EPA

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

DRAFT

U.S. Environmental Protection Agency
Office of Air and Radiation
Office of Mobile Sources

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CHAPTER 1: INTRODUCTION

The draft Regulatory Impact Analysis (RIA) for this proposal presents analysis and supporting data for the new provisions EPA is proposing 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 draft (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 and particulate matter. As part of the legally-required periodic review of the ozone and PM air quality standards, EPA has recently assessed the impacts of ozone and PM on human health and welfare, taking into account the most relevant, peer-reviewed scientific information available. Chapter 2 reviews some of EPA's key concerns at this time, as compiled in the Agency's Criteria Documents and Staff Papers for ozone and PM. The chapter also provides national NOx and VOC emissions inventories and emissions trends, 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 2004 standards, 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 2004 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 2004 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 2004 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 proposal. 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 proposed 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 proposed 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 proposed exhaust standards. The chapter also includes a description of the emission benefits from the proposed 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 proposed requirements for new heavy-duty engines, including the 2004 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. 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

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

A. Health and Welfare Effects from NMHC and NOx

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

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

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

Key EPA findings can be summarized as follows:

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

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

3. The key health effects categories associated with PM include premature death; aggravation of respiratory and cardiovascular disease, as indicated by increased hospital admissions and emergency room visits, school absences, work loss days, and restricted activity days; changes in lung function and increased respiratory symptoms; changes to lung tissues and structure; and altered respiratory defense mechanisms. Most of these effects have been consistently associated with ambient PM concentrations, which have been used as a measure of

population exposure, in a large number of community epidemiological studies. Additional information and insights on these effects are provided by studies of animal toxicology and controlled human exposures to various constituents of PM conducted at higher than ambient concentrations. Although mechanisms by which particles cause effects are not well known, there is general agreement that the cardio-respiratory system is the major target of PM effects.

4. Based on a qualitative assessment of the epidemiological evidence of effects associated with PM for populations that appear to be at greatest risk with respect to particular health endpoints, the EPA has concluded the following with respect to sensitive populations:

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

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

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

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

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

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

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

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

II. Current Compliance with the Ozone NAAQS

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 (CAA, or “the Act”).[a] As of August, 1998, 72 million people outside of California lived in 36 metropolitan areas and two counties designated nonattainment under the 1-hour ozone NAAQS.

In July 1997, EPA established a new 8-hour ozone NAAQS to better protect against longer exposure periods at lower concentrations than the current 1-hour standard. Under the July 1997 rule, the 1-hour NAAQS would still be applicable in certain areas during the transition to the 8-hour standard (62 FR 38856; July 17, 1997). EPA reviewed ambient ozone monitoring data for the period 1993 through 1995 to determine which counties violated either the 1-hour or 8-hour NAAQS for ozone during this time period.[b,c] Eighty-four counties violated the 1-hour NAAQS during this 3-year period, while 248 counties violated the 8-hour NAAQS. The 84 counties had a 1990 population of 47 million, while the 248 counties had a 1990 population of 83 million. EPA is reviewing more recent air quality data for 1996 and 1997. A preliminary assessment of 1994 through 1996 ozone monitoring data reveals only marginal changes in the number of counties experiencing a nonattainment problem with the 8-hour NAAQS, and essentially no change in the population levels impacted by nonattainment.

(a) See 42 U.S.C. 7401 et seq.

(b) This use of the term "nonattainment" in reference to a specific area is not meant as an official designation or future determination as to the attainment status of the area.

(c) See 63 FR 57356, October 27, 1998, “Finding of Significant Contribution and Rulemaking for Certain States in the Ozone Transport Assessment Group Region for Purposes of Reducing Regional Transport of Ozone .”

On May 14, 1999, a panel of the U.S. Court of Appeals for the District of Columbia Circuit found, by a 2-1 vote, that Clean Air Act sections 108 and 109, as interpreted by EPA in establishing the 8-hour ozone NAAQS (as well as the new NAAQS for $PM_{2.5}$ and PM_{10}), effect an unconstitutional delegation of Congressional power. American Trucking Ass'ns, Inc., et al., v. Environmental Protection Agency, Nos. 97-1440, 1441 (D.C. Cir. May 14, 1999). The Court remanded the record to EPA. One judge dissented, finding that the majority's opinion "ignores the last half-century of Supreme Court nondelegation jurisprudence." Id., slip op. at 31. The Court also ruled, regarding the 8-hour ozone NAAQS, that the statute permits EPA to promulgate a revised ozone NAAQS and to designate the attainment status of areas. However, the Court curtailed EPA's ability to require states to comply with the revised ozone NAAQS. Further the Court directed the Agency to determine whether tropospheric ozone has a beneficent effect, and if so, assess ozone's net adverse health effect. In general, the Court did not find fault with the scientific basis for EPA's determinations regarding adverse health effects from ozone. On June 28, 1999, EPA filed a petition for rehearing and petition for rehearing *en banc* seeking review of the panel's decision.

III. Future Compliance with the Ozone NAAQS

Local, state and federal organizations charged with delivering cleaner air have mounted significant efforts in recent years to reduce air quality problems associated with ground-level ozone, and there are signs of partial success. NOx and VOCs appear to have been reduced, and average levels of ozone seem to have begun gradually decreasing. However, this progress is in jeopardy. EPA projects that reductions in ozone precursors that will result from the full implementation of current emission control programs will fall far short of what would be needed to offset the normal emission increases that accompany economic expansion. By the middle of the next decade, the Agency expects that the downward trends will have reversed, primarily due to increasing numbers of emission sources. By around 2020, EPA expects that NOx levels will have returned to current levels in the absence of significant new reductions. (see Chapter 5 of this draft RIA for more information on HD diesel engine emission inventory modeling). To the extent that some areas are seeing a gradual decrease in ozone levels in recent years, EPA believes that the expected increase in NOx will likely result in an increase in ozone problems in the future.

The Agency has recently finalized a rulemaking requiring 22 States and the District of Columbia to submit State Implementation Plan (SIP) revisions to reduce specified amounts of emissions of NOx for the purpose of reducing NOx and ozone transport across State boundaries in the eastern half of the United States.[d] The specified NOx reduction for each State varies, but all are significant. In making this decision EPA relied upon, among other items, advanced ozone modeling studies for the eastern U.S. In the baseline scenario for these modeling runs EPA included the emission reductions expected from the 2004 HD diesel standards. These modeling runs then concluded that significant additional NOx reductions beyond the baseline case were necessary from 22 eastern States in order to meet the ozone NAAQS standards. Therefore, the NOx emission

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(d) See 63 FR 57356, October 27, 1998, "Finding of Significant Contribution and Rulemaking for Certain States in the Ozone Transport Assessment Group Region for Purposes of Reducing Regional Transport of Ozone ."

reductions from the 2004 HDDE standards are contemplated by these models to be part of the reductions that will be needed to meet the ozone NAAQS in these areas.

The deadline for submission of SIPs was recently stayed by a panel of the Court of Appeals for the D.C. Circuit pending further review. EPA believes that the October 27, 1998 rule is fully consistent with the Clean Air Act and should be upheld. However, it should be noted that in the absence of the controls mandated in that rule, the emission reductions from the standards in this proposal would be even more necessary for compliance with the NAAQS.

In addition, many states (including western states) have also included the emission reductions projected from the 2004 HDDE standards in their State Implementation Plans. This clearly demonstrates that these states are relying on these emission reductions to meet the ozone NAAQS.

A. Contribution of HD Diesel and Gasoline Engines to Total VOC and NOx Inventories

HD engines and vehicles are important contributors to the national inventories of NOx emissions, and they contribute moderately to national VOC pollution. The RIA for this proposal describes in detail recent emission inventory modeling completed by EPA for this proposal. Table 2-1 summarizes EPA's current estimates for national NOx and VOC contributions from major source categories.

Table 2-1
2000 National NOx and VOC Emissions, (thousand short tons per year)

Emission Source	NOx	NOx %	VOC	VOC %
Light-Duty Vehicles	4,420	19%	4,098	25%
Heavy-Duty Diesel Vehicles	2,274	10%	246	1%
Heavy-Duty Gasoline Vehicles	318	1%	198	1%
Nonroad Engines and Vehicles	5,343	23%	2,485	15%
Other (Stationary Point and Area Sources)	10,656	47%	9,567	58%
Total Nationwide Emissions	22,831		16,594	

As can be seen in Table 2-1, HD gasoline and diesel vehicles will represent approximately 11 percent of national NOx emissions and 2 percent of national VOC emissions in the year 2000. The Regulatory Impact Analysis document for this proposal contains updated emission inventory modeling for HD vehicles. The results show that without additional HD NOx control beyond the 1998 standards, national NOx emissions from HD vehicles would decline between 2000 and 2005, but this trend would stop in 2005. After 2005, NOx emissions from the HD vehicle fleet would increase as a result of future growth in the HD vehicle market without additional emission controls.

A similar trend is seen for national NMHC emissions from HD vehicles; however, NMHC emissions are projected to decrease until approximately 2010, after which changes in the make-up of the fleet result in an increase in the NMHC emissions from HD vehicles (see Chapter 6 and 7 of this draft RIA).

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

The first NAAQS for particulate matter regulated total suspended particulate in the atmosphere. In 1987, EPA replaced that standard with one for inhalable PM (PM_{10} - particles less than ten microns in size), because the smaller particles, due to their ability to reach the lower regions of the respiratory tract, are more likely responsible for the adverse health effects. The major source of PM_{10} is fugitive emissions from agricultural tilling, construction, fires, and unpaved roads. Some revisions to the PM_{10} standards were made in 1997. EPA has also recently added new fine particle standards ($PM_{2.5}$). Most of the particulate due to motor vehicles falls in the fine particle category. These standards have both an annual and a daily component. The annual component is set to protect against long-term exposures, while the daily component protects against more extreme short-term events.

Compliance with the current PM_{10} standard continues to be a problem. According to the 1996 EPA Air Quality and Emissions Trends report, there were 7 million people living in 15 counties across the U.S. which exceeded the PM_{10} NAAQS in 1996.[1]

EPA recently projected ambient PM_{10} levels and the number of U.S. counties expected to be in violation of the revised PM_{10} NAAQS in 2010.[2] Based on the 1990 census, about 10 million people lived in the 11 counties projected to be in nonattainment of the revised PM_{10} NAAQS.

A. Contribution of HD Diesel and Gasoline Vehicles to PM Inventories

1. Contribution to National PM10 Inventories

The national inventory of PM_{10} is dominated by natural sources (wind erosion) and so-called miscellaneous sources, which include paved and unpaved road dust, agricultural crops, fugitive dust, and dust from construction activities. Together natural and miscellaneous sources represented approximately 90 percent of national PM_{10} emissions in 1996. Since these sources are not readily amenable to regulatory standards and controls, it is appropriate to focus on more traditional "controllable" portions of the particulate pollution problem when considering the need for PM controls. Excluding natural and miscellaneous sources, HD vehicles (gasoline and diesel) represent approximately 5 percent of the remaining man-made sources of PM_{10} in 1996, virtually all (95 percent) of which is from diesel vehicles.[3]

In the proposal for the 1997 final rule for the 2004 standards, EPA presented data on future projections of mobile and stationary source PM_{10} national emission inventories out to the year 2010, as well as a break-down of mobile sources into on-highway light-duty, on-highway heavy-duty, and nonroad categories (see 61 FR 33432-33440, June 27, 1996). These projections showed that without additional future controls on PM or NOx emissions, the mobile source PM would begin to rise after the year 2000. The Regulatory Impact Analysis document for this proposal presents the results of updated emission modeling specifically for HD vehicles. These results show that the national PM_{10} emissions from HD vehicles are expected to decline between now and approximately the year 2010, after which increases in the size of the fleet will result in a steady increase into the future (see Chapter 5 of the draft RIA).

2. Source-apportionment Studies for Diesel PM

Discussion of PM inventories from HD vehicles, and in particular HD diesel vehicles which represent the vast majority of the HD PM emissions, can be discussed in terms other than just contributions to national yearly emission inventories. In recent years several research groups have been looking at the contribution of diesel PM in selected urban and rural areas. In several cases these studies indicate that the contribution from diesels in certain urban areas to PM emissions is much larger than is indicated by national PM inventories. Several studies have been performed in the past several years which have attempted to apportion particulate matter collected at specific sites to individual source categories, i.e., source apportionment studies. These studies collect particulate matter samples in the ambient air which are subsequently analyzed using various chemical techniques in order to estimate what sources contributed to the sample.

There have been a number of source apportionment studies for mobile source particulate emissions. Among the most recent and thorough are studies by the state of Colorado (the Northern Front Range Air Quality Study [NFRAQS]) for the Denver area and the California Institute of Technology for the Los Angeles area. These studies emphasize particulate smaller than 2.5 microns. Also, EPA has a cooperative agreement with the Desert Research Institute (DRI); under this agreement, DRI is completing a detailed report on mobile source particulates; a major portion of this report summarizes source apportionment studies for particulates that include mobile sources.[4]

Source apportionment work involves collecting and analyzing a number of ambient particulate samples from a number of specific sources such as gasoline and diesel vehicles. Some samples of high molecular weight hydrocarbons are frequently also collected and analyzed, these hydrocarbons can be transformed to particulates in the ambient air; such compounds include polycyclic organic matter. These samples are analyzed in detail to determine what specific compounds are present including those in trace amounts that are more common from one source type than from others, these traces are called source signatures. From these analyses, a number of source signatures are developed including those for gasoline and diesel vehicles. Frequently, though, a source apportionment study may use generally accepted source signatures from other work rather than obtaining new ones.

