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Air

EPA Regulatory Impact Analysis and Regulatory Support Document

Control of Air Pollution; Determination of Significance for Nonroad Sources and Emission Standards for New Nonroad Compression-Ignition Engines at or Above 37 Kilowatts (50 Horsepower)

FINAL

REGULATORY IMPACT ANALYSIS

and

REGULATORY SUPPORT DOCUMENT

CONTROL OF AIR POLLUTION; DETERMINATION OF SIGNIFICANCE FOR NONROAD SOURCES AND EMISSION STANDARDS FOR NEW NONROAD COMPRESSION-IGNITION ENGINES AT OR ABOVE 37 KILOWATTS (50 HP)

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Introduction

This regulatory impact analysis and support document provides additional information in support of the Final Rulemaking (FRM) entitled, "Control of Air Pollution; Determination of Significance for Nonroad Sources and Emission Standards for New Nonroad Compression-Ignition Engines at or Above 37 Kilowatts (50 hp)". This FRM will regulate all new nonroad compression-ignition engines greater than or equal to 37 kilowatts (50 hp), except engines which propel or are used on marine vessels, aircraft engines, engines which propel locomotives, and engines regulated by the Mining, Safety, and Health Administration. The regulated engines are hereafter referred to as "nonroad large CI engines." The goal of this regulation is to substantially reduce NO_x emission and smoke from nonroad large CI engines beginning in the 1996 model year. EPA has determined that this regulation for HC, CO, NO_x, PM and smoke emission standards is

- environmentally beneficial,
- technically feasible, and
- cost-effective.

EPA's rationale for these determinations will be addressed in the following three chapters of this support document.

Chapter 1: Environmental Benefit

This chapter presents the methodology used by EPA to quantify the benefits that would be realized through the NO_x emission standard for large nonroad CI engines. Benefits, in terms of oxides of nitrogen (NO_x) emission reductions, are presented in two forms: per-engine benefits and aggregate source benefits. "Per-engine" benefits are the emission reductions expected to occur during the life of an engine whose emissions are controlled in response to the standard. "Aggregate source" benefits are the estimated, future nationwide NO_x emission reductions from affected engines. Estimated "aggregate source" benefits illustrate the potential future effect of the standard on the emission inventory of this source. Air quality benefits are discussed qualitatively for both the NO_x and smoke emission standards. Due to emission measurement procedures uncertainty, no air quality benefit is assumed due to HC, CO or PM standards.

Chapter 1 is the only chapter that will be reported in English units. EPA is promulgating this regulation using all metric units. However, the data presented in Chapter 1 are, in large part, taken from the *Nonroad Engine and Vehicle Emission Study*(1) (i.e., the nonroad study) which was compiled and reported in English units. Therefore, to ensure accuracy and allow comparison back to the study, EPA will report only Chapter 1 in English units.

Many of the detailed results discussed below are presented in separate tables included in Appendix A - Supplementary Tables. Tables which are included in Appendix A are notated in the format A-## (e.g., A-01, A-02, A-03). Document cites denoted in parentheses (e.g., (#)) are located at the end of Chapter 1.

1.1. Estimated NO_x Emissions Reduction

To estimate the average annual NO_x emissions per current nonroad large CI engine, EPA used results from the nonroad study to represent the baseline emissions (i.e., emissions without controls). In that study, total emissions were calculated for each type of equipment using

$$MASS_{i,NOx} = N_i \times HP_{i,avg} \times LOAD_{i,avg} \times HOURS_{i,avg} \times EF_{i,NOx}$$

In this equation,

N_i - nationwide population of ith equipment type
$HP_{i,avg}$ - average rated horsepower of ith equipment type
$LOAD_{i,avg}$ - ratio (%) between average operational power output and rated power
$HOURS_{i,avg}$ - average annual hours of engine operation
$EF_{i,NOx}$ - brake specific emission rate (grams/bhp-hr)
$MASS_{i,NOx}$ - annual nationwide NO_x emissions (grams)

For the benefits analysis described here, EPA performed separate calculations for the following horsepower ranges because the applicable standards have separate implementation dates: (i) 50-100 hp, (ii) 100-175 hp, and (iii) over 175 hp.[1] Tables A-01 and A-02 show nonroad study data used to construct Inventories A and B. As discussed in the nonroad study, population and activity information used to construct Inventory A relied predominately on data available in a commercially available data base, while that used to construct much of Inventory B relied on data provided by manufacturers and manufacturer associations.(2)

1.1.1. Per-Engine NO_x Emissions Reduction

This section describes the calculation of the per-engine emission reductions which are expected to occur during the life of an engine whose emissions are controlled in response to the adopted standard. The annual per-engine NO_x emission reduction and the lifetime per-engine NO_x reduction calculations are described and summarized in this section.

1.1.1.1. Annual Reduction--For the baseline scenario, EPA calculated average annual per-source emissions using

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[1] The data supporting the nonroad study groups engines over 750 hp with smaller engines, such that they cannot be considered separately.

$$MASS_{avg,NOx} = \frac{\sum_i MASS_{i,NOx}}{\sum_i N_i}$$

Here, the summations are taken over those types of equipment with engines that, on average, fall in the applicable rated horsepower ranges. The average annual per-source NO_x emissions in that range is then given by $MASS_{avg,NOx}$.

EPA calculated baseline per-source emissions using NO_x emission factors given in the nonroad study. To obtain average annual per-source emissions for engines controlled to the levels required to comply with EPA's NO_x emission standard, EPA recalculated the results using 6.9 g/bhp-hr in place of the nonroad study emission factors.

The results of this calculation using data from both Inventory A and Inventory B are presented in Tables A-03 (50-100 hp), A-04 (100-175 hp), A-05 (over 175 hp), and A-06 (all engines over 50 hp). Due to the fact that the overall results for all of the horsepower ranges are similar for Inventories A and B, EPA used the average results calculated above in the remainder of the analysis rather than carrying separate figures. The averaged results are summarized below in Table 1-01, which shows that, for the less powerful engines, 39% reductions would be realized, while for the midrange and more powerful engines, reductions of 35% and 33%, respectively, would be attained. Table 1-01 also indicates that the NO_x standard represents, on average, a 37% reduction in annual NO_x emissions from engines to which the standard would apply.

Table 1-01
Nationwide Large Nonroad CI Engine Population,
Baseline and Controlled Annual Per-Engine Emissions

	Nationwide Population	Annual Per-Source NO_x (tons)	
		Baseline	Controlled
50-100 hp	3,264,500	0.38	0.23
100-175 hp	791,000	0.60	0.39
over 175 hp	303,500	1.42	0.96
total over 50 hp	4,359,000	0.49	0.31

1.1.1.2. Lifetime NO$_x$ Reduction--Because the average annual emissions calculated above would occur over the lifetime of a given engine, EPA has also estimated the lifetime per-source reduction in NO$_x$ emissions from the baseline that would be obtained if engines were to meet the adopted standard. In doing so, some estimate of the engine survival rate was needed. For all of the engines included in this FRM, EPA relied on the estimate of engine survival probability that was presented by Energy and Environmental Analysis (EEA) in a 1988 report to the California Air Resources Board (CARB).(3) Table A-07 presents the likelihood, given an engine's age, that it remains in service.

EPA also relied on the estimates contained in the EEA report to CARB of the change in annual usage over the useful life of an engine. For each year in an engine's useful life, the annual usage (hours) is expressed in Table A-07 as a percentage of the annual usage averaged over the entire useful life of the engine. As annual emissions are directly related to annual usage, EPA calculated lifetime per-engine NO$_x$ reductions using the following formula:

$$LIFERED_{NOx} = ANRED_{NOx,avg} \times \sum_{j=1}^{j=30} (S_j \times AU_{rel,j})$$

j	-	the age of the engine
S_j	-	the likelihood that an engine of age j remains in service,
$ANRED_{NOx},avg$	-	the average annual reduction in per-engine NO$_x$ emissions (grams),
$AU_{rel,j}$	-	the relative annual usage of an engine of age j (i.e., the ratio of $HOURS_j$ to annual hours of use averaged over the life of the engine),
$LIFERED_{NOx}$	-	the lifetime per-source reduction in NO$_x$ emissions (grams).

Because the reductions calculated above occur as a stream of annual reductions occurring over the lifetime of the engine, EPA also calculated the discounted "present value" of the reductions - the equivalent year-of-sale reductions ($LIFERED_{NOx}$,disc) of the entire stream. This was accomplished using

$$LIFERED_{NOx,disc} = ANRED_{NOx,avg} \times \sum_{j=1}^{j=30} \frac{S_j \times AU_{rel,j}}{(1+r)^{j-0.5}}$$

Here, the interest rate used for discounting is indicated by *r*. EPA guidance(4) on discounting provides a resolution to the dilemma of how to account for both displaced private investment and foregone consumption in evaluating environmental regulations. A brief summary of the approach is provided in Section 3.7.3. of this document. The relevance to the present section is, however, that benefits are discounted at the social rate of time preference, which is presumed in the economic literature to be substantially less than the opportunity cost of capital (and thus can be approximated by the consumption rate of interest). This after-tax rate is estimated in the *Supplemental Guidelines on Discounting* to be at most three percent. This analysis proceeds on the basis that a three percent rate is appropriate for discounting future emission benefits for these engines. Table 1-02 shows the average lifetime per-engine NO_x emission reductions without discounting and with three percent discount rates.

Table 1-02

Average Lifetime Per-Engine NO_x Reductions

Discount Rate	Lifetime NO_x Reduction (tons)
none	2.94
3%	2.33

1.1.2. Aggregate Source NO_x Reduction

The calculation of aggregate source NO_x reductions is described in this section. The calculation takes into account U.S. consumption of these engines, the U.S. population of these engines, usage, and related survival rates of these engines as described below. Together with estimates of the emissions from these engines, EPA has derived projected nationwide annual NO_x emissions from these engines through 2026.

1.1.2.1. Sales--To estimate future emission levels, some projection of the future population of uncontrolled and controlled engines is needed. Because engines are introduced into the field through sales, estimates are needed not only of sales prior to the standard, but also of sales after the standard goes into effect. For years between 1965 and 1990, sales of nonautomotive diesel engines are reported by the U.S. Department of Commerce (DOC). For this analysis, EPA has assumed that 70% of these are sold into applications covered by this FRM. This estimate is based on the portion of sales that, coupled with the estimated survival rates described above, lead to the average population estimate made in the nonroad study.

Although figures for total U.S. engine production are given for each year during this period, data for apparent U.S. consumption and for engines produced and incorporated into products used at the same establishment ("internal consumption") are only given for 1978 and 1980-1990. For other years from 1965-1990, EPA estimated U.S consumption and "internal consumption" by regressing data for 1978 and 1980-1990 against total U.S. engine production, and applying the regression results to U.S. engine production for 1965-1977 and 1979.

For 1960-1965 and 1990 to 2026, EPA estimated sales assuming a 2% rate of annual growth in total U.S. consumption. This is based on estimates of long-term growth of the economy, the internal combustion engine industry, the farm machinery and equipment industry, and the construction machinery industry.[2] EPA expects that this approach will better represent long-term trends than an approach that relies solely on DOC(5) diesel engine apparent consumption data, which only is available for the 1980s.

The results of this analysis are summarized in Table A-08 in Appendix A, which presents figures reported by DOC and estimates made by EPA. Figure 1-01 shows the estimated sales of engines affected by this FRM that was used in the remainder of the analysis. These sales estimates and projections are for all nonroad compression ignition engines included in the FRM. For the remaining analysis, EPA assumed the following distribution of sales to the different horsepower ranges included in the FRM.

Horsepower Range	Portion of Sales
50-100	75%
100-175	18%
175+	7%

This distribution is based on the population distribution observed in the nonroad study average results given in Table 1-01.

It should be recognized that, while national growth is measured at the level of the economy as a whole, growth in specific areas of the country is likely to vary from area to area in response to the specific demographic and commercial trends in those areas. These effects should be considered in estimating growth at the local level.

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[2] The rational for growth in sales is further explained in Section "3.1.2. United States Consumption."

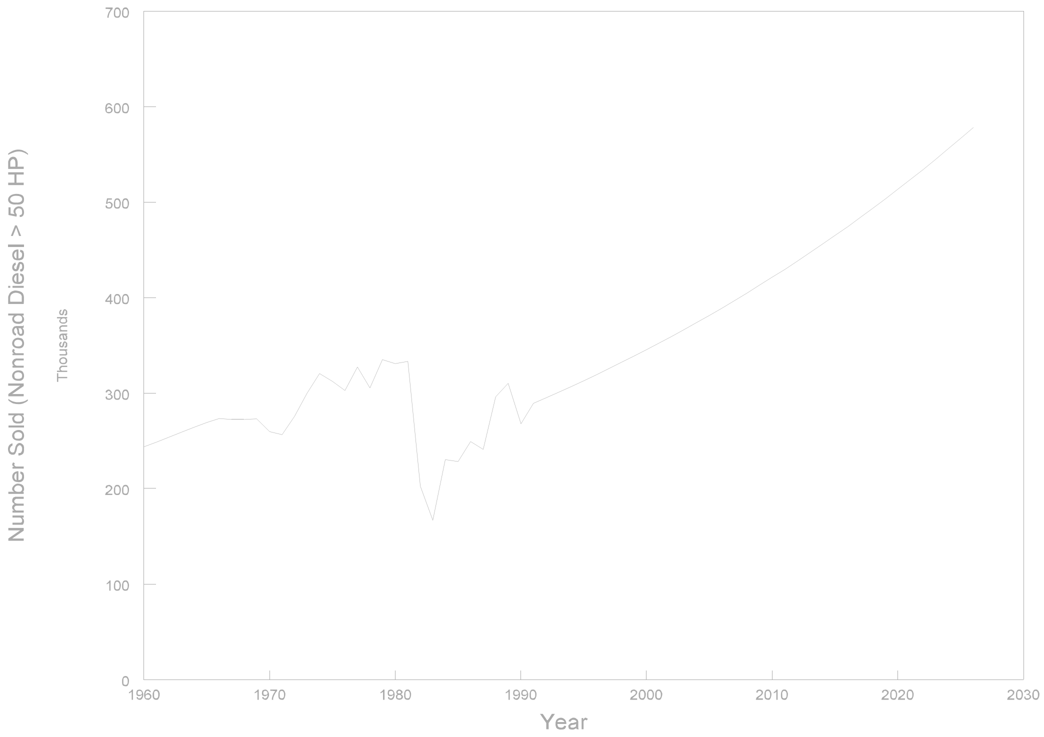

Figure 1-01
Estimated U.S. Sales - 1960-2026
Nonroad CI Engines Over 50 HP

Because the adopted standard would begin to take effect in 1996, EPA distinguished between sales of controlled and uncontrolled engines from 1990-2026. Beginning in 1998, all engines sold are assumed to comply with the standards. Although the averaging, banking and trading (ABT) provisions allow for engines to emit at rates above the standard, they must be balanced by cleaner (i.e., below the standard) engines. Consequently, the fleet as a whole should emit at or below the emission standards. Table 1-03 presents estimated sales of complying engines by horsepower range for 1995-1999, as these years bracket the phase-in period.

Table 1-03
Projected Consumption of Complying Engines
1995-1999

	-----------Complying Sales---------			
Year	All	<100hp	100-175hp	>175hp

1999	338,697	253,645	61,467	23,585
1998	332,056	248,672	60,262	23,123
1997	81,749	0	59,080	22,669
1996	22,225	0	0	22,225
1995	0	0	0	0

1.1.2.2. In-Use Population--By coupling the sales estimates and projections given in Table A-08 with the engine survival rate function described in Table A-07, EPA calculated the estimated population from 1990-2026 of engines addressed in the FRM. In doing so, EPA distinguished between controlled and uncontrolled engines, so that the effect of the standard could be ascertained. Tables A-09 and A-10 show the resulting projections for 1990-2026 for all engines and for controlled engines, respectively. These projections are summarized in Figure 1-02, which presents the projected total engine population and the portion that would be controlled in response to this regulation.

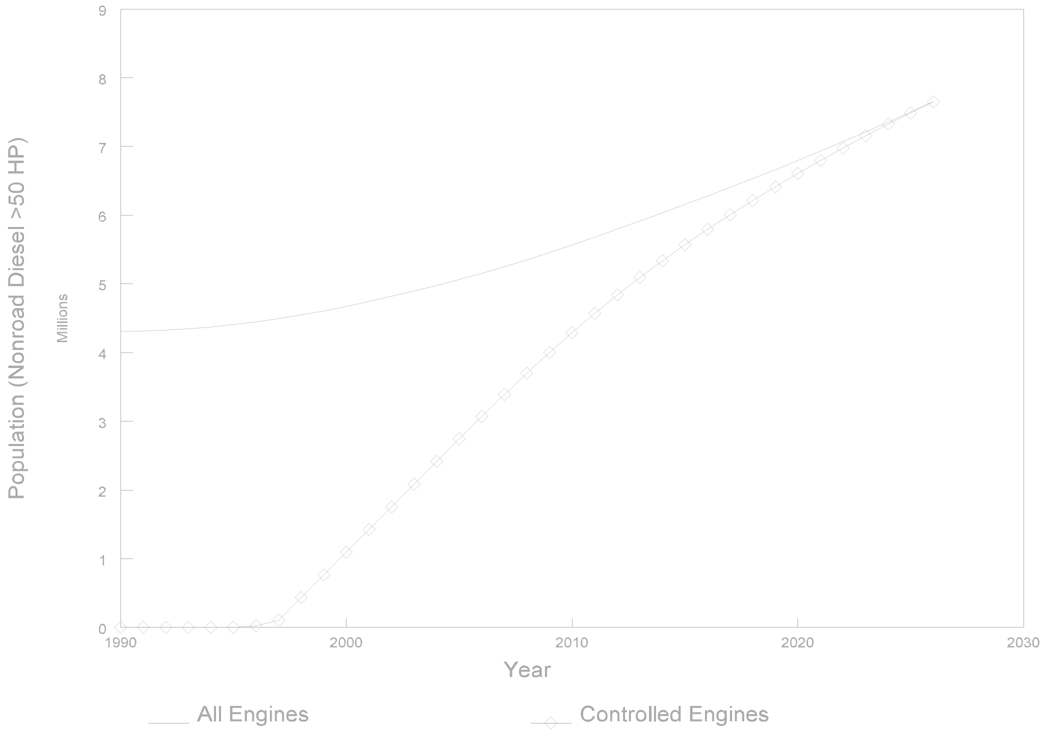

Figure 1-02
Estimated U.S. Population - 1960-2026
Large Nonroad CI Engines

1.1.2.3. Aggregate Source NO$_x$ Emission Inventory--EPA projected future annual nationwide NO$_x$ emissions from engines addressed in this FRM under the baseline (no controls applied) and controlled scenarios. This was accomplished using:

$$MASS_{NOx,y} = \sum_{j=y-31}^{y-1} (SALES_j \times s_{y-j} \times AU_{rel,y-j} \times MASS_{avg,NOx,j})$$

In this equation,

y - inventory year

j - year of sale

$SALES_j$ - engine sales in year j

S_{y-j} - fraction of engines sold in year j that survive in year y (from Table A-3)

$AU_{rel,y-j}$ - relative annual usage in year y of engine sold in year j, as percent of average annual usage over engine life (from Table A-3)

$MASS_{avg,NOx,j}$ - average annual per-engine NO_x emissions of engines sold in year j (from Tables 1-01, 1-02, 1-03)

For each year, this calculation is carried out for each of the three applicable rated power ranges (50-100 hp, 100-175 hp, and 175^+ hp). The sum of these three results yielded the total inventory of emissions from sources addressed by this FRM. The controlled and uncontrolled scenarios were accounted for through $MASS_{avg,NOx,j}$. All other parameters were the same in both scenarios.

Table A-11 presents total annual nationwide emissions from engines addressed in this FRM under the baseline scenario, and Table A-12 presents results for the controlled scenario. These are shown graphically in Figure 1-03.

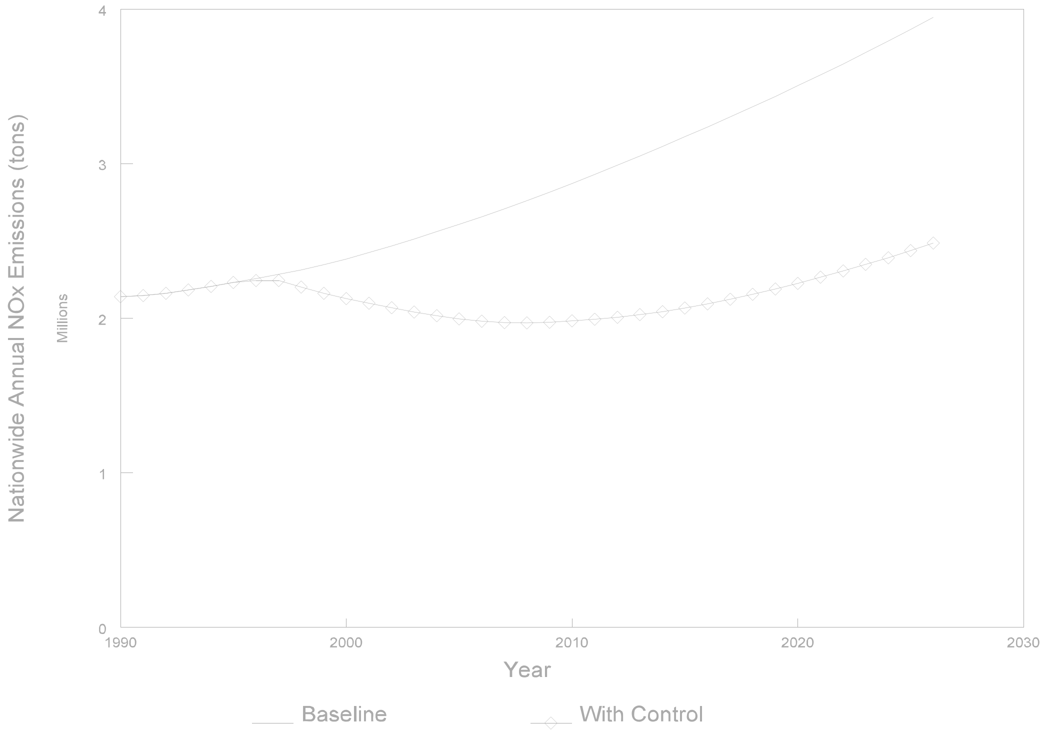

Figure 1-03
Projected Nationwide Annual NOx Emissions - 1960-2026
Nonroad CI Engines Over 50 HP

In Figure 1-03, the annual benefit of the regulation is indicated by the difference between the upper and lower curves. The area between the curves represents the net benefit of the regulation during the time required for the nonroad large CI engine fleet to completely turn over. Discounted at 3%, the net present value of the stream of benefits projected to occur between 1996 and 2025 is 13.1 million tons of NO_x.

1.2. Air Quality Benefits

Air quality benefits associated with reduction in NOx and smoke are discussed in this section. Health and welfare effects of the pollutants are discussed. Further, the role of these pollutants in ambient air quality problems are discussed.

1.2.1. NO_x

EPA expects that reducing NO_x emission from large nonroad compression ignition engines will help to mitigate the health and welfare impacts of ambient NO_x, ambient particulate matter, acidic deposition, as well as urban and regional tropospheric ozone formation and transport.

1.2.1.1. Health and Welfare Effects of NO_x Emissions--NO_x is the general term used to denote oxides of nitrogen, primarily nitrogen oxide (NO) and nitrogen dioxide (NO_2). As stated previously, NO_2 is a criteria pollutant for which the EPA has established a NAAQS.

At elevated concentrations, NO_2 can adversely affect human health, vegetation, materials, and visibility. Although the NAAQS for NO_2 is currently violated only in Southern California, EPA is concerned with maintaining the standard in the rest of the nation and meeting Prevention of Significant Deterioration (PSD) requirements for NO_2 in areas that are currently in attainment.

NO_x emissions also react in the atmosphere to form particulate nitrates, some of which may be toxic, mutagenic or carcinogenic.(6) These secondary PM_{10} particles contribute greatly in some areas, especially parts of California, to nonattainment of the NAAQS for PM_{10}, which applies to particles under 10 microns in diameter.(7) Because these small particles are carried deep into the lung, they are known to cause potentially serious respiratory effects. Particulate nitrates also contribute to impaired visibility, which, although not a direct health problem, is perceived by the public as evidence of serious air pollution.

Recent findings from a report by the National Academy of Sciences (NAS)(8) on ozone provide support for electric utility NO_x emission controls within the acid rain program. NAS indicates that these controls would benefit many areas, particularly in the northeastern United States by reducing not only ozone levels but also acidic deposition.

Acidic deposition is composed of acidic aerosols--liquid droplets and solid particles suspended in the atmosphere. Acidic aerosols are generated when NO_x either reacts to form nitrates or contributes to the formation of sulfates from sulfur dioxide gas. Acidic aerosols can irritate the respiratory system and increase the incidence and severity of respiratory diseases. Acidic aerosols can also accumulate airborne heavy metals and toxic chemicals and thereby deposit them in the most vulnerable areas of the lung. Interactions of ozone with NO_x and sulfur oxides may also contribute to the formation of acidic vapors which might have a direct effect on health and welfare, as well as other indirect effects following their deposition on surfaces.

1.2.1.2. Health and Welfare Effects of Tropospheric Ozone--EPA's primary reason for controlling NO_x emissions from large nonroad CI engines is the role of NO_x in forming ozone (O_3). Of the major air pollutants for which NAAQS have been designated under the CAA, the most widespread problem continues to be ozone, which is the most prevalent photochemical oxidant and an important component of smog. Ozone is a product of the atmospheric chemical reactions involving nitrogen oxides and other compounds. These reactions occur as atmospheric oxygen and sunlight interact with hydrocarbons and nitrogen oxides from both mobile and stationary sources.

A critical part of this problem is the formation of ozone both in and downwind of large urban areas. Under certain weather conditions, the combination of NO_x and VOC can result in urban and rural areas exceeding the national ambient ozone standard by a factor of three. The ozone NAAQS represents the maximum level considered protective of public health by the EPA.

Ozone is a powerful oxidant causing lung damage and reduced respiratory function after relatively short periods of exposure (approximately one hour). The oxidizing effect of ozone can irritate the nose, mouth, and throat causing coughing, choking, and eye irritation. In addition, ozone can also impair lung function and subsequently reduce the respiratory system's resistance to disease, including bronchial infections such as pneumonia.

Elevated ozone levels can also cause aggravation of pre-existing respiratory conditions such as asthma. Ozone can cause a reduction in performance during exercise even in healthy persons. In addition, ozone can also cause alterations in pulmonary and extrapulmonary (nervous system, blood, liver, endocrine) function.

The current NAAQS for ozone of 0.12 ppm is based primarily on the level at which human health effects begin to occur. However, ozone has also been shown to damage forests and crops, watershed areas, and marine life.(10) The NAAQS for ozone is frequently violated across large areas in the U.S., and even after 20 years of efforts aimed at reducing ozone-forming pollutants, the ozone standard has proven to be exceptionally difficult to achieve. High levels of ozone have been recorded even in relatively remote areas, since ozone and its precursors can travel hundreds of miles and persist for several days in the lower atmosphere.

Ozone damage to plants, including both natural forest ecosystems and crops, occurs at ozone levels between 0.06 and 0.12 ppm.(11) Repeated exposure to ozone levels as low as 0.04 ppm can cause reductions in the yields of some crops above 10%.(12) While some strains of corn and wheat are relatively resistant to ozone, many crops experience a loss in yield of 30% at ozone concentrations below the NAAQS.(13) The value of crops lost to ozone damage, while difficult to estimate precisely, is on the order of $2 billion per year in the U.S.(14) The effect of ozone on complex ecosystems such as forests is even more difficult to quantify. However, growth in many species of pine appears to be particularly sensitive to ozone. Specifically, in the San Bernardino Mountains of Southern California, the high ozone concentrations are believed to be the predominant cause of the decline of the endangered ponderosa pine.(15)

Finally, by trapping energy radiated from the earth, tropospheric ozone may contribute to heating of the earth's surface, thereby contributing to global warming (i.e., the greenhouse effect).(16)

1.2.1.3. Roles of VOC and NO_x in Ozone Formation--Both volatile organic compounds (VOC) and NO_x contribute to the formation of tropospheric ozone through a complex series of reactions. EPA's understanding of the importance of NO_x in this process has been evolving along with improved emission inventories and modeling techniques. The role of NO_x has been controversial because, depending on local conditions, NO_x reductions can either promote or retard ozone formation near the emission source(s), while downwind ozone concentrations will eventually decline in response to NO_x reductions.

In general, the ratio between the ambient concentrations of VOC and NO_x in a localized area is an indicator of the likely effectiveness of VOC and/or NO_x reductions as ozone control measures. If the level of VOC is high relative to the level of NO_x (that is, in a ratio of 20 to 1), ozone formation is limited by the amount of NO_x present, making reduction of NO_x emission an effective strategy for reducing ozone levels. Alternatively, if the level of VOC is low relative to the level of NO_x (that is, in a ratio of 8 to 1), efforts to control VOC would be expected to be a more effective means of reducing ozone concentration.

For many years, it was believed that ozone formation was VOC-limited in most nonattainment areas. Consequently, although both NO_x and VOC emissions are regulated for certain source types, the primary focus of past ozone abatement strategies has been VOC. However, many areas have yet to attain the ozone standard. In recent years, state-of-the-art air quality models and improved knowledge of atmospheric chemistry have indicated that control of NO_x in addition to VOC is necessary for effective reduction of ozone in many parts of the United States.

Based upon recent scientific research, NAS has determined that in many parts of the country NO_x control is generally a very beneficial strategy for ozone reduction. However, under some circumstances, NO_x reductions without accompanying VOC control may actually increase ozone in a few urban cores such as downtown Los Angeles and New York City.(17) In the recent report, researchers emphasize that both VOC and NO_x controls are needed in most areas of the U.S.(18)

Data presented in EPA's ROMNET study(19) indicate that a combined VOC/NO_x strategy would be more effective for ozone reductions than a VOC-only strategy. Based on the results of the ROMNET study, increased emphasis on NO_x reduction is necessary to attain the ozone standard in the ROMNET modeling domain.(20) The ROMNET report also stresses that in an effort to bring nonattainment areas into compliance, controls must be applied both in urban areas and in the outlying rural areas.

