleet Characterization Data for Use in MOBILE6,” prepared by Arcadis for EPA, May 1998.

4. “Updated Vehicle Survivability and Travel Mileage Schedules,” U.S. Department of Transportation, National Highway Traffic Safety Administration, November 1995.

5. “Development of Heavy-Duty Gasoline Emissions Inventories for the Tier 2/Sulfur NPRM,” EPA memo from John W. Koupal to Docket A-97-10, March 26, 1999.

6. “Final Regulatory Impact Analysis: Refueling Emission Regulations for Light Duty Vehicles and Trucks and Heavy Duty Vehicles,” U.S EPA, OAR, OMS, RDSD, SRPB, January 1994.

CHAPTER 8: COST-EFFECTIVENESS FOR HD DIESEL AND OTTO-CYCLE REQUIREMENTS

This chapter assesses the cost-effectiveness of the requirements for new heavy-duty engines, including the new standards, OBD, useful life, allowable maintenance, in-use testing, and rebuild provisions. This analysis relies in part on cost information from Chapters 4 and 5 and emissions information from Chapters 6 and 7 to estimate the cost-effectiveness of the provisions in terms of dollars per ton of total emission reductions.

Separate analyses were performed for otto-cycle engines and diesel engines. The analysis presented in this chapter for heavy-duty diesel vehicles is an updated version of the analysis performed for the 1997 FRM. Both the otto-cycle and diesel analyses were performed on a per-vehicle basis using total costs and total NOx plus NMHC emission reductions over the typical lifetime of heavy-duty vehicle, discounted at a rate of seven percent to the beginning of the vehicle's life. Analyses of the fleet cost-effectiveness for 30 model years after the new engine standards take effect are also presented.

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 Chapters 5 and 6, 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. It is important to note that 30-year estimates are discounted so that they emphasize the higher costs which occur during the first several years of these programs.

I. Cost-Effectiveness of the Diesel Requirements

Tables 8-1, 8-2, and 8-3 contain the total net present value costs based on the information presented in Chapter 4, the lifetime emission reductions as presented in Chapter 6, and the resulting cost-effectiveness values for light-, medium-, and heavy-heavy duty diesel vehicles, respectively. Tables 8-1, 8-2, and 8-3 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). As was noted in Chapters 4 and 6, we are modeling both the costs and benefits of the supplemental testing requirements as if they begin in model year 2004. We are doing this because we expect that manufacturers will design most, if not all, of their engine models to comply with these requirements in 2004.

Table 8-1
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 of NOx+NMHC)
		NOx	NMHC	
2004-05	$493	0.232	0.018	$1,969
2006-08	$417			$1,668
2009+	$249			$995
30 Year Fleet	—	—	—	$1,230

Table 8-2
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 of NOx+NMHC)
		NOx	NMHC	
2004-05	$706	0.764	0.067	$849
2006-08	$620			$746
2009+	$323			$389
30 Year Fleet	—	—	—	$506

Table 8-3
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 of NOx+NMHC)
		NOx	NMHC	
2004-05	$907	3.189	0.151	$272
2006-08	$792			$237
2009+	$472			$141
30 Year Fleet	—	—	—	$174

Table 8-4 contains the total net present value costs, the lifetime emission reductions, and the resulting cost-effectiveness values for all heavy-duty diesel vehicles. 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 8-4
Cost-Effectiveness for All Heavy-Duty Diesel Vehicles[a]

Model Year Grouping	Total NPV Costs per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton of NOx+NMHC)
		NOx	NMHC	
2004-05	$682	1.365	0.074	$474
2006-08	$591			$410
2009+	$342			$238
30 Year Fleet	—	—	—	$296

[a] combined cost-effectivness weighted by distribution of vehicles by class

II. Cost-Effectiveness of the Otto-cycle Requirements

A. Exhaust Emission Standards

We analyzed the cost-effectiveness of the new exhaust emission standards for three different categories of heavy-duty Otto-cycle vehicles. The three categories analyzed were incomplete vehicles, Class 2b complete vehicles, and Class 3 complete vehicles. Tables 8-5 through 8-7 contain the discounted lifetime per-vehicle cost based on the information in Chapter 5, the discounted lifetime emission reductions as presented in Chapter 7, and the resulting cost-effectiveness values for the three categories of heavy-duty Otto-cycle vehicles. Each of the tables also contains the fleet cost-effectiveness covering the first 30 model years after the new standards take effect (i.e., model years 2005 through 2034). Table 8-8 contains the cost-effectiveness of the new standards for all categories of heavy-duty Otto-cycle vehicles combined. A copy of the spreadsheet prepared for the heavy-duty Otto-cycle vehicle cost-effectiveness analysis has been placed in the public docket for the notice of new rulemaking.[1] The reader is directed to the spreadsheet for a complete version of the cost-effectiveness calculations.