Source apportionment work also involves collecting and analyzing a larger number of ambient particulate and, frequently, high molecular weight hydrocarbon. The compounds found in these samples can be compared to the source signatures to determine what and how much individual sources contribute to the ambient particulate. Source apportionment work is subject to complications and uncertainty. Thus, no single study should be considered definitive. Tracer compounds that are reasonably unique to the source of interest (gasoline, diesel vehicles) have to be identified. The emission rate of these compounds in typical driving conditions (not just steady-state conditions or simple driving cycles) and for a representative number of diesel/gasoline vehicles and engines has to be determined. Since, as usually happens, these compounds are emitted from other sources at lower levels, these emission levels have to be determined as well. Spatial variations have to be considered as ambient samples are collected (e.g., are samples located near a highway where motor vehicles could be represented differently than they would be at a site further away or a site nearer stationary sources). In addition, seasonal variations have to be considered (e.g., some sources are used primarily in the winter, emission rates can vary with temperature). Furthermore, deriving individual emission rates for vehicles and determining how many vehicles are high emitters is complicated. Finally, atmospheric reactions have to be considered and are especially critical for particulates where atmospheric reactions of NOx and SOx are important.

The NFRAQS study analyzed ambient particulate samples in the Colorado area including Denver using data it collected on the chemical speciation from specific source types to determine how much various mobile and stationary source types contribute to $PM_{2.5}$. The total study was funded by 37 government, industry, and trade association groups; it was authorized by Colorado state legislation. The many outputs and conclusions from the NFRAQS will not be discussed here, only source apportionment results for diesel engines are summarized. Complete copies of the NFRAQS are available from the following World Wide Web site, http://charon.cira.colostate.edu/. The NFRAQS included several time periods and several locations in and around Denver. Two locations, Brighton and Welby, during the winter of 1997 included the most detailed sampling and analysis, which allowed the researchers to estimate very detailed source specific contributions, including the contributions to $PM_{2.5}$ from diesel exhaust (all diesel, nonroad and on-highway sources were not differentiated). Based on this work, it was estimated that diesel exhaust sources contributed 10 percent of the total mass of $PM_{2.5}$ in the areas of Brighton and Welby in the winter of 1997.

Similar work has been done for the Los Angeles area by a group of researchers at the California Institute of Technology. This work concluded that direct emissions from diesel exhaust represented approximately 30 percent of fine PM mass on an annual basis in downtown Los Angeles in 1982.[5] In follow-on work looking at the city of Claremont, California in 1987, direct diesel exhaust was found to represent approximately 13 percent of $PM_{2.5}$ mass, and 9 percent of PM_{10} mass.[6]

The California Institute of Technology has also collected ambient particulate in the Boston, MA and Rochester, NY areas. These samples, especially those for Boston, show that carbonaceous particulate is the largest single constituent in $PM_{2.5}$ for these areas. Mobile source particulate, including diesels, is an important contributor to carbonaceous particulate. The Boston and Rochester samples have not yet been used for source apportionment work.

Other ambient samples collected in the eastern U.S. such as Washington DC show carbonaceous particulate to be an important constituent of $PM_{2.5}$, although sulfates is a somewhat larger constituent and nitrates a much smaller constituent. Particulate samples collected in the western U.S. such as in Spokane, Phoenix, and the San Joaquin valley show that carbonaceous particulate is the major constituent with sulfates/nitrates being lesser constituents although nitrates are more important in southern California than elsewhere in the United States. This work is summarized in the EPA report "National Air Pollutant Emission Trends, 1900-1996."[7]

The reports on source apportionment summarized in this section indicate that the contribution of diesel engines to PM inventories in several local areas around the U.S. are much higher than what would be assumed from looking only at the estimates presented in national PM emission inventories. One possible explanation for this is the concentrated use of diesel engines in certain local or regional areas which is not well represented by the national, yearly average presented in national PM emission inventories.

V. Air Toxins 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 otto-cycle 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. To the extent this proposal reduces exhaust hydrocarbons from HD vehicles and evaporative emissions from otto-cycle HD vehicles, impacts from these air toxics will be reduced. Diesel engine particulate matter is also a concern because of it's potential carcinogenic and mutagenic effects on people. Diesel PM is made of hundreds of chemical species, including many organic and metallic compounds. Researchers have been investigating the potential health hazards associated with exposure to diesel PM for many years.[8] EPA's Office of Research and Development is currently updating the EPA's diesel emission health assessment document. However, the document has only been released as a preliminary draft, and is currently undergoing review by the Clean Air Scientific Advisory Committee. A final version is not expected to be available until late 1999.[9]

The California Air Resources Board and the California Office of Environmental Health Hazard Assessment (COEHHA) have undertaken an assessment of the cancer and non-cancer effects from exposure to diesel exhaust, including the particulate matter component of diesel exhaust, to determine wether diesel exhaust should be classified as a Toxic Air Contaminant (TAC) under California law. The evaluation of diesel exhaust by CARB and COEHHA began in 1989. In June of 1998, a Staff Report was published which recommended that diesel exhaust be classified as a TAC.[10] In a CARB Board hearing held in August, the Board decided to identify diesel exhaust particulate matter (not whole diesel exhaust) as a TAC.[11]

Chapter 2 References

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3. U.S. EPA, December 1997, “National Air Pollutant Emission Trends, 1900-1996", EPA-454/R-97-011.

4. Draft report for EPA from the Desert Research Institute, June 30, 1998, Available in EPA Air Docket A-98-32, Item # II-A-01.

5. “Source Apportionment of Airborne Particulate Matter Using Organic Compounds as Tracers”, J.J. Schauer, W.F. Rogge, L.M. Hildemann, M.A. Mazurek, and G.R. Cass, Atmospheric Environment, Vol. 30, No. 22, 1996.

6. “Source Contributions to the Size and Composition Distribution of Urban Particulate Air Pollution”, M.J. Kleeman and G.R. Cass, Atmospheric Environment, Vol. 32, No. 16, 1998

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8. “Diesel Exhaust: A Critical Analysis of Emissions, Exposure, and Health Effects”, Health Effects Institute, April, 1995.

9.“Preliminary Draft - Health Assessment Document for Diesel Emissions”, U.S. EPA, February 1998, EPA 600/8-90/057C.

10. California Air Resources Board - Staff Report - “Proposed Identification of Diesel Exhaust as a Toxic Air Contaminant”, June 1998.

11. California Air Resources Board, Resolution 98-35, August 27, 1998.

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 2004 emission standards. 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 2004 standards. To meet the 2004 goals, 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. 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, EPA expects that no change in diesel fuel composition will be required to meet the 2004 standards. In addition, the current status of technologies which EPA does not believe will be either available or necessary for the 2004 model standards, but which could provide additional emission reductions beyond the 2.4/2.5 g/bhp-hr NMHC+NOx and 0.1 g/bhp-hr PM levels, are discussed (these technologies include NOx absorber catalysts, urea-based SCR systems, and PM traps).

This 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 nozzle turbo-chargers (VNT) 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 for the 2004 standards, but the analysis which lead EPA to the conclusion that cooled EGR would be the principle technology for meeting the 2004 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 draft 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-Presssure-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 nozzle turbo-chargers (VNTs), 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,[12] but the turbo-chargers extracted less energy in this configurations, and the re-circulated exhaust displaced fresh air without any increase in charge air pressure. 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 nozzle turbocharger (VNT) is a turbo-charger 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. VNTs 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 VNT.[19] One study combined a VNT 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 VNT by allowing the VNT to operate at lower back pressures and temperatures.[21] Another variation of the venturi concept that does not employ a VNT 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 VNTs 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 VNTs, venturis, EGR coolers, and control valves for complete EGR system implementation, EPA expects EGR to be a primary strategy for achieving the 2004 emission standards.

C. Fuel Injection Rate-shaping

Another key emission control strategy that EPA expects heavy-duty diesel engine manufacturers to use to meet the 2004 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 2004 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 proposing a reduction in the highway heavy-duty engine PM standard beyond the level of 0.10 g/bhp-hr (0.05 g/bhp-hr for urban buses), PM control will continue to be very important. PM will remain a primary consideration along with fuel economy and engine durability in the development of engines with lower NOx emissions. As discussed above, HC emissions control has not been a primary focus for diesel engines due to their relatively low HC emissions levels. With a NOx plus NMHC standard, HC emissions levels would become a greater consideration in the packaging of technologies to meet overall emission targets.

Exhaust aftertreatment technologies for PM and NOx control are discussed in this section. 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

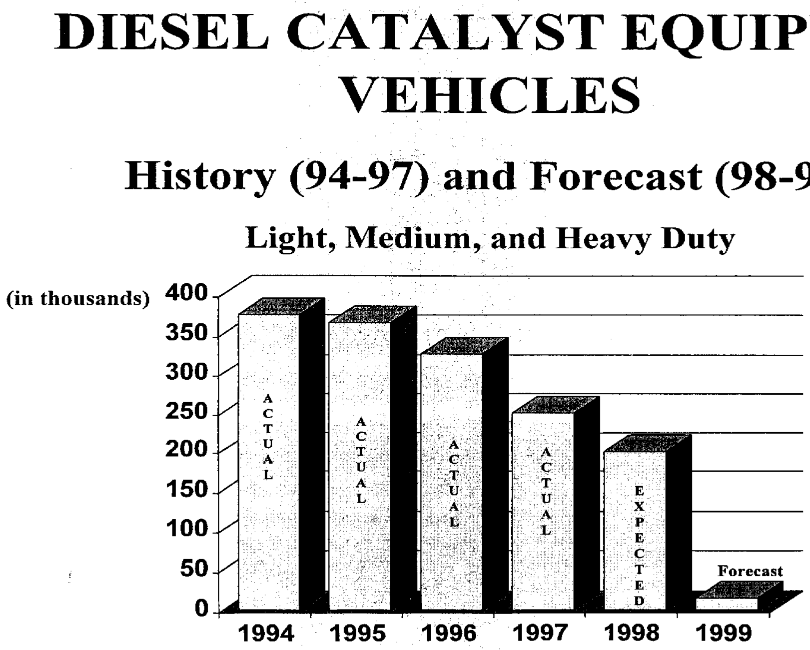
Two aftertreatment technologies have received the most attention for particulate control, the flow-through oxidation catalyst and the particulate trap. The oxidation catalyst provides relatively moderate overall PM reductions by oxidizing a portion of the particulate as the exhaust passes through it. 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.

(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.

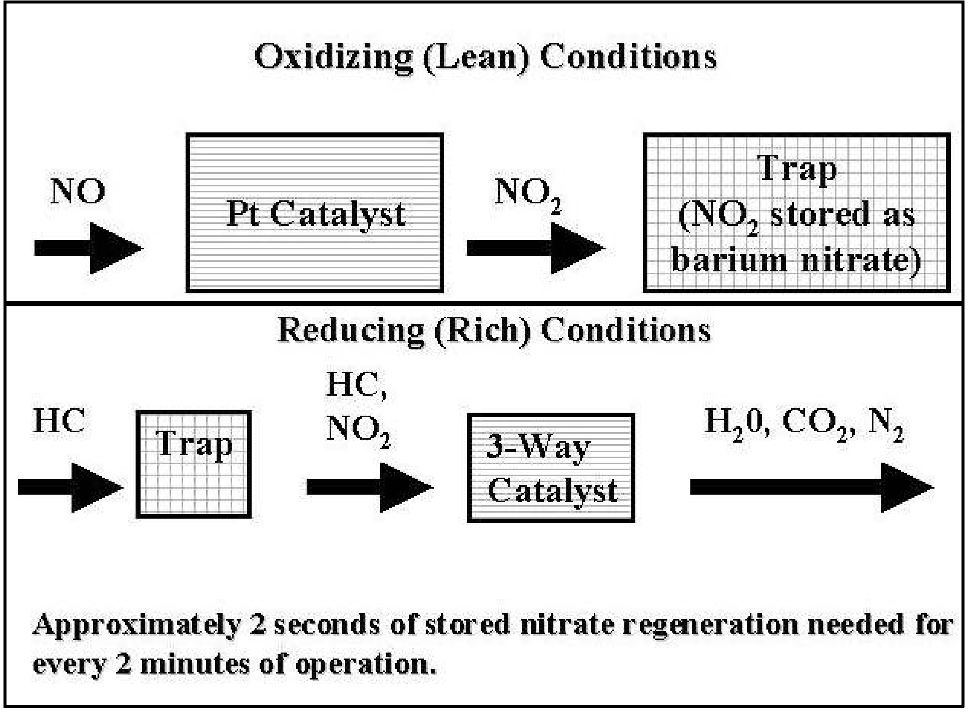
(a) NOx Storage Catalysts

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)[e]. 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.

(e) 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.