In some areas, VOCs emitted by vegetation combined with NO_x emitted by human activity can contribute to summertime ozone levels significantly exceeding EPA standards. For example, in some cities such as Atlanta, more VOC may be emitted by vegetation than by human sources, thus increasing the importance of NO_x reductions. Ozone formation in many rural areas is almost certainly controlled by NO_x emission due to of the large VOC inventories from biogenic sources such as crops and trees.

Although both the ROMNET and NAS studies stress the need for additional NO_x controls, the emphasis is not merely a NO_x-only strategy. Rather, the importance of both VOC and NO_x in air quality management is stressed.

1.2.2. Smoke

Smoke is defined as that portion of the particulate emissions that is visible which is mostly composed of carbon. Smoke is composed of large, visible particulate matter (above 10 microns) as compared to smaller particulate matter which is composed of minute, invisible particles below 10 microns. Due to their size, the larger, visible smoke particles do not penetrate to the deeper parts of the lungs during normal breathing but accumulate in the upper respiratory tract, throat, and mouth or they are expelled from the body upon exhale. Because smaller, invisible particles (those below 10 microns) are more likely to stay in the air stream, they are more likely to make it to the deeper parts of the lungs and remain there.(21) The effect upon human health of the smoke particles is uncertain because the particles do not penetrate deeply into the lungs. The particles which do penetrate deeply into the lungs are thought to be a greater health hazard.

Smoke from any source has also long been considered a major aesthetic nuisance. The large carbon particles remain suspended for long periods and refract light, causing the negative environmental effect of reducing visibility. These particles are often wet and cause costly damage through soiling of urban buildings, homes, cars, and other property, they also soil human skin and clothes. There are substantial costs to society in terms of living with a dirtier environment or alternatively, paying to clean it up. More than likely, reducing smoke from engine exhaust prevents pollution at a lower cost than the cost of paying to clean the soiling.

The offensive odor associated with diesel engine exhaust has a negative impact on public welfare. It is mostly caused by aldehydes. However, many people believe that there is a correlation, however weak, with smoke as well. It is certainly realistic to assume that the large carbon particles, which disperse and carry farther than the small invisible particles, carry the offensive odors further and help them to persist longer.

The invisible portion of the particulates that a diesel engine emits (termed particulate matter or PM) is the portion that has the greatest health hazard. Those strategies which are usually used to limit or control smoke (e.g., leaner fuel/air ratio, advanced end of injection, better mixing, better atomization) can be relied on to control PM as well, especially when applied to uncontrolled engines. As limits get lower and control strategies become more sophisticated the correlation becomes weaker and control of smoke is a poorer control of PM.

The public is uneasy about a highly visible pollutant that gets on them and their property and has an uncertain effect on their health. They support the elimination of smoke. A precedent for the reduction of smoke for purely aesthetic reasons was the agreement in 1991 to reduce smoke from the Navajo Generating Station, far from any nonattainment area, to increase the public's right to an unobstructed view of one of our nation's national treasures, Grand Canyon National Park.

Chapter 1: References

1. EPA, *Nonroad Engine and Vehicle Emission Study*, EPA Report Number 21A-2001, Washington, DC, November, 1991.

2. EPA, *Nonroad Engine and Vehicle Emission Study*, EPA/21A-2001, 1991, p. viii.

3. Energy and Environmental Analysis, *Feasibility of Controlling Emissions from Off-Road, Heavy-Duty Construction Equipment - Final Report*, Arlington, VA, December 1988, p. 6-19.

4. U.S. EPA, Office of Policy, Planning and Evaluation, *Guidelines for Performing Regulatory Impact Analysis*, EPA 230-01-84-003, March 1991.

5. U.S. Department of Commerce, Bureau of the Census, *Current Industrial Reports: Internal Combustion Engines*, Report Number MA35L, Washington, D.C.

6. California Air Resources Board, *The Effects of Oxides of Nitrogen on California Air Quality*, Report Number TSD-85-01, March, 1986, p. iii.

7. California Air Resources Board, *The Effects of Oxides of Nitrogen on California Air Quality*, Report Number TSD-85-01, March, 1986, p. v.

8. National Research Council, *Rethinking the Ozone Problem in Urban and Regional Air Pollution*, National Academy Press, Washington, DC, 1991.

9. Fisher, D. and Oppenheimer, M., *Atmospheric Deposition and the Chesapeake Bay Estuary*, Journal Ambio, Volume 20, pp. 102-108 (1991).

10. U.S. Environmental Protection Agency, *Review of the National Ambient Air Quality Standards for Ozone - Assessment of Scientific and Technical Information: OAQPS Staff Paper*, EPA-450/2-92-001, June 1989.

11. U.S. Environmental Protection Agency, *Review of the National Ambient Air Quality Standards for Ozone - Assessment of Scientific and Technical Information: OAQPS Staff Paper*, EPA-450/2-92-001, June 1989.

12. U.S. Environmental Protection Agency, *Review of the National Ambient Air Quality Standards for Ozone - Assessment of Scientific and Technical Information: OAQPS Staff Paper*, EPA-450/2-92-001, June 1989.

13. U.S. Environmental Protection Agency, *Review of the National Ambient Air Quality Standards for Ozone - Assessment of Scientific and Technical Information: OAQPS Staff Paper*, EPA-450/2-92-001, June 1989.

14. U.S. Environmental Protection Agency, *Review of the National Ambient Air Quality Standards for Ozone - Assessment of Scientific and Technical Information: OAQPS Staff Paper*, EPA-450/2-92-001, June 1989.

15. U.S. Environmental Protection Agency, *Review of the National Ambient Air Quality Standards for Ozone - Assessment of Scientific and Technical Information: OAQPS Staff Paper*, EPA-450/2-92-001, June 1989.

16. National Research Council, *Rethinking the Ozone Problem in Urban and Regional Air Pollution*, National Academy Press, Washington, DC, 1991.

17. National Research Council, *Rethinking the Ozone Problem in Urban and Regional Air Pollution*, National Academy Press, Washington, DC, 1991.

18. National Research Council, *Rethinking the Ozone Problem in Urban and Regional Air Pollution*, National Academy Press, Washington, DC, 1991.

19. U.S. Environmental Protection Agency, *Regional Ozone Modeling for Northeast Transport (ROMNET), Project Final Report*, EPA-450/4-91-002a, Research Triangle Park, NC, June, 1991.

20. National Research Council, *Rethinking the Ozone Problem in Urban and Regional Air Pollution*, National Academy Press, Washington, DC, 1991.

21. Seinfeld, John H., *Atmospheric Chemistry and Physics of Air Pollution*, 1986, p. 66.

Chapter 2: Technological Feasibility

To be technologically feasible by the 1996 model year timeline, there must be engine test procedures and engine technology available that, when applied to large nonroad CI engines, allows these engines to meet the emission standards in production and in actual use. At the same time, regulations that would require technologies that significantly impact the design of the equipment on which these engines will be installed will push back the timeline for implementation of the rules and may diminish the cost-effectiveness of the regulations. To verify technical feasibility, this chapter will demonstrate the following.

- Adequate test procedures are available to predict the promulgated levels of oxides of nitrogen ($NO_{x)}$ emission and smoke reduction.
- Necessary technology is feasible to meet the promulgated NO_x and smoke standards within the adopted timeline.
- Engine technology changes will not significantly impact equipment design with respect to powertrain, packaging, and maintenance.
- Engine technology changes will have minimal impact on fuel economy and power.
- On average, engine technology changes will not significantly impact emissions of hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM).

2.1. Emission Measurement

In order for EPA to successfully regulate tailpipe emissions, test procedures to accurately measure new and in-use engine emissions must be available. This section will discuss the feasibility of existing emission test procedures to measure the emittants at the emission standards levels, and EPA's determination that up front durability demonstration will not be needed to ensure full useful life emission compliance.

2.1.1. Exhaust Emission Test Cycle

EPA must ensure that manufacturers of nonroad engines produce engines that will perform as required over specific, repeatable test procedures. These test procedures must supply EPA with a reasonably accurate approximation of the actual emissions that an engine will discharge into the atmosphere in-use. The approximation would be reasonable if the magnitude of emission reduction demonstrated on the required test procedures should directionally approximate the magnitude of emission reduction realized during actual in-use operation of the engine. In the nonroad environment, one engine model is likely to be used in a large number of equipment applications each with potentially a wide range of in-use operation characteristics. It will take a substantial amount of EPA time to develop test procedures that would represent the range of use experienced by a nonroad engine in actual use. EPA is currently engaged in an analysis to determine the test method best suited to actual nonroad engine operation. However, EPA has decided that a meaningful first step in NO_x emission reduction can be realized in the near future from large nonroad CI engines using available test procedures. Two procedures available at this time are the ISO-8178-1 engine test procedures for nonroad engines developed by the International Standards Organization (ISO)[3] and the Federal Test Procedures (FTP) for heavy-duty on-highway engines developed by EPA. The rest of this section discusses the appropriateness of these two test procedures for approximating large nonroad CI engine exhaust emissions.

The ISO test procedures for nonroad engines (i.e., the "ISO procedures" or "ISO-8178-1") were developed in response to early inquiries by governments in the United States and Europe into the contribution of nonroad mobile source engines to air emission inventories. Engine manufacturers established a professional technical committee for the purpose of establishing a "recommended practice" for the measurement of engine exhaust emissions so that emission test results from all laboratories following these recommended practices could be reliably compared. The ISO procedures include a steady state test cycle comprised of a specified number of different load and speed conditions called "modes". Emission measurements are taken once per mode only after the engine reaches equilibrium temperatures in that mode. There are eleven different modes, five load conditions at maximum rated speed, five load conditions at maximum torque speed, and one idle mode. The goal is to allow the

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[3] The International Standards Organization (ISO) is an organization of national standards bodies united to promote standardization worldwide. ISO develops and publishes International Standards. ISO facilitates exchange of goods and services and fosters mutual cooperation in intellectual, scientific, technological and economic spheres of endeavor. ISO is affiliated with the American National Standards Institute.

engine manufacturer to test engines over these eleven modes then calculate "emission factors" by weighting the modes to correspond to the average, real in-use operation seen by the broad category of engines (as defined in ISO-8178-1) in which the test engine falls. For some applications, many of the modes do not occur and are weighted zero. Thus for a generator set three of the modes would be applicable, for farm and construction equipment eight modes, and different mode sets for other application categories. If done properly the tests are repeatable and require relatively simple dynamometers and exhaust sampling devices. The exhaust gas sampling method most commonly used is a raw gas sampling system, although the ISO procedures allow for use of a constant volume sampler (CVS) if a manufacturer prefers.

Figure 2-01

The ISO procedures do not incorporate all modes of operation seen in the actual use of nonroad engines. EPA's concern over the impact of modal differences on the ISO procedure's ability to accurately predict the magnitude of certain pollutants is discussed later in this chapter. Similar to the ISO procedures, nonroad engines do not experience frequent changes in hand or foot lever position by the equipment operator. However, lever position changes do occur and the ISO procedures don't collect emissions during lever position changes. In contrast to the ISO procedures, data provided to EPA show that nonroad engines do experience in use frequent changes in load and speed caused by load fluctuations that occur while a piece of equipment is working. This is typically referred to as "transient operation." For instance, shown in Figure 2-01 during the 8 minute "steady state" plowing mode, the engine operates within an operating range (shown in Figure 2-01 as an area with shading) where the maximum speed attained by the engine in the operating range is approximately 1.5 times the minimum speed. Further, the operating range maximum torque (shown in Figure 2-01 as an area with shading) required from the engine is over two times the minimum torque. The engine is continuously operating within a range and not at a steady speed or load. Because the engine is changing speed and load within the operating range, the engine is experiencing transient operating conditions. The ISO procedures do not account for these transient conditions, but only take an emission reading at 8 discrete stabilized points (typically referred to as "steady state" operation) where no speed or load fluctuations are occurring to the test engine.

The on-highway engine FTP are transient procedures developed to quantify the exhaust emission generated by an average engine in a highway truck which undergoes continuous variation of load and speed in actual use. The engine operates over a continuous twenty minute operating cycle that consists of following a defined speed/load trace. The engine experiences constant variations in speed and throttle position while emissions are collected continuously throughout the twenty minute cycle. To perform this test a motoring dynamometer and a computer are required. The exhaust gas sampling method also requires a CVS system.

The on-highway engine FTP test cycle incorporates modes of operation not seen in the actual use of nonroad engines. Similar to the on-highway FTP, nonroad engines do experience frequent changes in load and speed caused by work fluctuations that occur as a piece of equipment performs a task. In contrast to the on-highway FTP, the nonroad operator does not move the hand or foot lever that affects throttle position (controlling engine speed) as often as an on-highway operator. Therefore, the constant foot lever movement seen in the on-highway FTP is likely more frequent and rapid than would occur in nonroad engine applications (such as exemplified in Figure 2-01). Finally, there is also a part of the on-highway engine FTP which requires that the dynamometer drive the engine, rather than the engine drive the dynamometer. This part represents the on-highway truck inertia driving the engine during deceleration or going down a hill. Due to their steep gearing and lower operating speeds, nonroad engines are not driven by their equipment nearly as frequently as occurs in on-highway trucks.

EPA has concluded that real in-use operation is likely somewhere between the

ISO engine test cycle and the on-highway engine FTP test cycle. The on-highway engine FTP uses less power and is more transient in nature than the normal operation seen by nonroad engines. The ISO test procedure, on the other hand, is more steady state than the normal operation seen by nonroad engines. Should this transient operation represent a significant part of the duty cycle of the average nonroad engine, it would be important that EPA properly reflect the pollutants emitted during this transient operation.

While acknowledging that neither procedure will perfectly reflect real in-use operation, EPA with the cooperation of the Engine Manufacturers Association (EMA) ran a test program to determine how well these two test cycles could predict emission reductions (see Appendix C). Several back to back emission result comparisons were made between the on-highway FTP and the ISO test procedures. Eight engines were operated on both procedures, three by EPA, one by a manufacturer, and four by Southwest Research Institute. These engines represented current production unregulated engines (nonroad engines) and regulated engines (on-highway engines) built by five different manufacturers and tested at three different laboratories. In the winter and spring of 1992 a second series of tests was performed, again with the cooperation of EMA (see Appendix C). In the second series, one nonroad engine and one on-highway version of the same engine model were tested using both the FTP and the ISO test procedures.

The emission test results of 18 engine configurations (from the ten engines, a portion of which were recalibrated and retested) are reported in Table C-01 of Appendix C. This table compiles the results from 10 engines described above plus 8 cases where technicians retarded the injection timing on 4 of the 10 engines tested. Results are tabulated for each emittant for both test procedures for all 18 engine configurations. The percent difference between the emission test results measured over the two procedures is calculated for each emittant for each engine. Positive numbers indicate that the FTP gave a higher value. The differences are averaged for each engine group and the final "Average % Difference" for each emittant recorded at the bottom of Table C-01 is the average of the averages and not the average of the 18 engine configurations. These data are summarized in Table 2-01.

Table 2-01
Emission Difference Between the FTP and ISO

Pollutant	Percent Difference
HC	38 %
CO	35 %
NOx	3 %
PM	27 %

Examining Table 2-01, the following results are observed.

- On average, the FTP produced about 3% more NO_x than the 8-mode.
- The other three constituents average 27% to 38% lower on the ISO test.

EPA concludes from these test results that initial levels of NO_x emission reduction can be measured using either the FTP or ISO test procedures. NO_x emission was relatively unaffected by the differences between the two test procedures. It can be reasonably projected that actual in-use operation, which is likely somewhere between these two cycles, would also show similar emission results to these two test procedures. The major difference between the FTP and the ISO test cycles is the higher level of transient operation experienced over the on-highway FTP test cycle. It is consistent with scientific theory that NO_x should not be influenced greatly during transient operation, provided no other engine parameters change (e.g., radical timing changes). Refer to Appendix B.1 for a further discussion of NO_x formation during the combustion process.

The data are inconclusive whether HC, CO, or PM emissions from nonroad engines in actual use can be properly characterized using the FTP or the ISO test procedures. The results show that there is a large difference in measured emissions between the FTP and the ISO test procedures for these three emittants. Furthermore, there is no pattern or consistency in the emission offset between one test procedure and the other. This was not unexpected since the FTP has a great deal more transient operation than the ISO test procedures, and HC, CO, and PM emissions are known to be greatly influenced by transient operation (see Appendix B.2 & B.4). Further study will be required to better characterize the nature and level of transient operation experienced by nonroad engines in actual use before EPA would feel confident to claim emission benefits for HC, CO, and PM emission standards can be based on the ISO test procedures or whether new nonroad engine test procedures would be necessary to control these other emittants.

2.1.2 Use of On-Highway Federal Test Procedures

In the NPRM, EPA proposed to allow use of the On-Highway FTP as an alternative to use of the 8-mode FTP adopted in this regulation. As discussed in Section 2.1.1., the EPA/Industry test program showed minimal change in NO_x emission from 18 engine configurations tested over both test procedures. Based on these data, EPA saw little risk in allowing either of these two test procedures for certification to a NO_x emission standard.

John Deere objected to EPA's proposal to allow use of the On-Highway FTP, stating there are at least two on-highway certified engine families that produce very different NO_x emission levels over the two test cycles described above. These electronically fuel-injected engines use what Deere referred to as "transient-sensing timing algorithms". The purpose of these algorithms is to sense long periods of steady-state operation (presumably highway cruising operation), upon which the computer would advance the fuel injection timing to increase fuel economy. This would not show up in a NO_x emission increase on the on-highway FTP because there is no substantial time block of steady-state operation during the FTP test cycle. However, if the same engine were running on the 8-mode test cycle described in this regulation, the engine would advance the fuel injection timing during the test cycle in response to the long periods of steady-state operation encountered in the 8-mode test cycle. The result would be a marked difference between the NO_x emission measured over the on-highway FTP and the 8-mode test procedures.

John Deere submitted test data showing a Cummins 246kW engine and a Detroit Diesel Corporation (DDC) 317kW engine operated over the 8-mode test procedures. The NO_x emission results reported showed that the Cummins engine, certified at 4.5 g/bhp-hr on the on-highway FTP, produced 5.8 g/bhp-hr on the 8-mode test procedures. The DDC engine, which certified at 4.8 g/bhp-hr on the on-highway FTP, produced 7.4 g/bhp-hr on the 8-mode test procedures. These are increases of approximately 30 and 50 percent respectively. John Deere also provided photographs of the electronic signal commanding what it measured as a 12 degree timing change during the steady state test. The commenter stated, "Each engine's ECU rapidly advanced the timing during each phase of the eight mode test and as a result it was not possible to determine steady state emissions results at the retarded timing settings seen during transient operation."

The evidence presented by this commenter is thorough and addresses all questions raised by EPA as to its authenticity. Should a manufacturer use the on-highway FTP to certify, EPA would not be able to detect use of a "transient-sensing timing algorithm". Such an algorithm could greatly increase an engine family's actual in-use NO_x emission over that predicted on the on-highway FTP. Further, such an algorithm could give one engine manufacturer a fuel economy advantage over another manufacturer that did not incorporate such an algorithm. Therefore EPA concludes, based on this new information, it is unwise to assume that the on-highway FTP would be allowable for use in any aspect of this rule.

2.1.3. Exhaust Emission Test Procedures

The engine industry recognized that legislative controls on the emissions from nonroad engines would soon be on the European agenda. They recognized the need for the development of test procedures that would be appropriate for reciprocating internal combustion engines used in nonroad applications. The International Standards Organization (ISO) proceeded to produce test procedures to measure emission from nonroad engines. The resulting test procedures have been refined over the years in an attempt to develop test procedures that give accurate, repeatable results and that could be the basis for a harmonized certification procedure. ISO restricted its work to the development of test procedures and did not propose limit values. The result of this effort was ISO-8178-1, Revision 4, "Test Bed Measurement of Gaseous and Particulate Exhaust Emissions from Reciprocating Internal Combustion (RIC) Engines."

EPA's test procedures adopted in the FRM described in the regulations (draft 40 CFR Part 89, Subparts D & E) were developed to correspond with ISO engine test procedures more specifically titled "ISO-8178-1, Revision 4". EPA used Revision 4 to harmonize with the California regulations for nonroad farm and construction engines greater than or equal to 130kW (175hp). California developed their nonroad test procedures from Revision 4, which is an early version of the ISO-8178-1 portion of the ISO engine test procedures. These test procedures are also likely to be proposed to the European community for adoption as their test procedures. There will be at least one more revision to the ISO engine test procedures, which will incorporate some of the changes that were made during the development of draft 40 CFR Part 89, Subparts D & E (herein after termed "Subparts D & E"). EPA coordinated with CARB and ISO technical personnel to ensure compatibility between required and recommended test procedures.

EPA developed its regulatory test procedures (Subparts D & E) to be compatible with ISO and CARB. However, while Subparts D & E meet all the requirements of

ISO test procedures, ISO-8178-1 test procedures may not meet all the requirements of Subparts D & E.[4] ISO test procedures recommended practices are general enough to encompass all reciprocating internal combustion engines. As Subparts D & E are only concerned with compression-ignition engines at or over 37kW (50 hp), some aspects of the ISO test procedures were inappropriate for inclusion in Subparts D & E. Further, Subparts D & E are sections of a regulatory document, and as such, need to clearly define test procedures and measurements. ISO-8178-1 is a non-binding recommended practice, provides a range of specifications that allow some differences between manufacturers' testing techniques while still complying with ISO-8178-1.

Some examples of the differences between Subparts D & E and ISO test procedures are listed in Table 2-02. The result of this development process is EPA test procedures that are essentially a subset of both ISO engine test procedures and the California regulations. This ensures that if an engine is tested per the EPA procedures, it could be considered to have met the testing requirements as set forth by California or any European nation that adopts the ISO test procedures.

2.1.4. Need for Durability Test Procedures for NO_x

Analysis of on-highway historical data (10) leads to the conclusion that heavy-duty diesel engines do not generally produce more NO_x emission as they get older. In the 1990 model year the average deterioration factor, as determined by the durability data engines, was .247 or about 3.5% of the on-highway NO_x emission standard of 6.0 g/bhp-hr. The analysis also demonstrates that in-use data extending over 400,000 miles shows a slight decrease in NO_x emission with mileage. Therefore, no durability data engines or deterioration factors are required by this rulemaking.

Aftertreatment devices do deteriorate with use but EPA does not expect that aftertreatment devices will be used for this rule. As long as aftertreatment devices are not used, then this rule does not require a deterioration factor test.

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[4] The EPA test procedures allow a manufacturer to use any temperature and pressure at the engine inlet as long as it is used consistently. ISO-8178-1 test procedure dictates a specific inlet temperature and pressure. This is the only condition where a manufacturer must use the ISO inlet conditions in order to be compatible.

Table 2-02
Differences Between ISO-8178-1 and EPA Subparts D & E

Parameter	ISO-8178-1	EPA Part 89 Subparts D & E
Adjustments to Measured Power Output	Allows an accessory load to be added to the power to correct to gross power conditions if that accessory can not be removed from the engine. The power correction can not exceed 5 percent of the maximum observed power output.	Does not allow for any adjustments to the measured power output. Accessory loads are considered parasitic in nature and are discouraged from being included during testing. Tests should be conducted in gross power conditions.
Temperature and Pressure Specifications	Specifies standard conditions (STP) for temperature and pressure (273K and 101.3kPa).	Allows any temperature and pressures as long as consistency is maintained throughout the test. All measurements are on a mass basis.
Charge Air Cooling Simulation	Sets temperature and pressure limits for charge air cooling according the manufacturers recommended specifications.	Recommends SAE J1937 for charge air cooling simulation.
Air Cleaner Restriction Specifications	Specifies inlet pressure restriction to be set at the upper limit of a clean air filter as specified by the manufacturer.	The same as under ISO- 8178. However, the manufacturer is liable for emission compliance over the entire range of inlet pressure restrictions as specified in the manufacturers product literature.
Exhaust Restriction Specifications	Specifies exhaust pressure restriction to be set at the maximum (i.e., the upper limit) pressure as specified by the manufacturer.	The same as under ISO-8178. However, the manufacturer is liable for emission compliance over the entire range of exhaust pressure restrictions as specified in the manufacturers product literature.
Fuel Specifications	Does not specify particular test fuel properties.	Defines fuel type and chemical characteristics.
Alternate Emission Sampling Equipment	Allows alternate sampling equipment and systems if the equipment or system has been checked by performing a correlation study between the system under consideration and one of an accepted design.	Allows alternate sampling equipment and systems only with prior approval of the administrator.
Analyzer Response Time	Defines response time requirements for analyzers.	Does not define response time. However, response time must be accounted for before sampling begins during a mode.
Sampling System Characteristics	Is not very specific as to sampling system characteristics (e.g., temperature).	Is very detailed in its definition of sampling system characteristics.

2.2. Technology

To give some perspective on the types of emission control technology that would be available to engine manufacturers, EPA looked at certified on-highway engine families. As noted in Table 2-03, in the 1990 model year, the on-highway heavy-duty engine emission standard for NO_x emissions went from 10.7 g/bhp-hr down to 6.0 g/bhp-hr. While, for reasons discussed in Chapter 2.7, the NO_x emission standard promulgated for large nonroad CI engines is somewhat less stringent (i.e., 6.9 g/bhp-hr) than the 1990 model year on-highway standard, the on-highway heavy-duty engine family configurations certified and built in the 1990 model year represent the closest approximation to the range of technologies that will be available to nonroad engine manufacturers certifying to the standards adopted in this FRM.

Table 2-03
On-Highway Engine Emission Standards

Year	grams/bhp-hour				smoke % opacity		
	HC	CO	NO_x	PM	Acceleration Mode	Lug Mode	Peak Torque
1989	1.3	15.5	10.7	0.6	20	15	50
1990	1.3	15.5	6	0.6	20	15	50

Table 2-04 was constructed from EPA's data base of certified engines to assess the level of technology used in 1990 model year truck engines as well as the magnitude of change in technology that occurred between the 1989 and the 1990 model year. Information on the type of fuel pumps, injectors, and timing are not available from this source, but there is information on the type of air induction system used and whether electronic fuel control is used.

As seen in Table 2-04, between the 1989 and 1990 model year, naturally-aspirated engines decreased to 8% of all engine families certified for 1990. Aftercooled engines increased to 70% and air to air aftercoolers increased to 52% of all engine families in 1990. Electronic fuel control use rose to 16% in 1990. These percentages refer to engine families and may not be consistent with sales data which is unavailable. Total engine families certified increased by 14 families in the 1990 model year. Since manufacturers typically time the introduction of new technologies with the introduction of new engine families for cost and efficiency reasons, it is likely that these additional engine families would have been equipped with turbochargers and air to air aftercoolers.

Table 2-04
Change in On-Highway Technology Mix
in Percent of Total Engine Families (E.F.s)
From Data Base of Certificates

Model Year	Naturally Aspirated	All methods of Aftercooling	Air-to-Air Aftercooling	Electronic Control	Total E.F.s
1989	10%	50%	34%	8%	146
1990	8%	70%	52%	16%	160
% Change	-20%	40%	53%	100%	10%

Most on-highway heavy duty compression-ignition engines sold in the 1990 model year use fairly sophisticated technology. These engines easily meet the standards and the technology is readily available. However, due to the unique operating requirements, packaging constraints, and environment faced by nonroad engines, or due to high relative cost, nonroad engine manufacturers will most likely choose not to use some of the on-highway technologies in response to the nonroad regulations. The following examples of infeasibility of specific technologies are discussed in Chapter 2.2.3..

- Turbocharging facilitates very effective emission control strategies but turbochargers are difficult to apply, in many cases, because of the extra room required.
- Aftercooling with air, the method of choice on-highway, is difficult to apply to nonroad engines because lack of ram air means that a larger fan is needed, a dirtier environment means more maintenance or less effectiveness, and more room is required for the larger heat exchangers.
- Electronic fuel control, although the wave of the future, is expensive and manufacturers have doubts about the durability of current control technologies.

These are technologies EPA has determined will not be necessary to meet the nonroad engine NO_x emission standard adopted in the FRM.

2.2.1. Feasible NO_x Control Technology

In this section the technologies that are available for application to nonroad engines will be presented with some assessment of each technologies applicability and effectiveness in meeting the nonroad engine regulation requirements.

To access the applicability of on-highway engine technologies to the nonroad engine industry, it is necessary to access not only the available technology, but also predict the percentage of the existing unregulated nonroad engine population that already meet the emission standards. That a percentage of nonroad engines would already meet standards is not too surprising. Many of the technologies used in on-highway engines have already found their way to similar nonroad engines to provide greater power and fuel economy and, in some cases, production uniformity and economy of scale.

2.2.1.1 Percentage Requiring No Modification--As part of its technology assessment, EPA estimated the percentage of current production nonroad engine designs capable of meeting the 9.2 g/kW-hr (6.9 g/bhp-hr) NOx emission standard with no modification. As its criterion, the Agency assumed that engines that did not fall at or below the emission standard minus a statistical safety margin (to minimize the risk of in-use failures due to production variability and in-use deterioration) would have to be modified. For this analysis the 13 percent average available safety margin observed in the 1990 model year on-highway program was used because it is the closest approximation to what EPA expects to see for this rule. Therefore, all current production designs producing above a 8.0 g/kW-hr (6.0 g/bhp-hr) NOx emission level would require modification to comply with this FRM.

Table 2-05 shows the data of the current nonroad production engines that were emission tested by EPA and EMA. While the engines tested in this program were not randomly selected (but were provided by engine manufacturers), these engines do represent a reasonable mix of the large and small volume engine families in production in the nonroad market. Based on these data, only the indirect-injected naturally-aspirated (IDI-NA) technology engine design was well below the standard. Without further information, EPA is assuming that only this technology will generally escape some level of NOx emission control. Since IDI engines represent 2% of engine families, approximately 2% of yearly engine sales would not require modification under this regulation. All other engines (98%) will require varying levels of modifications to comply with the NOx standard.