Table 8-5
Cost-Effectiveness for Incomplete Heavy-Duty Otto-cycle Vehicles

<table>
<tr><th rowspan="2">Model Year Grouping</th><th rowspan="2">Total NPV Cost per Vehicle</th><th colspan="2">Discounted Lifetime Reduction (tons)</th><th rowspan="2">Discounted Per-Vehicle Cost-Effectiveness ($/ton of NOx+NMHC)</th></tr>
<tr><th>NOx</th><th>NMHC</th></tr>
<tr><td>2005-09</td><td>$296</td><td rowspan="2">0.45</td><td rowspan="2">0.07</td><td>$565</td></tr>
<tr><td>2010+</td><td>$256</td><td>$489</td></tr>
<tr><td>30 Year Fleet</td><td>—</td><td>—</td><td>—</td><td>$511</td></tr>
</table>

Table 8-6
Cost-Effectiveness for Class 2b Complete Heavy-Duty Otto-cycle Vehicles

Model Year Grouping	Total NPV Cost per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton of NOx+NMHC)
		NOx	NMHC	
2005-09	$274	0.38	0.05	$635
2010+	$273			$633
30 Year Fleet	—	—	—	$634

Table 8-7
Cost-Effectiveness for Class 3 Complete Heavy-Duty Otto-cycle Vehicles

Model Year Grouping	Total NPV Cost per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton of NOx+NMHC)
		NOx	NMHC	
2005-09	$274	0.40	0.06	$596
2010+	$273			$594
30 Year Fleet	—	—	—	$595

Table 8-8
Cost-Effectiveness for All Heavy-Duty Otto-cycle Vehicles

Model Year Grouping	Total NPV Cost per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton of NOx+NMHC)
		NOx	NMHC	
2005-09	$281	0.40	0.06	$612
2010+	$268			$586
30 Year Fleet	—	—	—	$598

B. Refueling Emission Standards

We also separately analyzed the cost-effectiveness of the new onboard vapor recovery requirements for complete Class 2b heavy-duty Otto-cycle vehicles. Table 8-9 contains the discounted lifetime per-vehicle cost based on the information in Chapter 5, the discounted lifetime emission reductions as presented in Chapter 7, and the resulting cost-effectiveness values for the new ORVR requirements for complete Class 2b heavy-duty otto-cycle vehicles.

Table 8-9
Discounted, Lifetime Cost-effectiveness of the New ORVR Requirements
for Complete Class 2b Heavy-duty Otto-cycle Vehicles

Model Year Grouping	Discounted Lifetime Cost	Discounted Lifetime NMHC + NOx Emission Reductions	Discounted Lifetime Cost-effectiveness
2005-2009	$5	0.035 tons	$141/ton of NMHC
2010+	$2	0.035 tons	$56/ton NMHC

III. Other Benefits

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 other benefits as well. These other benefits, which are discussed in Chapter 2, include impacts with respect to agricultural yields, visibility, soiling (due to secondary particulate), and ecosystems (e.g., through the reduced effects of acid deposition and eutrophication). These benefits are real, and they have monetary value. For the 1997 FRM for on-highway HD diesels, an EPA contractor report from 1996 was used to estimate the monetary value of a number of these other benefits.[2] However, EPA has been reevaluating the techniques used to estimate the value of these benefits since 1996. Therefore, it is not presented here.

IV. 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 or other costs. As noted in Chapter 4, EPA is projecting a small increase in operating costs associated with oil changes and EGR maintenance. However, based on the analysis discussed in Chapter 3 and 4, as well as the substantial lead time available for R&D, EPA is not projecting other significant maintenance costs, or losses in fuel economy or engine durability. Even if such impacts were to occur for a few engines, EPA believes that they could be eliminated with additional R&D, and would thus be short-term in nature. Nevertheless, as a sensitivity analysis, EPA estimated the discounted per-vehicle lifetime cost associated with a 1.0 percent fuel economy penalty calculated over the typical lifetime of each class of heavy-duty diesel vehicles. These costs are shown in Table 8-11. To calculate the effect on cost-effectiveness of the new standards with the fuel economy penalty, the fuel economy penalty costs in Table 8-11 were divided by the emission reductions (as presented in Table 8-4). Table 8-12 contains the resulting discounted per-vehicle cost-effectiveness numbers.