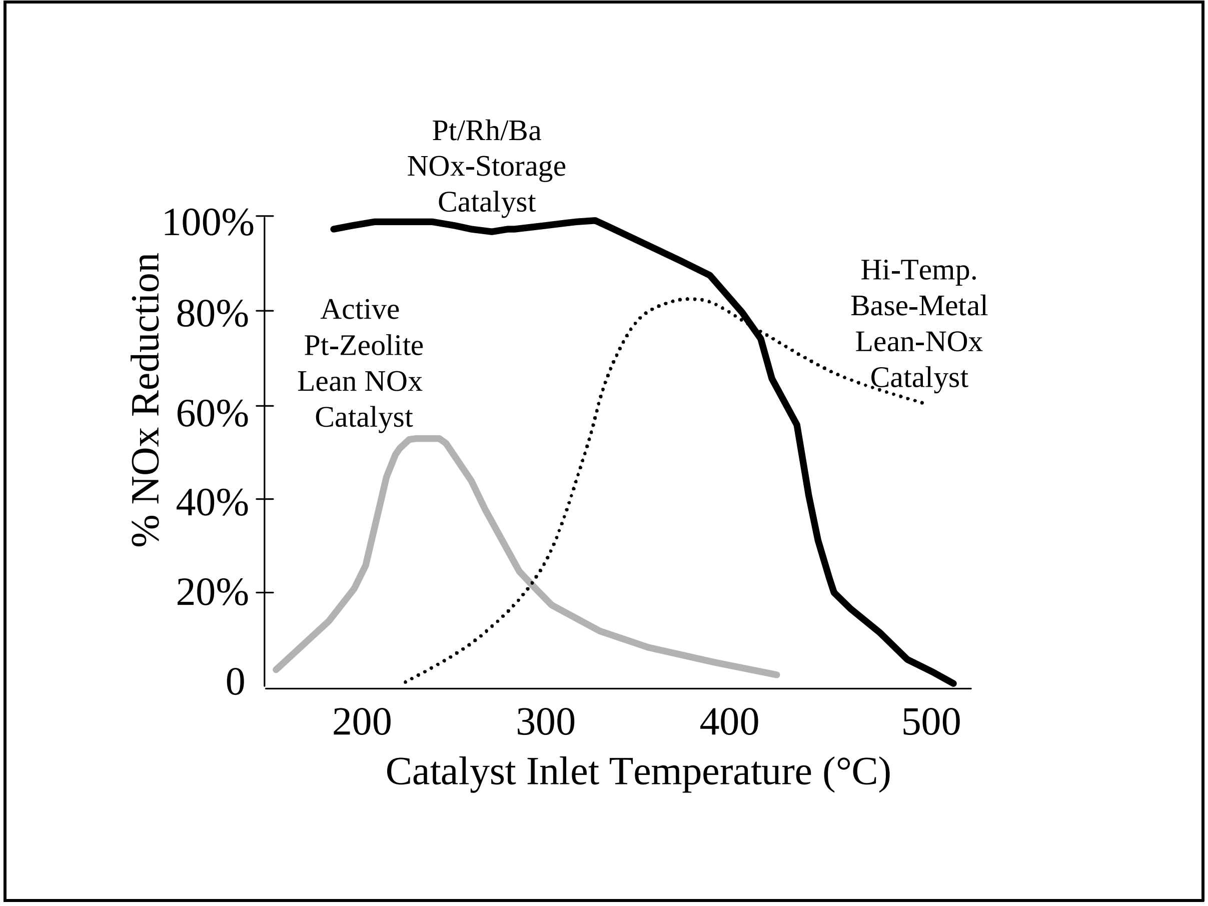
A number of new common rail fuel injection systems are capable of injecting fuel after combustion to provide additional hydrocarbons for use as a NOx reductant with active lean-NOx catalysts. One example is the introduction of an active lean-NOx catalyst system for a European light-duty diesel application[69]. 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[f]. 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.

(f) 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 proposed 2004 emission standards. 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 2004 technology HD diesel engines.

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, Mobile 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 proposed 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"[g]), 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.

(g) 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-aromatics %	% 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	-7.2	-25.8	-8.4
“Light”, High Cetane, Low Aromatic Fuel	830	52	10	2.5			

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.

(3) 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 2004 Engine 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 meet the 2004 standards under a large variety of operating conditions, not simply the test cycle contained in the Federal transient FTP. This assumption is no different then what was considered in the 1997 rulemaking, and the supplemental test procedures included in this proposal do not impose substantially new burdens. 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, including cycles used in Japan and Europe. 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 properly under a wide range of operating conditions, and could be designed to provide comparable levels of emission control under a wide range of operating conditions. 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.

In the past two years, the Agency has requested and received confidential emission maps (contour maps of NOx and PM over an engine's complete speed and torque operating range) on a large number of modern, 1998 model year heavy-duty diesel engine families.

The Agency's examination of these maps, and confidential discussions with several HD diesel engine manufacturers, led EPA to the conclusion that the 1.25 emission cap associated with the not-to-exceed zone requirement is technologically feasible. The Agency believes the 1.25 factor proposed for the not-to-exceed standard provides sufficient room to allow for the uneven nature of the emission maps. 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, as well as the supplemental test cycles, procedures and associated standards contained in this proposal, i.e., the supplemental steady-state cycle, not-to-exceed zone testing, and load response test discussed in the preamble.

G. Summary and Conclusions regarding HD Diesel 2004 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 draft RIA contains EPA's reassessment of the technological feasibility of the 2004 HD diesel standards, including a discussion of the role diesel fuel quality plays in the appropriateness of the 2004 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
VNT turbocharged, aftercooled, 4-valve/cyl, high-pressure fuel injection, HPL cooled EGR, with full-flow venturi mixer[80]	ECE R49 13-mode	2.24 g/hp-hr	0.08 g/hp-hr	No significant change
VNT turbocharged, aftercooled, high-pressure electronic fuel injection, HPL cooled EGR, with full-flow venturi mixer[81]	ECE R49 13-mode	1.80 g/hp-hr	0.08 g/hp-hr	2.3% inc. from no EGR
VNT turbocharged, aftercooled, HPL cooled EGR[82]	Japanese 13-mode	22% dec. from no EGR & VNT	No significant change	1.5% dec. from no EGR & VNT
waste-gate turbocharged, air-air aftercooled, 4 valve/cyl, MEUI fuel injection, HPL cooled EGR with partial flow venturi mixer[83]	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 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 four years of lead time available to them , and will be able to meet the reaffirmed and proposed 2004 NMHC+NOx emission standards, while continuing to meet the existing 0.1g/bhp-hr PM standard, and with minimal, if any, brake specific fuel consumption penalties. In addition, the averaging, banking and trading provisions included in the 2004 regulations provide manufacturers with considerable flexibility in determining how to meet the standards, and thus provide manufacturers with additional options for ensuring their engines can meet these standards on a fleet wide average basis.

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.[84] 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.[85,86] 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 being proposed in the rule.[87]

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[h] 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 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.

(h) 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.

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 ± 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

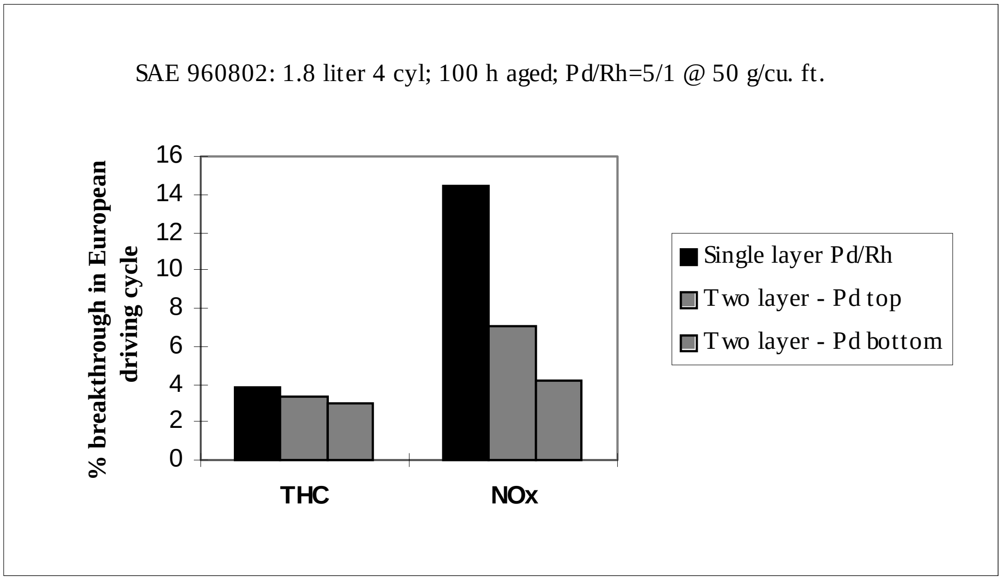
Over the last five years or so, there have been tremendous advancements in exhaust aftertreatment systems. Catalyst manufacturers are progressively moving to palladium (Pd) as the main precious metal in automotive catalyst applications. Improvements to catalyst thermal stability and washcoat technologies, 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 under the proposed standards 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 proposing to extend 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 the proposed 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. As new and more advanced engines are introduced, EPA anticipates that they will be capable of achieving the proposed standards.

Catalyst systems with increased precious metal loading will be the critical hardware change for meeting the proposed standards. 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 proposed standards. Precise air/fuel control is critical to meeting the proposed 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.[i] 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.

(i) 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.[j] 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 proposed 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 proposed standards. Of course with higher catalyst efficiencies,

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

manufacturers 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 proposing 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 proposed 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[88]. Because EPA expects manufacturers to implement electronically controlled emission control strategies such as EGR and fuel injection rate shaping, EPA is proposing 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. 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 proposed 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 aftertreatments, EPA believes a back-pressure sensor would be feasible to monitor a PM trap performance, 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 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 NOx and 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.[89] 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,[90,91] EPA expects that future advances might allow their use on-board. 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. This breakthrough technology might be used for closed-loop control, and, because it can accurately measure NOx in the 100 ppm range, it may enable monitoring of NOx aftertreatment technologies.[92] Furthermore, as part of the partnership for a new generation of vehicles (PNGV), researchers might be investigating technologies to enable real time PM measurement for closed-loop control. 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.[93] At their present state of development, it is unlikely any of these technologies will be available by 2004.

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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. This current analysis is generally a re-analysis of those previous analyses, but also addresses newly proposed requirements such as the NTE requirements. The reader should refer to the previous analyses for additional information and background. As was done in the previous analysis, all costs are described in terms of 1995 dollars. If these costs were presented in 1998 dollars, they would be 8 percent higher.

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.[1] For technologies sold by a supplier to the engine manufacturers, an additional 29 percent markup is included for the supplier's overhead and profit. Estimated variable costs for new technologies (i.e., EGR and VNT) 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, and are then recovered with a five-year amortization at the same rate. The analysis also includes consideration of lifetime operating costs where applicable. Projected costs were derived for four service classes of heavy-duty diesel vehicles, as depicted in Table 4-1. The cost for each technology applied to urban buses is the same as the cost of that technology when applied to heavy heavy-duty vehicles, unless specified otherwise.

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. EPA believes that without 2004 model year standards, manufacturers would continue research on and eventually deploy many technological upgrades to improve engine performance or more cost-effectively control emissions. For those cases, EPA is assuming that only a fraction of the fixed and variable 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 +
Urban Bus	—	—

II. Technologies for Meeting the 2004 Standards

The following discussion provides a description and estimated costs for those technologies EPA projects will be needed to comply with the new emission standards. EPA believes that a small set of technologies represent the primary changes manufacturers must make to meet the 2004 model year standards. Other technologies applied to heavy-duty engines, before or after implementation of new emission standards, will make smaller 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). Thus, this assumption, that 100 percent of the cost of adding EGR is attributable to compliance with the 2004 standard, is conservative and actual compliance costs for the 2004 standard 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 the 2004 emission standards. The reader is referred to the RIA for the 1997 FRM for more information regarding the potential costs of these secondary technologies.

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)	38	197	7	100%
Combustion optimization	20	0	0	100%
Improved fuel injection	8	124	0	50%
Variable geometry turbochargers	14	172	0	50%
Onboard diagnostics	3	0	0	100%
Emission map testing	9	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)	94	221	45	100%
Combustion optimization	50	0	0	100%
Improved fuel injection	18	117	0	50%
Variable geometry turbochargers	32	227	0	50%
Onboard diagnostics	0	0	0	100%
Emission map testing	23	0	0	100%
Certification	8	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)	94	307	96	100%
Combustion optimization	50	0	0	100%
Improved fuel injection	18	128	0	50%
Variable geometry turbochargers	32	273	0	50%
Onboard diagnostics	0	0	0	100%
Emission map testing	23	0	0	100%
Certification	8	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.

Urban Buses (Dollars per Engine)

Item	Fixed Cost	Variable Cost	Operating Cost	Fraction of Cost For Emissions*
Cooled EGR (high-flow)	94	234	127	100%
Combustion optimization	50	0	0	100%
Improved fuel injection	12	97	0	50%
Variable geometry turbochargers	32	273	0	50%
Onboard diagnostics	0	0	0	100%
Emission map testing	23	0	0	100%
Certification	8	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 proposed emission standards, first for fixed costs, then for hardware and operating costs of the individual technologies.

The cost analysis anticipates an extensive ongoing research program to develop these technologies. 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 proposed emission standards. EPA previously developed a detailed methodology for calculating certification costs.[2] Adjusting those figures to account for inflation results in an estimated certification cost of $230,000 per engine family. This is the same estimate that was used in the 1997 analysis, because EPA believes that the new supplemental steady-state certification requirement will not significantly affect certification costs. Because certification costs will be incurred on average one year before the beginning of production, the calculated cost is increased by seven percent. The calculated certification costs for heavy-duty diesel engines can be rounded up to $23 million. Distributing those costs across the different engine categories, amortizing the costs over five years, and dividing by the number of projected 2004 model year sales for each category results in per-engine costs between $2 and $8 for each category of heavy-duty diesel vehicles.

1. Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is projected to be the most important area of technology development that will enable manufacturers to achieve the targeted NOx emission levels. Unlike the other technological developments, which are largely evolutionary, introduction of EGR would be a step change in the design of heavy-duty diesel engines. While 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 per engine depending on the service class. Factoring in the fixed costs and the appropriate markups results in an increased purchase price of $235, $315, $401, and $328 for light, medium, and heavy heavy-duty diesel vehicles, and urban buses, respectively.

2. Combustion Optimization

Manufacturers can make a variety of changes to the basic engine design that do not require additional components. Programming the engine's electronic controls, optimizing intake air characteristics and distribution, and making changes to piston bowl shape, the compression ratio, and the injection timing strategy add little or no variable cost, but require significant expenses for R&D and retooling. 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 $20 and $50 per engine.

3. Fuel System Upgrades

Manufacturers are expected to improve their fuel injection systems by increasing fuel injection pressure, improving spray patterns, and adding rate shaping and split injection capability; however, much of this improvement is expected to occur independently of 2004 model year emission standards. For cam-driven electronic unit injection systems, the expected fuel system improvements will require stronger and better performing fuel injectors and solenoids. Advanced systems such as 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 $132 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 $135 and $146 per engine. Urban buses, currently equipped with four-cylinder engines, have the lowest estimated total cost of about $109. 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 and bus engines will have cam-driven unit injectors (and that the remainder will have common rail, HEUI, or similar systems). 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.