2.2.1.2. Injection Timing--NO_x control is achieved by retarding the start of injection by a few degrees(5). The easiest way to do this is to retard the whole injection process, thereby retarding the end of injection as well as the start. However, retarding the end of injection shortens the time available to complete the combustion process. As a result, HC, CO and PM pollutants and fuel consumption are increased as NO_x is being reduced.

Table 2-05
Current Production Nonroad Engines
8-Mode Emission Test Results

Engine Manufacturer & Combustion Chamber Type	Power		g/bhp-hr (g/kW-hr)				smoke % opacity		
			HC	CO	NO_x	PM	Accel	Lug	Peak
37-75kW (50 - 100hp) engines tested									
Teledyne IDI	hp	66	0.19	2.57	5.4	1	12	21	22
	kW	50	0.25	3.45	7.2	1.34			
Confidential DI	hp	51	0.92	3.94	12.5	0.44			
	kW	38	1.23	5.28	16.7	0.59			
Ford NH DI	hp	53	0.80	3.00	7.40	0.46			
	kW	39.5	1.07	4.02	9.9	0.62			
Deutz DI	hp	56	1.36	2.62	6.9	0.36			
	kW	39.5	1.74	3.51	9.2	0.48			
Ford NH DI	hp	67	0.98	8.80	7.10	0.64			
	kW	50	1.31	11.8	9.5	0.86			
Ford NH DI	hp	69	1.20	4.00	9.00	0.39			
	kW	51.5	1.61	5.36	12.0	0.52			
John Deere DI	hp	76	0.64	3.50	7.24	0.59	12	23	24
	kW	56.7	0.86	2.82	9.7	0.64			
average under 100 hp	hp	62	0.87	4.06	7.93	0.54	12	22	23
	kW	46.2	1.17	5.44	10.6	0.72			
75 + kW (100 + hp) engines tested									
Cummins DI	hp	105	0.75	2.20	11.10	0.41	25	6	54
	kW	78.3	1.01	2.95	14.8	0.55			
Ford NH DI	hp	130	0.70	5.58	9.27	0.96	11	26	27
	kW	96.9	0.94	7.48	12.4	1.29			
John Deere DI	hp	141	0.43	3.14	11.76	0.42	13	9	22
	kW	105	0.58	4.21	15.7	0.56			
Caterpillar DI	hp	288	1.14	1.44	6.5	0.18	31	3	60
	kW	215	1.53	1.93	8.7	0.24			
Detroit Diesel DI	hp	450	0.36	0.80	12.1	0.12	20	2	38
	kW	336	0.48	1.07	16.2	0.16			
average	hp	223	0.68	2.63	10.1	0.42	20	9	40
	kW	166	0.91	3.53	13.5	0.56			

EPA believes most of the 98% of uncontrolled engines that do not meet the NO_x standard will have some retardation of injection timing. As discussed in Chapter 2.4., sufficient retardation of injection timing to lower NO_x from current levels down to the standard level could cost about 3-5% of fuel economy and power. Most manufacturers will have to apply additional technology to recover the lost fuel economy and performance. These additional technologies are discussed in the rest of this section.

2.2.1.3. Fuel Pump and Injector Nozzles--Improved fuel atomization reduces the amount of injection timing retard required to meet the standards. To improve atomization, a manufacturer can improve its fuel delivery by increasing fuel pump pressure, improving fuel pump advance strategies, and incorporating smaller injector nozzle tip holes. When the liquid fuel is finely atomized, combustion is improved in the combustion chamber. Ignition delay, and thus NO_x production, is reduced. Combustion is completed quicker and HC, CO, and PM are reduced because the quicker combustion allows more time for the oxygen to unite with the pollutants. Fuel consumption is also reduced because the combustion takes place nearer Top Dead Center (since injection is less retarded) and efficiency is increased. Many manufacturers currently using rotary fuel injection pumps will upgrade their rotary fuel injection systems to incrementally increase fuel injection pressure in order to regain fuel economy and power. EPA expects that these manufacturers will not find it necessary or cost-effective to convert to inline fuel pumps or unit injectors. Manufacturers that already use inline fuel pumps or unit injectors will likely upgrade to incrementally increase fuel injection pressures.

Variable fuel injection timing provides more flexibility to optimize a timing strategy. An optimized strategy would both provide appropriate retardation of beginning of injection during traditionally high NOx operating conditions, as well as minimize timing retard during operating conditions that would compromise fuel economy or power (i.e., engine efficiency). Because of the shorter time to achieve full combustion afforded by systems designed with higher fuel injection pressures, these systems can vary both beginning of injection and end of injection. This allows the increased flexibility to both reduce NOx while minimizing power and fuel economy loss by not retarding end of injection for NOx reduction under certain operating conditions.

2.2.1.4. Combustion Chamber Design--The basic design of the combustion chamber can impact emissions because it can substantially impact the means of fuel delivery as well as the nature and the completeness of the combustion process. There are two major distinctions in chamber design: indirect injection (IDI) and direct injection (DI). Sometimes called prechamber engines, IDI engines have a small combustion chamber hollowed out of the cylinder head (usually) or the piston. This prechamber is separated from the main chamber by a narrow opening. The fuel is injected into the prechamber. Combustion takes place at a richer air/fuel ratio within the prechamber, then exits the prechamber with a high velocity to complete the combustion process amid a high level of turbulence and mixing.

Characteristics of IDI engines are the following.

- Reduced emission of pollutants. NO_x is lower(7) because of the rich air/fuel ratio and resulting lower combustion temperature, and the decreased detonation. Emissions of HC, CO, and PM are also lower due to the more complete utilization of the oxygen after injection is over.
- Higher compression ratio (20:1 to 25:1) needed for starting reliability, increases friction.
- 5 to 10% lower fuel economy over a DI engine(6), primarily due to the pumping losses (pushing air and combustion products back and forth through the small opening exiting the prechamber uses energy) and high friction from the high compression ratio.
- Higher speeds are attainable because the high velocity mixing and turbulence helps the combustion process to proceed to completion faster.

IDI is fast losing market share to DI because IDI engines have higher fuel consumption. This regulation should slow down the rate of conversion of IDI to DI. However, very few if any small naturally-aspirated DI engines would be converted back to IDI due to this FRM because the cost of retooling would exceed other options for reducing NOx emissions from DI engines.

Sometimes called "open chamber," DI engines usually have a flat cylinder head surface with the combustion chamber hollowed out of the piston. The chamber can be almost any shape but it is not restricted at the top. In effect the fuel is injected into the whole mass of air. These engines have become popular in recent years due to their lower fuel consumption. The majority of large nonroad CI engines (about 98%) use this type chamber. Although DI engines are at a disadvantage over IDI engines with respect to NO_x emission, there are a range of technologies, such as medium pressure injection systems, that can reduce NO_x emission at lower cost than converting a DI engine to IDI. EPA has concluded that the level of standard promulgated in this rule is not so stringent as to require manufacturers to redesign DI engines to be IDI.

2.2.1.5. Derating the Engine--Another method by which manufacturers can control emissions is to reduce the fuel flow to the engine, commonly referred to as "derating." A great deal of engine development time is spent to maximize the density of the air charge in a cylinder for each combustion cycle, primarily because the air consumption effectively limits the amount of work the cylinder can do. Increasing the fuel rate increases the work output and the emission factors, but specific emissions will decrease because the work output increases faster than the emission factors up to a point. At some point, depending on engine design but usually near the smoke limit, the emissions will start to rise faster than the work output. Manufacturers will normally set their engines at a "smoke limit" which generally means no visible smoke at full load. There may also be a higher rating allowable for short periods when some smoke is visible. The "smoke limit" will normally be at an air/fuel ratio of about 21:1 or 22:1.

Derating is undesirable to the manufacturer because the engine's power has been reduced, effectively reducing the engine's value. For example, a manufacturer may have to sell for the same price an engine which now produces 71kW (95hp) but which produced 75kW (100hp) in an earlier year. The manufacturer could also certify a larger displacement version of the same engine that has been derated from a higher horsepower down to the desired 75kW (100hp). One manufacturer has indicated it is considering such a strategy to replace one of its currently unregulated engine models. This strategy is most likely to be used when both versions are already in production since the cost to switch over is minimized. Packaging changes are minimized since the differences would most likely be in the bore or stroke of the affected engines, which has little or no impact on the exterior dimensions of the engine.

2.2.1.6. Increased Turbocharger Boost--To increase the air consumption of an engine a manufacturer may install a pump to supply air at higher pressure, thereby increasing the mass of air retained in the cylinder. There are a variety of different pumps and methods of driving them available but the system of choice today is a centrifugal compressor driven by a radial gas turbine and colloquially called a "turbocharger," or more simply a turbo. The turbo packs more air into the cylinder and thereby increases the air/fuel ratio, decreasing emission factors, provided the manufacturer does not also increase the fuel flow.

Increasing the turbo boost on engines that are already turbocharged is an effective, low cost means to regain the efficiency lost to retarding the injection timing. Increasing air flow while maintaining fuel flow decreases HC, CO, and PM emissions for the same reasons that they are reduced when decreasing the fuel flow and maintaining air flow. NO_x responds somewhat differently, however. Since the same fuel amount is injected, the detonation level in the combustion chamber stays similar to that level before the turbo was added, while the increased mass of air provided by the turbo prevents the peak combustion chamber temperature from rising as high as it did before adding the turbo. Maintaining detonation level while reducing peak cylinder temperature will result in lower NO_x emission. Manufacturers do not usually increase turbo boost to decrease emissions, but to decrease fuel consumption at the same power level or to allow the manufacturer to increase fuel flow and power for a relatively small cost. Use of turbo boost increase and/or aftercooling substantially offsets any fuel economy penalty associated with NO_x emission reduction.

2.2.1.7. Aftercoolers--Like any other pump, the turbocharger heats the air while compressing it. To further increase the air supply to an engine, a cooler can be installed after the compressor and before the intake manifold. The effect is to increase the mass flow of air (by increasing the density) and thus increase the air/fuel ratio.

If fuel rates are not changed, aftercooling usually results in the reduction of all four of the major pollutants. NO_x is reduced due to the lower combustion temperature. HC, CO, and PM are reduced because of the increased amount of oxygen available to combine with these constituents.

Aftercooling with jacket water is an inexpensive and effective way to gain increased air consumption and reduce NO_x emission. EPA estimates that about 10% of large nonroad CI engines will have aftercoolers added by the 1996 model year due to emission requirements (see Chapter 2.2.6.2, Table 2-10).

2.2.2. Feasible Smoke Control Technology

The Federal Smoke Test and its standard values of 20% opacity for the acceleration mode, 15% for the lug mode and 50% peak have been on-highway requirements for a number of years. Three pairs of engines were tested cooperatively with industry. This test program is described further in Appendix C. Each pair of engines tested in the program consisted of a production nonroad engine and an on-highway equivalent, or in the case of the smaller engine, a prototype which represented an attempt to meet the 1996 California standards. One pair was turbocharged and aftercooled. One pair was turbocharged. One pair was naturally aspirated.

The nonroad engine smoke results are shown in Table 2-06 and the on-highway engine smoke results are shown in Table 2-07. Although the average nonroad engine comes fairly close to meeting the smoke standard, Table 2-06 shows that each engine fails significantly in one or more modes. Table 2-07 shows that each of the on-highway and prototype engines is significantly below the smoke requirements.

Table 2-06

Smoke Test Results - Current Nonroad Engines

Engine Type	Rated hp(KW)	Technology	Smoke % Opacity

		naturally aspirated	turbo-charged	after-cooled	accel. mode	lug mode	peak
Nonroad	283(211)		*	*	31	3	60
Nonroad	100(74.6)		*		25	6	45
Nonroad	72(53.7)	*			12	23	24
Average Nonroad Engine Smoke Results					23	11	43
Smoke Standards					20	15	50

To explain the smoke results reported above requires a short discussion of why smoke occurs. Turbocharged engines are the most likely engines to exceed smoke standards. When a compression-ignition engine is operating at part load, the exhaust temperature is reduced and the turbocharger is operating at reduced speed. To increase load, the fuel rate to the cylinder is increased, which decreases the air/fuel ratio. If the air/fuel ratio is decreased enough (below about 21:1), the engine will smoke. The increased fuel rate increases the temperature of the exhaust which will accelerate the turbocharger. It takes some time (turbo lag) for the turbine to come up to speed in response to increasing exhaust temperature and restore the air/fuel ratio to the "smoke limit". While the naturally-aspirated nonroad engine above exceeded the "lug" standard, it is generally accepted (see Chapter 2.2.6.1) that naturally-aspirated engines as a whole will not be as dramatically over fueled, and thus will in most cases require only minor adjustments to meet the smoke requirements.

Table 2-07

Smoke Test Results - On-Highway and Nonroad Prototype Engines

Engine Type	HP(KW)	Technology			Smoke % Opacity		
		naturally aspirated	turbo-charged	after-cooled	accel. mode	lug mode	peak

On-highway	285(213)		*	*	11	4	15
On-highway	105(78.4)		*		5	11	11
Prototype	73(54.5)	*			3	4	4
Average On-highway and Prototype Engine Smoke Results					6	6	13
Smoke Standards					20	15	50

Strategies for decreasing "turbo lag" include use of low inertia turbine/compressor wheels to increase the acceleration of the compressor, and use of smoke control technology which may take the form of a dashpot in the fuel pump linkage which slows down the rate of fuel increase, an aneroid bellows activated by turbocharger pressure from the intake manifold which limits the fuel delivery until the turbine comes up to speed, or a waste gate which maintains high intake manifold air pressures under all operating condition.

Manufacturers have stated that most turbocharged engines already have some smoke control system as an offshoot of standardization with similar on-highway engine models. Some turbocharged engines will employ a smoke control system to meet the smoke standards. Most existing smoke control systems will need some adjustment to meet the new smoke regulations. Most naturally-aspirated engines do not currently have smoke control systems. A small percentage of naturally-aspirated engines may need a smoke control system to meet the standards. Based on manufacturers comments, it is projected by EPA that industry will use the existing on-highway smoke control technology on engines subject to this FRM.

In more limited cases, smoke control technology could cause a negative performance impact that could require alteration of the equipment hydraulics or power train, and could present a safety concern. In these cases a manufacturer would opt to use waste gate technology. While more costly other smoke control systems, when used to forego equipment modifications, waste gate technology is cost-effective.

2.2.3. Infeasible NO_x Control Technology

There are certain technologies that are used extensively in 1990 model year on-highway engines that are either incompatible for use in nonroad engine applications or are much more expensive than the alternative emission control strategies and thus will not be used to attain the adopted level of NO_x emission control. The technologies that would in most cases fit this category are discussed in this section.

2.2.3.1. Addition of a Turbocharger--The diesel industry is adding turbochargers rapidly, independent of any emission regulations. Most large engines already have turbochargers and they are being phased in on lower and lower horsepower models. The lower limit at which engines can be effectively turbocharged today is about 22-30kW (30-40hp). Turbochargers are generally not fitted to decrease emissions, but to decrease fuel consumption at the same power level or to allow the manufacturer to increase fuel flow and power at a reasonable cost. While nonroad engine manufacturers do not have as strong a market incentive to incorporate turbochargers on their engines as on-highway engine manufacturers,[5] nonetheless use of turbochargers is increasing among nonroad engine manufacturers as well.

Adding a turbocharger to a naturally-aspirated engine is one possible method by which a manufacturer may regain the efficiency lost by retarding injection timing to reduce NO_x emission. The technical rationale is the same as the reasoning stated for increasing turbo boost stated above. However, to add turbochargers to those engines not currently so equipped would be costly compared to other technologies available to meet the requirements of this rule (i.e., fuel injection system improvements). Furthermore, in many cases the equipment modifications required to accommodate a turbocharger are not feasible within the implementation timelines required by the FRM.

2.2.3.2. Electronic Control--Technology exists to electronically control the fuel system, the turbocharger, the transmission, slippage of the wheels, et cetera. Use of electronic controls enables engine designers to minimize emissions while maximizing fuel economy and performance. Manufacturers of nonroad engines have resisted the use of electronic controls mainly due to cost and reliability concerns. However, such systems have been in use for several years in trucks and locomotives and the usage of such equipment is expanding rapidly. Advertising by Cummins engine company and others suggests that electronic controls will be introduced in the near future, citing advantages in fuel efficiency, operating versatility, et cetera.(11) This suggests that

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[5] The incentive for on-highway manufacturers is that on-highway truck fleets owners shop around for engines that deliver higher fuel economy. By contrast, nonroad engine users value durability and power over fuel economy. The industry has stated that the critical fuel consumption design constraint for nonroad engine and equipment designers is that a piece of equipment can only be refueled once per work shift. This can be controlled by fuel tank size and by engine fuel economy.

electronically controlled engines could become popular on nonroad engines for reasons other than emissions. EPA suspects that such a move by manufacturers to produce and sell these systems would occur slowly, driven by market forces rather than this rule. While use of electronic fuel control systems could greatly benefit emissions, fuel economy and power, such sophisticated controls will not be necessary to meet the emission standards promulgated in this FRM and will not generally be available within the implementation requirements of this FRM..

2.2.3.3. Air to Air Aftercoolers--Air to Air aftercoolers are even more effective than jacket water aftercoolers. The ambient air used as the cooling medium starts out approximately 56° C (100° F) cooler than the engine coolant used as the cooling medium for the jacket water aftercooler. A much denser air charge can be delivered to the combustion chamber by the air to air system, thus increasing efficiency and, again, reducing NO_x emission even further.

For on-highway applications, which operate for long periods at higher vehicle speeds (thus drawing a large volume of ambient air across the cooler core at high speed) and draw air through the cooler from outside the engine compartment, air to air aftercoolers are very efficient and their use has grown quickly. Air to air aftercoolers are more difficult to apply to nonroad engines than on-highway engines because they require design and implementation of special hardware to maintain sufficient ambient air velocity past the cooling fins and to keep dirt from building up around the cooling fins. To reduce dirt around the engine, many nonroad applications also use pressurized engine compartments which blow hotter engine compartment air through the aftercooler, further reducing the coolers effectiveness. On-highway engines are incorporating air to air cooler systems to help them attain very low NO_x emission levels between 5.3 and 8.0 g/kW-hr (4.0 and 6.0 g/bhp-hr). Air to air coolers will rarely be necessary to meet a NO_x emission standard of 9.2 g/kW-hr (6.9 g/bhp-hr), and would rarely be feasible within the implementation requirements of this FRM.

2.2.3.4. Exhaust Gas Recirculation--Recirculating some of the exhaust gas back into the ambient intake manifold is an effective way to reduce NO_x emissions(8,5), especially in naturally-aspirated engines, without increasing HC or PM. Diesel manufacturers have been reluctant to use this technique, however due to the following unresolved issues.

- Sulfur and soot from combustion gases can cause increased wear of piston rings, valves, and turbocharger components; and/or shorten the oil change interval.
- If Exhaust Gas Recirculation cannot be introduced into the inlet of the

> turbo compressor, then a more sophisticated pumping system must be used to overcome the intake manifold air pressure in turbocharged engines.(5)

Manufacturers do not generally use Exhaust Gas Recirculation for on-highway engines and it is doubtful if any will employ it for this rule. Further development and the use of low sulfur fuels for on-highway applications may make this strategy more attractive, especially in small naturally-aspirated engines. A more extensive discussion of low sulfur fuels follows in Chapter 2.2.4.2.

2.2.3.5. Aftertreatment Devices--After the exhaust gases have left the engine, further reduction of pollutants can be achieved by catalytic converters and/or particulate traps. Oxidizing catalysts can be particularly effective in reducing CO or HC emission. PM can be oxidized as well or it can be trapped in a filter which then is periodically cleaned.

NO_x emission cannot easily be treated in diesel exhaust using catalytic converters because compression-ignition engines always run leaner than the stoichiometric air/fuel ratio. The excess oxygen makes the reducing catalyst less effective. Manufacturers of heavy-duty diesel engines, both nonroad and on-highway, have been reluctant to use aftertreatment devices because of cost, complexity of installation (the engine manufacturer does not install the engine in the vehicle), and durability concerns. As discussed further in Chapter 2.2.6.1, both EPA and engine manufacturers agree that aftertreatment devices will not be necessary to meet the requirements of this rule.

2.2.4. Certification Fuels

EPA believes that all manufacturers will be able to certify to the requirements of this FRM with available commercial fuels. EPA believes that certification should be accomplished with the fuel most likely to be used in use.

2.2.4.1. Cetane Number (CN)--Since a great deal of the NO_x emission is formed during the detonation phase (see Appendix B.1), reducing the ignition time delay, which will reduce the amount of fuel present in the combustion chamber at the time of detonation, will reduce the detonation pressure and temperature and less NO_x will be formed. Raising the cetane number does reduce the ignition delay period. Some tests done by McConnel in 1963 (2) indicate a reduction of about 35% in NO_x emissions when the cetane number is increased from 35 to 59. More recently, Terry Ullman, et.al., found in 1990 that changing cetane number from about 37 to about 55 decreased NO_x by about 10%, HC by about 73%, CO by about 53% and PM by about 31%.(3)

In the winter of 1991, diesel fuel available in the United States had an average cetane number of about 44.4.(4). The minimum was 37.8 and the maximum was 58.5 for a spread of 20.7 numbers. The regulations would allow a cetane spread for Certification test fuels of 48 to 54 for #1 diesel fuel and from 42 to 50 for #2 diesel fuel. Testing for this rule performed at EPA was conducted with 46 cetane number fuel and at SWRI with 45 cetane number. The average cetane number in Japan in a similar period was 55 and in Europe about 52. This data was supplied by a Japanese and a European manufacturer. Under the Clean Air Act (CAA) as amended, CAA § 211(i) mandates that on-highway diesel fuel for sale in the United States on or after October 1, 1993, have a minimum cetane index of 40 and a maximum sulfur concentration of 0.05 percent (by weight).

2.2.4.2. Low Sulfur--Certification fuels for on-highway engines are changing from .2-.5% total sulfur to .02-.05% total sulfur due to CAA § 211(i). Lower sulfur content of the fuels reduces the PM emissions but does not materially change NO_x emission and has not been demonstrated to substantially impact smoke emission. The sulfur reduction should reduce corrosion within the engine, especially when EGR is used, making the use of EGR a more viable strategy for controlling NO_x.

Although most fuel suppliers have the ability to supply low sulfur fuel to the nonroad market, due to the higher cost of production, low sulfur fuels are not likely to be made available unless nonroad low sulfur diesel fuel is mandated. A recent informal survey of the petroleum industry indicated that some refiners welcomed an extension of the on-highway requirement for low sulfur fuel to the nonroad market, but that the majority did not. All agreed that unless low sulfur fuel was mandated for the nonroad market, the higher sulfur fuel would continue to be supplied for nonroad use.

In the scientific community it is generally accepted that fuel sulfur has the most noticeable impact on PM emissions. Since fuel sulfur levels available in the 49-States will generally be higher than fuel available in California (where the only available fuel will have low sulfur content), PM emissions in the federal fleet will be higher in actual use than in the California fleet. While this rationale would argue against allowing use of low sulfur certification fuel, at the same time, it is likely that the engines certified on low sulfur fuel will have no higher PM emission in actual use than would have resulted had EPA promulgated NO_x and smoke only emission standards. Because harmonization, rather than emission benefits, is the driving factor behind EPA's decision to impose the PM standard, EPA sees no need to increase the testing burden by requiring a different certification fuel specification to demonstrate compliance with the PM standard.

California's particulate standard is predicated on the use of low sulfur fuel, which is the state-wide fuel standard. Therefore, the particulate standard EPA is adopting is likewise predicated on the use of low sulfur fuel. Should a manufacturer or EPA choose to perform certification or in-use compliance testing with commercially available fuel containing higher sulfur, the particulate measurement will be adjusted by using the following equation to reflect the effects of higher sulfur content of the fuel on particulate emissions:

$$PM_{adj} = PM - [BSFC * 0.0917 *(FSF - USLF_{CA})]$$

Where:

PM_{adj} = adjusted measured PM level [g/KW-hr]

PM = measured weighted PM level [g/KW-hr]

BSFC = measured brake specific fuel consumption [G/KW-hr]

FSF = fuel sulfur weight fraction

$USLF_{CA}$ = upper sulfur level weight fraction of California specification.

This adjustment only applies to engines with no exhaust gas aftertreatment. No adjustment is provided for engines with exhaust gas aftertreatment.

2.2.5. Useful Life of Engines

EPA adopts an expected full useful life period for engines covered by this FRM of 8,000 hours or 10 years. These values were based on discussions with nonroad engine manufacturers and analysis of the useful life of comparable on-highway large CI engines.

Nonroad engine manufacturers have indicated that the great majority of engines covered by this rule would have a useful life hour range from 6,000 to 10,000 hours, and within one engine family there are likely applications that will span the entire useful life hour range. This range of useful lives can be determined in one of two ways. Either useful life is designed into the engine (i.e., engine components with various life expectancies), or useful life is dictated by the severity of the engine application. A manufacturer could build a subset of engines from an engine family with less durable components when those engines are destined for an application that has an equipment useful life of less than the engine's normal useful life. This is purely a cost decision and it would result in two physically different engines in terms of materials or manufacturing techniques used to make components. Alternatively, a manufacturer could build all engines with equally durable components, but a subset of those engines could be installed on a relatively more severe application which could result in the subset engines having a shorter useful life. In this second case, manufacturers also indicated that the more severe applications tend to be those that are not used as many hours per year such that the useful life years is approximately 10 years whether useful life hours are 6,000 hours or 10,000 hours.

EPA also analyzed the useful life of comparable on-highway engines. It was determined that the medium-heavy and heavy-heavy engines were most similar in durability features to the large nonroad CI engines. Table 2-08 specifies the current on-highway useful lives by engine categories:

Table 2-08
On-Highway Engine Useful Life Definition

On-highway Category	Miles(Kilometers)	Hours @ 33 MPH(44KPH)	Years
Medium-Heavy Diesel	185,000(248,000)	5,550	8
Heavy-Heavy Diesel	290,000(389,000)	8,700	8

On-highway engines have been divided into categories with different useful lives. This is possible since all applications within a category experience very similar operating conditions. For example, medium-heavy duty engines are generally used in trucks and buses with a specified range of load carrying capability, while heavy-heavy duty engines are only used in trucks with a higher range of specified load carrying capability. By contrast, nonroad engines that are identical can end up in a variety of different applications with varying operational severity. Assuming average on-highway speeds of 33 miles per hour (MPH)[44 kilometers per hour (KPH)], the comparable on-highway useful lives for medium-heavy and heavy-heavy engines range between 5,500 and 8,700 hours, and the useful life years in all cases is 8 years. These results are reasonably comparable to nonroad engine manufacturers information.

Finally, the length of time an engine actually pollutes before finally being retired may depend more on how often it is likely to be rebuilt than on the initial useful life. Nonroad equipment generally outlives its power train (engine and driveline). The rebuild market has grown more and more sophisticated in its efforts to fill the demand for rebuilt and remanufactured engines to put in equipment that is still operational when the original engines have worn out. The options include engines designed with fully replaceable cylinder kits (liners and pistons), as well as special machining tools to resurface cylinder blocks, cylinder heads, and all bearing surfaces. Having said this, EPA is confident that all engines covered by this FRM are rebuildable. Thus the amount of total hours or years a particular engines performs from cradle to grave does not necessarily correspond to its original useful life, but corresponds more closely to the number of times the engine is rebuilt before it is permanently retired. Should a 10,000 hour engine be scrapped after it reaches 10,000 hours while a 6,000 hour engine is rebuilt once before it is scrapped, the 6,000 hour engine will accumulate an effective lifetime hours of 2,000 more than the 10,000 hour engine. While the term "useful life" used in context of this rule only applies to the period of time an engine is expected to operate before the initial rebuild, because of the common practice of rebuilding these engines, EPA is assuming the every engine covered by this FRM has an equal probability of lasting for an equal total lifetime.

Commenters to the NPRM stated that some specific engine families are expected to have a useful life less than 8,000 hours. These engines are designed to be used in severe conditions, often in seasonal equipment, or equipment with a short useful life. They pointed out that, should all engines be assumed to last for 8,000 hours, in-use testing of these severe application engines at 5,600 hours (i.e. 70 percent) would unfairly penalize severe application engines that could in fact be outside of their designed shorter useful life. EPA understands that such a situation could exist, and thus is providing means for the manufacturer to petition the Administrator for an alternative useful life as stated above. Solid engineering data should accompany the request so that a reliable engineering judgment can be made.

Information available to EPA does not indicate that an entire subcategory of engines (i.e., representing a number of engine families) could inherently be expected to have a greater total life on average than any other subcategory. Two commenters to the NPRM requested that EPA adopt a shorter useful life period for the subcategory of all engine families with individual cylinder displacement below a specified volume. It appears that this suggestion was intended to provide a straightforward method to administer useful life at the time of certification. However, EPA is not aware of a supportable technical rationale that would suggest there is correlation between cylinder volume and useful life, or that engines with smaller cylinder volumes wear out faster than engines with larger cylinder volumes. Smaller engines are also installed in smaller equipment and the relative work expectation is no greater than larger engines in larger equipment. Most engines covered by this rule are built to operate at full load/rated speed most of the time. Therefore, in relative terms, engines are generally equally stressed during their lifetime regardless of their size or power. For the above reasons, EPA does not believe it is appropriate to define a shorter useful life for all engines under a specified cylinder volume. EPA has provided a means for a manufacturer to provide evidence that would allow severe service engines to be held to a shorter useful life.

Based on engine manufacturers input and analysis of comparable on-highway engine information, EPA considered and rejected specifying more than one useful life category for large nonroad CI engines. Whether engines within an engine family use different components, or are installed in equipment of different severity, the fact that any one engine family will likely span the full range of useful lives (i.e., 6,000 to 10,000 hours) would make it infeasible to have multiple ranges of useful lives without greatly proliferating engine families and/or greatly complicating the selection of the worst-case certification emission demonstration vehicles.