Table 8-11
Increase in Discounted Per-Vehicle Lifetime Operating Costs
Associated with a One Percent Fuel Economy Penalty
For Diesel Fuel Cost of One Dollar per Gallon

Light HD	Medium HD	Heavy HD
$102	$178	$891

Table 8-12
Effect on Cost-Effectiveness for All Heavy-Duty Diesel Vehicles
For a One Percent Fuel Economy Change

Fuel Price ($/Gal)	Average NPV Fuel Cost	Discounted Lifetime Reduction from New Standards (tons)		Increase in Per-Vehicle Cost-Effectiveness ($/ton) for Each One Percent Increase in Fuel Consumption
		NOx	NMHC	
$1.00	$390	1.365	0.074	$271
$1.50	$585	1.365	0.074	$407

EPA performed a similar sensitivity analysis to show the effect of assuming that only 50 percent of the costs for VGT and improved fuel injection are attributable to emission control. In this sensitivity analysis, EPA included the full costs for VGT and improved fuel injection in the estimates of per vehicle costs, and recalculated the total cost effectiveness of the program. The results are shown in Table 8-13. The effect of this assumption can be seen by comparing this table with Table 8-4.

Table 8-13
Cost-Effectiveness for All Heavy-Duty Diesel Vehicles
Assuming Full Costs for VGT and Improved Fuel Injection

Model Year Grouping	Total NPV Costs per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness With Full Costs ($/ton)	Discounted Per-Vehicle Cost-Effectiveness With Partial Costs (From Table 8-4)
		NOx	NMHC		
2004-05	$896	1.365	0.074	$623	$474
2006-08	$766			$532	$410
2009+	$466			$324	$238
30 Year Fleet	—	—	—	$396	$296

V. Comparison of Cost-Effectiveness with Other Mobile Source NOx Control Strategies

In an effort to evaluate the cost-effectiveness of the new standards, EPA has summarized the cost-effectiveness results for other recent EPA mobile source rulemakings that required reductions in NOx emissions, the primary focus of the new standards. Both EPA and states have previously adopted numerous NOx emission control measures, and remaining measures may be more expensive than those previously employed. As additional control measures are applied, more expensive ones may be necessary over time. Table 8-14 summarizes the cost-effectiveness results from the Clean Fuel Fleet Vehicle Program, Phase II of the Reformulated Gasoline Program, Tier 2 and Tier 3 Standards for Nonroad Diesel Engines, and Standards for Locomotives.

The projected long-term cost-effectiveness of the diesel vehicles is $296 per ton of NMHC and NOx. The projected long-term cost-effectiveness of the Otto-cycle vehicles is $598. The cost-effectiveness of these standards in this rule falls within the range of these other programs. The cost-effectiveness of these standards compare favorably with the other programs listed in Table 8-14.

Table 8-14
Summary of Cost-Effectiveness Results for Recent EPA Mobile Source Programs

EPA Final Rule	Pollutants Considered in Calculations	Cost-Effectiveness ($/ton)
Clean Fuel Fleet Vehicle Program (Heavy-duty)	NOx	$1,300-1,500 (1994 dollars)
Reformulated Gasoline—Phase II	NOx	$5,000 (1990 dollars)
Nonroad Diesel Engines—Tiers 2 and 3	NMHC+NOx	$410-600 (1995 dollars)
Locomotives	NOx	$160 (1997 dollars)

Chapter 8 References

1. "Cost Effectiveness Analyses of Proposed Heavy-Duty Gasoline Engine and Vehicle Standards," EPA memo from Phil Carlson to Docket A-98-32.

2. See Chapter 7, Section 1 of "Final Regulatory Impact Analysis: Control of Emissions of Air Pollution from Highway Heavy-Duty Engines", September, 1997. Available in EPA Air Docket A-95-27, Docket Item # V-B-01.

APPENDIX A

ANNUALIZED COST EFFECTIVENESS ANALYSIS

This appendix contains tables that show EPA's estimates of 20-year annualized costs and emission reductions. These data come from the analyses contained in Chapters 4 through 8. The analyses assume a 7 percent discount rate.