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 VNT 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. The revised estimates of the variable cost increase to manufacturers for VNT (relative to current technology turbochargers) range from $90 to $150. Fixed costs for R&D and retooling are estimated at about $3.5 million per engine line. Combining the costs with the appropriate markups results in costs of $186, $259, and $305 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. The preamble for this proposal contains additional discussion of this 50 percent estimate, including a request for comment on the issue. 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 proposed HD diesel 2004 standards cost-effectiveness.[3] This cost sensitivity is also summarized in Table 8-13 of Chapter 8, Section IV of this draft RIA.

5. Onboard Diagnostics

Manufacturers are not expected to make significant hardware modifications in response to the proposed 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. This testing will add $3 to the fixed costs for light heavy-duty engines, but will not affect variable or operating costs. EPA is making the conservative assumption that this cost will apply to all light heavy-duty engines, even though only those light heavy-duty engines for vehicles at or under 14,000 pounds would be subject to the proposed OBD requirements.

6. Engine Map Testing

While manufacturers are not expected to make significant hardware modifications in response to the proposed 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 $9, $23, and $23 to the fixed costs for light, medium, and heavy heavy-duty engines, respectively, but will not affect variable or operating costs.

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 are increased, then manufacturers may need increase the use of aftertreatment. This increase hardware costs and there would be a greater potential for increased operating expenses.

As noted above, EPA believes it is not appropriate to assign the full cost of fuel system upgrades or the addition of VNT to the proposed emission standards. Much of the anticipated improvements will come independently of the 2004 model year standards and any remaining system improvements for 2004 and later model year vehicles will provide benefits beyond lower NOx emissions. 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 proposed emission standards. Projected cost increases are $428, $587 and $701 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 seven years will be to resolve potential operating cost impacts related to the use of EGR; thus the current state of the technology is not representative of what is expected for 2004.

While engine-out particulate emissions are dramatically lower than only a few years ago, recirculating even a small amount of particulate matter through an engine introduces a concern for engine durability. To prevent wear, manufacturers might specify more frequent oil change intervals or a greater oil sump volume to accommodate any effects of acidity or particulate agglomeration in the oil. However, EPA expects manufacturers to make a great effort to minimize any potential new maintenance burden for the end user. Alternatively, changing fuel or oil formulations may be the most cost-effective way to reduce the potential for particulate-related wear. EPA therefore believes that manufacturers will be able to keep engine costs lowest by investing in research to address these concerns—an expenditure of $10 million to $15 million industry-wide, or about $25 per engine when amortized over the fleet, should provide sufficient development potential to prevent durability problems in a way that is transparent to the user. To include the affect of improved materials resulting from the R&D effort, the analysis incorporates a 2 percent increase in the cost of engine oil. The increased expense of oil changes over the lifetime of vehicles ranges from $7 to $30 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.[4] Rebuilding engines from light heavy-duty vehicles is rare. EPA estimates that engine rebuild occurs at 240,000 miles for medium heavy-duty vehicles, at 500,000 miles for heavy heavy-duty vehicles, and at 300,000 miles for urban buses. These mileage figures represent an approximate average across the various applications within each service class, which experience widely differing mileage accumulation rates. For example, garbage trucks have much different operating characteristics than line-haul trucks. According to the MOBILE model, these mileage figures translate into a rebuild in the eleventh year for both truck categories and in the ninth year for urban buses. EPA expects that rebuild procedures for EGR systems will include solvent cleaning of the EGR tubing and replacement of the electronic control valve. Removal, cleaning, and replacement of the tubing are estimated to take 30 minutes at a $65 per hour labor rate. Replacing the control valve on an aftermarket basis is expected to cost three times the manufacturers' long-term direct cost, or $65 and $95 for medium and heavy heavy-duty vehicles, respectively. Calculated in terms of net present value at the point of sale, the net effect of EGR servicing comes to about $50 for medium heavy-duty vehicles and $65 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 sensitivity of the projected costs to this conclusion was investigated. Acurex estimated the burden of 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, $145, and $95 for light, medium, and heavy heavy-duty vehicles, and urban buses, respectively.

With respect to fuel economy, while EGR has the potential to incur a fuel economy penalty, EPA believes that these will be more than offset by improvements in fuel injection and the use of VNT. In fact, EPA believes that the combined effect of these three technologies may decrease fuel consumption by as much as 1.5 percent. EPA estimates that for each one percent decrease in fuel consumption, there would be cost savings, calculated as a net present value at the point of sale, of $100, $211, and $985 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.

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). In addition to the emission testing performed at SwRI, MECA members also agreed to provide EPA with cost information on each of these technologies. MECA submitted a cost report to EPA which contained estimated per-vehicle unit costs for DOC's, particulate traps, and SCR systems for the light-, medium-, and heavy-heavy diesel engine market, using typical engine displacement, engine family production volumes, and industry wide production volumes for each of subset of the heavy-duty diesel market.[5]

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, an it is likely some number of engine families may continue to rely on DOC's for modest PM reductions. As discussed in Chapter 4, 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, the cost information provide by MECA is useful to gain an understanding of the potential impacts on engine costs which could occur if the wide spread use of DOC's, PM traps, or SCR systems were to take place in the HD market. Table 4-3 presents a summary of the cost information provided by MECA

Table 4-3:
Estimated Unit Costs for Aftertreatment Devices Provided by MECA

	Light, Heavy-Duty Engines	Medium, Heavy-Duty Engines	Heavy, Heavy-Duty Engines
Assumed Displacement (L)	6	8	13
Assumed Annual Engine Family Production	75,000	30,000	26,000
Assumed Annual Industry Production	280,000	140,000	220,000
Range of Costs for DOC's	$230 to $500	$285 to $600	$320 to $750
Range of Costs for PM Traps	$250 to $550	$570 to $700	$625 to $2250
Mean Cost for SCR System	$1,317	$1,617	$1,967

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.[6,7] 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. Accordingly, in the preamble to this proposed rule, EPA has requested comment and information that would lead to a better understanding of the relevant 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. The Preamble for this proposal contains additional discussion regarding the Agency's use of the learning curve, including request for comment on a number of aspects of the learning curve methodology. The reader is directed to Section VIII(A)(1) of the preamble for additional discussion on this topic.

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 proposed 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 proposed emission standards in any year. The result of this analysis is a projected total cost starting at $424 million in 2004. Per-vehicle cost savings over time reduce projected costs to a minimum value of $223 million in 2009, after which the growth in truck population leads to an increase to $285 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 $30 million by 2020.

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

Vehicle Class	Model Year	Change	Purchase Price	Life-cycle Operating Cost (NPV)
Light heavy-duty	2004	—	428	7
	2006	20 percent learning curve applied to variable costs	359	7
	2009	Fixed costs expire; 20 percent learning curve applied to variable costs	221	7
Medium heavy-duty	2004	—	593	45
	2006	20 percent learning curve applied to variable costs	514	45
	2009	Fixed costs expire; 20 percent learning curve applied to variable costs	252	45
Heavy heavy-duty	2004	—	701	96
	2006	20 percent learning curve applied to variable costs	606	96
	2009	Fixed costs expire; 20 percent learning curve applied to variable costs	324	96

Table 4-5
Baseline Costs for Heavy-Duty Engines and Vehicles

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

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

Year	Category	Cost Elements (millions of dollars)			
		Fixed	Variable	Operation	Total
2004	Light heavy-duty	27	114	0.2	142
	Medium heavy-duty	33	65	0.2	98
	Heavy heavy-duty	52	132	1.1	185
	Total Annual Cost	**112**	**311**	**1.6**	**424**
2009	Light heavy-duty	0	79	1.4	81
	Medium heavy-duty	0	45	1.1	46
	Heavy heavy-duty	0	91	5.3	97
	Total Annual Cost	**0**	**216**	**7.8**	**223**
2020	Light heavy-duty	0	93	2.7	95
	Medium heavy-duty	0	53	6.7	59
	Heavy heavy-duty	0	107	23	130
	Total Annual Cost	**0**	**253**	**33**	**285**

Chapter 4 References

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3. EPA Air Docket A-98-32, “Analysis of Costs and Benefits of VGT and Improved Fuel Injection”, EPA Memorandum from Charles Moulis.

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7. “Learning Curves in Manufacturing,” L. Argote and D. Epple, *Science*, February 1990, Vol. 247, page 920. Copy Available in EPA Air Docket A-98-32.

CHAPTER 5: ECONOMIC IMPACTS OF HD OTTO-CYCLE STANDARDS

This chapter contains an analysis of the economic impacts of the proposed 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 proposed regulations. Finally, an analysis of the aggregate cost to society of the proposed regulations is presented. The costs presented here are in 1997 dollars. The costs would be 2.3 percent higher if presented in 1998 dollars.

I. Methodology for Estimating Costs

Using the information on emission reduction technology presented in Chapter 4, EPA identified packages of technologies that would be likely to be used by the manufacturers to comply with the proposed emission standards. These technology packages are those which are being implemented to meet California's low emission vehicle (LEV) standards. To quantify the costs of most of these technologies, EPA relied on the contracted study of heavy-duty gasoline vehicle technology conducted by Arcadis Geraghty & Miller.[1] 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.[2]

The costs of meeting the proposed 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 Proposed Regulations

The various technologies that could be used to comply with the proposed regulations were discussed in the previous chapter on technological feasibility. EPA expects that the technology mixes being used to meet the California LEV standards fairly accurately represent those that will be used to comply with the proposed federal standards beginning with the 2004 model year. Thus, in developing costs for the associated technologies EPA 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. 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 such as sequential multi-port fuel injection and EGR, while important to meeting the proposed 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, such technologies 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 2004
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, EPA expects that catalyst washcoat and precious metal compositions and loadings will change.

2. ORVR is only proposed to apply to complete vehicles 10,000 lbs GVWR and under, and is proposed to be phased in over three years, with 100% application to those vehicles in 2006.

Table 5-2

Current and Expected Technology Packages for Engine-based Standards

Technology	Baseline Federal	Estimated 2004
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, EPA expects that catalyst washcoat and precious metal compositions and loadings will change.

2. The estimated breakdown for 2004 reflects OBD requirements for all HDGEs. However, OBD is only proposed to apply to HDGEs under 14,000 lbs GVWR (approximately 60 percent of HDGEs).

III. Technology Costs

The following sections outline in detail the costs of both current technologies and the technologies EPA expects will be used to comply with the proposed 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, EPA 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. EPA expects that the usage of the single floor catalyst system will drop to 13 percent as a result of the proposed standards, and usage of the dual catalyst system will drop to 50 percent. The Agency expects 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 proposed standards. The cost dual underfloor/dual close-coupled catalyst system was only analyzed in an enhanced configuration for use in compliance with the proposed 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, EPA analyzed catalysts for two engine sizes, standard and large. For purposes of developing an average per-vehicle cost EPA 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 use 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, since Pd usage is going up, EPA has 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, EPA expects that no increase in catalyst volume will be required to comply with the proposed 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, EPA is 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. EPA is 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.

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 EPA is applying to products supplied to the manufacturers by component suppliers is not being applied to the cost of precious metals. EPA chose to use September, 1998 precious metal spot prices for the purposes of this analysis. These are $288 per troy ounce for Rh and $670 per troy ounce for Pd.

3. Changes in Washcoat

In addition to the changes to precious metals just discussed, EPA expects that the proposed 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. The Agency 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 Agency assumed that a slightly higher ceria concentration (75/25 ratio of ceria to alumina) will be used in compliance with the proposed vehicle-based standards and that an even higher ceria concentration (80/20 ratio of ceria to alumina) will be used in compliance with the proposed engine-based standards.

Current washcoat loadings range from 160 to 220 g/L of catalyst substrate volume. EPA assumed an average loading of 190 g/L for the baseline configuration, and that this loading would remain unchanged for compliance with the proposed vehicle-based standards. For compliance with the engine-based standards, EPA assumed that the washcoat loading will increase to 220 g/L. In addition, EPA expects 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 proposed 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	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

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. Since the increased costs of the metal substrates will tend to cancel out any savings in precious metal costs, EPA assumed that the current ceramic substrate would continue to be used in compliance with the proposed standards. 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

has been shown to be 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 EPA's 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 proposed 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	$25	$30	$25	$30	$25	$30
Washcoat	$18	$21	$18	$22	$22	$26
Precious Metals	$105	$126	$199	$241	$199	$241
Can	$5	$5	$5	$5	$5	$5
Total Material Cost	$153	$183	$248	$298	$251	$303
Labor	$4	$4	$4	$4	$6	$6
Labor Overhead @40%	$1	$1	$1	$2	$2	$2
Supplier Markup @29%[1]	$16	$18	$15	$18	$17	$20
Manufacturer Cost	$174	$207	$268	$322	$276	$331

[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	$25	$30	$25	$30	$25	$30
Washcoat	$18	$21	$18	$22	$22	$26
Precious Metals	$105	$126	$199	$241	$199	$241
Can	$6	$6	$5	$6	$5	$6
Total Material Cost	$154	$184	$248	$299	$252	$303
Labor	$5	$6	$7	$8	$11	$12
Labor Overhead @40%	$2	$2	$3	$3	$4	$5
Supplier Markup @29%[1]	$16	$19	$17	$20	$20	$23
Manufacturer Cost	$176	$211	$275	$330	$287	$343

[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		Projected Engine-based Standards	
Engine Size	Standard	Large	Standard	Large
Catalyst Volume (L)	4.8	5.8	4.8	5.8
Substrate	$28	$33	$30	$36
Washcoat	$19	$23	$24	$29
Precious Metals	$232	$273	$301	$363
Can	$6	$7	$7	$8
Total Material Cost	$285	$336	$361	$436
Labor	$14	$15	$18	$20
Labor Overhead @40%	$6	$6	$7	$8
Supplier Markup @29%[1]	$21	$24	$25	$29
Manufacturer Cost	$326	$382	$412	$493

[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 proposed standards. Thus, the percentage of the fleet with EGR is not expected to change as a result of the proposed standards. However, some improvements are expected to be made to those EGR systems that are currently being used. In addition to minor changes in control algorithms, EPA expects 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. EPA 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 $65 per vehicle. EPA expects 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 proposed 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. 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 has only been proposed to apply to HDGVs weighing 14,000 lbs GVWR or less. Thus, only 60 percent of HDGVs certified according to the proposed engine-based program would be required to comply with the proposed OBD requirements. This is reflected in the cost summary table later in this chapter.