2.2.6. Market Penetration of NO_x and Smoke Control Technologies

EPA, with input from engine manufacturers, analyzed the likely changes in engine technology that would be driven by the requirements of this FRM. This was not an easy task considering the diversity of engines and equipment potentially impacted by this rule. The task was also complicated by a lack of available information about specific engine sales and the percentage of sales used in each equipment type. While some manufacturers provided this information, most were unwilling to do so, citing concerns that leakage of this information to the public would provide their competitors an unfair advantage over them in the marketplace. EPA has supplemented the available industry information with information collected from contractors, state agencies, marketing brochures and reports, information from test programs, and EPA's analysis of its own on-highway heavy-duty data base. From these diverse sources EPA developed a list of assumptions concerning the types of technology that would be needed to meet the standards in this FRM and the impact on market mix.

2.2.6.1. Industry Input--The general technical assumptions were shared with engine manufacturers and a number of manufacturers elected to provide feedback. The respondents were Caterpillar, Cummins, Detroit Diesel, Deutz, Ford-New Holland, Komatsu-Dresser, Kubota and Yanmar. The assumptions were adjusted after consideration of industry comments and used in the draft Regulatory Support Document to the NPRM. The responses are shown in Table 2-09 and discussed below.

In three of the assumptions, manufacturers had indicated prior to the NPRM that they anticipated higher engine costs would result should we adopt HC, CO and PM standards in the FRM. However, after further study, commenters to the NPRM stated that no additional hardware costs would result from the addition of the HC, CO and PM standard as long as the standards were consistent with those adopted by California. This document does not revise the assumptions as reported, however, the new information has been added as an additional unreviewed assumption for consideration by EPA in adjusting the hardware cost figures for the FRM.

Assumption: It is expected that the market mix of indirect injection (IDI) engines to direct injection (DI) engines will not change as a result of emission standards in this rule.

As explained elsewhere in this document, IDI engines produce lower NOx emissions than DI engines. However, the industry has been rapidly moving towards DI engines because of superior fuel economy. EPA believes that some IDI engines that might have been phased out sooner may be kept in production longer due to this rule. However, since the cost to convert back to IDI would be much more than applying less expensive technologies to DI engines, there will be no movement back to IDI. IDI engine families are approximately 2% of the total number of families now in production. Most manufacturers agreed with EPA's assessment. However one manufacturer said it would change one DI family to IDI for this rule and another said it would change one family to meet the California standards.

Assumption: There are few IDI engines and few naturally-aspirated engines over 130 kW (175 hp). Therefore, only the IDI and naturally-aspirated engines between 37 and 130 kW (50 and 175 hp) will be considered in the technology market mix penetration estimates.

EPA determined that the error caused by ignoring those few IDI and naturally-aspirated engines above 130 kW (175 hp) will be negligible. Manufacturers agreed that this was a reasonable approximation.

Assumption: Most naturally-aspirated DI engines will meet the NOx and smoke standards with changes to the fuel system, combustion chamber, and/or swept volume. Turbocharging will not be needed unless standards are adopted for HC and PM emissions.

Meeting NO_x and smoke standards is usually only a matter of retarding the injection timing, resulting in about a 3% to 5% loss in performance and fuel economy. To regain this loss the manufacturer may increase injection pressure and change the injector nozzle tip angle and/or hole size, change the injection timing strategy, or possibly increase the swept volume of the engine. Four of six manufacturers agreed that turbochargers will not be needed to meet NO_x and smoke standards.

Manufacturers asked EPA to adopt standards conforming to the 1996 MY

California rule. EPA had noted in the draft Regulatory Support Document to the NPRM that, if the Agency were to adopt California standards in a final rule, a number of manufacturers reported they would have to use turbochargers to meet the HC and PM emission standards. However, commenters to the final rule reported that no additional hardware would be required as long as the HC and PM standards were consistent with those adopted in California. As this is the latest information available, and no actual emission data has been submitted demonstrating the need to convert naturally-aspirated engines to turbocharged engines, EPA believes that no additional turbochargers will be needed to meet the FRM requirements.

Assumption: Engines covered by this notice will not require low sac injectors to meet the NO_x and smoke standards. However, low sac injectors are generally necessary to maintain lower HC emissions.

Low sac injectors affect only HC and do not affect NO_x and smoke. All manufacturers agreed on this assumption.

Traditional injector designs typically maintain a small reservoir of fuel at the injector tip between injection events. A percentage of this fuel may leak into the combustion chamber between power strokes and escape the chamber as unburned fuel. The low sac injector eliminates the need for this reservoir of fuel and thus, in large part eliminates this source of HC in the exhaust stream.

EPA is assuming that use of low sac injectors will not increase to meet this FRM, except when fuel pump upgrades occur. When newer fuel pump models that perform at higher pressures are used, low sac injectors will likely be used. Low sac nozzles are included directly in the fuel system improvements line for both Table 2-10 and Table 3-02. Since pump modifications will likely increase by 55 percent, the estimate of increase in low sac injector use is also 55 percent.

Assumption: Some turbocharged engines will need extra boost and jacket water aftercoolers (JWC) to comply with the standards.

As in the previous assumption above, turbocharged engines will need only retarded injection timing and smoke control systems to meet emission standards. Some manufacturers may need to improve aftercooling and/or increase boost to get power and fuel economy back. Should California standards for HC and PM emission be considered, some manufacturers will also need to increase the boost and cooling to improve PM. There was general agreement on this assumption.

Assumption: Turbocharged engines will almost always require use of a smoke control device to meet the required smoke standards. Conversely, naturally-aspirated engines will seldom need a smoke control device to meet the standards.

If, for estimating purposes, we assume that all naturally-aspirated engines have no smoke control device and all turbocharged engines have a smoke control device, the error will be small. Therefore, our technology changes table in Chapter 2.2.6.2 (Table 2-10) assumes this. There was general agreement on this assumption.

Assumption: Air-to-air aftercoolers are used in limited high output applications. It is expected that no additional use of this technology will be needed to meet the NOx and smoke standards. However, this technology might be necessary should EPA adopt California's HC and PM emission standards.

There was general agreement to this assumption, although one manufacturer pointed out that air cooled engines could not use jacket water so any aftercooling must be with air. To meet the California standards, however, several manufacturers had said in the pre-NPRM survey that they would not rule out air-to-air aftercoolers although, as described in Chapter 2.2.1.7, their application to nonroad was more difficult than on-highway. Subsequently, commenters to the NPRM stated that no additional hardware would be
required should EPA adopt the HC and PM standards adopted by California in the FRM. Therefore, based on the latest available information, EPA believes this assumption still holds.

Assumption: In-line fuel pumps will not be needed to meet the standards. In-line fuel pumps would be required for those engines with fuel systems which cannot otherwise meet the incremental fuel pressure increases needed if the California standards for HC and PM emissions were adopted by EPA.

All seven of the manufacturers that responded to this assumption said that in-line high pressure fuel systems would not be needed to meet requirements of this rule. Three of the six manufacturers that responded to this assumption said that in-line pumps would be necessary to meet the

Table 2-09
Pre-NPRM Responses by Engine Manufacturers to EPA Technology Mix Assumptions

Assumption	Response for the EPA NOx and Smoke Proposal			Response for the CARB 1994 NOx, HC, CO, PM, and Smoke Standards		
	agree	disagree	No Answer	agree	disagree	No Answer
The market mix of indirect injection (IDI) engines to direct injection (DI) engines will not change as a result of standards proposed in this rule.	5	1	3	4	2	3
There are few IDI engines and few naturally-aspirated engines over 175 hp. Therefore, only the IDI and naturally-aspirated engines between 50 and 175 hp will be considered in the technology market mix penetration estimates.	4	1	4	2	2	5
Most naturally-aspirated DI engines will meet the proposed standards with changes to the fuel system, combustion chamber, and/or swept volume. Turbocharging will not be needed since standards are not proposed for HC, CO, and PM emissions.	4	2	3	0	9	0
Engines do not require low sac injectors to meet the proposed standards.	5	0	4	0	5	4
Some turbo engines will need extra boost and jacket water aftercoolers.	5	1	3	6	0	3
Turbocharged engines will require smoke limiters. Naturally aspirated engines won't need smoke limiters.	6	1	2	6	1	2
Air-to-air aftercoolers will not be needed.	5	1	3	3	3	3

In line fuel pumps will not be needed.	7	0	2	3	3	3
Aftertreatment devices are not necessary.	6	0	3	6	0	3
Manufacturers will choose technologies without loosing power or fuel economy	5	4	0	5	4	0

California 1996 MY standards. However, commenters to the NPRM stated that no additional hardware would be required should EPA adopt the HC and PM standards adopted by California in the FRM. EPA believes that manufacturers will upgrade existing fuel systems to incrementally increase fuel injection pressure and to incorporate other refinements in order to maintain fuel economy and performance without switching from rotary pumps to more expensive in-line pumps.

Assumption: Aftertreatment devices will not be necessary to meet the standards.

There was total agreement on this assumption.

Assumption: Engine manufacturers will choose a technology mix that not only ensures the standards are met, but will also maintain the power and fuel economy at levels that will minimize the impact of engine changes on equipment.

Five manufacturers agreed with this assumption and four manufacturers disagreed. Those that disagreed thought that they would not be able to maintain the fuel economy and performance. Those manufacturers that agreed included manufacturers of small naturally-aspirated engines which are most likely to have trouble maintaining fuel economy and performance while reducing emissions. Engine manufacturers will experience substantial pressure from the market to minimize increases in fuel consumption and decreases in performance. EPA has determined that applying available engine technology can eliminate fuel consumption increases and power losses at the lowest cost to consumers. That is the cost applied to this regulation in Chapter 3.

In order to use the ten general technical assumptions discussed above to construct an estimate of the fleet penetration of various technologies caused by this rule, additional assumptions were added based on data acquired by EPA before the NPRM and information acquired during the comment period. The assumptions are as follows.

Assumption: Two percent of engines are IDI.

EPA has estimated from published catalog data, that there would be about 213 engine families and of those four engine families (about 2% of engine families) would be IDI (see Table D.1 in Appendix D). Since no sales data were available, and based on the assumption that these engines will not be converted to DI, EPA assumed the same percentage of engines would be sold as IDI in the 1996 MY.

Assumption: IDI engines will need little more than minor adjustments to meet the rule requirements.

Four of the five manufacturers that responded to this assumption agreed. All agreed that the job is easier with IDI than with DI, and the one that disagreed with the assumption stated that they will change some small DI engines to IDI. Data collected from tests on one IDI engine provided to EPA for testing were reported previously in Table 2-05. These data support this conclusion.

Assumption: About 35% of all engines are naturally-aspirated.

EPA has estimates ranging from 20% to 35% but considered that using the higher number would correspond to "worst case". This is based on manufacturers' statements that the naturally-aspirated DI engines would be the hardest engines to redesign to improve emission performance.

Assumption: About half of the turbocharged large nonroad CI engines are currently equipped with smoke control systems and about one quarter have jacket water aftercoolers.

Estimate based on limited data submitted confidentially by manufacturers and gathered by EPA from market brochures. These are rough projections.

Assumption: Adopting the HC, CO and PM emission standards will result in no additional hardware costs to comply with emission standards.

In the draft RSD, EPA had projected that additional hardware might be needed if the Agency required compliance with HC, CO and PM standards in addition to the NO_x and smoke standards. Based on comments to the NPRM, manufacturers stated that adoption of the California standards for HC, CO and PM emissions would result in no additional cost to comply beyond that required to comply with the NO_x and smoke standards. EPA did adjust hardware cost figures based on updated information from commenters. However, commenters did not identify whether the HC, CO and PM emission standard requirements had any bearing on those figures.

2.2.6.2. EPA Assessment of Market Mix--Using the above assumptions, Table 2-10 lists the usage prediction of the technologies that will be applied to meet the adopted emission standards. Since these are technologies that are currently used on some percentage of the engine sales fleet, the first column estimates the current percent penetration of each of these technologies by the 1996 model year if no regulations had been promulgated. This column represents that base from which EPA has predicted the changes due to regulation. The second column is EPA's estimate of the percent of the engine sales fleet that will use each of these technologies upon full implementation of this rule (i.e., the 2000 model year). These two columns are based on EPA's best estimate from the data available from industry, market data, and EPA's own on-highway regulation experience.

The third column is the projected change in each technology listed due to adoption of emission standards. EPA projects that when the standards have been fully implemented, about 2% of the engines will experience no change since all IDI engines (i.e., 2% of all engines) will meet the regulation requirements without fuel injection timing retard. The remaining 98% of the engines will have had their timing retarded. The mix of IDI and DI will not change significantly. Although one manufacturer said they would change one engine family from DI to IDI it was not enough to change the rounded percentage calculation. EPA expects that 55% of the engines will need improvements in the fuel system, 20% using rotary pump systems and 35% using in-line pumps or unit injected systems. The changes include upgrades to increase injection pressures, improved timing control, increased use of medium or low sac injectors, and better spray patterns. No engine currently using rotary fuel pump systems will need to convert to in-line pump or unit injector systems. Without averaging, banking and trading, naturally-aspirated engines should decline by 5% with a corresponding increase in turbocharged engines to 70 % of production, with jacket water aftercooling increasing from 10% to 25% of the total and no change in air-to-air aftercooling. Since the averaging, banking and trading program provides substantial flexibility for manufacturers to average small naturally-aspirated engines against larger turbocharged engines, EPA believes that no additional turbochargers will be needed to meet the FRM requirements. All turbochargers need either smoke limiters or waste gate technology, so use of smoke control devices will increase from 30% to 70%.

Table 2-10
Effect of Emission Standards on Technology Mix

Technology	Market Percentages in 1996 MY with no standard	2000 MY Market Percentages With EPA Standards	Additive % Change due to EPA Standards
No Changes	----	2 %	2%
Retard timing	0%	98 %	98%
Indirect injection	2%	2 %	0%
Direct injection	98%	98 %	0%
Fuel System Improvements - Rotary Systems	0%	20 %	20%
Fuel System Improvements - In-Line or Unit Injector Systems	0%	35 %	35%
Naturally-aspirated	35%	30 %	-5%
Turbocharged	65%	70 %	5%*

JWC aftercooled	15%	25 %	10%
Air to air coolers	5%	5 %	0%
Waste Gate	0%	30%	30%
Smoke limiter	30%	40 %	10%

* With averaging, banking and trading, EPA expects this number will be 0%.

2.3. Impact on Equipment

The needs of nonroad equipment users are somewhat different than on-highway users. Fuel economy is not as important because of the lower cost of fuel (no road taxes), although it is important that a given piece of equipment operate for a full shift without refueling. Power to weight ratio is less important for some types of equipment (tractors). Durability in a more hostile environment is more important, especially in those areas where service facilities are less available. The ability to survive and perform well in a dusty environment is important to nonroad users since they often operate in such an environment. Finally, large nonroad CI engines often have a flatter torque curve than on-highway engines due to the greater lugging requirements experienced in many nonroad applications.

2.3.1. Industry Information on Equipment Impacts.

Before the NPRM was published, equipment manufacturers provided EPA with their assessment as to the impact of proposed regulations on equipment manufacturing costs. Fifteen manufacturers replied to one or more of the questions posed in Table 2-11. Of the respondents, four were part of large integrated companies. It appeared that all but one responded to the preliminary information received from their engine suppliers about the 1996 California rule.

Equipment manufacturers generally stated that they did not know what engine manufacturers would have to do to comply with emission standards, and based on that, what redesign would be necessary to the equipment itself. Many of these responses were not quantified, but instead used qualitative statements such as "expensive changes" and "increased fuel consumption." Many of the responses presented the worst-case assumptions. For example, one manufacturer said that there would be a 20% loss in power, which seemed excessively high in light of other test data showing 1 to 5 percent maximum power loss before using restorative technologies.

The equipment manufacturers' responses were compiled in three categories and reported in Table 2-11. The three categories were impacts on packaging, powertrain, and operation and maintenance costs.

Table 2-11

Equipment Manufacturers' Responses to EPA Questions Prior to NPRM

Question	major	minor	No Answer	Comments
1. What is the impact of regulation on power train design?	4	2	9	Poor low speed response can be sacrificed in some applications (no reason to modify power train). Hydraulic pump and transmissions changes may be needed to overcome power & speed losses.
2. What is the impact of regulation on packaging design?	1	1	3	Increased cooling may be necessary and would be limited by design constraints. Sheet metal changes necessary to accommodate engine changes. A larger fuel tank is needed for several applications. Noise reduction modifications may be necessary.
3. What is the impact of regulation on operation/maintenance requirements?	8	2	5	These responses seem to be based on what their engine suppliers have told them: less reliable, less durable, loss in power, additional maintenance and wear, and performance degradation. Two of 15 OEM's aren't expecting these problems.

Question: What is the impact of the regulation on powertrain design?

Of the fifteen manufacturers that responded to the enquiry, nine expressed general concern and lack of knowledge as to what would happen. Two manufacturers thought that there would be no major changes to drivetrain, and four thought that there would be major changes. Concerns were centered around loss of power and lower speeds. One manufacturer claimed the demise of direct drive although another division of the same company foresaw no major changes.

Question: What is the impact of the regulation on packaging?

Eleven manufacturers claimed major changes, three were generally concerned and lacked the necessary information to respond, and one thought there would be no major changes. Major concerns were sheet metal, radiator size, and fuel tank size. This was based on equipment manufacturers expectation that the cost of a 3% to 5% increase in fuel consumption and a 3% to 5% increase in heat rejection to the radiator from the unregulated nonroad engine design would be passed on by the engine manufacturer. Since this is not the most cost-effective approach, EPA does not expect it will happen (see EPA assessment in Chapter 2.3.2).

Question: What is the impact of the regulation on operation/maintenance?

Five manufacturers cited the loss of power or performance degradation, 4 were concerned with increased fuel consumption of about 5%, and 2 cited increased maintenance or loss of reliability. On the other hand one thought there would be no loss of performance or durability and one thought there would be no effect on maintenance, reliability, durability, or serviceability. Five did not respond.

At the public hearing, after the NPRM was published, EPA and USDA requested that manufacturers submit additional data substantiating performance loss and the likely cost. While many commenters provided cost estimates should a performance loss occur, no commenter provided data demonstrating that a fuel consumption penalty or power loss was a necessary result of the adopted emission standards. Additionally, no commenter refuted the validity of data provided in the NPRM by EPA as evidence that performance impacts of meeting the emission standards would be minimal. One commenter stated that, over time, it expected regulated systems could be optimized that retain or lower fuel consumption.

2.3.2. EPA Assessment

EPA has determined that the engine changes required to meet the emission standards should have a minimal impact on equipment design. EPA considered factors such as impacts on engine packaging, power, and fuel consumption.

Based on input from engine manufacturers with respect to what technologies will actually be needed, EPA has determined that this regulation will have minimal impact on engine packaging since the technologies predicted to be necessary in these engines such as fuel injection retard, fuel system upgrades, and combustion chamber upgrades, will not alter the external dimensions of the engine.

In Chapter 2.2.3., EPA discussed those technologies that are infeasible based on larger impact on engine packaging and longer development leadtime requirements.

Only use of turbochargers and air-to-air aftercoolers will substantially change external engine dimensions. As summarized in Table 2-10 of Chapter 2.2.6.2., EPA projects no significant new use of air-to-air aftercoolers and, with averaging, banking, and trading, no significant new use of turbochargers to comply with this rule. All remaining changes projected in Table 2-10 have little impact on external engine dimensions, and thus little to no impact on equipment package design.

EPA has determined that the technologies necessary to restore engine performance and fuel economy are available such that the changes will have minimal impact on equipment design. As seen in Chapter 2.4.1., once fuel injection timing is retarded sufficiently to meet the NO_x standards, the remaining technologies projected to meet the requirements of this regulation are used to restore or maintain engine performance (i.e., restore fuel economy and power). The technological tools available to manufacturers, as discussed in Chapter 2.4.1., are various combinations of fuel pump and nozzle changes, combustion chamber changes, engine derating, turbocharger boost increases, aftercooler efficiency gains or new use, and smoke control systems to reduce smoke levels. As discussed in Chapter 2.2.1., these are internal engine modifications meant to minimize impacts on performance and engine packaging.

EPA has determined that the projected engine changes discussed in Chapter 2.2.1. are feasible within the adopted leadtime and can be implemented cost-effectively (see also Chapter 3.2.). Engine manufacturers have stated they are responsive to their customers' (the equipment manufacturers') needs and engine manufacturers' responses to EPA's technical assumptions in Chapter 2.2.6.1. demonstrate that they are expecting to use the technologies identified by EPA as necessary to minimize equipment impacts.

Equipment manufacturers have not provided evidence to support their claims that EPA's regulation will cause significant equipment impacts. Comments to the NPRM by equipment manufacturers centered around an unsupported technical assumption that regulated engines would experience a performance loss. Commenters stated that regulated engines would suffer higher fuel consumption, lower power, and as a result higher heat rejection. As a result of these assumptions, commenters estimated a need to increase cooling capacity and/or cooling fan speed, and to increase the size of the fuel tank to maintain work capacity per fill-up.

By contrast, engine manufacturers and EPA have provided evidence and test data summarized in this document showing that the impact of changes on equipment design are minimal. In Section 2.4, EPA has laid out the rationale for its conclusion that fuel consumption and power will be minimally impacted by this regulation. In most cases, there would be no need to increase cooling capacity or fuel tank size.

2.4. Impact on Operation and Maintenance

At the adopted emission standard levels, effects on operation and maintenance will be minimal. This section discusses briefly EPA's assessment of the effects of this FRM on fuel consumption, power, and maintenance.

2.4.1. Fuel Economy and Power

EPA recognizes that the first step manufacturers would take to reduce NO_x emission would be to retard fuel injection timing. Chapter 2.1.6. presents the results of an EPA study that demonstrated that retarding injection timing by 4 to 7 degrees is required to allow the current production nonroad engine to meet the NO_x emission standard with no further modification. Table 2-12 compiles the BSFC and Power data from six engine configurations that produced NO_x emission levels at or near the 9.2 g/kW-hr (6.9 g/bhp-hr) level when retarded by 4 to 7 degrees. Table 2-12 shows that, taken by itself, fuel injection retard could result in a 1 to 5 percent increase in fuel consumption and a similar loss in power. The nonroad market is sensitive to any losses in power large enough to require power train changes or increases in fuel consumption large enough to cause an equipment application to be fueled more than once during a full working shift. Most manufacturers have designed their fuel tanks with sufficient excess capacity to accommodate small increases in fuel consumption. However, EPA has concluded that the amount of fuel economy loss and power loss realized under the adopted emission standards can be recovered within a reasonably short leadtime and at a reasonably low cost by applying engine technologies discussed in Chapter 2.2.1. Some examples of these technologies are as follows.

- Increasing the air/fuel ratio by increasing turbo boost, aftercooling, or derating will in many cases improve fuel economy and performance at any particular emission level.
- Increasing injection pressure will atomize the fuel better, get the main combustion over quicker, which will again result in improvements in fuel economy and performance at any particular emission level.
- Adding fuel injection timing control will allow more efficient fuel injection timing for all loads and speeds. Calibrators can then optimize emissions and fuel economy.

Table 2-12
Impact of Injection Timing Retard on BSFC* and Power

Manufacturer and Test Number	Performance Parameter	Baseline Level	Degree Retard	Retarded Level	% Difference
John Deere A-3	Power (HP) (kW)	141 189	7	134 180	- 5 %
	BSFC (lbs/bhp-hr) (g/kW-hr)	0.348 158		0.363 221	4 %
John Deere A-4	Power (hp) (kW)	141 189	7	137 184	- 3 %
	BSFC (lbs/bhp-hr) (g/kW-hr)	0.348 158		0.352 214	3 %
Cummins B-3	Power (hp) (kW)	105 141	4	100 74.6	- 5 %
	BSFC (lbs/bhp-hr) (g/kW-hr)	0.372 227		0.378 230	2 %
Detroit Diesel D-1	Power (hp) (kW)	450 603	7	--	--
	BSFC (lbs/bhp-hr) (g/kW-hr)	0.361 220		0.372 227	3 %
Detroit Diesel D-3	Power (hp) (kW)	450 603	9	--	--
	BSFC (lbs/bhp-hr) (g/kW-hr)	0.361 220		0.379 230	5 %
Ford New Holland F-3	Power (hp) (kW)	130 174	5	131 176	1 %
	BSFC (lbs/bhp-hr) (g/kW-hr)	0.337 205		0.314 191	- 7 %

* Note: Detroit Diesel BSFC is at maximum power and the others are over the 8-mode cycle.

Engine manufacturers have indicated (see Chapter 2.2.6.1.) that they will use combinations of these technologies to minimize the performance losses associated with meeting the emission standards. Faced with the options described above, equipment manufacturers will, in most cases, choose to pay the relatively small increase in per engine cost required to maintain an engine's pre-regulation fuel economy to avoid a potentially long delay in leadtime and higher cost to redesign their equipment to accommodate fuel economy or power losses accompanying low cost NO_x emission reduction strategies.

To regain the loss of power and fuel economy a manufacturer would add some combination of technologies. For naturally-aspirated engines, the options currently identified by EPA and industry are a moderate increase in injection pressure, mechanical fuel injection timing control, larger displacements, and redesigned combustion chambers. For turbocharged engines, the options are higher boost pressures, air to water aftercooling, moderate increase in injection pressure, mechanical fuel injection timing control, and redesigned combustion chambers.

If the NO_x standard had been set lower than the 9.2 g/kW-hr (6.9 g/bhp-hr) level additional, more expensive and invasive technology would have to be used. Among these are technologies such as extremely high pressure in-line pumps or unit injectors, turbochargers added to naturally-aspirated engines, air to air aftercoolers in place of air to water, and electronic fuel control.

EPA history with on-highway engines shows that the emission standards can be met without impacting fuel economy or engine power. While the impact of specific technologies used to lower emissions can be to reduce fuel economy or power, in the on-highway market manufacturers have historically used a combination of technologies that not only maintain the fuel economy and power of an engine redesigned to meet emission requirements, but have actually improved fuel economy and increased power. EPA analyzed the impact of increasingly stringent emission standards on fuel consumption and power by comparing fuel consumption and power for engine models over a number of model years when emission standards were changing. Table 2-13 shows the percent change in emissions, fuel economy, and power from on-highway engines between the 1988 and the 1991 model year.

From the 1988 to the 1991 model year HC emission decreased on average by 44 %, CO emission decreased by 29%, NOx emission decreased by 37%, particulate matter(PM) decreased 51% and smoke decreased about 45%. During this period of substantial improvement in emission performance, manufacturers also managed to realize a specific power output <u>increase</u> of 4% and a fuel consumption <u>decrease</u> of about 1%.

These results are consistent with those presented by Caterpillar Inc. in their historical analysis plotting the best rated BSFC (usually at 1800 RPM) of Caterpillar's production engines at various points in Caterpillar's history from the 1930 to the 1990 model year. This analysis was presented at the American Petroleum Institute Off-Highway Forum conducted on September 14, 1993 in Milwaukee, Wisconsin. This analysis shows a second order BSFC reduction by model year beginning in 1930, with the slope of the reduction becoming steeper in the last twenty years when emission regulations were in place. This analysis has been submitted to the docket in a January 6, 1994 letter to Ted Trimble of EPA from Jim Sibley of Caterpillar.

Table 2-13
Average On-Highway Emission Factors

Performance Parameter		1988	1991	% Change
HC	(g/bhp-hr) (g/kW-hr)	0.66 0.88	0.37 0.49	- 44 %
CO	(g/bhp-hr) (g/kW-hr)	2.86 3.83	2.04 2.73	- 29 %
NO_x	(g/bhp-hr) (g/kW-hr)	7.13 9.55	4.49 6.01	- 37 %
PM	(g/bhp-hr) (g/kW-hr)	0.45 0.60	0.22 0.29	- 51 %
Smoke (% Opacity)	Acceleration	12.1	7	- 42 %
	Lug	6.5	2.9	- 55 %
	Peak Load	21.4	12.3	- 43 %
BSFC	(lbs/bhp-hr) (g/kW-hr)	0.359 219	0.355 216	- 1 %
Power	hp/in^3 kW/l	0.476 21.7	0.494 22.5	4 %

On-highway experience demonstrates that it is technologically possible, even probable, that manufacturers will design engines that make fuel efficiency gains even as they are required to meet tighter, more demanding emission standards.

2.4.2. Maintenance

EPA's review of a number of available on-highway engine service manuals revealed no significant difference in required service between engines that are currently built with the various component packages projected to be needed to meet the emission standards adopted in this FRM (see Table 2-10). The full range of technologies expected to be used are current production components with a long history of use both in on-highway and nonroad applications. The EPA review uncovered no unique operation or maintenance requirement for any expected changes in technology caused by this regulation. Therefore, EPA has concluded there will be no significant impact caused by changes in operation and maintenance requirements in response to this rule.

2.5. Impact on Noise and Safety

No hard test data has been gathered on either noise or safety but based on the accumulated knowledge and experience of the EPA staff the following conclusions can be drawn.

2.5.1. Noise

Due to the retarded fuel injection timing, the detonation, which is the noise heard as the typical diesel "knock" will be reduced. The later timing might also increase the exhaust noise slightly but exhaust is quite easily muffled, detonation is not.

Heat rejection to the cooling water will be increased if fuel economy is allowed to decrease. In that case, fan noise will tend to increase if larger fans are used or if fans are run at higher tip speeds. However, EPA has determined, through analysis of data and input from manufacturers discussed previously, that technologies will be applied to engines to restore the efficiency losses associated with fuel injection timing retard. Therefore, heat rejection changes will be minimized, and its impact on noise will likely be insignificant.

2.5.2. Safety

There are no apparent safety issues attached to this rule. Manufacturers will likely use only proven technology that is currently used on on-highway and nonroad engines. This regulation presents no apparent new safety issues associated with use of these technical solutions.

2.6. Feasible Emission Standards

EPA has determined that the NO_x emission and smoke standards are technologically feasible and can be achieved through the application of technologies that will be available within the allotted leadtime for reasonable cost. There are a broad range of technologies currently available for on-highway engine use that are capable of ensuring reductions well below the emission standards as demonstrated by the range and average of NO_x emission and smoke levels for on-highway heavy-duty diesel engine families certified for the 1990 model year as shown in Table 2-14.