Annual Diesel NOx and NMHC Benefits (Tons) and Costs

With Annualized 20-Year Cost-Effectiveness

(All numbers were rounded after calculation)

Year	NOx (tons)	NMHC (tons)	Total (tons)	Discounted Benefits (tons)	Total Costs (Undiscounted)	Discounted Costs
2004	97,000	5,000	103,000	103,000	$479,000,000	$479,000,000
2005	266,000	14,000	280,000	262,000	$489,000,000	$457,000,000
2006	417,000	23,000	440,000	384,000	$427,000,000	$373,000,000
2007	555,000	30,000	586,000	478,000	$436,000,000	$355,000,000
2008	681,000	37,000	718,000	548,000	$444,000,000	$338,000,000
2009	795,000	43,000	838,000	597,000	$248,000,000	$177,000,000
2010	900,000	49,000	949,000	632,000	$253,000,000	$169,000,000
2011	999,000	55,000	1,054,000	656,000	$258,000,000	$161,000,000
2012	1,093,000	60,000	1,152,000	670,000	$262,000,000	$153,000,000
2013	1,180,000	64,000	1,244,000	677,000	$267,000,000	$145,000,000
2014	1,260,000	69,000	1,329,000	676,000	$296,000,000	$151,000,000
2015	1,336,000	73,000	1,409,000	669,000	$301,000,000	$143,000,000
2016	1,407,000	76,000	1,483,000	658,000	$306,000,000	$136,000,000
2017	1,474,000	80,000	1,554,000	645,000	$311,000,000	$129,000,000
2018	1,537,000	84,000	1,621,000	629,000	$316,000,000	$122,000,000
2019	1,597,000	87,000	1,684,000	610,000	$320,000,000	$116,000,000
2020	1,654,000	90,000	1,744,000	591,000	$325,000,000	$110,000,000
2021	1,709,000	93,000	1,802,000	570,000	$330,000,000	$104,000,000
2022	1,762,000	96,000	1,858,000	550,000	$335,000,000	$99,000,000
2023	1,813,000	99,000	1,912,000	529,000	$339,000,000	$94,000,000
		20-Year Total =	23,760,000	11,134,000	$6,741,000,000	$4,011,000,000
		20-Year Annualized NPV =		1,051,000 tons	$379,000,000	

20-Year Cost-Effectiveness
Discounted 20-Year $/ton (NOx+NMHC) = $360
Undiscounted 20-Year $/ton (NOx+NMHC) = $283

Annual Otto-Cycle NOx and NMHC Benefits (Tons) and Costs

With Annualized 20-Year Cost-Effectiveness

(All numbers were rounded after calculation)

Year	NOx (tons)	NMHC (tons)	Total (tons)	Discounted Benefits (tons)	Total Costs (Undiscounted)	Discounted Costs
2005	13,000	3,000	16,000	16,000	$110,000,000	$110,000,000
2006	39,000	7,000	46,000	43,000	$117,000,000	$109,000,000
2007	63,000	11,000	74,000	65,000	$124,000,000	$109,000,000
2008	86,000	15,000	101,000	82,000	$126,000,000	$103,000,000
2009	107,000	19,000	126,000	96,000	$129,000,000	$98,000,000
2010	128,000	23,000	151,000	108,000	$124,000,000	$89,000,000
2011	146,000	26,000	172,000	115,000	$126,000,000	$84,000,000
2012	165,000	30,000	195,000	121,000	$128,000,000	$80,000,000
2013	181,000	33,000	214,000	125,000	$131,000,000	$76,000,000
2014	197,000	36,000	233,000	127,000	$133,000,000	$72,000,000
2015	213,000	39,000	252,000	128,000	$135,000,000	$69,000,000
2016	224,000	42,000	266,000	126,000	$137,000,000	$65,000,000
2017	235,000	44,000	279,000	124,000	$139,000,000	$62,000,000
2018	248,000	47,000	295,000	122,000	$141,000,000	$59,000,000
2019	263,000	50,000	313,000	121,000	$144,000,000	$56,000,000
2020	278,000	52,000	330,000	120,000	$146,000,000	$53,000,000
2021	288,000	54,000	342,000	116,000	$148,000,000	$50,000,000
2022	298,000	56,000	354,000	112,000	$150,000,000	$47,000,000
2023	308,000	58,000	366,000	108,000	$152,000,000	$45,000,000
2024	318,000	60,000	378,000	105,000	$154,000,000	$43,000,000
		20-Year Total =	4,503,000	2,080,000	$2,694,000,000	$1,478,000,000
		20-Year Annualized NPV =		196,000 tons	$139,000,000	

20-Year Cost-Effectiveness
Discounted 20-Year \$/ton (NOx+NMHC) = \$710
Undiscounted 20-Year \$/ton (NOx+NMHC) = \$598