1. Oxygen Sensors/Catalyst Efficiency Monitoring

The proposed 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 proposed 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. EPA also expects them to be used in compliance with the proposed standards. Heated oxygen sensors have an average manufacturer's cost of $10 to $15. Thus, EPA 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 proposed 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 proposed 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 $15 for the fuel tank pressure transducer. Wiring and labor bring the incremental cost of this system to around $30.

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. EPA expects that many non-California vehicles will have 32 bit processors as well in order to reduce parts complexity. Thus, EPA assumed that, as a baseline, 50 percent of non-California vehicles will be equipped with 32 bit processors prior to 2004. EPA expects that all vehicles will be equipped with 32 bit processors in order to comply with the proposed standards. EPA expects that this move to 32 bit processors will result in a $20 increase over the baseline vehicle. However, the need for 32 bit processors is only partly driven by the proposed OBD requirements. The proposed lower emission limits will also result in a move to more powerful ECMs. Thus, EPA is assigning half of the incremental cost of the improved ECM to the proposed OBD requirements and the other half to the proposed emission reduction requirements.

4. Manifold Vapor Pressure Sensor Improvements

EPA expects that the proposed 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.

5. Exhaust Systems

EPA expects that insulated exhaust systems will be used in close-coupled catalyst-equipped vehicles in order to improve catalyst light-off time. EPA estimates that such systems will cost $40 per vehicle. Since EPA projects that 40 percent of chassis-based vehicles will use close-coupled catalysts, the cost per vehicle on average will be $16.

E. 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. Thus, EPA projects that ECM improvements due to the increased stringency of the proposed exhaust emission standards will result in a $10 per vehicle increase.

F. Onboard Refueling Vapor Recovery

EPA estimated the costs for onboard refueling vapor recovery (ORVR) equipment by updating the estimates of ORVR technology cost that were developed in support of the original ORVR regulations. EPA assumed that the technology required to meet that standards has not changed since the adoption of ORVR regulations for light-duty vehicles and light-duty trucks, 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. Thus, EPA simply took the cost estimates for light heavy-duty vehicles from that rule and adjusted them to account for inflation. 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 1997 dollars) to $7.25 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 original analysis this operating cost was estimated to be a $5.50 per-vehicle lifetime credit. 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 risen with inflation. Thus, a lifetime operating credit of $5.50 per vehicle is used in this analysis.

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 proposed 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 there are no R&D or tooling costs associated with the proposed vehicle-based requirements. However, in the case of the engine-based standards, EPA expects that some R&D and new tooling will be required. EPA believes 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, EPA estimates that the R&D and tooling costs will be $33 per engine for the first five years of the program.

B. Certification Costs

EPA relied on a previous analysis for estimating certification costs.[4] Updating those costs for inflation results in an estimated certification cost of $243,500 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 its CAP 2000 regulations, EPA projects that the in-use testing requirement will cost $1 per vehicle. This cost will be incurred indefinitely for each year of production, rather than being recovered over five years as with the other fixed costs.

V. Summary of Costs

Table 5-7 contains a summary of per-vehicle costs associated with the proposed 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 Proposed Otto-cycle Vehicle Emission Standards

	Chassis-based Standards	Engine-based Standards
Catalyst	$160	$150
On-board Diagnostics	$80	$45
ORVR	$7	--
Other Emissions Hardware	$50	$53
Total Hardware	**$297**	**$248**
Fixed Costs	$5	$39
Operating Costs (ORVR)	-$6	--
Total Incremental Cost	**$296**	**$287**

VI. Aggregate Cost to Society

In addition to the per vehicle costs just described, EPA also calculated the aggregate cost to society. This was done by combining the per vehicle costs with assumed future sales of HDVs. The results of this analysis are summarized in Table 5-8. The recovery of fixed costs results in slightly reduced costs beginning in 2009, 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 Proposed Heavy-duty Otto-cycle Requirements

Year	Cost ($million)
2004	$124
2005	$133
2006	$143
2007	$153
2008	$155
2009	$151
2010	$153
2011	$155
2012	$158
2013	$160
2014	$163
2015	$165
2016	$167
2017	$170
2018	$172
2019	$175
2020	$177

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 reaffirmed and proposed HD diesel engine NMHC plus NOx emissions standards described in the preamble for this proposal. Specifically, this chapter includes an estimated nationwide NOx, VOC, and inventory for 1999, heavy-duty diesel vehicle 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.[k]

While the proposed standards are combined NMHC plus NOx levels, it is necessary to consider the NMHC and NOx emissions impacts separately. Given the technologies that are expected to be used on heavy-duty diesel engines to comply with the proposed standards, it is reasonable to model the fleet-average impact of the proposed standards as being equivalent to a 2.0 g/bhp-hr NOx standard and a 0.4 g/bhp-hr NMHC standard. This is because the application of these technologies to heavy-duty engines would be expected to lead to very large reductions in NOx emissions for all engine families, and small NMHC emission reductions for some engine families. It should be emphasized , however, that this is only an analytical approach; manufacturers are actually expected to optimize each 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 used in this analysis.

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 vehicles (HDDV).[1] However, recent studies have been performed with the intent on improving EPA's understanding of the emissions impact of mobile sources. These studies and their effects on the calculated HDDV emissions inventories are discussed in this chapter.

II. Modifications to the 1997 Inventory Analysis

A. Conversion Factor

(k) 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.

Because these proposed standards are for engines and not for vehicles, the emissions limits are given on a brake-specific basis. However, to model engine emissions, emissions must be known for each mile traveled. To estimate emissions on a gram-per-mile basis, EPA multiplies the brake-specific emission (g/bhp-hr) by "conversion factors."

In the 1997 RIA, EPA used conversion factors for specific vehicle classes derived from the information contained in a 1988 EPA technical report.[2] In addition, EPA used the fraction of vehicle miles traveled (VMT) presented in this report for light-, medium-, and heavy-heavy duty diesel engines.

Recently, a new study was performed that included conversion factors for light, medium, and heavy HDDVs.[3] These conversion factors are used in this analysis and are similar to those from the 1988 technical report. In addition, this analysis used the newer VMT fractions of heavy-duty diesel vehicle classes used in EPA's PM emission factor model (PART5). These VMT fractions indicate that a larger fraction of heavy-duty diesel VMT is from HHDDVs than was shown in the 1988 technical report. Table 6-1 presents the 1997 RIA and current conversion factors by vehicle class, VMT fractions, and weighted total conversion factors.

Table 6-1
Conversion Factors (bhp-hr/mile)

Vehicle Category	1997 HDDV RIA		Current Estimates	
	VMT Fraction	Conversion Factor	VMT Fraction	Conversion Factor
LHDDV	41%	0.92	25%	1.13
MHDDV	20%	2.07	19%	2.09
HHDDV	39%	3.13	56%	2.92
All HDDV	--	2.03	--	2.32

B. Scrappage Rates

The mileage accumulation rates contained in Table 6-2 represent the number of miles a heavy-duty diesel vehicle would drive in a given year assuming the vehicle had not been scrapped (i.e. removed from the fleet) for some reason. The 1997 RIA used the mileage accumulation rates used in the EPA emission factor model for NMHC, CO, and NOx from on-highway vehicles (MOBILE5). In the development of the next stage of this model (MOBILE6), a study was performed by Acurex to update EPA's understanding of how on-highway vehicles are used.[4] Mileage accumulation rates from the Acurex study were used to characterize the HDDV fleet for this analysis.

Table 6-2
Mileage Accumulation Rates by Heavy-Duty Vehicle Category

Vehicle Age	LHDDV	MHDDV	HHDDV
1	28,446	38,962	113,227
2	25,800	35,471	102,229
3	23,404	32,297	92,305
4	21,236	29,410	83,348
5	19,272	26,785	75,264
6	17,494	24,398	67,967
7	15,883	22,226	61,381
8	14,423	20,251	55,436
9	13,100	18,454	50,070
10	11,900	16,818	45,224
11	10,813	15,331	40,850
12	9,826	13,976	36,901
13	8,931	12,744	33,335
14	8,119	11,622	30,115
15	7,383	10,601	27,207
16	6,714	9,671	24,581
17	6,107	8,824	22,210
18	5,555	8,052	20,068
19	5,054	7,350	18,134
20	4,600	6,710	16,387
21	4,186	6,126	14,808
22	3,811	5,595	13,383
23	3,469	5,111	12,095
24	3,159	4,669	10,931
25	2,877	4,267	9,880
26	2,620	3,899	8,930
27	2,386	3,565	8,072
28	2,174	3,259	7,297
29	1,981	2,981	6,596
30	1,805	2,727	5,963
Total	292,526	412,149	1,114,197

In order to estimate the per-vehicle average mileage accumulation rates for the average vehicle in the fleet it is necessary to factor in the effect of scrappage. In the 1997 RIA, EPA used the registration distribution contained in the EMFAC7F model developed by the California Air Resources Board. However, for this analysis, EPA turned to the same study that it is using for mileage accumulation rates. This study looked at the 1996 registration distribution of on-highway vehicles by vehicle class. By looking at the fraction of vehicles surviving by age, EPA was able to determine a rate of scrappage. Because the 1996 data was just a snapshot of the fleet, the data included the effects of year-to-year sales fluctuations. For this reason, EPA fit a curve through the data to smooth out the effects of the sales fluctuations. Table 6-3 contains the resulting survival rates for heavy-duty diesel vehicles used in this analysis. In other words, this presents the fraction of the original number of vehicles sold that are still in existence at that point in time.

Table 6-3
Registration Distribution by Heavy-Duty Vehicle Category

Vehicle Age	LHDDV	MHDDV & HHDDV
1	0.550	0.535
2	1.000	1.000
3	0.910	0.935
4	0.828	0.875
5	0.753	0.818
6	0.685	0.765
7	0.623	0.716
8	0.567	0.670
9	0.516	0.626
10	0.469	0.586
11	0.427	0.548
12	0.388	0.513
13	0.353	0.479
14	0.322	0.448
15	0.293	0.419
16	0.266	0.392
17	0.242	0.367
18	0.220	0.343
19	0.200	0.321
20	0.182	0.300
21	0.166	0.281
22	0.151	0.263
23	0.137	0.246
24	0.125	0.230
25	0.114	0.215
26	0.103	0.201
27	0.094	0.188
28	0.086	0.176
29	0.078	0.165
30	0.071	0.154

Table 6-4 shows the average annual mileage accumulation rates for heavy-duty diesel vehicles factoring in the effect of scrappage. The average life totals at the bottom of this table represent the number of miles that an average heavy-duty diesel vehicle accumulates over a 30-year life. These numbers represent changes in average mileage accumulation of 12 percent for LHDDVs, negative 8 percent for MHDDVs, and 28 percent for HHDDVs when compared to the analysis in the 1997 RIA.

Table 6-4
Average Mileage Accumulation Rates by Heavy-Duty Vehicle Category
Factoring in Scrappage

Vehicle Age	LHDDV	MHDDV	HHDDV
1	15,634	20,828	60,527
2	25,800	35,471	102,229
3	21,293	30,208	86,337
4	17,577	25,730	72,918
5	14,513	21,918	61,588
6	11,985	18,674	52,021
7	9,899	15,912	43,943
8	8,179	13,560	37,121
9	6,758	11,558	31,359
10	5,585	9,853	26,493
11	4,617	8,400	22,384
12	3,817	7,163	18,912
13	3,157	6,109	15,980
14	2,611	5,211	13,503
15	2,160	4,446	11,410
16	1,787	3,793	9,643
17	1,479	3,237	8,149
18	1,224	2,763	6,887
19	1,013	2,359	5,821
20	839	2,104	4,920
21	694	1,720	4,159
22	575	1,470	3,515
23	476	1,256	2,972
24	395	1,073	2,512
25	327	917	2,124
26	271	784	1,795
27	224	670	1,518
28	186	573	1,283
29	154	490	1,085
30	128	420	918
Avg. Lifetime Miles	163,000	259,000	714,000

To determine the average lifetime, in years, for each class of heavy-duty vehicles, the commutative sum for each year in service of the milage accumulation from Table 6-2 was compared to the average lifetime miles presented in Table 6-4 (ie, LHDDVs = 163,000, MHDDVs = 259,000, HHDDVs = 714,000), the year value where the commutative sum in Table 6-2 equaled the average lifetime miles in Table 6-4 is called the average lifetime. The average lifetimes of LHDDVs, MHDDVs, and HHDDVs were thereby estimated to be 8, 10, and 10 years, respectively.

C. Total Annual VMT

To calculate national emissions from HDDVs, the emission factor in grams per mile is multiplied by the total vehicle miles traveled by heavy-duty diesel vehicles. In the 1997 RIA, EPA used the national annual VMT used in the 1994 Trends Report.[5] For this analysis, EPA relies on the more recent 1997 Trends Report.[6] The 1997 report estimates about 5 percent higher HDDV VMT for 1996 and later calender years when compared the 1994 report. This 5 percent change is smaller than the change seen on a per-vehicle basis between this analysis and the 1997 RIA. This is not necessarily inconsistent since the annual VMT is developed by monitoring the use of the nation's roads rather than being built up from per-vehicle mileage.