Table 2-14
Fleet NO_x Emission and Smoke Statistics for
1990 Model Year On-Highway Heavy-Duty Diesel
Engine Family Emission Data Engines

	NO_x (g/bhp-hr)	ACC (percent)	LUG (percent)	PEAK (percent)
AVERAGE	5.2	12	6	20
STD.DEV.	.5	4	3	8
MAX	6	20	14	45
MIN	3.5	2	1	3
STANDARD	6	20	15	50

EPA has determined that a subset of these technologies (discussed below and described in Chapter 2.2.1.) can be effectively used to meet the requirements of this regulation and are compatible with nonroad applications. EPA believes that these standards can be met without substantial engine redesign, and thus can be implemented by the required model years.

2.6.1. Effect of Available Technologies on Emissions and Performance

Chapter 2.2.1. describes the technologies that EPA and industry have determined will be used and will be capable of meeting the emission standards. These technologies include fuel injection base timing changes, fuel injection pump improvements such as variable injection timing and increased injection pressures, fuel injection nozzle modifications, combustion chamber modifications, air to water aftercooler improvements and additions, turbocharger improvements, and increased application and optimization of smoke control systems. These technologies will allow all engines covered by this regulation to meet the emission standards while substantially maintaining fuel economy and power (see also Chapter 2.4.1.). Additionally, these technologies are not impeded by certain constraints specific to nonroad engines that affect the feasibility of using other technologies, as will be discussed in Chapter 2.7.

An EPA test program of a number of production nonroad engines demonstrated that the average large nonroad CI engine can be brought into compliance with the NO_x emission standard by retarding injection timing alone. For the NO_x levels required by this regulation, EPA observed that retarding injection timing causes small increases in HC and PM emissions and small increases in brake specific fuel consumption (BSFC) and losses in brake horsepower (BHP). However, EPA believes these impacts are manageable because they can be offset by use of various combinations of technologies as discussed in Chapter 2.4.1. For example, variable fuel injection timing and increased fuel injection pressure improve atomization and timing optimization, thus providing more fuel injection base timing flexibility to recover fuel efficiency and power losses without losing the NOx reduction benefit. Data from this test program, listed in Table C-01 of Appendix C, are summarized in Table 2-15.

The test program results demonstrate that the amount of NOx emission reduction per degree of fuel injection timing retard as tabulated in the column titled "Emission Change per Degree Retard - NO_x 8-Mode," was consistent for most of the current production nonroad engines tested in this program. These were engines with base NO_x emission levels around 12.1 to 16.1 g/kW-hr (9 to 12 g/bhp-hr). At least one manufacturer indicated that this observation is consistent with its observations as well.[6] NO_x emission is reduced by approximately 1.0 g/kW-hr (0.8 g/bhp-hr) for each degree the fuel injection timing is retarded.

Generally, a manufacturer would be capable of calibrating the fuel injection timing to meet its NO_x emission target level while minimizing BSFC increase and power loss. Averaging all the BSFC and Power percent change data, then averaging them again for only those engines that were reduced to just above 8.0 g/kW-hr (6.0 g/bhp-hr) NO_x, a reasonable range of expected BSFC increase and power loss expected under this rule can be estimated. The average fuel consumption increase would be approximately 2% - 3 % and the average power loss would be approximately 3% - 4 %. These losses in efficiency can be substantially offset using the technologies listed previously.

As discussed in Chapter 2.4., EPA believes these technologies will be adequate to offset any fuel consumption increases or power losses caused by this rule. Design modifications to fuel pumps and nozzles to increase pressure, introduce variable timing, and affect spray pattern and atomization all act to not only reduce NO_x emission at lower levels of injection timing retard, but also act to encourage more complete combustion, thus increasing engine efficiency (i.e., reducing fuel consumption and increasing power) while also reducing HC and PM emissions. Modifications to combustion chamber design that increase displacement, which allows derating, or that change the shape of the combustion chamber, which impacts complete combustion,

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[6] Meeting with Engine Manufacturer Association members on October 28, 1992.

can also be optimized to improve complete combustion and increase engine efficiency. Additional modifications are also available to those engines that are currently turbocharged. Modifications that increase intake air density such as increased turbocharger boost or new or more efficient air to water aftercooling can

Table 2-15
Effect of Fuel Injection Timing Retardation on Emissions From Current Production Nonroad CI Engines

Engine Manufacturer and Test Number		NO$_x$ Level at Degree of Retardation				Emission Change per Degree Retard			Percent Change	
		0°	4°	7°	9°	NO$_x$ 8-mode	HC FTP	PM FTP	BSFC*	power
John Deere A-3	g/bhp-hp	11.8		6.3		-0.8	0.1	0.08	+4%	-5%
	g/kW-hr	15.8		8.4		-1.0	0.1	0.1		
John Deere A-4	g/bhp-hr	11.8		7.1		-0.7	0	0.06	+3%	-3%
	g/kW-hr	15.8		9.1		-0.9		0.08		
Detroit Diesel D-1	g/bhp-hr	12.1		7.0		-0.7	0	0	+3%	---
	g/kW-hr	16.2		9.3		-0.9		0.02		
Detroit Diesel D-3	g/bhp-hr	12.1			5.8	-0.7	0	0.03	+5%	---
	g/kW-hr	16.2			7.7	-0.9		0.04		
Ford New Holland F-3	g/bhp-hr	9.3	5.9			-0.8	0.4	0.1	-7%	+1%
	g/kW-hr	12.4	7.9			-1.0	0.5	0.1		
Cummins B-3	g/bhp-hr	11.1	5.6			-1.4	0.07	0	+2%	-5%
	g/kW-hr	14.8	7.5			-1.8	0.09	0		
Average of All Data	g/bhp-hr	11.4	5.8	6.7	5.8	-0.9	0.10	0.05	+2%	-3%
	g/kW-hr	15.2	7.8	8.9	7.8	-1.1	0.12	0.06		
Average of >6.0 NO$_x$ Engines	g/bhp-hr	11.9		6.7		-0.7	0.03	0.05	+3%	-4.0%
	g/kW-hr	15.9		8.9		-0.9	0.04	0.07		

*Reported in BSFC over entire 8-mode cycle. Comparable table in preamble reports BSFC at maximum power.

increase efficiency.

Increases in PM emission and, to a lesser extent, HC emission are also common as fuel injection timing is retarded on any particular large nonroad CI engine. However, Table 2-15 shows that PM and HC emission increases between 4 and 9 degrees of fuel injection retard are small enough to be restored using the technologies described above. For example, since the fuel injection system modifications expected would improve atomization, the time needed to complete combustion would be shortened, thus reducing HC and PM emissions (see Chapter 2.2.1). This is consistent with the technical literature (an example of which is pictured in Chapter 2.7, Figure 2-02) showing that NO_x to PM emission trade-off is reasonably flat down to approximately a 8 to 9.3 g/kW-hr (6 to 7 g/bhp-hr) NO_x level of control, below which the trade-off emissions increase exponentially.(12,13,14) The remainder of this section discusses information on prototype engines which exemplify how these emission trade-offs can be mitigated.

John Deere provided EPA with one early prototype engine and one current nonroad production engine from each of two engine models. While these prototypes were not yet optimized, they do provide the best available approximation to the technologies from the list of feasible approaches discussed above.[7] For each of the two engine sets, Table 2-16 shows changes in emissions, fuel consumption at maximum power[8], and maximum horsepower due to modifications made to the prototype engine compared to the comparable production engine.

Results of Table 2-16 show that the NO_x and smoke standards can be reasonably achieved without causing significant increases in other pollutants or significant losses in fuel efficiency or power. The prototypes met all emission standards. HC emission increased in one case but was still below the standard. The improvements, observed in HC and PM emissions measured over the transient FTP, provide a concrete example of how the same technologies can be used to both offset fuel efficiency and power losses, and directionally reduce the negative impact of fuel injection timing retard on HC and PM emissions. This is consistent with current

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[7] The 140 hp engine uses a somewhat low-efficiency air-to-air aftercooler that is not on the list. However, this engine also uses a range of technologies from the list of feasible approaches. The 75 hp engine only uses technologies on the list.

[8] Since the prototype engines are not yet optimized, EPA chose to use the BSFC at maximum power as a more accurate indication of potential fuel efficiency gains. BSFC over the test cycle is useful once the engine has been optimized over the entire operating range.

understanding of each of these technologies, as discussed in Chapter 2.2.1, that the specific technologies EPA expects to see being used to meet the requirements of this regulation often cause general efficiency gains that show up simultaneously as relatively little change in BSFC and power, and reductions in HC, CO, NO_x, and PM emissions. Refer back to Chapter 2.2.1 for specific discussion of the general trends of specific technologies.

These prototype results show NO_x levels of 8.1 g/kW-hr (6.1 g/bhp-hr), well below the 9.2 g/kW-hr (6.9 g/bhp-hr) standard, and smoke levels of 3% opacity during acceleration mode, 4% during lug mode, and 4% during peaks in either mode, all well below the 20% acceleration, 15% lug, and 50% peak standards. These prototype results, as well as the information in this document, demonstrate that the emission standards can be achieved with technologies that are feasible within the constraints of this rule and without causing significant negative impacts on BSFC, or power. As discussed in Chapter 2.3.2, applying these technologies to the engine will likely be the most timely and cost-effective manner to offset the impact of a NO_x and smoke standard on other pollutants and on fuel efficiency and power.

2.6.2. Leadtime and Cost

The technologies used on the prototype engines characterized in Table 2-16 are the closest approximation available to the technologies that can be applied within the required timeline and at low cost. Engines at or above 130kW (175hp) require the shortest leadtime. These engines are comparable to current on-highway designs and will require the least additional redesign work. Further, manufacturers have already started developing these larger engine designs to meet standards adopted in California for the 1996 model year for farm and construction engines at or above 130kW (175hp). EPA's adopted implementation date of the 1996 model year is thus reasonable and feasible for the engine at or above 130kW (175hp). As discussed below, Table 2-16 demonstrates that the same range of technologies that allow engines with power at or above 130kW (175HP) to meet the emission standards will also allow smaller engines to meet the standards. Therefore, in order to ensure that smaller engines meet the standards, manufacturers must apply the available technologies to specific engine families with horsepower less than 130kW (175HP). EPA believes that additional leadtime of one year (implementation in the 1997 model year) for engines with power from 75 to 130kW (100 to 175hp),

Table 2-16
Impact of John Deere Prototype Modification on HC, PM, BSFC and Power

Engine Modification Set Number		Power	Baseline (BL) and Prototype (P) NO_x level		Prototype Smoke (Acceleration= A Lug Mode=L Peak Load=P)			Percent Change Between Baseline Engine and Prototype Engine				
			BL	P	A	L	P	NOx 8-mode	HC FTP	PM FTP	BSFC @ Max. Power	Max. Power
1	g/bhp-hr	140 hp	11.8	6.1	--	--	--	-48 %	-15 %	-17 %	-2 %	9 %
	g/kW-hr	104 kW	15.8	8.2								
2	g/bhp-hr	75 hp	7.2	6.1	3 %	4 %	4 %	-15 %	+20 %	-5 %	1 %	1 %
	g/kW-hr	56 kW	9.7	8.2								

and additional leadtime of two years (implementation in the 1998 model year) for engines less than 75kW (100hp) is appropriate in order for manufacturers to make design changes to these smaller engines to incorporate the necessary technology.

2.6.3. Effect on Engines Below 175 Horsepower

EPA studies indicate that the NO_x emission and smoke levels of current production smaller nonroad engines produce comparable emissions to those for larger nonroad engines. EPA analyzed the emission test data comparing emissions from engines over and under 75kW (100hp). The results of this analysis are summarized in Table 2-17.

Table 2-17 is split in two parts, engines at or under 75kW (100hp) on top and engines over 75kW (100hp) on the bottom. All these engines were supplied by their respective manufacturers, through EMA, as representative of current production. Based on these data, EPA concludes that current production small engines do not generate more NOx and smoke than do large engines, at least down to 37kW (50hp).

EPA also has evidence that the same level of fuel injection timing retard will generally bring these smaller engines into compliance. The same technologies used for the larger engines can be used on these smaller engines to effectively restore efficiency loss. This was demonstrated by the results presented in Table 2-16 that show engines less than 130kW (175hp) are capable of meeting the emission standards using the technologies listed in this discussion. One of the prototype engines listed in Table 2-16 is less than 130kW (175hp) while the other is less than 75kW (100hp). The technologies used on these engines are the best available approximation of those feasible technologies listed earlier in this discussion. While some increase in HC occurred in one of the not yet optimized prototype engines, it still met the HC standard. HC and PM emissions measured over the transient on-highway FTP were reduced and fuel consumption and horsepower remained relatively unaffected.

Table 2-17
Current Production Nonroad Engines
8-Mode Emission Test Results

Engine Manufacturer & Combustion Chamber Type	Power		g/bhp-hr (g/kW-hr)				smoke % opacity		
			HC	CO	NO_x	PM	Accel	Lug	Peak
37-75kW (50 - 100hp) engines tested									
Teledyne IDI	hp	66	0.19	2.57	5.4	1	12	21	22
	kW	50	0.25	3.45	7.2	1.34			
Confidential DI	hp	51	0.92	3.94	12.5	0.44			
	kW	38	1.23	5.28	16.7	0.59			
Ford NH DI	hp	53	0.80	3.00	7.40	0.46			
	kW	39.5	1.07	4.02	9.9	0.62			
Deutz DI	hp	56	1.36	2.62	6.9	0.36			
	kW	39.5	1.74	3.51	9.2	0.48			
Ford NH DI	hp	67	0.98	8.80	7.10	0.64			
	kW	50	1.31	11.8	9.5	0.86			
Ford NH DI	hp	69	1.20	4.00	9.00	0.39			
	kW	51.5	1.61	5.36	12.0	0.52			
John Deere DI	hp	76	0.64	3.50	7.24	0.59	12	23	24
	kW	56.7	0.86	2.82	9.7	0.64			
average	hp	62	0.87	4.06	7.93	0.54	12	22	23
	kW	46.2	1.17	5.44	10.6	0.72			
75 + kW (100 + hp) engines tested									
Cummins DI	hp	105	0.75	2.20	11.10	0.41	25	6	54
	kW	78.3	1.01	2.95	14.8	0.55			
Ford NH DI	hp	130	0.70	5.58	9.27	0.96	11	26	27
	kW	96.9	0.94	7.48	12.4	1.29			
John Deere DI	hp	141	0.43	3.14	11.76	0.42	13	9	22
	kW	105	0.58	4.21	15.7	0.56			
Caterpillar DI	hp	288	1.14	1.44	6.5	0.18	31	3	60
	kW	215	1.53	1.93	8.7	0.24			
Detroit Diesel DI	hp	450	0.36	0.80	12.1	0.12	20	2	38
	kW	336	0.48	1.07	16.2	0.16			
average	hp	223	0.68	2.63	10.1	0.42	20	9	40
	kW	166	0.91	3.53	13.5	0.56			

Commenters did not contest the NO_x and smoke standards for smaller engines but requested a higher PM standards than that adopted by California for engines at or above 130kW. EPA agrees that some level of PM increase will occur for these smaller engines and has found the European proposed values will not result in increases in PM emission beyond what would occur if EPA had no PM emission standard as originally proposed in the NPRM.

Based on the information discussed above, and elsewhere in this document, EPA finds that the emission standards adopted in the FRM are feasible for the affected engines, considering the cost of implementing the necessary technology within the available leadtime.

2.7. Lowest Feasible Emission Standard

In setting emission standards for large nonroad CI engines, EPA's goal is to realize the greatest degree of emission reduction achievable through the application of technologies which will be available to these engines considering the cost of such technologies within the period of time available as well as noise, energy and safety factors.[9] Consideration of these criteria has resulted in EPA's decision to adopt the NO_x emission standard at 9.2 g/kW-hr (6.9 g/bhp-hr) and smoke standards at the current on-highway certification level as proposed in the NPRM. Additionally, for harmonization purposes, EPA has also decided to adopt standards at this time for HC, CO and PM emissions at levels consistent with those adopted by California. EPA's decision to set standards at these levels was affected in particular by the following goals: (1) EPA's intent to implement emission standards that could feasibly be met at the earliest practicable date, given leadtime constraints; and (2) EPA's concern that its methods of testing emissions accurately represent in-use emissions from nonroad engines.

It is EPA's assessment that the significant test procedure and timeline constraints that must be overcome to meet emission reductions greater than those adopted are not achievable given the timeline constraints required for implementation.

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[9] See CAA, Section 213(a)(3).

The emittant most sensitive to the feasibility limit and most critical to this regulation is NO_x. Thus, the feasibility discussion will center around EPA's ability to adopt a lower NO_x emission standard at this time.

2.7.1. Lowest Feasible NO_x Emission Standard

Under Section 213(a)(3), the emission standards in this rulemaking shall achieve the greatest emission reduction available, given the constraints mentioned above. Moreover, in determining what degree of reduction is available, EPA shall first consider standards equivalent in stringency to standards for comparable motor vehicles; taking into account technological feasibility, costs, safety, noise and energy factors.

It will not be feasible in the near future for nonroad engines to attain as low a NO_x emission standard as is currently required for on-highway engines. This is because nonroad engines operate in a very different environment than on-highway engines. These differences in operation and function create unique constraints that a nonroad engine manufacturer must consider even when designing engines that are very similar to on-highway engines.

Since this FRM represents EPA's first regulation of these nonroad engines, there has previously been no incentive for engine manufacturers to use emission performance as a design constraint. Thus, these engines currently produced for the nonroad market do not incorporate the range of emission control technologies typically used in current on-highway engines.

Nonroad operational characteristics are substantially different from on-highway characteristics. Thus, the process of setting standards for engines installed in nonroad equipment is influenced by some unique constraints that EPA has not faced when regulating on-highway engines. For example, while on-highway trucks generally haul merchandise as their only function, nonroad equipment perform a large number of functions, among them hauling, digging and loading. These functional differences limit the ability of existing test procedures to adequately represent nonroad emission reductions for all pollutants, and limit the flexibility of nonroad equipment to easily accommodate on-highway emission control systems that cause physical changes in engine performance and packaging.

EPA has determined that 9.2 g/kW-hr (6.9 g/bhp-hr) represents the lowest feasible NO_x standard achievable nationally in the near future. This determination was made based on the analysis discussed in the following sections, which include the following assessments.

- An assessment of the range of technology that EPA expects will be

available to meet a lower NO_x standard than adopted,
- An assessment of the ability of nonroad engine and equipment manufacturers to meet a national NO_x standard lower than that adopted given the timeline constraints, and
- An assessment of the ability of existing test procedures to characterize NO_x emissions at levels lower than the adopted standard.

2.7.1.1. Technology Required for Lower than Adopted NO_x Standard--EPA has determined that a 9.2 g/kW-hr (6.9 g/bhp-hr) NO_x standard represents the limit for most engine families of what can be achieved with fuel injection system and combustion chamber design changes without causing significant and irretrievable losses in performance (e.g., fuel economy, power).[10] The next step in emission reduction would require the application of more sophisticated technologies that can achieve even lower NO_x emission levels without significantly sacrificing performance. EPA analyzed the technologies that would have to be used to maintain engine performance while meeting a NO_x standard lower than adopted. Turbochargers, air to air aftercoolers, and/or electronic fuel injection systems were commonly used in on-highway engines in the 1990 model year to meet a 8.0 g/kW-hr (6.0 g/bhp-hr) NO_x standard. EPA believes that nonroad engine manufacturers would generally be capable of meeting a 8.0 g/kW-hr (6.0 g/bhp-hr) standard if each of these three technologies were readily applicable to nonroad engines. This makes 8.0 g/kW-hr (6.0 g/bhp-hr) the next logical tighter NO_x emission standard should a standard below 9.2 g/kW-hr (6.9 g/bhp-hr) be considered.

EPA tabulated in Table 2-18 the range of emission control technology required to achieve the NO_x standard of 9.2 g/kW-hr (6.9 g/bhp-hr) based on data collected on engines tested by EPA and industry, and the range required to achieve the next logical lower NO_x standard of 8.0 g/kW-hr (6.0 g/bhp-hr) based on EPA's 1990 model year certification on-highway heavy-duty engine database. Using these data EPA estimated the change in technology mix that would occur should EPA require a tighter NO_x standard than that adopted.

Table 2-18 shows a shift from the more conventional technologies projected to be needed to meet the 9.2 g/kW-hr (6.9 g/bhp-hr) NOx standard to the more sophisticated systems to meet the next logically lower (i.e., 8.0 g/kW-hr (6.0 g/bhp-hr)) NO_x standard. The most significant shifts to meet a standard below that adopted

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[10] See Chapter 2.4. Beyond a reasonable level, reduction of fuel economy and power are particular problems for nonroad engines because a percentage of equipment manufacturers could have to redesign fuel tank sizes to meet customer demands for full day operation between refuelings and/or redesign of powertrain component as necessary to minimize the impact of engine power and torque changes on equipment.

involve a substantial increase in the use of turbochargers, air to air aftercoolers, and electronic fuel injection systems. Table 2-18 shows an increase in turbocharged market share of 28 percentage points. This represents those engines that would be converted from naturally-aspirated engines to turbocharged engines. Table 2-18 also shows an increase of 51 percentage points in engines using air to air aftercooler technology, and an increase of 13 percentage points in engines using electronic fuel control technology.

For a number of reasons discussed in the following sections, increased use of these three technologies would not be feasible for nonroad use within the adopted timeline.

2.7.1.2. Timeline Constraints of a Lower NO_x Standard-- A national NO_x standard lower than that adopted would require increased leadtime to allow engine manufacturers to make engine design changes needed to incorporate more advanced emission control systems, and to allow equipment manufacturers to make equipment design changes necessary to accommodate turbochargers and air to air aftercoolers. EPA believes that the setting of a lower national NO_x standard would thus delay the implementation of standards by at least four years. Such a delay is not justified given the significant benefits available from implementing a 9.2 g/kW-hr (6.9 g/bhp-hr) NO_x standard.

Table 2-18
Estimated Technology Market Percent Change
Due to Tighter NOx Standard

Technology	9.2 g/kW-hr	8.0 g/kW-hr	Market Change
	market %	market %	market %
Naturally Aspirated	35	7	-28
Turbocharged	65 *	93	+28
Air-Water Aftercooler	25	13	-12
Air-Air Aftercooler	5 *	56	+51
Elect. Fuel Inject	0	13	+13

* This represents the current market share. EPA expects no increase due to this rule.

As discussed in Chapter 2.3.2, EPA has determined that the adopted NO_x emission standard can be met with a range of engine emission control technologies that will have minimal impact on engine and equipment design and thus can be reasonably developed on the adopted timeline. However, EPA has also determined that a more stringent NO_x standard would directly impact a large percentage of engine and equipment manufacturers that would have to design engines and equipment to accommodate turbocharger systems, or air to air aftercooler systems.

EPA believes that such a large design effort to accommodate more advanced technologies would require additional leadtime. First, engine manufacturers would need more leadtime to implement more stringent standards because the aggressive time lines in this FRM are based on the timetable used in California's nonroad regulations, which mandate a NO_x emission standard of 9.2 g/kW-hr (6.9 g/bhp-hr) for similar engines. Under this regulation, manufacturers would be able to use the same engine designs to meet both California and EPA standards. Manufacturers began developing systems to meet California requirements three years ago. To begin now to develop more advanced systems for EPA would require more leadtime and a later implementation date. EPA estimates that lower national standards than those adopted would require a delay of two to four years for implementation because manufacturers would lose the two year head start they currently have developed for designs to meet a 9.2 g/kW-hr (6.9 g/bhp-hr) NO_x standard, and manufacturers would require an additional two years to design the more advanced technologies required to meet a lower national standard than 6.9 (9.2).

Moreover, to meet lower standards than those adopted, significant design changes would be required for the nonroad equipment which such engines would operate. Turbochargers would have to be used on a percentage of low horsepower engines (i.e., less than 75 kW (100hp)) that were previously naturally aspirated designs. These are engines that are more likely to be used in equipment applications with the tightest powertrain and packaging design constraints. Thus, there is increased risk that a percentage of equipment applications that would need to convert from naturally aspirated to turbocharged engines could require substantial redesign to accommodate the resulting packaging and performance changes.

Air-to-air aftercoolers would have to be used on higher horsepower engine designs (i.e., greater than 75 kW (100hp)) that are currently at the efficiency limit of the engine designs' aspiration systems. Use of air-to-air aftercoolers would require substantial space for the large heater core assemblies required to make these nonroad systems efficient on any application. Moreover, there are technical limitations that cause air-to-air aftercoolers to perform less effectively on nonroad applications than on-highway applications. Nonroad engine applications generally operate at lower speeds and in dirtier environments than on-highway applications. As a result, additional hardware, such as high volume fans and dust scrapers would be necessary to maintain the high air flow around the aftercooler core that is needed for effective use of air-to-air aftercooling. Even large equipment cannot accommodate this level of packaging alteration without substantial redesign. Therefore, equipment impacts are highly likely when either of these technologies is employed.

Coping with such substantial equipment impacts on the entire U.S. product line within the regulatory implementation schedule would be extremely difficult. An equipment manufacturer's assessment of the impact cannot begin until the engine manufacturer has determined which control strategy it will employ and shares that decision with its customers. It is estimated that making the necessary design changes to the equipment powertrain or packaging would require an effort of similar magnitude to that required to design the engine changes. EPA estimates that two to four years of additional leadtime over the time needed by engine manufacturers would be required by equipment manufacturers to redesign their entire product lines to meet a lower NO_x emission standard.

Therefore, EPA concludes that a lower NO_x emission standard than adopted would require a delay of the initial implementation of standards by at least four years.

2.7.1.3. Ability of Test Procedures to Measure Emissions From Nonroad Engines Built to Meet a Lower NO_x Standard--When setting a standard, EPA must consider not only the ability of manufacturers to meet that standard in the available leadtime, but must also consider its ability to test compliance with that standard. As discussed in Chapter 2.1.1 and again below, EPA believes that the test procedures currently available have only been adequately shown to measure NO_x emission from nonroad engines at the adopted levels. EPA is working on an aggressive schedule to develop test procedures that adequately characterize the in-use emission performance of the range of technologies that could be used to reduce nonroad engine emissions beyond the 9.2 g/kW-hr (6.9 g/bhp-hr) NO_x standard.

As discussed in Chapter 2.1.1, current data and research indicate the 8-mode steady state test procedures are capable of measuring NO_x reductions when the standard is set at 9.2 g/kW-hr (6.9 g/bhp-hr) or above. However, information is not available to support the suitability of these test procedures for more stringent NO_x standards. The adopted test procedures may not be capable of measuring NO_x emission from the most advanced electronic fuel injection technology which some manufacturers could be forced to use should the NO_x standard be lower. Moreover, a lower NO_x emission standard could significantly increase HC and PM emissions, but the 8-mode test procedures have not yet been demonstrated to accurately measure these emittants.

2.7.1.3.1 The Test Procedures Lack of Demonstrated Ability to Properly Characterize NO_x Emissions from Electronic Fuel Injected Engines--EPA has determined that it is feasible for the 8-mode steady-state test procedures to accurately measure NO_x emission reductions on engines using conventional analog (mechanical) fuel control systems. As discussed in Chapter 2.1.1, these systems have been shown through data collected by industry and EPA to generate comparable NOx emission levels on both the more transient on-highway FTP and the steady-state 8-mode test procedures. These data suggest that a lower percentage of the composite NO_x emission was generated during transient portions of the test cycle as compared to steady-state portions, and therefore NO_x emission generated by engines using analog fuel system designs is less sensitive to test procedure variances that involve transient operation. Since engines using analog fuel system designs are insensitive to transient operation with respect to NO_x emission, EPA can use the 8-mode steady-state test without concern. This is consistent with the science of NO_x control since analog systems have no ability to make instantaneous step changes in critical operating parameters such as fuel delivery and timing.

On the other hand, the more sophisticated electronic fuel control systems are digital in nature. Such systems can be customized to actually generate higher levels of NO_x during transient operation, thus compromising EPA's ability to predict that emission test results generated on the 8-mode steady state test procedures are representative of any possible in-use operation. For example, should a manufacturer decide to use its electronic control system to reduce engine smoke by advancing fuel injection timing during heavy accelerations, smoke would decrease, but NOx_x emission would increase. Such a strategy would increase NO_x in-use in a manner that could not be accounted for in an 8-mode steady state emission test.

Electronic fuel control systems would not be necessary to meet the adopted emission standards. In addition, engine manufacturers have indicated they would not use electronic fuel control to meet the standards, due to development time lines and significantly higher cost. As shown in Table 2-18, should EPA require the next lower feasible NOx standard of 8.0 g/kW-hr (6.0 g/bhp-hr), engines with electronically controlled fuel control systems would be needed on 13% of the market. EPA could not be sure that the in-use performance of these engines would be properly characterized by the steady-state test procedures. By adopting a 9.2 g/kW-hr (6.9 g/bhp-hr) NO_x

standard today, EPA is forcing only those technologies the emission effects of which are within the range that the test procedures are able to measure. As discussed in the next section, EPA is aggressively working with industry to determine appropriate test procedures to ensure that the emissions impact of all technologies that become available in the future, including electronic fuel control systems, will be properly characterized.

2.7.1.3.2 The Test Procedures Lack of Demonstrated Ability to Measure HC and PM Emissions-- Some technologies that reduce NOx emissions also have a tendency to increase PM emission and, to some extent, HC emission. This phenomenon is known as "emission trade-off" and is based on the chemistry by which these pollutants are formed (pollution formation is discussed in Appendix B). Technical literature published by EPA and industry (12,13,14,15) demonstrate that the rate of PM emissions trade-off tends to increase exponentially as the NO_x emission standard gets lower. For example, Figure 2-02, taken from one of these publications(12), shows the NO_x and PM emission relationship. The "current technology average" line represents on-highway heavy-duty engines produced between the 1988 and 1990 model years. Observing this line, as a manufacturer reduces NO_x emission levels from current nonroad baseline levels (14.7 g/kW-hr (11 g/bhp-hr)) down to levels necessary to comply with the NO_x emission standard, or a reduction of about 5.5 g/kW-hr, the amount of PM emission tradeoff is small. To reduce NO_x emission levels even further below the 9.2 g/kW-hr (6.9 g/bhp-hr) standard, the rate of PM tradeoff begins to increase rapidly as characterized by the increasing slope of the NO_x versus PM curve.