Table 6-5
Annual VMT for Heavy-Duty Diesel Vehicles

Calendar Year	Million Miles
1999	154,067
2000	159,931
2002	171,272
2005	188,361
2007	199,580
2008	205,211
2010	216,487

III. Total Nationwide Inventories

A. Current Inventories

Total nationwide emissions of NOx, VOC, and PM are estimated in the 1997 Trends Report. 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 developed, adjustments are made to the HDDV NOx and VOC estimates to reflect the changes described above. In addition, the nonroad inventories are adjusted to be consistent with a recently finalized rule for land-based nonroad diesel engines[7] and a recently proposed rule for marine diesel engines.[8]

The national NOx, VOC, and PM_{10} inventories for HDDVs are summarized in Table 6-6. These data indicate that emissions from "current" heavy-duty diesel vehicles account for about 10 percent of total NOx emissions and only 1.2 percent of total VOC emissions. The PM numbers presented in this table represent total vehicle emissions which include brake wear, and exhaust. Excluding fugitive dust and wind erosion, HDDVs account for about 1.4 percent of total PM emissions.

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

Emission Source	NOx	VOC	PM_{10}
Light-Duty Vehicles	4,420	4,098	99
Heavy-Duty Diesel Vehicles	2,274	246	131
Heavy-Duty Gasoline Vehicles	318	198	8
Nonroad	5,343	2,485	642
Other	10,656	9,567	8,206
Total Nationwide Emissions	22,831	16,594	9,086

B. NOx Emission Projections and Impacts

NOx emissions are calculated 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. EPA is using the same corrected emission factors as were used in the 1997 RIA. These emission factors are consistent with recent certification data and are presented in Table 6-7.

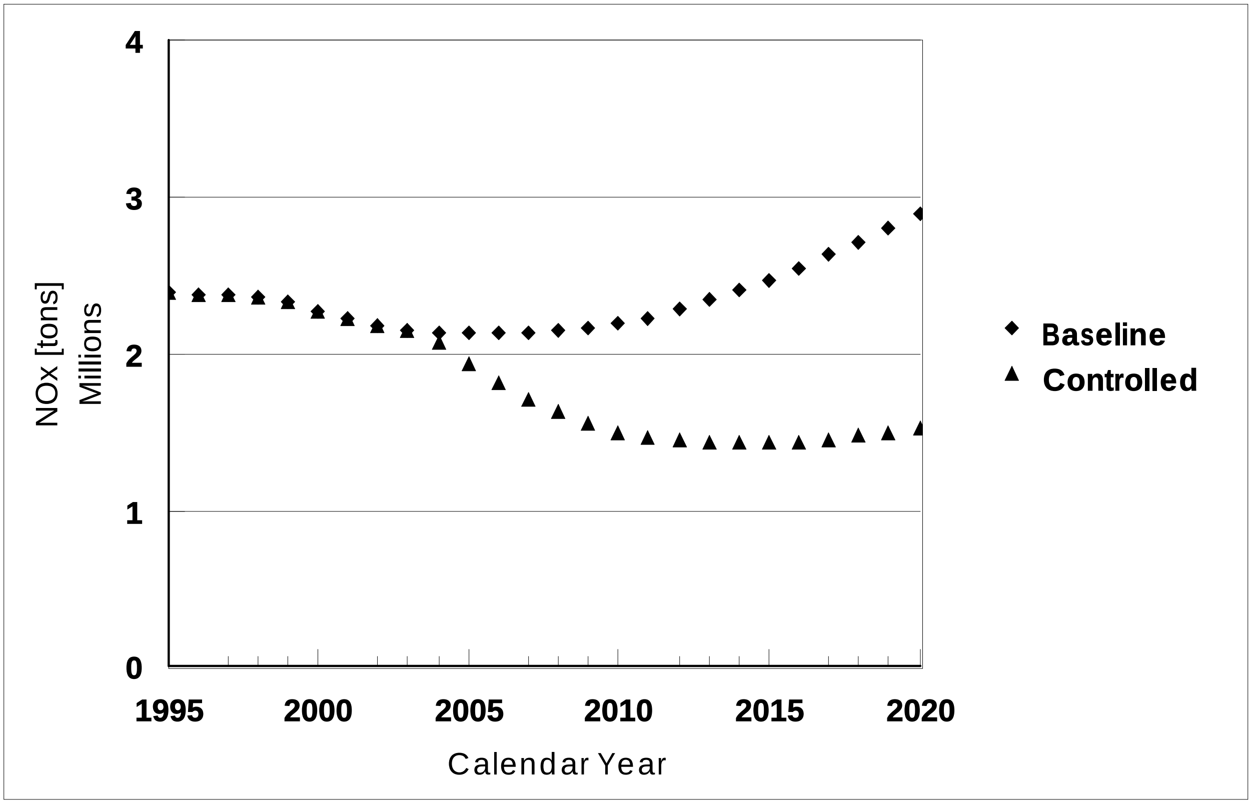
Table 6-7
NOx Emission Factors and Deterioration Rates for
2004 and Later Heavy-Duty Diesel Engines

	Zero-Mile Level g/bhp-hr	Deterioration Rate g/bhp-hr per 10,000 miles
Baseline	3.68	0.000
Controlled	1.84	0.000

It should be noted that each of these basic emission rate equations[l] predict that emissions at the end of the useful life would be below the applicable standard. This is because manufacturers include a compliance cushion in the design of their engines to account for production variability, which results in the average end-of-useful life emissions for an engine being below the level of the standard to which it was certified.

Figure 6-1 shows the national projections of total NOx emissions with and without the proposed engine controls. The emissions are projected to decline over the next several years, due to implementation of stricter controls, but then begin to increase due to growth in the number of vehicle miles traveled, unless there are additional controls. By the year 2015, without these additional controls, total national NOx emissions are projected to exceed current levels. Table 6-8 presents these projections with the estimated NOx benefits for selected years.

Figure 6-1: Projected National NOx Emissions from HDDVs



(l) Basic emission rate (BER) equations describe emissions as a function of vehicle mileage, for properly maintained non-tampered vehicles, at specific standard conditions. The equations are in the form of zero mile level (ZML) plus the product of a deterioration rate (DR) and mileage (M): BER = ZML + DR×M.

Table 6-8
Estimated National NOx Emissions and Proposed Benefits
from Heavy-Duty Diesel Vehicles (thousand short tons per year)

Year	Baseline	Controlled	Benefit
2005	2,136	1,933	203
2010	2,191	1,504	686
2015	2,479	1,433	1,046
2020	2,900	1,535	1,365

C. NMHC Emission Projections and Impacts

Estimates of the impact of the proposed standards on NMHC emissions are described below.[m] For this analysis, it is assumed that the effect of the combined standards is equivalent to 0.4 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.

This analysis uses the same emission factors that were developed and described in the 1997 RIA. These emission factors were based on certification data with the assumption that the zero-mile level was equal to the sales weighted average certification emission level. Table 6-9 presents the baseline and controlled emission factors and deterioration rates.

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

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

	Zero-Mile Level g/bhp-hr	Deterioration Rate g/bhp-hr per 10,000 miles
Baseline	0.283	0.000
Controlled	0.257	0.000

Figure 6-2 shows the national projections of total NMHC emissions with and without the proposed engine controls. The emissions are projected to decline over the next several years, due to implementation of stricter controls, but then begin to increase due to growth in the number of vehicle miles traveled. Table 6-10 presents these projections with the estimated NOx benefits for selected years.

Figure 6-2: Projected National NMHC Emissions from HDDVs

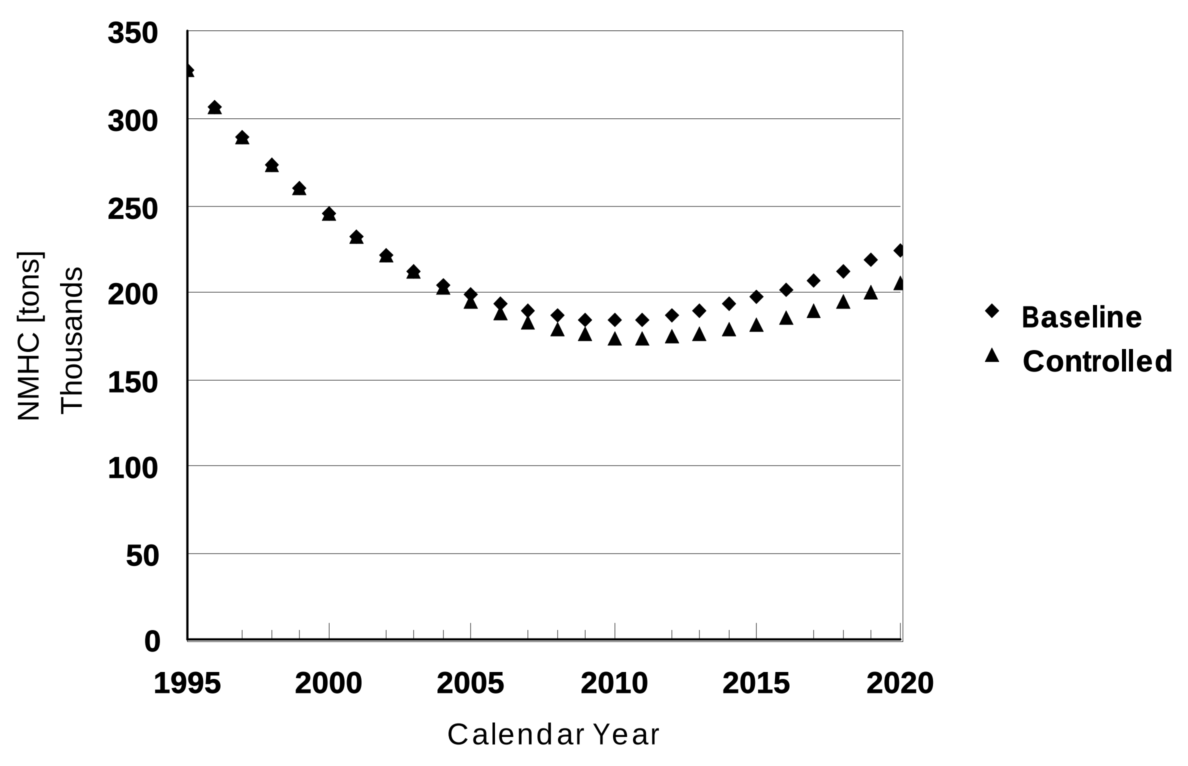


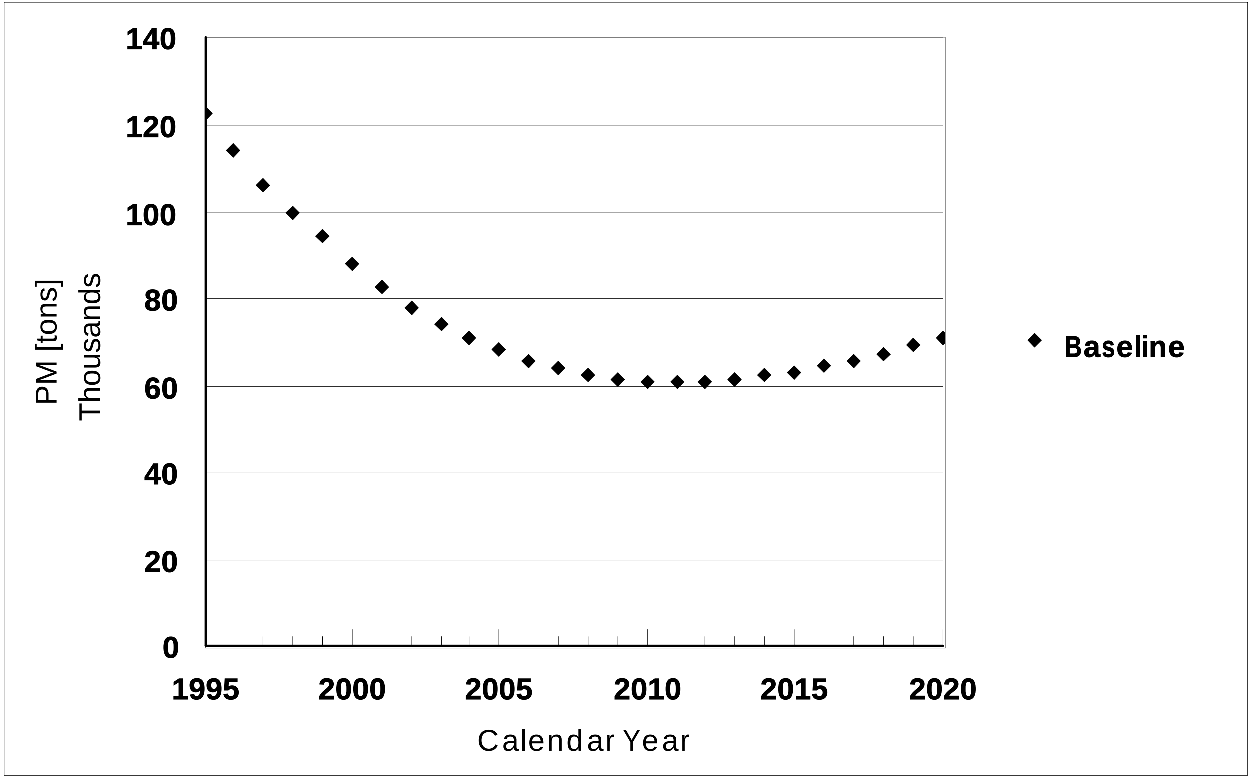
Table 6-10
Estimated National NMHC Emissions and Proposed Benefits
from Heavy-Duty Diesel Vehicles (thousand short tons per year)

Year	Baseline	Controlled	Benefit
2005	198	196	3
2010	184	174	10
2015	197	182	15
2020	225	205	20

D. PM Emission Projections

To show the contribution of particulate matter from heavy-duty diesel engines on national air quality, EPA used the PART5 emission factor model for PM. This model assumes that engines certifying to the current HDDV PM standard would have a zero-mile emissions level of 0.09 g/bhp-hr. No deterioration was included in this analysis. Figure 6-3 presents the HDDV national PM emissions inventory.

Figure 6-3: Projected National PM Emissions from HDDVs



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 proposed control program on a per-vehicle basis. Because emissions reductions are considered to be more valuable in the present than in the future, these benefits are presented 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 Proposed Standards for Heavy-Duty Diesel Engines

Vehicle Category	Undiscounted Reductions (lbs.)		Discounted Reductions (lbs.)	
	NOx	NMHC	NOx	NMHC
LHDDV	748	11	620	9
MHDDV	2,190	31	1,774	25
HHDDV	8,450	119	6,803	96

V. Environmental Impacts of Emission Reductions

A. Ozone Impacts

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

B. Particulate Impacts

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

EPA contracted with Systems Applications International (SAI) to investigate the formation of secondary nitrate particulates in the United States.[9] SAI used a combination of ambient concentration data and computer modeling that simulates atmospheric conditions to estimate the conversion of NOx to PM nitrate. For the purpose of modeling, the continental 48 states were divided into nine regions, and rural areas were distinguished from urban areas. The model was designed to perform the equilibrium calculations to estimate particulate nitrate formation for different regions, seasons, and times of day and then was calibrated using ambient data.

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

The results from the SAI report state that the fraction of NOx converted to nitrates (g/g) ranges from 0.01 in the northeast to 0.07 in southern California. Based on the vehicle miles traveled (VMT) in the various regions, the average fraction of NOx converted to nitrates is approximately 0.04. This value changes slightly from year-to-year due to the effects of ozone and SOx projections on the calculations for future years. The effects of the conversion fraction on future PM reductions is shown in Table 6-12. It should be noted that these estimates include VMT weighting of the southern California conversion rate of 0.07, but the Federal standards do not regulate new vehicles sold in California. Therefore, these nationwide estimates are over estimated.

Table 6-12
Estimated Equivalent National Particulate Emission Reductions
from 2004 Model Year Heavy-Duty Engines (thousand short tons per year)

Year	Total NOx Emission Reductions	Equivalent Particulate Emission Reductions
2005	203	9
2010	686	29
2020	1,365	56

C. 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.[10,11,12,13] 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 6-13 shows the estimated air toxics reductions associated with the hydrocarbon reductions in this proposed rule.

Table 6-13:
Estimated Annual Air Toxics Reductions [short tons]

Year	Benzene	Formaldehyde	Acetaldehyde	1,3-Butadiene
2005	30	225	83	18
2010	102	758	279	59
2015	155	1,155	425	90
2020	202	1,508	555	118

D. Other Impacts of Emission Reductions

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 proposed action on visibility should be small but potentially significant, given that it is expected to reduce overall NOx emissions by several percent. For example, the new engine controls are expected to result in about five percent less total NOx in the year 2020, and therefore would be expected to decrease haze by about one percent where NO_2 and nitrate particulates cause 20 percent of the haze.

The proposed standards are also expected to provide benefits with respect to acid deposition. The 1.4 million ton per year reduction expected in 2020 as a result of this proposed 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 proposed 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. Table 6-14 summarizes a 1994 Report to Congress that presented data from several studies regarding the contribution of air deposition to nitrogen loading relative to other sources in various water bodies. The report acknowledged that stationary fuel combustion (e.g., power plants) and motor vehicles are major sources of nitrogen emissions and that separate studies have concluded that the majority of nitrogen compounds in the air over Chesapeake Bay originate from these sources. Other sources of nitrogen include agricultural fertilizer application and animal waste. However, the report also highlights the many difficulties associated with linking air pollutants over these water bodies to specific sources, concluding that the specific sources and source categories contributing to atmospheric deposition to water bodies are not well known.[14]

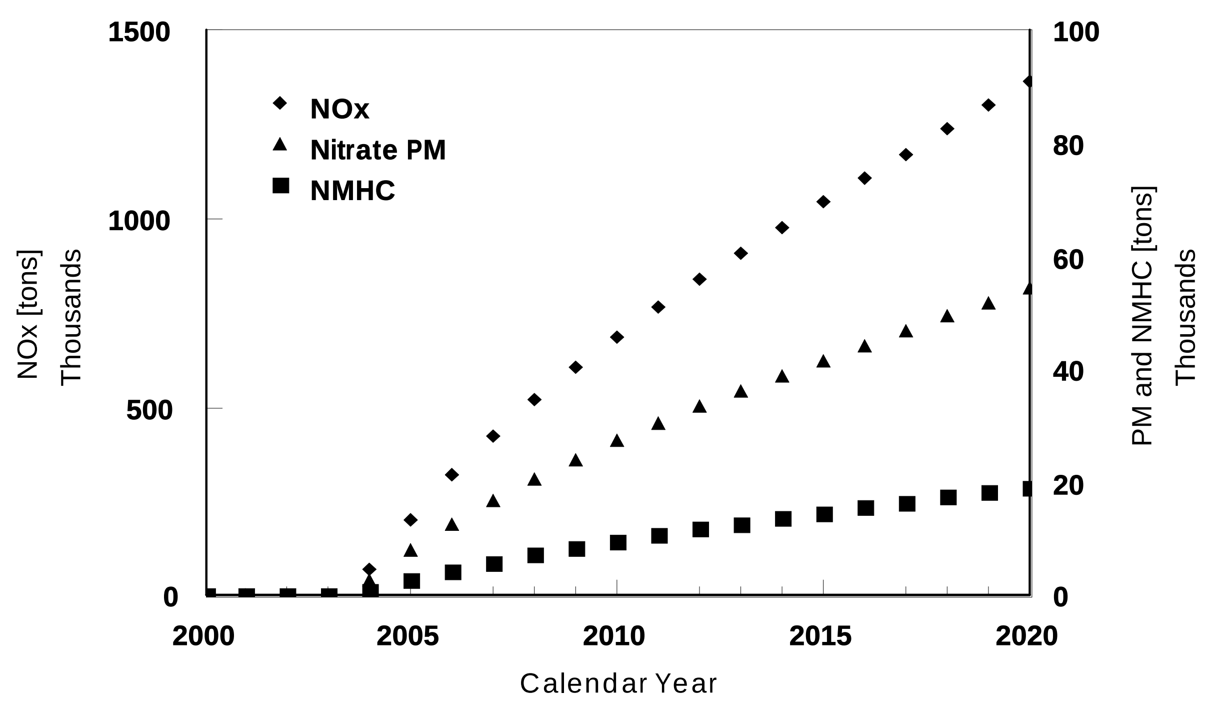
Table 6-14:
Contribution of Air Deposition to Total Loadings of Nitrogen for Selected North American Water Bodies

Water Body	**Nitrogen (%)**
Chesapeake Bay	25-40
Delaware Bay	14-25
Narragansett Bay	12
New York Bay	10
Ocholockonee Bay, FL	100
Potomac River	28
Rehoboth/Indian River Inland Bays, DE	8
Rhode River, MD	40

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 1.4 million tons per year in 2020. NMHC reductions are projected to be much smaller, about 20,000 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 nitrate particulates, visibility, acid deposition, and estuary eutrophication.

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



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

I. Introduction

The following chapter describes the expected environmental impacts of the proposed 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 proposed 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 proposed exhaust standards. Last of all, the chapter concludes with a description of the emission benefits from the proposed ORVR requirements for Class 2b heavy-duty gasoline vehicles.

II. Development of Exhaust NOx and NMHC Emission Factors

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

In order to determine the impact of the proposed standards, EPA first estimates the emission levels of vehicles currently in the fleet and then estimates the emission levels of vehicles that will meet the proposed standards. For the emission rates of engines currently in the fleet, EPA has used the recently updated zero-mile level and deterioration rates developed for EPA's MOBILE6 program for 1988 and later model years.[1] (For pre-1988 model year heavy-duty gasoline vehicles, EPA used the standard MOBILE5 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
1998-2003	2.59	0.33	0.038	0.021

Using the 120,000 mile useful life for heavy-duty gasoline engines, EPA estimates 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. Assuming manufacturers maintain the same amount of cushion below the standard, EPA estimated the end of useful life level emissions levels associated with the proposed standards. From these reduced levels, EPA determined 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 7-2 presents the resulting baseline zero-mile levels and deterioration rates for the three classes of heavy-duty gasoline engines and vehicles presented in this analysis (i.e., Class 2b complete vehicles, Class 3 complete vehicles, and incomplete HDGVs).

Table 7-2
Estimated Baseline Exhaust Emission Rates for 2004 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*	0.510	0.085	0.007	0.005

* - The units for Incomplete HDGVs are g/bhp-hr for zero mile levels and g/bhp-hr per 10,000 miles for deterioration rates.

B. Conversion Factors

Up until this proposed rulemaking, the emission standards for heavy-duty gasoline engines were expressed in units of g/bhp-hr. To convert the emissions of engines certified to g/bhp-hr standards to g/mi levels, EPA multiplies the g/bhp-hr levels by a conversion factor that are expressed in units of bhp-hr/mi. The conversion factor is determined as a function of fuel density, brake specific fuel consumption and fuel economy. EPA recently updated the conversion factors for heavy-duty engines.[2] Table 7-3 contains the conversion factors assumed in this analysis for heavy-duty gasoline engines.

Table 7-3
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. In-use Operation Adjustments

The emission factors described in section A. of this chapter represent the emission levels of an engine or vehicle tested and operated over EPA's federal test procedure for heavy-duty gasoline engines or vehicles. EPA believes that the current test procedures used to measure emissions from heavy-duty gasoline engines and vehicles do not fully reflect the wide range of in-use operating characteristics for such vehicles. Specific types of operation that EPA believes are not covered by the current heavy-duty gasoline engine and vehicle test procedures include high speed operation, heavy accelerations, and the use of air-conditioning. Because these types of operation affect emissions, EPA has developed "in-use" adjustments to the base emission rates to more accurately estimate the emissions from heavy-duty gasoline vehicles in use. Table 7-4 contains the "in-use" adjustments for heavy-duty gasoline vehicles used in this analysis. The "in-use" adjustments for model years 1988-2003 are additive factors that can be added to the zero-mile levels. The "in-use" adjustments for 2004 and later model years are multiplicative factors that are applied to both the zero-mile levels and deterioration rates. The determination of the "in-use" adjustment factors is detailed in a memo that has been placed in the docket for this rulemaking.[3]

Table 7-4
In-Use Operation Adjustments for Heavy-duty Gasoline Vehicles

Model Year	NOx Adjustment	NMHC Adjustment
1980-2003	1.03 g/mi	0.15 g/mi
2004+	1.51	1.17

D. Non-Sulfur Fuel Adjustments

When heavy-duty gasoline engines and vehicles are tested for certification purposes, the properties of the gasoline used in the vehicle must comply with regulations set forth by EPA. Once vehicles are sold and operated in use, the properties of the gasolines available in the market place will be different in some ways from the test fuel. For the MOBILE5 emissions model, EPA has developed adjustment factors to account for the impact that variations in in-use gasoline properties such as volatility and aromatic content will have on emission levels. Table 7-5 presents the fuel adjustments, excluding the effects of sulfur (which are described separately in the following section), on heavy-duty gasoline emissions based on the MOBILE5 fuel adjustments. The factors listed are multiplicative and are applied to both the zero-mile levels and deterioration rates. The determination of the non-sulfur fuel adjustments is detailed in a memo that has been placed in the docket for this rulemaking.[4]

Table 7-5
Non-sulfur Fuel Adjustments
for Heavy-duty Gasoline Vehicles

NOx	NMHC
1.032	1.075

E. Sulfur Adjustments

The amount of sulfur in gasoline has been shown to impact the emission levels of vehicles by affecting the efficiency of the catalytic converter.[5] The amount of impact is dependent on a number of factors including level of sulfur in the gasoline as well as catalyst design. The amount of sulfur in current in-use gasoline is higher than most fuels used for the purposes of certification testing, resulting in higher emissions in use compared to the certification levels. To account for this emissions increase, EPA estimated the impact of sulfur at current typical levels on the emissions from gasoline-fueled vehicles.[6] Table 7-6 presents the sulfur fuel adjustments for heavy-duty gasoline vehicles.. The factors listed are multiplicative and are applied to both the zero-mile levels and deterioration rates.

Table 7-6
Sulfur Fuel Adjustments for Heavy-duty Gasoline Vehicles

Model Year	NOx Adjustment	NMHC Adjustment
1980-2003	1.11	1.05
2004+	1.30	1.16

F. High-emitter Adjustments

As the emission standards of vehicles are tightened and more complicated emission control systems are adopted, the potential for “high-emitter” vehicles that have significantly higher emissions compared to the original certification levels because of emission control systems failures increases. Onboard diagnostic controls and inspection and maintenance programs can help to identify such high-emitting vehicles. Because the standards for heavy-duty gasoline engines and vehicles contained in this proposal represent significant reductions from current technology engines and will result in more complex emission control systems similar to those already used on light-duty vehicles, EPA believes that high-emitter heavy-duty gasoline vehicles will lead to increased fleet average emissions compared to the base emission levels presented in section A. of this chapter. Based on experience with light-duty gasoline vehicles and trucks, EPA estimated the impact of the proposed standards on heavy-duty gasoline vehicles.[7] Table 7-7 contains the high-emitter adjustments for heavy-duty gasoline vehicles used in this analysis.

Table 7-7
High-Emitter Adjustments for Heavy-duty Gasoline Vehicles

Model Year	NOx Adjustment	NMHC Adjustment
2004+	1.11	1.49

III. Per-Vehicle Exhaust NOx and NMHC Emission Reductions

In order to determine the cost-effectiveness of the proposed standards, EPA has estimated 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

In order to estimate the per-vehicle lifetime emission reduction from the proposed standards, EPA 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 7-8 presents the zero-mile levels and deterioration rates that result from combining the information on baseline emission rates and all of the adjustments presented in section II. of this chapter. (In order to convert the g/bhp-hr levels in Tables 7-1 and 7-2 to g/mi for incomplete HDGVs, EPA used a sales-weighted conversion factor of 1.19 based on the conversion factors for the different classes of incomplete HDGVs and confidential sales information provided by HDGV manufacturers.)