Figure 2-02 suggests that, to accomplish a NO_x standard lower than adopted, it would also be necessary to, at the very least, set upper emission limits for HC and PM emissions to preclude significant increases in these emittants. However, since data collected using the 8-mode steady-state test procedures are inconclusive as to whether increases to HC and PM emissions can be accurately measured (see Chapter 2.1.1), EPA currently would have no way of knowing how well it was controlling HC and PM emission levels in actual use. It would be inappropriate to promulgate a lower NO_x standard when no means are currently available to measure accurately and verify that no significant increases in HC and PM emissions result from a lower NO_x standard. EPA is adopting the NO_x standard at 9.2 g/kW-hr (6.9 g/bhp-hr) because it not only provides a substantial NO_x emission reduction, but also minimizes the risk of causing a large in-use HC and PM emission tradeoff.

2.7.1.3.3 Time for Test Procedure Evaluation and Validation-- EPA is currently involved in an aggressive program, in partnership with the Engine Manufacturers Association (EMA), to determine what realistic test procedures should be in order to predict even greater emission reductions than those in this rule. These test procedures would be capable of predicting emissions of NO_x from the full range of advanced technologies, such as electronic fuel control, that are expected to result should tighter standards be promulgated at a later date. These test procedures would also be capable of predicting HC, CO and PM emissions. It will take time to develop such procedures for reasons explained as follows. The operating characteristics of a representative range of equipment must first be evaluated. Existing emission test procedure options must then be evaluated against prototype test procedures based on real in-use operation data. Should it be determined that new test procedures must be developed, additional time would be required to develop the new test procedures, and to collect sufficient data with the new test procedures to determine effective emission standards.

Figure 2-02
Particulate to NOx Trade-Off
Transient Emission Data

Given the aggressive timeline for implementation of the emission standards in this FRM, EPA does not believe that it can complete its development of new test procedures and finalize such procedures in time to implement these procedures in testing the engines subject to these regulations. Moreover, manufacturers will not be able to design their engines to comply with new test procedures until those procedures are promulgated.

2.7.1.4 Conclusion--EPA estimates that adoption of a lower NO_x emission standard would delay implementation of nonroad standards by at least four years. This regulation will realize substantial NO_x emission reduction in the near future because the adopted NO_x standard is within the measurement capability of the adopted test procedures. This regulation thus results in significant NO_x emission reductions in the near term while work is going on to develop test procedures for more stringent standards and while manufacturers work to design engines and equipment capable of meeting a lower standard at a later date.

Chapter 2 References

1. Bozek, John, *Use of Compressed Natural Gas or Methanol In Lieu of Diesel Fuels in Nonroad Applications*, Internal EPA memo, September 26, 1991.

2. McConnel, G., *Proceedings of Institute of Mechanical Engineers 178,1,38*, 1963-1964 p.1001-1014.

3. Ullman, Terry L., et al, *Effects of Fuel Aromatics, Cetane Number, and Cetane Improver on Emissions from a 1991 Prototype Heavy-Duty Diesel Engine*, SWRI SAE paper #902171 October 22, 1990.

4. *MVMA National Diesel Fuel Survey* Winter 1991.

5. Needham, J.R., et al, *The Low* NO_x *Truck Engine*, SAE paper # 910731 March 1, 1991.

6. Stump, Gerhard, et al, *Fuel injection equipment for Heavy Duty Engines for the U.S. 1991/1994 Emission Limits*,mpp, SAE paper # 890851.

7. Hil, R.W., et al, *The optimized Direct Injection Diesel Engine for Future Passenger Cars*, SAE paper # 880419, February 29, 1988.

8. Ikegami, Makoto, et al, *Combustion Chamber Shape and Pressurized Injection in High-Speed Direct-Injection Diesel Engines*, SAE paper # 900440 Feb. 1990.

9. Shindoh, Shigeru, et al, *The Effect of Injection Parameters and Swirl on Diesel Combustion with High Pressure Fuel Injection*, SAE paper # 910489 Feb. 1991.

10. McCarthy, John H., *Study of the Significance of* NO_x *Deterioration Factors in Proposed Regulation of Nonroad Diesel Cycle Engines Greater Than or Equal to 50 Horsepower*, EPA memorandum dated December 20, 1991.

11. Brezonick, Mike, *Cummins' New Off-Highway Electronic Control System, by Mike Brezonick,* Diesel Progress Engines and Drives, July, 1992.

12. Toepel, R., et al, *Development of Detroit Diesel Allison 6V-92TA Methanol Fueled Coach Engine*, SAE#831744, October, 1983.

13. Stumpp, G., et al, *Fuel Injection Equipment for Heavy-Duty Diesel Engines for U.S. 1991/1994 Emission Limits*, SAE#890851.

14. Gill, A., *Design Choices for 1990's Low Emission Diesel Engines,* SAE# 880350, February, 1988.

15. U.S. Environmental Protection Agency, Office of Mobile Sources, *Regulatory Impact Analysis, Oxides of Nitrogen Pollutant Specific Study and Summary and Analysis of Comments: Control of Air Pollution from New Motor Vehicles Engines: Gaseous Emission Regulations for 1987 and Later Model Year Light-Duty Vehicles, and for 1988 and Later Model Year Light-Duty Trucks and Heavy-Duty Engines; Particulate Emission Regulations for 1988 and Later Model Year Heavy-Duty Diesel Engines*, March 1985.

Chapter 3: Cost

This chapter estimates the costs of complying with the NO_x emission and smoke opacity standards for the applicable 1996 and later model year compression-ignition engines at or above 37 kilowatts (50 hp). Four main types of cost are analyzed: 1) variable hardware costs, 2) production life cycle fixed costs including engineering development costs, mechanical integrity testing costs, and test facility costs; 3) annual fixed costs including engine certification costs, in-use enforcement costs, emission defect reporting costs, and selective enforcement auditing costs; and 4) consumer costs including the increase in the retail price and engine operating costs.

Several underlying assumptions are used in this analysis due to the difficulty in obtaining data and to the proprietary nature of some data which was obtained. EPA assumes that

- all engines comply in model year 1996 (i.e., no staggering of horsepower groups).
- cost savings due to averaging would be positive and so were not estimated. Therefore, compliance costs are considered to be "worst case."
- the number of years which a manufacturer produces an engine family is ten years on average[11] (i.e., the production life). Consequently, EPA assumes that a new engine design will be introduced after ten years.
- manufacturers will amortize and discount all costs which are recoverable from future year production (e.g., mechanical integrity testing cost).
- the hourly rate for labor is $60 including overhead.
- for purposes of calculating research and development costs, the future sales distribution is equivalent to the current engine family distribution.
- the annual rate of growth of sales for these engines is 2 %.
- the number of engine families does not grow over time.
- no future regulations setting more stringent emission standards are considered.

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[11] The 10 year estimate is the typical production cycle over the last 20 years as described by manufacturers in conversations with EPA.

- the increase in retail price to the consumer is equivalent to the on-highway mark-up percentage over manufacturer cost.

All costs are summarized at the end of the chapter in section 3.7.

3.1. Industry Description

The industries which manufacturer nonroad large CI engines and which incorporate such engines into equipment sell a wide variety of equipment types, some of which are as follows.

- crawler dozers
- farm tractors
- graders
- combines
- cranes
- paving equipment
- generator sets
- aircraft support equipment and terminal tractors
- bore/drill rigs
- forestry equipment
- pumps and compressors
- off-highway tractors and trucks
- oil field equipment

All the engine manufacturers are large international corporations or subsidiaries of such corporations. There are no small manufacturers, although there is a group of approximately 22 manufacturers who have marginal market share (<10 % total). The largest engine manufacturers and their approximate market share on a unit basis are Caterpillar (~20%), Wisconsin/Teledyne (~20%), Cummins (~10%), John Deere (~10%), Detroit Diesel (~10%), Deutz (~10%), and Perkins (~10%). Caterpillar and John Deere are vertically integrated companies that also manufacture most types of equipment using nonroad large CI engines. By virtue of the existence of just a few large sellers, the engine industry structure appears to exhibit characteristics of oligopoly with product differentiation (there are a wide range of engine models and calibrations available). The engine industry thus has sufficient market power that increases in cost of production can be expected to be passed on to the engine equipment purchasers.

The equipment industries are also characterized by the existence of a few large sellers, but a number of smaller firms also exist. The following table presents concentration ratios for the farm and construction equipment industries as measured by share of value of shipments.(1)

Table 3-01
Concentration Ratios by Industry (1987)

# of Companies	SIC 3523 Farm Machinery and Equipment	SIC 3531 Construction Machinery
4 largest	45	48
8 largest	52	56
20 largest	60	66
50 largest	69	79
total # of companies	1,576	872

It may be that the larger producers have permitted conditions characteristic of monopolistic competition to be created. There is a high degree of product differentiation in the equipment which is available for purchase. Most equipment manufacturers produce equipment in various size categories designed to get specific types and sizes of work done. These categories are commonly called market niches in the industry. Many equipment manufacturers have chosen to market only to a few of these niches. However, for farm equipment, John Deere appears to be a market leader in most categories of equipment. Not only is John Deere vertically integrated, it is also horizontally integrated, producing and incorporating their own engines into a wide variety of equipment for practically every agricultural use. A similar situation exists for Caterpillar with respect to construction equipment. Further, it does appear that there are relatively high advertising expenditures,[12](2) moderately high capital requirements,[13](3) and there may be a certain amount of brand loyalty existing in these markets. Thus, it appears that there is significant competition to the larger manufacturers from the niche marketers who, for the most part, purchase engines from companies such as Cummins, Detroit Diesel, Wisconsin/Teledyne, Deutz, etc.

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[12] For farm machinery (IRS Statistics of Income Classification Code 3520), the ratio of advertising outlays to total revenue is 0.019, which is the largest outlay of all the nonroad equipment industries. For construction and related machinery (IRS Statistics of Income Classification Code 3530), this ratio is 0.004.

[13] "The Farm Machinery and Equipment industry appears to be capital intensive, with an assets to output ratio of 44.2%. capital thus plays an important role int he production process. ... The [Construction Machinery] industry also appears to be capital intensive. In 1987, it had an assets to output ratio of 42.8 %.

Capacity utilization has increased in these industries,[14] brought about by increased foreign competition and widespread industry restructuring in the 1980's and 1990's[15]. This restructuring allowed increased competition from foreign equipment producers such as Komatsu to be rebuffed. In the long run, the competition probably serves to restraint the market power the largest equipment manufacturers have on product price, although product differentiation still serves to allow these manufacturers some range of price flexibility (particularly in the short run) before sales are affected.

Consumers of these types of equipment are commercial businesses. These businesses purchase the equipment as an input into production of their products. The final goods produced range from commodities such as agricultural, petroleum, forestry, and mineral products to infrastructure such as roads, highways, and buildings to transportation goods such as airline travel. In other words, these types of equipment are either used directly or indirectly to provide consumers with goods and services. The end markets appear to be markets which are characterized by competition. Therefore, it is reasonable to assume that any increased costs will be eventually passed on to consumers in the form of higher prices, displacing consumption expenditures.

3.2. Variable Hardware Cost

Variable hardware costs are those costs for hardware changes made to engines in order to comply with new emission standards. Hardware costs are variable since they depend on production volumes.

3.2.1. Estimation of Weighted Average Variable Hardware Cost Per Engine

EPA has developed a fleet-wide weighted average variable hardware cost per engine estimate. The weighting is based on the percentage of the fleet which is estimated to require the use of each technology in order to meet the emission standard.[16] EPA's estimates of the technology required to meet the proposed NO_x

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[14] Current Industrial Reports, Survey of Plant Capacity indicates that for the period 1985 to 1990 capacity utilization for SIC code 3523 has increased from 37% in 1985 to 66% in 1990. For SIC code 3531 Construction Machinery, capacity utilization has increased from 48% in 1985 to 72% in 1990.

[15] The Census of Manufacturers, General Summary, 1987 and 1982 reports that for SIC code 3523 Farm Machinery and Equipment the number of companies has declined 11.8% between 1982 and 1987. For SIC code 3531 Construction Machinery, the number of companies in this period increase 6.7 % but the number of companies with 20 or more employees decreased by 5%.

[16] Refer to Section 2.2.6., for the discussion of the technology required for the fleet to meet the NOx emission standard.

emission and smoke standards are multiplied by the estimated engine manufacturer's cost for each technology. This variable hardware cost per technology was determined from proprietary manufacturer submissions. These submissions formed a range of cost which varied by the size of the engine employing the technology to reduce NO_x and smoke emissions. For instance, the cost of a turbocharger is low because it is estimated that the engines which would convert to a turbocharger for emissions purposes would be the small, naturally-aspirated engines. Therefore, the weighted average variable hardware cost was calculated using the formula

$$\sum_{t=1}^{n} W_t \times C_t$$

In this equation,

t - technology
n - number of technologies required to meet the emission standard
W_t - percentage of the fleet requiring the use of this technology to meet the emission standard
C_t - cost of the technology

Table 3-02 summarizes EPA's fleet-wide weighted average variable hardware cost estimate. The cost estimates inherently include costs to cover the allowable maintenance provisions and the useful life definition.

EPA considered developing an analysis of all engines available for sale in the United States in order to estimate the increase in manufacturer cost due to emission control strategies. Complete sales information would be necessary. Further, manufacturers would need to disclose engine development plans to EPA. However, this industry is very sensitive to the disclosure of this information. The industry would not authorize release of proprietary information in the Regulatory Support Document and, in many cases, would not provide proprietary information to EPA for analysis. Therefore, EPA decided to use the weighted average variable cost methodology, as a reasonable alternative methodology.

Table 3-02
Weighted Average Variable Hardware Cost

Technology	Cost ($)	Market (%)	Weighted Cost ($)
Fuel System Improvements (Rotary)	55	20	11
Air-to-water Charge Air Cooler	100	10	10
Turbocharger[17]	400	5	20
Fuel System Improvements (In-Line/ Unit Injection)	210	35	73
Waste Gate Technology	115	30	35
Smoke Limiter	25	10	3
Average Per Engine Variable Hardware Cost to Engine Manufacturer			152

3.2.2. Average Annual Growth Rates in Output Utilized for the RSD

The total annual United States' apparent consumption (production - exports + imports) of diesel engines[18] is based on the national sales information available to EPA from the U.S. Department of Commerce, Bureau of the Census (DOC/BOC). For instance, in 1989 DOC/BOC estimates that 217,456 nonautomotive diesel engines were produced in the United States. This number includes the following end applications.

1. Oil field and petroleum related generating and stationary equipment.
2. Other generating sets

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[17] EPA expects that manufacturers will not have to use turbochargers because of the flexibilities afforded under the averaging program. This is further discussed in 2.2.6.2.. However, because EPA assumes for this cost analysis that only ten manufacturers participate in the averaging program, EPA has included turbochargers in the hardware cost estimate. If turbochargers are added to engines, they will likely be added to engines which are incorporated in equipment designs without packaging constraints due to the short leadtime of this rule. Therefore, in order to calculate what EPA considers the worst case cost estimate under an averaging program, EPA has assumed only ten manufacturers participate in averaging and that 5% of the engines still incorporate turbochargers. Even in this instance, the cost analysis shows the rule to be very cost-effective.

[18] The estimate of U.S. consumption is provided in Table A-08 in Appendix A.

3. Irrigation
5. Off-highway mobile construction equipment
6. Marine, except outboard
7. Railroad, motive power type
8. Agriculture vehicular
9. Other general industrial

The Bureau estimates that 42,331 were exported and 240,712 were imported. This implies that the 1989 apparent consumption of diesel engines in the United States was 415,837.

The FRM excludes engines used in locomotives, marine propulsion and auxiliary power generation, stationary sources, and nonroad engines under 50 horsepower. EPA estimates these exclusions decrease the apparent consumption by about 30%, based on consideration of nonroad diesel engine population data by equipment category which were obtained for the Nonroad Engine and Vehicle Emission Study. Based on this 30 % reduction, EPA estimates the 1989 United States apparent consumption of all compression-ignition engines greater than or equal to 50 hp to be approximately 290,000 units.

EPA feels that it is reasonable to assume an average annual rate of growth in sales of these engines of 2%. This growth rate is estimated based on the long term growth rate of the economy, the farm machinery and equipment industry, the construction equipment industry, and the internal combustion engine industry. The basis for selecting this rate is discussed below.

Gross national product (GNP) for the United States is estimated by the Department of Labor (DOL)(4) to have a long term average annual rate of change between 1.5 and 2.9 percent (2.3 percent in the moderate growth of the economy scenario) over the period 1990 to 2005.

According to the U.S. Industrial Outlook for 1992, the outlook for the farm machinery and equipment industry is not easy to predict, depending in large part on the global economy, global weather, and foreign and domestic agricultural policies. While the number of farms has declined over the last four decades, farms have become larger and agriculture has become more mechanized further complicating growth estimates. According to the DOL, in the agricultural industry, output (in dollars) is expected to increase between 1.4 and 2.4 percent. Projected average annual growth in output for the farm and garden machinery industry between 1990 and 2005 is 1.0 percent in a moderate growth scenario. This range is generally consistent with the conclusions in the U.S. Industrial Outlook and indicate that output growth for the farm equipment and machinery industry will increase but by less than the rate for GNP. The DOL based their projections on the assumption that demand will increase in the farm and garden machinery industry as a result of capital spending by the real estate and farming sectors.

According to the U.S. Industrial Outlook, the construction machinery industry is expected to see a 2.2 percent increase in sales for the period of 1992 to 1996. Increased expenditures in infrastructure, as well as construction of new power generating plants, resource recovery plants, and water treatment facilities are given as potential reasons for the increase in sales in this industry. The report also notes that construction machines will be more efficient, meaning that fewer machines will be required. Such changes could serve to reduce the amount by which the industry is expected to expand. According to the DOL, output for the construction industry is expected to increase between 1.0 and 2.6 percent which is less than the 1975-1990 average annual rate of change of 2.8 percent. In a moderate case scenario, the construction equipment industry is projected to have an average annual growth rate of output of 2.2 percent. The DOL based this projection on the assumption that there will be increased purchases of construction machinery due to investment. DOL assumed that demand should be strong because of maintenance of the nation's infrastructure. This data seems to indicate that the average annual rate of growth for the construction machinery industry correlates well with the projected rates of GNP.

The DOL estimates the projected average annual growth rate of output in the engines and turbines manufacturing industry to be 0.9 percent over the 1990-2005 period.

Based on this information, EPA is assuming that sales will have an average annual growth rate of 2% over the 1996 to 2026 time period. This is a rough estimate that is itself based on two assumptions. First, that the average annual growth rate of sales is equivalent to the average annual growth rate of output. Second, that the average annual growth rate of output for the engines covered by this regulation is similar to the rates given above. It should be noted that the data presented above applies to larger categories of activity than the industries which produce the specific engines covered by this FRM, was deemed adequate for selecting an average annual growth rate range for this analysis. EPA's rationale for the assumed rate applicable to the engines covered by this FRM was to choose a rate below the projected rates for construction machinery industry and above the projected rates for farm machinery industry.

3.2.3. Annual Variable Hardware Cost

The total annual variable hardware cost is calculated according to the following formula.

$$C_{VH_i} = \$152 * SALES_i$$

In this equation,

C_{VHi}	- total variable hardware cost
$SALES_i$	- sales in year i
$152	- constant representing average annual unit hardware cost

The annual total variable hardware cost is presented in Table 3-05 in section "3.6. Cost Summary."

3.3. Production Cycle Fixed Costs

The production cycle is the time period starting the first year a new engine model is sold and ending in the last year of sale. For engines required to comply with this FRM, the production cycle for engines appears to be 10 years. During this typical production cycle, two minor calibration changes to an engine model appear to be typical.

Some costs recoverable in the production cycle are incurred one to three years before production begins. Recalibration, design, mechanical integrity testing, and some initial certification costs are such costs which are recoverable across the production cycle. These costs are estimated in this section, with the exception of some initial certification costs which are described in section 3.5.1.

3.3.1. Engineering Development Costs

These costs include costs for engine recalibration, engine redesign and accumulation of hours on all engine families to ensure their mechanical integrity. EPA estimates the number of engine families to be 213. See Appendix D for a detailed discussion of the criteria for categorizing engine families and the quantitative estimation per manufacturer.

3.3.1.1. Engine Recalibration--Engine recalibration costs reflect the costs associated with recalibrating the injection timing system to achieve optimized emissions and performance under the constraints of the NO_x emission standard, maintaining constant performance, and current levels of reliability/durability. EPA assumes that the injection timing system will be retarded on 98% of these engine families (209 engine families). This analysis assumes that, for engine families which require recalibration, the manufacturer would recalibrate two emission data engines four separate times to meet the 1996 model year NO_x emission standard. EPA expects that the manufacturer will set a calibration for the entire engine family such that the worst case configuration from an emissions perspective will meet emission standards. It is estimated that each recalibration would require 20 person-days, 15 for the technician and 5 for the engineer. The cost estimate assumes an eight hour day and a cost of $60/hour including labor and overhead. The cost was calculated according to the following formula.

$$C_R = (PD_t + PD_e) * 8 hr/day * \$60/hour * 209 \text{ engine families} \\ * 2 EDE * 4 \text{ recalibrations}/EDE$$

where

C_R - total recalibration cost
PD_t - number of technician person-days required
PD_e - number of engineer person-days required
EDE - emission data engine

EPA believes that these recalibration costs will recur every production cycle. Therefore, EPA accounted for these costs three times over the 30 years it takes the fleet to turn over. These costs are thus amortized at 7% over each 10 year production cycle of each engine family.

3.3.1.2. Development Costs--This cost is for development work for modifying engine families to meet the adopted standards. The development costs are limited to actual development work by the engine manufacturer. The design cost for the components (e.g., the turbocharger) is considered in the variable cost estimate for each component because it is expected that any supplier's development costs are passed on to the engine manufacturer through the price of the component.

EPA estimates that the following pollution control systems would need to be developed for a percentage of current engine families without such systems in order to meet the adopted standards. The system categories are:

1. combustion chamber design
   It is assumed that engines requiring higher pressure rotary pumps, turbochargers, and air-to-water charge air coolers will require some further development of the combustion chamber. This involves adjustments to the injectors, redesign of the combustion bowl, adjustment of the bore or stroke, or similar modifications to the

combustion chamber.

2. turbocharger system
   Applying a turbocharger to the engine family involves determining the proper induction and exhaust system piping, bracketing, placement of the turbocharger, determination of proper boost pressure, etc..
3. aftercooler/intercooler system
   Applying an aftercooler/intercooler system involves the determination of the proper air supply, the proper placement of the system, the proper connecting hardware, etc.
4. smoke limitation system & waste gate technology
   Applying a smoke limitation system or waste gate technology involves mostly calibration work.

The following table presents the estimate of the number of days of personnel effort required to address the system redesign on average.

Table 3-03
Development Person-Days

system categories:	1	2	3	4
# redesigns	2	2	2	2
	Person-Days per Redesign			
machinist's days	9	3	0	0
mechanic's days	5	2	9	8
Technician's days	58	63	87	49
engineer's days	58	63	35	8
Total Person-Days:	260	262	262	130

The total person-days required for each system category is therefore calculated according to the following equation.

$$TPD = R * (MA + ME + T + E)$$

where

TPD - total person-days
R - number of redesigns
MA - machinist's days
ME - mechanic's days
T - technician's days
E - engineer's days

It is assumed that the manufacturers would undertake two candidate redesigns for each engine family and pick the one which best met their objectives.

The total development cost for these engines is based on the development person-days per system redesign, the percentages of engine families incorporating each technology[19], an assumed eight hour person-day, and an hourly rate of $60 including labor and overhead. The total unamortized and undiscounted development cost estimate is presented in Table 3-04 below. In order to arrive at an annual cost estimate, the total cost was amortized at 7 percent over the assumed 10 year production life of the engine families. EPA does not account for further design costs for future production cycles for two reasons. First, there is a good deal of uncertainty over what additional future design changes might occur. Second, if manufacturers decide to redesign certified engine families that are already capable of meeting the standards, the redesign would be for purposes other than complying with emission standards, such as cost savings or performance enhancement. Therefore, it would be inappropriate to account for these design costs in this analysis.

Table 3-04
Development Costs

design	Full-Time Person-Days	% engine families	$/hr	Approximate Total ($million)
combustion chamber	260	35	60	$7.8
aftercooler	260	10	60	2.2
turbocharger	262	5	60	1.1
smoke limitation & waste gate technology	130	40	60	4.4
TOTAL				$15.5

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[19] Refer to Section 2.2.6.

3.3.2. Mechanical Integrity Testing Costs

Mechanical integrity testing costs represent useful life accumulation and effort to prove the mechanical integrity of redesigned engine families. It is assumed that manufacturers will do this testing only on engine families which change from naturally-aspirated to turbocharged, those which become aftercooled, and those which receive medium pressure fuel injection systems (i.e., 35% of the engine families). EPA assumes that manufacturers would not test engines for mechanical integrity which have not received these design changes because mechanical integrity should already be proven. It is assumed that manufacturers would perform one test sequence for mechanical integrity assurance. The length of the test is assumed to be 1000 hours. The number of engine families to be tested for mechanical integrity is estimated to be 75 (35% of 213 engine families). The cost estimate assumes a cost of $60/hour for labor and overhead and is calculated according to the following formula.

$$C_{mit} = \$60/hour * 1000\ hours * 75\ engine\ families$$

where

C_{mit} - total mechanical integrity testing cost

The annual cost would be approximately $1,700,000, which represents the total mechanical integrity cost amortized over the expected 10 year production life of the engine family at 7%.

3.4. Test Facility Cost

These are the costs for construction and/or expansion of certification quality test facilities. Most manufacturers already have test facilities capable of conducting the adopted test procedures. EPA estimates that each manufacturer will build one additional steady-state certification quality basic test cell. Only 1 per manufacturer would be needed because most manufacturers already have built test facilities to meet their development testing needs. The additional one cell accounts for test capacity needed for certification. Therefore, industry-wide there will be 28 additional test facilities built.

For the adopted test procedure, EPA estimates that the basic test cell would need to consist of a water brake or eddy current dynamometer, basic instrumentation and analyzers, and automated data processing and wiring. For the adopted procedures, the test cell would not need a motoring dynamometer and would only need the capability to do raw gas sampling. EPA assumed that the manufacturers have room within currently existing facilities for test facilities, and therefore, would not need to build the walls of a test cell. The estimated cost of each basic cell is $200,000. This $200,000 consists of approximately $75,000 for a water brake or eddy current dynamometer, $100,000 for basic instrumentation and analyzers, and $25,000 for automated data processing and wiring. EPA estimates that the water brake or eddy current dynamometer can be amortized over 30 years, the basic instrumentation and analyzers can be amortized over 10 years, and the automated data processing and wiring can be amortized over 5 years. These costs are amortized at 7 percent.

These amortization periods are based on the useful life of the equipment. Therefore, for the thirty year period covered by this cost analysis, the basic instrumentation and analyzers would be replaced twice and the automated data processing and wiring would be replaced five times. As shown in table 3-05, the annual cost is approximately $900,000, which represents the total test cell cost amortized at 7%.

3.5. Annual Administrative Cost

Annual fixed costs described in this section are certification and enforcement costs which the manufacturers are estimated to incur due to the regulatory program which is being promulgated. Variable hardware costs are also considered to be annual costs but have been previously presented[20].

3.5.1. Certification

The certification program mandates testing, record keeping, and reporting costs a manufacturer incurs in year one. These costs are incurred because the engine manufacturer must prove to EPA that its engines are designed and will be built such that they are capable of complying with the emission standards over their full useful life. Manufacturers are required to submit descriptions of their planned product line, including detailed descriptions of the emission control system, and test data. This information is organized by "engine family" groups expected to have similar emission characteristics. All manufacturers must describe their product and supply test data to verify compliance. EPA will conduct a limited number of "confirmatory tests" to audit manufacturer results. Confirmatory tests require shipment to EPA's laboratory.

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[20] See Section 3.1. Variable Hardware Cost

Manufacturers must also retain records. These tasks are repeated for each model year, typically previous data and information can be "carried over" when no significant changes have occurred. EPA's estimate of the total certification program costs to the manufacturers is explained in EPA's Statement for Information Collection Request. The result is presented in Table 3-05 and is approximately $9,000,000 per year.(5)

3.5.2. Averaging, Banking, and Trading

The cost savings attributable to the use of the averaging, banking, and trading (ABT) program for the engines covered by this FRM were not estimated. Hence, compliance costs were "worst case" estimates. For any firm that participates in ABT, it will do so only if cost savings make it cheaper than the command-and-control alternative. Information collection will be accounted for in this determination and thus are not relevant.

3.5.3. In-Use Enforcement Costs

EPA's enforcement program will be based on testing "properly maintained and used" in-use engines. This testing program for nonroad engines will be the same program EPA currently uses for in-use testing of motor vehicles and engines under section 207(c) of the Act. Because nonroad engines will be subject to in-use testing by EPA, manufacturers may choose to begin monitoring the performance of their in-use engines. However, with the information currently available, EPA is unable to estimate the amount manufacturers would spend on in-use testing. EPA believes that in-use testing by the manufacturers will be a relatively small cost of the FRM because NO_x emission deterioration on compression-ignition engines is typically very low.(6)

3.5.4. Emission Defect Reporting Costs

EPA's enforcement program includes emission defect warranty reporting requirements. EPA estimates that manufacturers would have a burden of 262 hours per year per manufacturer for emission defect reporting requirements for this proposal.(7) As shown in Table 3-05, EPA estimates that this information collection will cost the respondents approximately $13,000 per year.

3.5.5. Selective Enforcement Auditing Costs

EPA is adopting a new nonroad engine assembly line audit program, a Selective Enforcement Auditing (SEA) program.(8) This program will be similar to the on-highway heavy-duty engine SEA program. For nonroad engines, EPA believes this program is especially important due to the nature of the nonroad industry. Since most nonroad equipment (and engines) are not registered as are on-highway vehicles, nonroad vehicle in-use enforcement would be more difficult and costly for EPA and industry, than for on-highway vehicles. Additionally, manufacturers' recall response rates to have repairs performed would be low since contacting engine owners through registration records would not be possible. Other than emission defect reporting, no in-use enforcement is thus planned, at least in the short run. Therefore, detecting noncompliance at the assembly line, through SEAs, will be the most cost-effective enforcement means for EPA and industry.

EPA estimates that more than half of the nonroad engine manufacturers will voluntarily collect assembly line emission test data. EPA requests that manufacturers submit this data to EPA, but EPA does not set requirements for manufacturers to follow during voluntary testing.

Manufacturers are required to provide EPA with projected annual sales data. This data is used by EPA to help determine which manufacturers will receive SEAs. EPA estimates that ten SEAs will be conducted per year with an average of eight tests per audit. These estimates are consistent with the on-highway heavy-duty engine SEA program. For every SEA, the manufacturer has reporting, recordkeeping, and testing requirements. Table 3-05 presents the total annual SEA cost estimate.

3.5.6. Importation of Nonconforming Nonroad Engines

EPA is adopting certain restrictions on the importation of nonconforming nonroad engines. Such restrictions are based on the existing regulations for the importation of nonconforming motor vehicles and motor vehicle engines. The FRM permits independent commercial importers (ICIs) who hold valid certificates of conformity issued by EPA to import nonconforming nonroad engines. Under this program, the ICI must certify the engine to applicable U.S. regulations via the certification process before an engine is imported. The forms used for importation will be identical to those used for motor vehicles and engines currently imported into the United States.

Discussions with specialists on the industry to be regulated by this FRM suggest that there is at present no significant importation of nonroad engines by non-manufacturers. However, EPA has provided a cost estimate based on a total of 50 engines imported by ICIs to reflect the possibility that some such importation may occur. Table 3-05 provides the annual cost estimate for importation.

3.5.7. Exemptions

Under the FRM, manufacturers and Independent Commercial Importer (ICIs) of these engines must report and keep records of nonroad engines on exempt status. ICIs will submit reports when they want to import a nonconforming precertification nonroad engine. A manufacturer or business will submit a report when it wants to conduct a test program which uses nonconforming nonroad engines. EPA will use this information to verify the need for the exemption, to verify the validity of the program, and to insure that the terms and conditions of the regulations are met. Table 3-05 shows the estimate of the total annual cost to industry which is approximately $13,000.

3.5.8. Exclusions

Under the FRM, a manufacturer may make an exclusion determination by itself; however, nonroad engine manufacturers or importers may routinely request EPA to make such determination to ensure that their determination does not differ from EPA's. The information EPA needs to make an exemption determination are information such as engine type, horsepower rating, intended usage, method of usage, other descriptive information on the vehicle powered, etc. Table 3-05 shows the estimate of the total annual cost to industry, which is approximately $3000.

3.6. Consumer Cost

3.6.1. Increase in Retail Price

The increase in retail price, commonly referred to as a retail price equivalent (RPE), is estimated according to the method developed for EPA by Jack Faucett Associates for on-highway engines.(9) Full cost pass-through is assumed. According to this method, the weighted average variable hardware per engine cost is multiplied by a manufacturer factor that accounts for manufacturer overhead and profit. Recalibration, design, mechanical integrity, certification, emission defect reporting, and Selective Enforcement Auditing costs are added to the result and multiplied by the dealer factor. The manufacturer factor used here is 1.282 and the dealer factor used here is 1.062. The RPE increase due to the FRM are shown in Table 3-08 and discussed in section "3.7. Cost Summary."

3.6.2. Engine Operating Cost

In addition to the increased cost of the engine and equipment, EPA evaluated any change in the cost of operation due to changes in fuel or maintenance requirements. EPA found little to no change.

3.6.2.1. Fuel Cost--It is expected that all nonroad engine manufacturers will retard the fuel injection timing on large CI engines in order to reduce NO_x emissions. EPA testing suggests that retarding fuel injection timing to meet the 6.9 g/bhp-hr NO_x

standard will increase fuel consumption in the range of 3 to 5 percent.[21] Day-to-day operations require that the equipment manufacturer design its fuel storage systems to allow a full day of work between refueling. Therefore, equipment manufacturers design fuel tanks to exceed the daily work hours by approximately 10 percent (e.g., 11-12 hours on a 10 hour shift). While fuel economy itself is not as important as power and durability, the ability to work a full shift without refueling is apparently critical to sales.

The magnitude of the fuel consumption penalty due to the adopted emission standards will dictate how the engine manufacturer proceeds. If the fuel consumption penalty is minimal, the manufacturer may avoid adding additional technology by optimizing existing designs to restore fuel economy. However, if the fuel consumption penalty is between 3 to 5 percent, the engine manufacturer will often have to add the technology necessary to maintain the baseline fuel consumption rate. Should an engine manufacturer forego adding the necessary engine technology, the cost would be passed on to those equipment manufacturer customers with applications that cannot absorb these levels of fuel consumption increase without redesigning their fuel tank systems.

For this cost analysis, EPA assumed, when system optimization would not suffice, the engine manufacturer would add those technologies necessary to restore pre-regulation fuel consumption. Therefore, any costs normally attributed to higher fuel costs are reflected in higher variable hardware costs (e.g., for additional aftercoolers and higher pressure rotary pumps) in Section 3.1. This is a reasonable costing approach since, as discussed in Section 2.4.1., EPA experience with similar on-highway large CI engines has demonstrated that the industry-wide fuel consumption will not increase as regulations become increasingly stringent.

3.6.2.2. Maintenance Cost--The only technology which EPA felt could likely increase maintenance cost was the addition of a turbocharger to a naturally-aspirated engine. However, EPA has determined that addition of turbocharger technology is not necessary to meet standards adopted in this FRM.

To cover those rare cases when a manufacturer might have to incorporate a turbocharger (e.g., 1998 model year), EPA reviewed maintenance manuals for on-highway large CI engines which were certified in turbocharged and naturally aspirated versions. The recommended maintenance schedules for oil changes appeared no

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[21] Refer to Section 2.4.1.

different in the two versions.(10) EPA could not identify an increase in any other turbocharger recommended maintenance over a similar naturally-aspirated engine. Therefore, EPA is not including any maintenance cost impact.

3.7. Cost Summary

This section summarizes the total industry cost accounted for over the 30 years in which the fleet turns over.

3.7.1. Accounting for Costs as They Occur

Manufacturers incur some costs years ahead of when the costs are recovered by sales. Manufacturers must allow time to design, test, evaluate, certify, and produce the engine before sale. Typically, design work occurs in the year before mechanical integrity testing and recalibration work. The following year certification is undertaken. Production begins the year after certification.

Table 3-05 shows these costs as they were accounted for in EPA's cost estimate.

3.7.2. Accounting for Costs as They are Recovered

EPA assumes that costs which occur in years preceding production are recovered over sales throughout the production cycle. For instance, EPA assumes the annualized design cost for 1993 is recovered within four years on 1996 sales. Similarly, annualized design costs occurring in 1994 are recovered in 1997 sales. Therefore, the methodology attributes the first year of amortized costs to the first year of sales, the second year of amortized costs to the second year of sales, et cetera. These costs are shown in year of recovery in future value[22].

Table 3-06 shows the total costs which are recovered in each sales year through fleet turn over in 2026.

3.7.3. Evaluation of the Stream of Costs

The stream of costs recovered over sales throughout the turnover of the fleet must be analyzed in the present value[23] of the yearly costs. The present value of the recoverable costs is stated in Table 3-06 in 1992 dollars. The methodology used to determine the present value is calculated according to Agency guidance (i.e., the Kolb-Scheraga two-stage procedure).(11) Kolb-Scheraga point out that the economics literature has established the social rate of time preference as the appropriate rate for

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[22] Future value means the value at a future date of money that has been paid or received in prior periods.

[23] Present value means the value of money at a present date that will be paid or received in future periods.

discounting the benefits and costs of public projects, once they are expressed in terms of consumption gained and foregone, and provide a procedure for doing this. According to this methodology, capital costs are amortized at 7 percent. Annualized capital costs are then added to operating costs (e.g., variable hardware costs, administrative costs). The total cost stream and the total benefit stream is then discounted at 3 percent to present value. This methodology is appropriate in this case because capital costs imposed by this FRM are likely to be passed directly through to consumers in the form of higher prices and thus reduce the consumption of goods and services. This methodology is more appropriate in this instance than simply discounting all costs at 7 percent. This is because the two-stage procedure accounts for both displaced private investment (in the annualization process) and foregone consumption (by discounting both costs and benefits by the social rate of time preference).

Table 3-07 presents the total annualized stream of costs, the present value stream of the total annualized costs, the increase in retail price, the present value of the increase in retail price, and the per engine present value increase in retail price. Further, Table 3-07 presents the present value per engine cost-effectiveness in dollars per ton NO_x reduced. The present value per engine cost-effectiveness represents the annual cost discounted according to the Kolb-Scheraga two-stage procedure, divided by the present value per engine emission reduction benefits discounted at 3 percent.

3.8. Cost-Effectiveness of the Proposed Rule

In evaluating various pollution control options EPA considers the cost-effectiveness of the control. The cost-effectiveness of a pollution control measure is typically expressed as the cost per ton of pollutant emissions reduced. Other things being equal, EPA prefers to target emission reductions that cost less per ton of emissions reduced.

3.8.1. Cost Per Ton of NO_x Reduction

The NO_x standard for large nonroad CI engines is estimated to have a cost-effectiveness of $188 per ton of NO_x removed from the exhaust of the affected engines. This cost per ton of NO_x reduction is based on the ratio of the net present value of the stream of costs divided by the net present value of the stream of benefits. The cost and benefit stream are calculated over the 30 years it takes the fleet to turn over.

The cost-effectiveness of the FRM on a per engine basis was presented in Table 3-07. When cost-effectiveness is calculated on a per engine basis, a different cost-effectiveness ratio is achieved. This is because yearly sales and attrition do not enter the calculation. This is an important distinction for mobile sources for two reasons. First, benefits are achieved on new engine sales. This means that relatively small benefits are achieved in the beginning years of an emission reduction regulation and that benefits increase throughout the years as the fleet turns over. Second, it is inappropriate to compare per engine benefits from this regulation to other regulatory programs. This is because the source dynamics (e.g., sales, attrition, usage) of other emission sources likely differ from the source dynamics of the engines under this FRM.

It is appropriate to compare the per engine cost-effectiveness for different options for reducing emissions from the engines under this FRM as long as the regulatory schedule and affected engines are identical between the options. However, in order to understand and evaluate emission reductions which occur over time it is appropriate to evaluate the net present value of the stream of costs in comparison to the net present value of the stream of benefits.

3.8.2. Comparison to Cost-Effectiveness of Other Emission Control Strategies

The cost-effectiveness of the nonroad NO_x standards may be compared to other CAA measures that reduce NO_x emissions. Title I of the 1990 Clean Air Act Amendments requires certain areas to provide for reductions in volatile organic compounds and NO_x emissions as necessary to attain the NAAQS for ozone. Title I specifically outlines provisions for the application of reasonably available control technology (RACT) and new source review (NSR) for major NO_x emitters. In addition, EPA anticipates that more stringent reductions in NO_x emission will be necessary in certain areas. Such reductions will be identified through dispersion modeling analyses required under Title I. The cost-effectiveness of these measures is generally estimated to be in the range of \$100 to \$5,000 per ton of NO_x reduced.(12) In addition to applying NO_x control technologies to meet requirements under Title I of the Clean Air Act, many point sources will also be required to meet NO_x emission rate limits set forth in other programs, including those established under Title IV of the Act, which addresses acid deposition (i.e., acid rain). EPA anticipates that the cost of complying with regulations required under section 407 of the Clean Air Act (Nitrogen Oxides Emission Reduction Program), which proposes nationwide limits applicable to NO_x emission from coal-fired power plants, will be between \$200 and \$250 per ton.

The cost-effectiveness of controlling NO_x emissions from on-highway mobile sources has also been estimated. The Tier I NO_x standard for light-duty vehicles, which will be phased in starting in 1994, is estimated to cost (undiscounted) \$3,490 per ton of NO_x reduced. The 1998 heavy-duty highway engine NO_x standard is estimated to cost between \$210 and \$260 per ton of NO_x reduced and the on-board diagnostics regulation is estimated to cost \$1974 per ton of NO_x reduced from malfunctioning in-use light-duty vehicles. The cost-effectiveness of the VOC and NO_x control measures discussed above are summarized in Table 3-08.

In summary, the cost-effectiveness of the standard included in the FRM is favorable relative to the cost-effectiveness of several other NO_x control measures required under the Clean Air Act. To the extent that cost-effective nationwide controls are applied to large nonroad CI engines, the need to apply in the future more expensive additional controls to mobile and stationary sources that also contribute to acid deposition, as well as ozone nonattainment, nutrient loading, visibility, and particulate matter and nitrogen dioxide nonattainment may be reduced.

Furthermore, the cost-effectiveness of the NO_x control program adopted here is also favorable relative to several mandated VOC control measures. Because many state air quality planners will need to develop a mix of programs to reduce both VOC and NO_x in their nonattainment areas, the overall cost of reducing ambient ozone will be dependent on the cost-effectiveness of both VOC and NO_x controls. Hence, cost-effective NO_x control programs such as the one adopted here should result in lower overall ozone control costs. However, direct comparisons of dollar/ton estimates for NO_x and VOC control measures are difficult because the relationship between NO_x, VOC, and ambient ozone levels varies from area to area.

Table 3-05
Annualized Costs as Incurred

Year	Variable Hardware Cost	Recalibration	Design	Test Facility	Mechanical Integrity Testing	Certification	Emission Defect Reporting	Selective Enforcement Auditing	Importation	Exclusions	Exemptions	ANNUALIZED TOTAL
1993	0	0	2,209,000	739,000	0	0	0	0	0	0	0	2,948,000
1994	0	2,273,000	2,209,000	739,000	1,516,000	0	0	0	0	0	0	6,737,000
1995	0	2,273,000	2,209,000	739,000	1,516,000	8,881,000	0	0	0	0	0	15,618,000
1996	48,513,000	2,273,000	2,209,000	739,000	1,516,000	8,945,000	13,000	1,605,000	34,000	3,000	13,000	65,813,000
1997	49,483,000	2,273,000	2,209,000	739,000	1,516,000	8,945,000	13,000	1,605,000	34,000	3,000	13,000	66,783,000
1998	50,473,000	2,273,000	2,209,000	739,000	1,516,000	8,945,000	13,000	1,605,000	34,000	3,000	13,000	67,773,000
1999	51,482,000	2,273,000	2,209,000	739,000	1,516,000	8,945,000	13,000	428,000	34,000	3,000	13,000	67,605,000
2000	52,512,000	2,273,000	2,209,000	739,000	1,516,000	8,945,000	13,000	428,000	34,000	3,000	13,000	68,635,000
2001	53,562,000	2,273,000	2,209,000	739,000	1,516,000	8,945,000	13,000	428,000	34,000	3,000	13,000	69,685,000
2002	54,633,000	2,273,000	2,209,000	739,000	1,516,000	8,945,000	13,000	428,000	34,000	3,000	13,000	70,756,000
2003	55,726,000	2,273,000	0	739,000	1,516,000	8,945,000	13,000	428,000	34,000	3,000	13,000	69,640,000
2004	56,840,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	69,238,000

Year	Variable Hardware Cost	Recalibration	Design	Test Facility	Mechanical Integrity Testing	Certification	Emission Defect Reporting	Selective Enforcement Auditing	Importation	Exclusions	Exemptions	ANNUALIZED TOTAL
2005	57,977,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	70,375,000
2006	59,137,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	71,535,000
2007	60,319,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	72,717,000
2008	61,526,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	73,924,000
2009	62,756,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	75,154,000
2010	64,432,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	76,830,000
2011	65,292,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	77,690,000
2012	66,597,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	78,995,000
2013	67,929,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	80,327,000
2014	69,288,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	81,686,000
2015	70,674,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	83,072,000
2016	72,087,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	84,485,000

Year	Variable Hardware Cost	Recali-bration	Design	Test Facility	Mechanical Integrity Testing	Certification	Emission Defect Reporting	Selective Enforcement Auditing	Importation	Exclusions	Exemptions	ANNUALIZED TOTAL
2017	73,529,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	85,927,000
2018	75,000,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	87,398,000
2019	76,500,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	88,898,000
2020	78,029,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	90,427,000
2021	79,590,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	91,988,000
2022	81,182,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	93,580,000
2023	82,806,000	2,273,000	0	739,000	0	8,945,000	13,000	428,000	34,000	3,000	13,000	95,204,000
2024	84,462,000	2,273,000	0	0	0	8,945,000	13,000	428,000	34,000	3,000	13,000	96,121,000
2025	86,151,000	0	0	0	0	8,945,000	13,000	428,000	34,000	3,000	13,000	95,537,000
2026	87,874,000	0	0	0	0	8,945,000	13,000	428,000	34,000	3,000	13,000	97,260,000

Table 3-06
Annualized Costs as Recovered

Year	Variable Hardware Cost	Recalibration	Design	Test Facility	Mechanical Integrity Testing	Certification	Emission Defect Reporting	Selective Enforcement Auditing	Importation	Exclusions	Exemptions	ANNUALIZED TOTAL
1996	48,513,000	2,411,426	2,413,834	807,525	1,608,324	9,147,430	13,000	686,000	34,000	3,000	13,000	65,600,539
1997	49,483,000	2,411,426	2,413,834	807,525	1,608,324	9,213,350	13,000	1,605,000	34,000	3,000	13,000	67,555,459
1998	50,473,000	2,411,426	2,413,834	807,525	1,608,324	9,213,350	13,000	1,605,000	34,000	3,000	13,000	68,545,459
1999	51,482,000	2,411,426	2,413,834	807,525	1,608,324	9,213,350	13,000	1,605,000	34,000	3,000	13,000	69,554,459
2000	52,512,000	2,411,426	2,413,834	807,525	1,608,324	9,213,350	13,000	1,605,000	34,000	3,000	13,000	70,584,459
2001	53,562,000	2,411,426	2,413,834	807,525	1,608,324	9,213,350	13,000	1,605,000	34,000	3,000	13,000	71,634,459
2002	54,633,000	2,411,426	2,413,834	807,525	1,608,324	9,213,350	13,000	1,605,000	34,000	3,000	13,000	72,705,459
2003	55,726,000	2,411,426	2,413,834	807,525	1,608,324	9,213,350	13,000	1,605,000	34,000	3,000	13,000	73,798,459
2004	56,840,000	2,411,426	2,413,834	807,525	1,608,324	9,213,350	13,000	1,605,000	34,000	3,000	13,000	74,912,459
2005	57,977,000	2,411,426	2,413,834	807,525	1,608,324	9,213,350	13,000	1,605,000	34,000	3,000	13,000	76,049,459
2006	59,137,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	73,187,301
2007	60,319,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	74,369,301
2008	61,526,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	75,576,301
2009	62,756,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	76,806,301
2010	64,432,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	78,482,301
2011	65,292,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	79,342,301
2012	66,597,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	80,647,301
2013	67,929,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	81,979,301
2014	69,288,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	83,338,301
2015	70,674,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	84,724,301
2016	72,087,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	86,137,301
2017	73,529,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	87,579,301

Year	Variable Hardware Cost	Recalibration	Design	Test Facility	Mechanical Integrity Testing	Certification	Emission Defect Reporting	Selective Enforcement Auditing	Importation	Exclusions	Exemptions	ANNUALIZED TOTAL
2018	75,000,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	89,050,301
2019	76,500,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	90,550,301
2020	78,029,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	92,079,301
2021	79,590,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	93,640,301
2022	81,182,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	95,232,301
2023	82,806,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	96,856,301
2024	84,462,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	98,512,301
2025	86,151,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	100,201,301
2026	87,874,000	2,411,426	0	807,525	0	9,213,350	13,000	1,605,000	34,000	3,000	13,000	101,924,301

Table 3-07
Annualized Costs and Corresponding Present Values

(1) Year	(2) Annualized Total (1992$)	(3) Present Value of (2) (1992$)	(4) Total Increase in Retail Cost (1992$)	(5) Present Value of (4) (1992$)	(6) Present Value, Per-Engine (4) (1992$)	(7) Present Value, Per-Engine Cost-Effectiveness ($/ton NOx reduced) (1992$)
1996	65,600,539	57,430,000	80,341,000	70,335,000	220	108
1997	67,555,459	57,419,000	82,630,000	70,232,000	216	109
1998	68,545,459	56,564,000	83,899,000	69,233,000	208	108
1999	69,554,459	55,724,000	85,193,000	68,253,000	202	108
2000	70,584,459	54,903,000	86,513,000	67,292,000	195	107
2001	71,634,459	54,096,000	87,859,000	66,349,000	188	107
2002	72,705,459	53,306,000	89,232,000	65,423,000	182	107
2003	73,798,459	52,531,000	90,634,000	64,515,000	176	106
2004	74,912,459	51,771,000	92,062,000	63,623,000	170	106
2005	76,049,459	51,026,000	93,519,000	62,748,000	165	105
2006	73,187,301	47,676,000	90,735,000	59,106,000	152	100
2007	74,369,301	47,035,000	92,250,000	58,343,000	147	100
2008	75,576,301	46,406,000	93,798,000	57,594,000	142	99
2009	76,806,301	45,787,000	95,375,000	56,857,000	138	99
2010	78,482,301	45,424,000	97,523,000	56,444,000	134	99
2011	79,342,301	44,584,000	98,626,000	55,420,000	129	99
2012	80,647,301	43,997,000	100,299,000	54,718,000	125	98
2013	81,979,301	43,421,000	102,006,000	54,029,000	121	98
2014	83,338,301	42,856,000	103,749,000	53,351,000	117	98
2015	84,724,301	42,299,000	105,525,000	52,684,000	113	97
2016	86,137,301	41,752,000	107,337,000	52,028,000	110	97
2017	87,579,301	41,215,000	109,186,000	51,383,000	106	97
2018	89,050,301	40,686,000	111,071,000	50,747,000	103	97

2019	90,550,301	40,167,000	112,994,000	50,122,000	100	96
2020	92,079,301	39,655,000	114,955,000	49,507,000	96	96
2021	93,640,301	39,153,000	116,956,000	48,902,000	93	96
2022	95,232,301	38,659,000	118,997,000	48,306,000	90	96
2023	96,856,301	38,173,000	121,079,000	47,720,000	88	95
2024	98,512,301	37,695,000	123,202,000	47,142,000	85	95
2025	100,201,301	37,224,000	125,367,000	46,573,000	82	95
2026	101,924,301	36,762,000	127,576,000	46,013,000	80	95

Table 3-08
Cost-Effectiveness of Several NO_x Control Measures

Control Measure	Cost-Effectiveness ($/ton)
Tier I NO_x Standard (LDVs)	3,490
Title I Stationary Source Control	100-5,000
Heavy Duty Diesel Standard (1998 On-Highway)	210-260
Title IV Stationary Source Control	200-250
On Board Diagnostics (LDVs)	1,974
Large Nonroad CI Engine Standards	188

Chapter 3: References

1. Census of Manufacturers, Concentration Ratios in Manufacturing, 1987 and 1982.

2. Jack Faucett Associates, *Small Nonroad Engine and Equipment Industry Study* (JACKFAU-92-413-14), December 1992.

3. ibid, pgs 56, 59.

4. U.S. Department of Labor, Bureau of Labor Statistics, *Outlook: 1990-2005*, BLS Bulletin 2402, May 1992.

5. *Statement for Information Collection Request, Control of Air Pollution from New Nonroad Mobile Source Engines, Proposed Regulations for 1996 and Later Model Year Nonroad Compression-Ignition Engines At or Above 5 Horsepower, Amending Application for Motor Vehicle Emission Certification and Fuel Economy Labelling* (OMB No. 2060-0104), EPA No. 783, September 1992.

6. McCarthy, John H., *Study of the Significance of NOx Deterioration Factors in Proposed Regulation of Nonroad Compression-Ignition Cycle Engines Greater Than or Equal to 50 Horsepower*, EPA Memorandum, December 20, 1991.

7. *Statement for Information Collection Request, Control of Air Pollution from New Nonroad Engines, Proposed Regulations for 1995 and Later Model Year Nonroad Engines, Amending Application for Motor Vehicle Emission Defect Information Report and Records* (OMB Control No. 2060-0048) EPA No. 0282, July 1992, page 10.

8. *Statement for Information Collection Request, Control of Air Pollution from New Nonroad Engines, Proposed Regulations for 1996 and Later Model Year Nonroad Engines, Application for Selective*

Enforcement Auditing, Reporting, and Recordkeeping (OMB Control No. 2060-0064) EPA No. 11, September 1992.

9. Jack Faucett Associates, *Update of EPA's Motor Vehicle Emission Control Equipment Retail Price Equivalent (RPE) Calculation Formula* (JACKFAU-85322-2), September 1985.

10. Navistar International, *Application for Certification 1992 Navistar Heavy Duty Diesel Engine Families*, Section 06.01-3.

11. U.S. Environmental Protection Agency, Office of Policy, Planning, and Evaluation, *Guidelines for Performing Regulatory Impact Analyses, Appendix C*, EPA-230-01-84-003, March 1991, Washington, DC.

12. *The Clean Air Act Section 183(d) Guidance on Cost-Effectiveness*, EPA-450/2-91-008, November 1991.

Appendix A: Supplementary Tables for Chapter 1

Table A-01
Inventory A
Equipment Populations, Horsepower Ratings, Load Factors, Average Annual Hours of Use, NO_x Emission Factors

Equipment Types	Population	Hrs/Year	Avg. HP	Load Factor	Baseline g/hp-hr NO_x
Concrete/Industrial Saws	135	487	56	73%	11.0
Other Agricultural Equipment	18,042	330	57	51%	11.1
Wood Splitters	79	81	58	50%	8.0
Trenchers	50,510	522	60	75%	10.0
Balers	4,260	93	74	58%	7.8
Tractors/Loaders/Backhoes	299,265	1,004	77	55%	10.1
Swathers	50,032	89	79	55%	11.5
Forklifts **	160,583	1,607	83	30%	14.0
Asphalt Pavers	15,536	681	91	62%	10.3
Sprayers	9,692	88	92	50%	7.8
Rough Terrain Forklifts	53,853	569	93	60%	8.0
Terminal Tractors **	64,598	1,200	96	82%	14.0
Sweepers/Scrubbers	36,977	1,244	97	68%	14.0
Agricultural Tractors	2,519,295	411	98	70%	11.2
Chippers/Stump Grinders	17,087	437	99	37%	8.0
Paving Equipment	43,615	507	99	53%	11.0
Rollers	36,300	626	99	56%	9.3
Total 50-100 HP	3,379,859				
Other General Industrial Equipment	18,366	812	107	51%	14.0
Other Material Handling Equipment	5,258	406	111	59%	14.0
Crushing/Proc. Equipment	7,207	840	127	78%	11.0
Concrete Pavers	5,511	665	130	68%	10.0
Aircraft Support Equipment	9,529	732	137	51%	14.0
Skidders	30,911	1,158	150	74%	11.3

Table A-01
(cont.)

Equipment Types	Population	Hrs/Year	Avg. HP	Load Factor	Baseline g/hp-hr NO_x
Combines	284,854	124	152	70%	11.5
Crawler Tractors	285,923	847	157	58%	10.3
Rubber Tired Loaders	209,454	723	158	54%	10.3
Other Construction Equipment	11,867	500	161	62%	11.0
Graders	70,045	686	172	61%	9.6
Total 100-175 HP	938,925				
Excavators	61,336	747	183	57%	10.8
Fellers/Bunchers	15,581	1,110	183	71%	11.3
Cranes	98,357	701	194	43%	10.3
Bore/Drill Rigs	7,761	389	209	75%	11.0
Off-Highway Tractors	38,921	859	214	65%	11.9
Scrapers	26,700	823	311	72%	8.7
Rubber Tired Dozers	7,757	818	356	59%	9.6
Off-Highway Trucks	16,529	1,502	489	57%	9.6
Total >175 HP	272,942				
Total	4,591,726				

Table A-02
Inventory B
Equipment Populations, Horsepower Ratings, Load Factors, Average Annual Hours of Use, NO_x Emission Factors

Equipment Types	Population	Hrs/Year	Avg. HP	Load Factor	Baseline g/hp-hr NO_x
Concrete/Industrial Saws	61,336	487	56	73%	11.0
Other Agricultural Equipment	18,042	330	57	51%	11.1
Wood Splitters	79	81	58	50%	8.0
Tractors/Loaders/Backhoes	189,000	700	71	38%	10.1
Asphalt Pavers	12,000	814	77	56%	10.3
Concrete Pavers	8,400	814	77	56%	10.0
Swathers	50,032	100	82	62%	11.5
Forklifts **	47,068	850	83	30%	14.0
Rough Terrain Forklifts	25,132	873	84	35%	8.0
Sprayers	9,692	88	92	50%	7.8
Terminal Tractors **	64,598	1,200	96	82%	14.0
Sweepers/Scrubbers	36,977	1,244	97	68%	14.0
Balers	4,260	308	98	58%	7.8
Agricultural Tractors	2,519,295	411	98	70%	11.2
Chippers/Stump Grinders	17,087	437	99	37%	8.0
Paving Equipment	43,615	507	99	53%	11.0
Rollers	42,800	682	99	59%	9.3
Total 50-100 HP	3,149,413				
Other General Industrial Equipment	18,366	812	107	51%	14.0
Other Material Handling Equipment	5,258	406	111	59%	14.0
Crushing/Proc. Equipment	7,207	840	127	78%	11.0
Skidders	30,911	1,398	131	49%	11.3
Crawler Tractors	159,050	1,021	134	57%	10.3
Aircraft Support Equipment	9,529	732	137	51%	14.0

Table A-02
(cont.)