Table 7-8
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	1998-2003	4.45	0.58	0.048	0.023
	2004+	1.29	0.26	0.017	0.018
Class 3 Completes	1998-2003	4.61	0.60	0.051	0.027
	2004+	1.43	0.31	0.020	0.020
Incomplete HDGVs*	1998-2003	4.73	0.61	0.052	0.028
	2004+	1.36	0.22	0.019	0.013

B. Mileage Accumulation and Scrappage Rates

Table 7-9 presents the HDGV mileage accumulation rates and scrappage rates used in this analysis. The mileage accumulation rates come from EPA's recently updated rates for heavy-duty gasoline vehicles developed for the MOBILE6 emissions model.[8] The scrappage rates were taken from a National Highway Traffic Safety Administration (NHTSA) study and are based on light-duty truck (LDT) scrappage rates.[9] (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. EPA believes 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 7-9
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

Age	Class 2b/3 Annual Mileage	Class 4+ Annual Mileage	Scrappage Rate
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 7-10 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, EPA sales-weighted the mileage accumulation rates for Class 2b/3 and Class 4+ vehicles in Table 7-9 based on sales data on incomplete vehicles submitted by manufacturers to EPA.)

Table 7-10

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 7-11 presents the NOx and NMHC emissions from typical heavy-duty gasoline vehicles over the life of the vehicle. The levels were determined by combining the emission rate information contained in Table 7-8 with the mileage accumulation rate information contained in Table 7-10.

Table 7-11
Lifetime NOx and NMHC Emissions from Heavy-duty Gasoline Vehicles

Vehicle Category	Model Year Grouping	Undiscounted, Lifetime Emissions, tons	
		NOx	NMHC
Class 2b Completes	1998-2003	1.07	0.18
	2004+	0.32	0.09
Class 3 Completes	1998-2003	1.11	0.19
	2004+	0.36	0.11
Incomplete HDGVs*	1998-2003	1.11	0.19
	2004+	0.33	0.07

Table 7-12 contains the expected per vehicle NOx and NMHC emission benefits for heavy-duty gasoline vehicles from the proposed 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 7-12 contains the reductions for all HDGVs calculated on a sales-weighted basis from the three individual categories.

Table 7-12
Per Vehicle Exhaust Emission Reductions
from the Proposed 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	0.75	0.09	0.47	0.05
Class 3 Completes	0.75	0.08	0.47	0.05
Incomplete HDGVs	0.78	0.11	0.49	0.07
All HDGVs	0.76	0.09	0.48	0.06

IV. HDGV Exhaust Inventory and Reductions

In order to estimate the exhaust NOx and NMHC inventories from heavy-duty gasoline vehicles, EPA calculated the average emissions of all heavy-duty gasoline vehicles in the fleet for a variety of years. In order to estimate the fleet average emissions for heavy-duty gasoline vehicles, EPA ran the MOBILE5b emissions model with the updated information on emission levels, adjustments, and vehicle usage characteristics as described in sections II. and III. of this chapter. These resulting fleet average emission levels were multiplied by the estimated fleetwide vehicle miles traveled (VMT) for heavy-duty gasoline vehicles for the corresponding year to yield the exhaust emission inventories. Table 7-13 presents the exhaust NOx and NMHC fleet average emissions, VMT, and inventories from heavy-duty gasoline vehicles both without the proposed standards and with the proposed standards taking effect in the 2004 model year. The inventories presented in Table 7-13 represent nationwide inventories excluding California, Hawaii and Alaska. A more detailed description of the inventory development has been placed in the docket for this rulemaking.[10]

Table 7-13
Fleetwide Exhaust NOx and NMHC Emission Factors, Vehicle Miles Traveled, and Inventories from Heavy-duty Gasoline Vehicles (47-state analysis)

Pollutant	Calendar Year	47-State Vehicle Miles Traveled (10^{10} miles)	Heavy-duty Gasoline Vehicle Fleet Emission Levels			
			w/o the proposed standards		w/ the proposed standards	
			g/mi	tons	g/mi	tons
NOx	2000	5.18	5.34	304,641	5.34	304,641
	2005	5.93	5.03	328,786	4.44	290,394
	2010	6.79	4.88	365,090	2.98	223,473
	2015	7.52	4.76	394,417	2.21	182,669
	2020	8.29	4.73	432,405	1.84	168,320
	2030	9.84	4.71	511,124	1.54	166,904
NMHC	2000	5.18	4.76	271,831	4.76	271,831
	2005	5.93	3.61	236,109	3.54	231,792
	2010	6.79	3.00	224,671	2.77	207,596
	2015	7.52	2.85	235,772	2.53	209,262
	2020	8.29	2.79	254,764	2.42	221,045
	2030	9.84	2.76	299,647	2.35	254,749

Table 7-14 contains the estimated exhaust NOx and NMHC emission reductions due to the proposed standards for heavy-duty gasoline vehicles. As noted above, the reductions are for the entire United States excluding California, Hawaii, and Alaska. Figures 8-1 and 8-2 present also present the heavy-duty gasoline vehicle exhaust NOx and NMHC inventories, respectively.

Table 7-14
Exhaust Emission Reductions due to the Proposed Standards for Heavy-duty Gasoline Engines and Vehicles

Calendar Year	Emission Reductions due to the Proposed Standards, tons	
	NOx	NMHC
2000	0	0
2005	38,392	4,317
2010	141,618	17,075
2015	211,747	26,510

Calendar Year	Emission Reductions due to the Proposed Standards, tons	
	NOx	NMHC
2020	264,085	33,719
2030	344,220	44,898

Figure 7-1

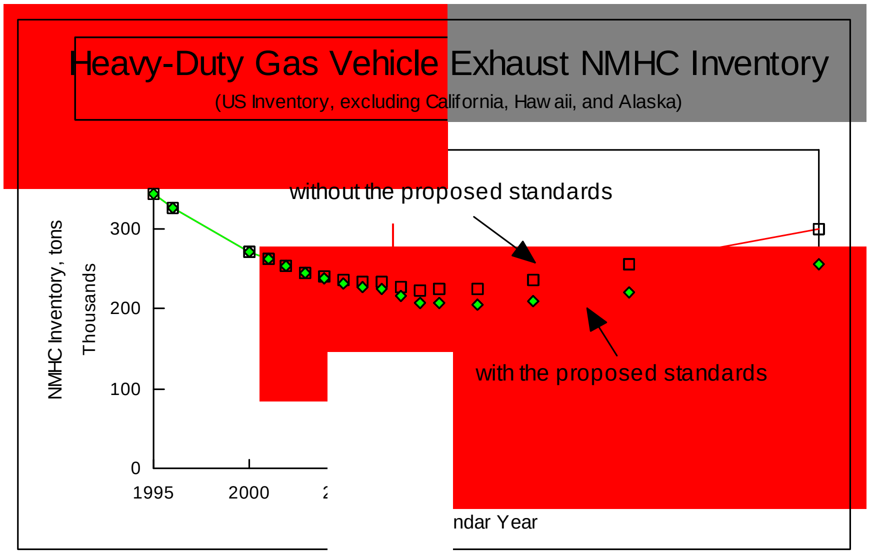
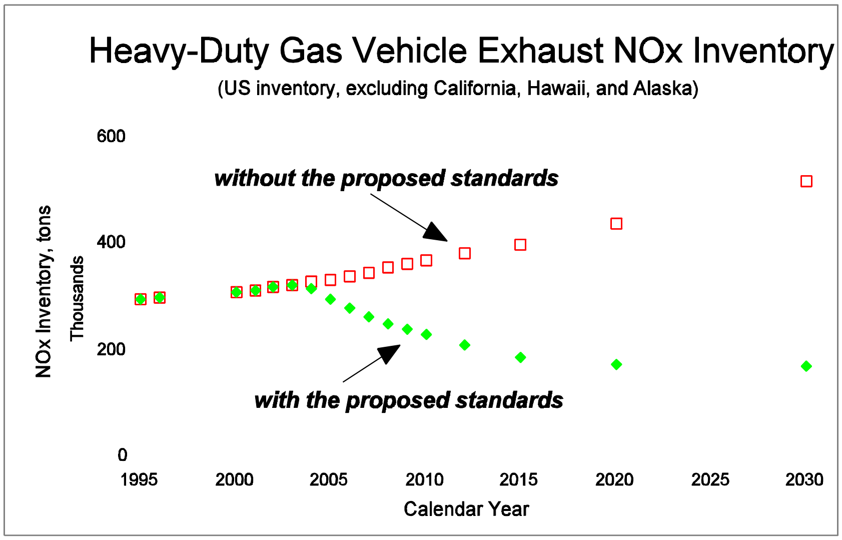


Figure 7-2



As described in Chapter 6, Section V(B), reducing NOx emissions will lead to a decrease in secondary particulate emissions. Table 7-15 presents the estimated secondary particulate emission reductions attributable to the proposed standards for heavy-duty gasoline engine and vehicle emission standards. Table 7-15 uses the same mass conversion estimates for calender years 2005, 2010, and 2020 used in Chapter 6. As discussed in Chapter 6, these estimates are overestimated do to the inclusion of VMT weighting of the secondary PM conversion factor for southern California, which has the highest estimated NOx conversion factor.

Table 7-15
Estimated Equivalent National Particulate Emissions Reductions
from the Proposed NOx Standards for Heavy-duty Gasoline Engines and Vehicles

Calendar Year	Total NOx Emissions Reductions (tons)	Equivalent Particulate Emissions Reductions (tons)
2005	38,392	1,693
2010	141,618	6,018
2020	264,085	10,853

V. ORVR Benefits

Along with the proposed exhaust standards, EPA is proposing ORVR regulations for Class 2b heavy-duty gasoline vehicles. Back in the early 1990s, EPA proposed, but never finalized, ORVR requirements for heavy-duty gasoline vehicles.[11] For this analysis, EPA has relied on the earlier analysis to estimate the HC benefits of ORVR requirements. Because many areas of the country have Stage II vapor recovery on fuel pumps at the gas station, EPA developed an estimate of the HC benefits that were attributable to the ORVR equipment. For this analysis, EPA has assumed 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 results in a conservative estimate of benefits and cost-effectiveness as well. Table 7-16 presents the assumptions used in estimating the per-vehicle HC emission benefits attributable to the proposed 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 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.) The benefits were determined over the lifetime mileage accumulation of a typical Class 2b heavy-duty gasoline vehicle as specified in Table 7-10 of this chapter on both an undiscounted basis and a discounted basis (at a rate of seven percent).

Table 7-16
Determination of Per-Vehicle Hydrocarbon Benefits from the Proposed 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. “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.

4. “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.

5. “EPA Staff Paper on Gasoline Sulfur Issues,” EPA Technical Report EPA420-R-98-005, May 1998.

6. “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.

7. “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.

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

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

10. “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.

11. “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 proposed 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).

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	$435	0.310	0.004	$1,383
2006-08	$366			$1,164
2009+	$228			$725
30 Year Fleet	—	—	—	$881

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	$638	0.872	0.012	$721
2006-08	$559			$632
2009+	$296			$335
30 Year Fleet	—	—	—	$433

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	$803	3.401	0.048	$233
2006-08	$701			$203
2009+	$420			$122
30 Year Fleet	—	—	—	$149

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

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	$606	1.496	0.021	$399
2006-08	$524			$345
2009+	$309			$204
30 Year Fleet	—	—	—	$252

II. Cost-Effectiveness of the Otto-cycle Requirements

A. Exhaust Emission Standards

The Agency analyzed the cost-effectiveness of the proposed 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 proposed standards take effect (i.e., model years 2004 through 2033). Table 8-8 contains the cost-effectiveness of the proposed 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 proposed 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

Model Year Grouping	Total NPV Cost per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton of NOx+NMHC)
		NOx	NMHC	
2004-08	$287	0.53	0.08	$475
2009+	$248			$410
30 Year Fleet	—	—	—	$429

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	
2004-08	$296	0.50	0.06	$529
2009+	$291			$520
30 Year Fleet	—	—	—	$523

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	
2004-08	$296	0.50	0.05	$531
2009+	$291			$522
30 Year Fleet	—	—	—	$525

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	
2004-08	$294	0.51	0.06	$515
2009+	$281			$492
30 Year Fleet	—	—	—	$500

B. Refueling Emission Standards

EPA has also analyzed the cost-effectiveness of the proposed onboard vapor recovery requirements for 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 proposed ORVR requirements for Class 2b heavy-duty otto-cycle vehicles.

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

Model Year Grouping	Discounted Lifetime Cost	Discounted Lifetime NMHC + NOx Emission Reductions	Discounted Lifetime Cost-effectiveness
2004-2008	$5	0.035 tons	$134/ton of NMHC
2009+	$2	0.035 tons	$50/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 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, the techniques for estimating these types of benefits have changed substantially since 1996, and the analysis has not been updated for this proposal.

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. Based on the substantial lead time available and the R&D expected, EPA is not projecting losses in fuel economy, engine durability, or increased maintenance. Even if such impacts were to occur for a few engines, they would be short-term in nature. 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 cost-effectiveness of the new standards with the fuel economy penalty, the fuel economy penalty costs in Table 8-11 were added to the per-vehicle costs (contained in Table 8-4) and then 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
Discounted Per-Vehicle Lifetime Operating Costs
Associated with a One Percent Fuel Economy Penalty

Light HD	Medium HD	Heavy HD
$100	$211	$985

Table 8-12
Cost-Effectiveness for All Heavy-Duty Diesel Vehicles
Assuming an Average One Percent Fuel Economy Penalty

Model Year Grouping	Total NPV Costs per Vehicle	Discounted Lifetime Reduction (tons)		Discounted Per-Vehicle Cost-Effectiveness ($/ton)
		NOx	NMHC	
2004-05	$1,034	1.496	0.021	$682
2006-08	$952			$627
2009+	$737			$486
30 Year Fleet	—	—	—	$534

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 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 ($/ton)
		NOx	NMHC	
2004-05	$795	1.496	0.021	$524
2006-08	$679			$448
2009+	$418			$276
30 Year Fleet	—	—	—	$336

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. 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.

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.