Equipment Types	Population	Hrs/Year	Avg. HP	Load Factor	Baseline g/hp-hr NO_x
Excavators	52,295	1,190	143	59%	10.8
Graders	64,000	924	147	54%	9.6
Combines	284,854	124	152	70%	11.5
Other Construction Equipment	11,867	500	161	62%	11.0
Total 100-175 HP	643,337				
Rubber Tired Loaders	130,000	1,398	175	54%	10.3
Fellers/Bunchers	15,581	1,110	183	71%	11.3
Cranes	98,357	701	194	43%	10.3
Bore/Drill Rigs	7,761	389	209	75%	11.0
Off-Highway Tractors	38,921	859	214	65%	11.9
Scrapers	16,400	1,385	290	60%	8.7
Rubber Tired Dozers	7,757	818	356	59%	9.6
Off-Highway Trucks	19,400	3,293	658	25%	9.6
Total >175 HP	334,177				
Total	4,126,927				

Table A-03

50-100 HP
Nationwide Engine Population,
Baseline and Controlled Annual Per-Engine Emissions

	Nationwide Population	Annual Per-Source NO_x (tons)	
		Baseline	Controlled
Inventory A	3,380,000	0.39	0.24
Inventory B	3,149,000	0.36	0.22
Average	3,265,000	0.38	0.23

Table A-04

100-175 HP
Nationwide Engine Population,
Baseline and Controlled Annual Per-Engine Emissions

	Nationwide Population	Annual Per-Source NO_x (tons)	
		Baseline	Controlled
Inventory A	939,000	0.63	0.41
Inventory B	643,000	0.58	0.37
Average	791,000	0.60	0.39

Table A-05

175 and greater HP
Nationwide Engine Population,
Baseline and Controlled Annual Per-Engine Emissions

	Nationwide Population	Annual Per-Source NO_x (tons)	
		Baseline	Controlled
Inventory A	273,000	1.29	0.87
Inventory B	334,000	1.55	1.05
Average	304,000	1.42	0.96

Table A-06

50 and Greater HP

Nationwide Engine Population, Baseline and Controlled Annual Per-Engine Emissions

	Nationwide Population	Annual Per-Source NO_x (tons)	
		Baseline	Controlled
Inventory A	4,592,000	0.50	0.31
Inventory B	4,127,000	0.49	0.31
Average	4,359,000	0.49	0.31

Table A-07
Engine Survival Rate and Relative Usage vs Age

Age	Survival Probability	Relative Usage
1	100%	120%
2	98%	120%
3	96%	120%
4	94%	120%
5	92%	120%
6	90%	120%
7	88%	120%
8	86%	112%
9	84%	103%
10	80%	95%
11	75%	86%
12	70%	86%
13	65%	86%
14	60%	86%
15	55%	86%
16	50%	86%
17	45%	82%
18	40%	77%
19	35%	73%
20	30%	69%
21	27%	64%
22	24%	60%
23	21%	60%
24	18%	60%
25	15%	60%
26	12%	60%
27	9%	60%
28	6%	60%
29	4%	60%
30	2%	60%

Table A-08
Diesel Engine Consumption
Estimates and Projections 1960-2026

Year	DOC Figures (All Nonautomotive Diesels)			EPA Estimates and Projections	
	Apparent Consumption	Total Engines Produced	Apparent + "Internal" Consumption	Apparent + "Internal" Consumption (All Nonautomotive	Total U.S. Consumption of Nonroad CI Engines Over 50 HP
2026					578,118
2025					566,782
2024					555,669
2023					544,773
2022					534,091
2021					523,619
2020					513,352
2019					503,286
2018					493,418
2017					483,743
2016					474,258
2015					464,959
2014					455,842
2013					446,904
2012					438,141
2011					429,550
2010					421,127
2009					412,870
2008					404,775
2007					396,838
2006					389,057
2005					381,428
2004					373,949
2003					366,617
2002					359,428
2001					352,381

Table A-08
(cont.)

Year	DOC Figures (All Nonautomotive Diesels)			EPA Estimates and Projections	
	Apparent Consumption	Total Engines Produced	Apparent + "Internal" Consumption	Apparent + "Internal" Consumption (All Nonautomotive	Total U.S. Consumption of Nonroad CI Engines Over 50 HP
2000					345,471
1999					338,697
1998					332,056
1997					325,545
1996					319,162
1995					312,904
1994					306,768
1993					300,753
1992					294,856
1991					289,075
1990	364,400	199,905	382,841	382,841	267,989
1989	415,837	217,456	443,087	443,087	310,161
1988	388,726	212,720	422,696	422,696	295,887
1987	318,597	167,804	344,405	344,405	241,084
1986	331,088	160,755	356,272	356,272	249,390
1985	300,198	173,258	326,341	326,341	228,439
1984	293,953	211,019	328,901	328,901	230,231
1983	211,160	169,552	238,407	238,407	166,885
1982	255,442	209,496	289,127	289,127	202,389
1981	422,327	349,262	475,984	475,984	333,189
1980	418,345	344,119	472,606	472,606	330,824
1979		383,108		478,584	335,009
1978	436,251	388,438	436,251	436,251	305,376
1977		367,039		467,599	327,319
1976		315,274		432,211	302,548

Table A-08
(cont.)

Year	DOC Figures (All Nonautomotive Diesels)			EPA Estimates and Projections	
	Apparent Consumption	Total Engines Produced	Apparent + "Internal" Consumption	Apparent + "Internal" Consumption (All Nonautomotive	Total U.S. Consumption of Nonroad CI Engines Over 50 HP
1975		335,116		445,776	312,043
1974		352,429		457,611	320,328
1973		309,549		428,297	299,808
1972		259,274		393,928	275,750
1971		219,344		366,631	256,642
1970		225,853		371,081	259,756
1969		253,732		390,139	273,098
1968		251,869		388,866	272,206
1967		252,452		389,264	272,485
1966		254,489		390,657	273,460
1965		245,598		384,579	269,205
1964					263,927
1963					258,752
1962					253,678
1961					248,704
1960					243,827

Table A-09
Projected Total Nonroad CI Engine Population
1990-2026

Year	---------Total Population---------			
	All	<100HP	100-175HP	>175HP
2026	7,653,005	5,731,223	1,388,868	532,913
2025	7,502,946	5,618,846	1,361,636	522,464
2024	7,355,829	5,508,673	1,334,937	512,219
2023	7,211,598	5,400,660	1,308,762	502,176
2022	7,070,194	5,294,764	1,283,100	492,329
2021	6,931,562	5,190,946	1,257,941	482,676
2020	6,795,649	5,089,162	1,233,275	473,212
2019	6,662,093	4,989,144	1,209,038	463,911
2018	6,531,796	4,891,566	1,185,391	454,838
2017	6,404,529	4,796,258	1,162,295	445,976
2016	6,279,101	4,702,326	1,139,532	437,242
2015	6,156,208	4,610,294	1,117,230	428,684
2014	6,035,400	4,519,822	1,095,305	420,272
2013	5,916,269	4,430,607	1,073,685	411,976
2012	5,797,737	4,341,841	1,052,174	403,723
2011	5,680,408	4,253,974	1,030,881	395,552
2010	5,567,015	4,169,056	1,010,303	387,656
2009	5,456,976	4,086,650	990,333	379,994

Year	---------Total Population---------			
	All	<100HP	100-175HP	>175HP
2008	5,350,519	4,006,925	971,013	372,581
2007	5,249,408	3,931,205	952,663	365,540
2006	5,153,975	3,859,737	935,344	358,894
2005	5,062,869	3,791,508	918,810	352,550
2004	4,976,342	3,726,709	903,107	346,525
2003	4,894,551	3,665,458	888,264	340,830
2002	4,817,061	3,607,426	874,201	335,434
2001	4,742,401	3,551,515	860,652	330,235
2000	4,671,161	3,498,164	847,723	325,274
1999	4,605,991	3,449,359	835,896	320,736
1998	4,547,195	3,405,327	825,226	316,642
1997	4,494,648	3,365,976	815,689	312,983
1996	4,447,094	3,330,363	807,059	309,671
1995	4,405,958	3,299,557	799,594	306,807
1994	4,371,663	3,273,875	793,370	304,419
1993	4,344,341	3,253,413	788,412	302,516
1992	4,324,464	3,238,527	784,804	301,132
1991	4,312,074	3,229,249	782,556	300,269
1990	4,307,452	3,225,788	781,717	299,947

Table A-10
Projected Controlled Nonroad CI Engine Population
1990-2026

Year	---------Controlled Population---------			
	All	<100HP	100-175HP	>175HP
2026	7,648,129	5,726,347	1,388,868	532,913
2025	7,487,255	5,604,314	1,360,477	522,464
2024	7,323,066	5,479,798	1,331,484	511,784
2023	7,153,188	5,350,409	1,301,902	500,877
2022	6,977,154	5,216,244	1,271,161	489,749
2021	6,794,866	5,077,395	1,239,286	478,185
2020	6,606,447	4,933,955	1,206,298	466,194
2019	6,412,017	4,786,014	1,172,219	453,785
2018	6,211,695	4,633,659	1,137,071	440,965
2017	6,005,595	4,476,978	1,100,874	427,743
2016	5,793,832	4,316,056	1,063,650	414,126
2015	5,571,639	4,146,098	1,025,417	400,123
2014	5,338,063	3,967,284	985,039	385,741
2013	5,092,893	3,779,786	942,555	370,551
2012	4,836,354	3,583,774	898,009	354,570
2011	4,568,670	3,379,417	851,440	337,813
2010	4,290,059	3,166,876	802,889	320,294
2009	4,000,736	2,946,313	752,393	302,030

Year	---------Controlled Population---------			
	All	<100HP	100-175HP	>175HP
2008	3,700,911	2,717,885	699,991	283,035
2007	3,390,789	2,481,746	645,721	263,322
2006	3,070,573	2,238,047	589,618	242,907
2005	2,742,898	1,989,375	531,720	221,802
2004	2,413,366	1,740,704	472,640	200,022
2003	2,083,389	1,492,032	413,560	177,797
2002	1,753,412	1,243,360	354,480	155,573
2001	1,423,436	994,688	295,400	133,348
2000	1,093,459	746,016	236,320	111,123
1999	763,483	497,344	177,240	88,899
1998	433,506	248,672	118,160	66,674
1997	103,529	0	59,080	44,449
1996	22,225	0	0	22,225
1995	0	0	0	0
1994	0	0	0	0
1993	0	0	0	0
1992	0	0	0	0
1991	0	0	0	0
1990	0	0	0	0

Table A-11

Projected Annual Nationwide Nonroad CI NO_x Emissions
1990-2026, Baseline Scenario

Year	Baseline Annual NO_x Emissions (tons)			
	All	<100HP	100-175HP	>175HP
2026	3,945,678	2,274,245	877,442	793,991
2025	3,868,312	2,229,652	860,238	778,423
2024	3,792,463	2,185,933	843,370	763,160
2023	3,718,101	2,143,071	826,833	748,196
2022	3,645,197	2,101,050	810,621	733,525
2021	3,573,722	2,059,853	794,727	719,142
2020	3,503,649	2,019,464	779,144	705,042
2019	3,434,859	1,979,814	763,846	691,199
2018	3,367,607	1,941,051	748,891	677,666
2017	3,301,815	1,903,129	734,260	664,426
2016	3,237,118	1,865,838	719,872	651,407
2015	3,173,712	1,829,292	705,772	638,648
2014	3,111,454	1,793,407	691,927	626,120
2013	3,050,211	1,758,107	678,308	613,796
2012	2,989,654	1,723,203	664,841	601,610
2011	2,929,874	1,688,747	651,547	589,580
2010	2,871,894	1,655,328	638,654	577,913
2009	2,815,528	1,622,839	626,119	566,571

Year	Baseline Annual NO_x Emissions (tons)			
	All	<100HP	100-175HP	>175HP
2008	2,760,587	1,591,171	613,901	555,515
2007	2,707,686	1,560,680	602,137	544,869
2006	2,656,833	1,531,369	590,828	534,636
2005	2,607,716	1,503,058	579,905	524,752
2004	2,559,605	1,475,328	569,207	515,071
2003	2,512,630	1,448,252	558,760	505,618
2002	2,467,754	1,422,386	548,781	496,588
2001	2,424,460	1,397,431	539,153	487,876
2000	2,382,789	1,373,413	529,886	479,490
1999	2,345,160	1,351,724	521,518	471,918
1998	2,312,538	1,332,921	514,264	465,353
1997	2,283,264	1,316,048	507,754	459,463
1996	2,256,469	1,300,604	501,795	454,071
1995	2,230,445	1,285,603	496,008	448,834
1994	2,205,738	1,271,362	490,513	443,862
1993	2,182,411	1,257,917	485,326	439,168
1992	2,160,877	1,245,505	480,537	434,835
1991	2,146,231	1,237,063	477,280	431,887
1990	2,139,061	1,232,931	475,686	430,445

Table A-12

Projected Annual Nationwide Nonroad CI NO_x Emissions 1990-2026, With Controls

Year	Controlled Annual NO_x Emissions (tons)			
	All	<100HP	100-175HP	>175HP
2026	2,485,320	1,378,555	570,987	535,778
2025	2,437,611	1,352,400	559,938	525,272
2024	2,391,544	1,327,197	549,253	515,094
2023	2,347,306	1,303,145	538,924	505,237
2022	2,304,933	1,280,221	529,018	495,694
2021	2,264,451	1,258,405	519,526	486,521
2020	2,225,823	1,237,673	510,441	477,709
2019	2,188,919	1,217,952	501,734	469,234
2018	2,154,364	1,199,759	493,460	461,145
2017	2,122,282	1,183,132	485,726	453,425
2016	2,092,519	1,167,938	478,478	446,103
2015	2,065,960	1,154,933	471,786	439,242
2014	2,042,827	1,144,161	465,833	432,833
2013	2,023,335	1,135,672	460,634	427,029
2012	2,006,573	1,128,619	456,156	421,798
2011	1,992,425	1,123,031	452,200	417,194
2010	1,981,704	1,119,479	448,985	413,240
2009	1,974,193	1,117,836	446,464	409,893
2008	1,969,671	1,117,974	444,588	407,109

Year	Controlled Annual NO_x Emissions (tons)			
	All	<100HP	100-175HP	>175HP
2007	1,971,071	1,122,577	443,488	405,007
2006	1,979,422	1,131,895	443,945	403,582
2005	1,994,978	1,145,587	445,973	403,418
2004	2,016,333	1,162,541	449,357	404,435
2003	2,040,656	1,180,149	453,892	406,615
2002	2,067,820	1,198,966	458,893	409,960
2001	2,096,566	1,218,696	464,247	413,623
2000	2,126,936	1,239,361	469,961	417,613
1999	2,161,347	1,262,356	476,575	422,417
1998	2,200,766	1,288,237	484,301	428,227
1997	2,243,532	1,316,048	492,772	434,712
1996	2,244,094	1,300,604	501,795	441,695
1995	2,230,445	1,285,603	496,008	448,834
1994	2,205,738	1,271,362	490,513	443,862
1993	2,182,411	1,257,917	485,326	439,168
1992	2,160,877	1,245,505	480,537	434,835
1991	2,146,231	1,237,063	477,280	431,887
1990	2,139,061	1,232,931	475,686	430,445

Appendix B: Formation and Control of Pollutants

B.1. Oxides of Nitrogen, NO_x

At high temperatures and pressures, normally inert nitrogen combines with the oxygen in the air to form NO and NO_2. Combustion affects this process only by altering the pressure and temperature in the cylinder. Since the oxygen and nitrogen content of the air inducted by an engine cannot be controlled, the only two physical factors that can be controlled to control NO_x emissions are temperature and the time the nitrogen and oxygen are exposed to high temperatures. Strategies which enable the combustion to be completed quickly effectively shorten the time for NO_x formation and tend to reduce HC and PM emissions as well. However those same strategies may also increase the combustion temperature. Since NO_x formation is a much stronger function of temperature than time, the majority of NO_x formation is accomplished in the initial, uncontrolled, stage of combustion (detonation) and it is important to reduce the temperature spike formed from detonation by such methods as retarding the start of fuel injection, using a slower injection rate at the initial injection period, using of higher cetane fuel, increasing the amount of air in the cylinder, using of EGR, or some other method.

B.2. Hydrocarbons

When hydrocarbons are heated to a high enough temperature in the presence of oxygen, they turn into oxides of carbon and hydrogen. If hydrocarbons appear in the exhaust of a properly operating engine they are the result of molecules either hidden away from the air, or molecules that have been cooled to a temperature too low for the reaction to take place in the amount of time available. One of these two situations occurs under many circumstances, such as the following.

- Fuel droplet size is too large. Combustion takes place on the surface of the droplet only and as the fuel is consumed more molecules are available for combustion. If the drop size is too large the internal molecules never get to see any air and never get a chance to burn.

- Fuel sprayed on combustion chamber walls. Assuming a normally cooled surface, fuel impinging on the wall will be too cool to burn even though there is plenty of air.
- Fuel dribbling from nozzle tip. Drop size is large and fuel may be introduced at the wrong time in the cycle.
- Lubricating oil passing the piston rings, the intake valve guides, and the turbine seals is cold and sees very little oxygen because it is not atomized.
- Poor mixing, or too low air/fuel ratio. As fuel is introduced into the cylinder it must find unused oxygen. If some of it finds only combustion products, it will not burn.

B.3. Carbon Monoxide (CO)

When the hydrocarbon fuel burns it forms, among other things, CO. Unlike HC which is typically a liquid, or Carbon (C) which is a solid, CO is a gas which readily mixes and combines with available oxygen to form CO_2. An Otto cycle engine can, and at times does, operate at an air/fuel ratio that supplies insufficient oxygen for complete combustion. CO formation can be a problem under those conditions. The richest air/fuel ratio found in a diesel-fueled compression-ignition engine is about 50% leaner than a Otto cycle engine and much leaner still at part load. With all this excess oxygen available, CO tends not to be a problem in diesel-fueled compression-ignition engines.

B.4. Particulates and Smoke

Although there is not a one to one correspondence, smoke and particulate are related. Smoke is the visible portion of particulate emissions and generally the conditions which generate one generate the other. Particulates are formed during the combustion process and they are oxidized to gases during the expansion stroke after combustion is complete. Some particulates, such as ash, cannot be oxidized. Some strategies for reducing particulates are ending combustion sooner, using better fuels (lower ash and lower sulfur), improving atomization, using a leaner air/fuel ratio.

Appendix C: EPA/EMA Engine Test Program

At the start of the rulemaking process, the following three important questions had to be answered.

- At what level are current production nonroad engines polluting the atmosphere?
- What test procedure should be adopted to simulate the real world operation of these engines?
- What level of emission standards can be tolerated without putting undue strain on either the engine manufacturers, the equipment manufacturers or on the end users of the equipment?

To help answer these questions a test program was devised. Five engine manufacturers agreed to supply one engine each which represented current production nonregulated engines. Test data from these engines would be used along with the data supplied by EMA to determine the current emission levels. To meet the emission standards, it is likely that engine manufacturers would apply emission control technologies similar to some of the technologies used to meet the 1990 on-highway engine emission standards. Therefore, the same five manufacturers agreed to supply an engine that was the same basic engine model but would meet the 1990 MY on-highway emission standards and develop about the same performance. Four of these engines were to be comparable on-highway 1990 MY versions of the nonroad engines and the fifth was to be a prototype. These five pairs of engines were then to be tested in three different laboratories, two pairs at the EPA National Vehicle and Fuel Emission Lab in Michigan, two pairs at Southwest Research Institute in Texas and the Detroit Diesel engine pair at Detroit Diesel's Romulus test facility. To help with the decision about a test cycle, all ten engines were to be operated over the Federal Test Procedure (FTP), which is the on-highway transient test, and an Eight Mode steady state cycle which is similar to the adopted ISO 8178 procedure being developed by the manufacturers, through the Society of Automotive Engineers (SAE) and the International Standards Organization (ISO).

Two of the manufacturers were unable to supply the on-highway versions of their engines. In these cases the nonroad engine was modified and retested with sufficient injection timing retard to meet the 9.2 g/kW-hr (6.9 g/hp-hr) standard.

In addition, a second matching set of engines was provided by one manufacturer. With the eight engines provided in the first round, the program consisted of ten engines tested in a total of eighteen engine configurations. The test results for the eighteen configurations are summarized in the following reports.

1. "DRAFT: Heavy-duty Engine Testing Report, Nonroad Engine Configurations, Test Results" - 1991 by Mark Doorlag and Mike Samulski, U.S.EPA.
2. "DRAFT: Heavy-duty Engine Testing Report, Nonroad Engine Configurations, Injection Timing Effects, Test Results" - 1992 by Mark Doorlag, U.S.EPA.
3. Dynamometer Testing of Heavy-duty Diesel Engines to Support Nonroad Regulations" - by Steven G. Fritz, SWRI 08-3426-010, Sept. 1991.
4. Dynamometer Testing of Nonroad Diesel Engines to Support Nonroad Regulations" - by Michael J. Smith, SWRI 08-4855-150 dated June 1992.
5. Detroit Diesel Corporation letter to T. Trimble, EPA, from John Fisher, DDI, dated September 18, 1991.

The following table summarizes the data provided in these eight reports. Table C-01 provides the composite emission test results of both the 8-mode test and the on-highway FTP for eighteen engine configurations tested in the test program and the percent difference in the results. This table is referenced in different parts of this document.

Table C-01

FTP and 8-Mode Emission Test Results and Comparison of Results

ENGINE		HC g/hp-hr (g/kw-hr)			CO g/hp-hr (g/kw-hr)			NO_x g/hp-hr (g/kw-hr)			P.M. g/hp-hr (g/kw-hr)			Smoke % opacity				Max. Power hp (kw)	BSFC over cycle lbs/ bhp-hr (g/ kw-hr)
		ftp	8mod	%dif	ftp	8mod	%dif	ftp	8mod	%dif	ftp	8mod	%dif	accel	lug	peak	snap		
141hp 6-cyl turbo John Deere	A-1	0.73 (0.97)	0.31 (0.42)	58	2.57 (3.44)	1.21 (1.62)	53	6.09 (8.16)	6.10 (8.18)	0	0.34 (0.45)	0.18 (0.24)	47					154 (115)	0.361 (219)
	A-2	0.86 (1.15)	0.43 (0.58)	50	3.61 (4.83)	3.14 (4.21)	13	10.81 (14.49)	11.76 (15.76)	-9	0.40 (0.53)	0.42 (0.56)	-5	13	9	22		141 (105)	0.348 (212)
	A-3	1.58 (2.11)	0.93 (1.24)	41	5.43 (7.27)	4.77 (6.39)	12	5.65 (7.57)	6.34 (8.49)	-12	0.99 (1.33)	1.09 (1.46)	-10	20	20	41		134 (100)	0.363 (221)
	A-4	0.84 (1.12)	0.77 (1.03)	8	4.26 (5.71)	3.56 (4.77)	16	6.04 (8.09)	7.10 (9.51)	-18	0.81 (1.09)	0.87 (1.16)	-7	23	20	47		137 (102)	0.352 (214)
	ave			39			24			-10			6						
100hp 4-cyl turbo Cummins	B-1	0.70 (0.93)	0.37 (0.37)	48	1.63 (1.63)	1.13 (1.13)	31	4.90 (6.56)	4.60 (6.16)	6	0.46 (0.61)	0.42 (0.75)	9	5	11	11	21	106 (79)	0.408 (248)
	B-2	1.08 (1.44)	0.75 (1.00)	30	2.70 (3.61)	2.20 (2.95)	19	12.14 (16.27)	11.00 (14.74)	9	0.59 (0.79)	0.40 (0.53)	33	25	6	54	67	105 (78)	0.372 (226)
	B-3	1.38 (1.84)	0.93 (1.24)	33	2.51 (3.36)	1.54 (2.06)	39	6.18 (8.28)	5.58 (7.47)	10	0.59 (0.79)	0.47 (0.63)	21					100 (75)	0.378 (230)

ENGINE		HC g/hp-hr (g/kw-hr)			CO g/hp-hr (g/kw-hr)			NO_x g/hp-hr (g/kw-hr)			P.M. g/hp-hr (g/kw-hr)			Smoke % opacity				Max. Power hp (kw)	BSFC over cycle lbs/ bhp-hr (g/ kw-hr)
		ftp	8mod	%dif	ftp	8mod	%dif	ftp	8mod	%dif	ftp	8mod	%dif	accel	lug	peak	snap		
	B-4	4.24 (5.68)	1.50 (2.01)	65	5.23 (7.01)	2.51 (3.36)	52	3.99 (5.34)	3.81 (5.10)	5	0.83 (1.11)	0.64 (0.85)	23					89 (66)	0.439 (267)
	ave			44			35			7			21						
285hp 6-cyl turbo Cater-pillar	C-1	0.51 (0.68)	0.53 (0.71)	-4	2.10 (2.81)	1.21 (1.62)	42	3.65 (4.89)	3.44 (4.61)	6	0.36 (0.48)	0.21 (0.28)	40	11	4	15	13	270 (201)	0.362 (220)
	C-2	1.70 (2.27)	1.14 (1.52)	33	5.06 (6.78)	1.44 (1.44)	72	6.55 (8.78)	6.49 (8.69)	1	0.58 (0.77)	0.18 (0.24)	69	31	3	60	97	288 (215)	0.356 (216)
	ave			15			57			3			54						
450hp 8-cyl turbo Detroit Diesel	D-1	0.39 (0.52)	0.32 (0.42)	18	3.85 (5.19)	0.87 (1.16)	77	6.24 (8.36)	7.00 (9.38)	-12	0.39 (0.52)	0.13 (0.17)	67	41	2	69	69		0.372 (226)
	D-2	0.38 (0.50)	0.36 (0.48)	5	3.87 (5.19)	0.80 (1.07)	79	11.18 (14.87)	12.10 (16.21)	-8	0.26 (0.34)	0.12 (0.16)	54	20	2	38	42	450 (336)	0.361 (219)
	D-3	0.39 (0.52)	0.32 (0.42)	18	4.56 (6.11)	0.88 (1.17)	81	5.27 (7.06)	5.80 (7.77)	-10	0.54 (0.72)	0.13 (0.17)	76						0.379 (230)
	ave			14			79			-10			66						

Table C-01
(cont.)

ENGINE		HC g/hp-hr (g/kw-hr)			CO g/hp-hr (g/kw-hr)			NO_x g/hp-hr (g/kw-hr)			P.M. g/hp-hr (g/kw-hr)			Smoke % opacity				Max. Power hp (kw)	BSFC over cycle lbs/bhp-hr (g/kw-hr)
		ftp	8mod	%dif	ftp	8mod	%dif	ftp	8mod	%dif	ftp	8mod	%dif	accel	lug	peak	snap		
130hp 6-cyl na Ford New Holland	F-1	2.57 (3.44)	0.95 (1.27)	63	6.26 (8.39)	6.39 (8.56)	-2	9.65 (12.93)	7.60 (10.18)	21	1.03 (1.38)	1.02 (1.36)	1					131 (98)	0.358 (218)
	F-2	2.12 (2.84)	0.70 (0.93)	67	5.29 (7.09)	5.58 (7.48)	-5	10.59 (14.19)	9.27 (12.42)	12	0.90 (1.20)	0.96 (1.28)	-7	11	26	27		130 (97)	0.337 (205)
	F-3	3.64 (4.87)	1.40 (1.87)	62	5.90 (7.90)	4.77 (6.39)	19	7.06 (9.46)	5.90 (7.90)	16	1.26 (1.68)	1.31 (1.75)	-4	21	34	35		131 (98)	0.314 (191)
	ave			64			4			17			-3						
75hp 4-cyl na John Deere	J-1	1.68 (2.25)	0.89 (1.19)	47	2.10 (2.81)	1.54 (2.06)	27	7.07 (9.47)	6.08 (8.15)	14	0.59 (0.79)	0.38 (0.50)	35	3	4	4	6	76 (57)	0.378 (230)
	J-2	1.40 (1.88)	0.64 (0.85)	54	3.37 (4.52)	3.50 (4.69)	-4	7.57 (10.14)	7.24 (9.70)	4	0.63 (.84)	0.59 (.79)	7	12	23	24	17	75 (56)	0.380 (231)
	ave			51			12			9			21						
Average				38			35			3			27						

Table C-01
(cont.)

Appendix D: Estimation of the Number of Engine Families

EPA has reviewed information from manufacturers and has estimated the number of engine families in two ways. One estimate is based on the current engine family definition in CFR 86.090-24 is as follows.

> (a)(1) The vehicles or engines covered by an application for certification will be divided into groupings of engines which are expected to have similar emission characteristics throughout their useful life. Each group of engines with similar emission characteristics shall be defined as a separate engine family.
>
> (2) To be classed in the same engine family, engines must be identical in all the following respects:
>
> (i) The cylinder bore center-to-center dimensions.
> (ii) [Reserved]
> (iii) [Reserved]
> (iv) The cylinder block configuration (air cooled or water cooled; L-6, 90 degree V-8, etc.)
> (v) The location of the intake and exhaust valves (or ports).
> (vi) The method of air aspiration.
> (vii) The combustion cycle.
> (viii) Catalytic converter characteristics.
> (ix) Thermal reactor characteristics.
> (x) Type of air inlet cooler (e.g., intercoolers and aftercoolers) for diesel heavy-duty engines.

This section also allows the Administrator to further categorize by criteria in addition to that listed in paragraph (2). However, for this analysis it is assumed that all engine families are categorized by the criteria in paragraph (2) to determine the number of engine families under the current on-highway definition.

EPA would allow the manufacturer to categorize nonroad compression-ignition engine families differently than the current on-highway engine family definition. If a manufacturer determined that a series of engine with the same individual cylinder displacement had sufficiently similar emission characteristics, the manufacturer could forego the engine family description that uses the number of cylinders and cylinder arrangement (i.e., In-Line vs. V-shape) as unique engine family identifiers if the engine does not have aftertreatment. Therefore, to be classified in the same engine family, engines must be identical in all of the following respects.

1. fuel
2. engine cooling medium (air-cooled, water-cooled)
3. method of air aspiration
4. method of exhaust after-treatment (e.g., catalytic converter, particulate trap)
5. combustion chamber design
6. bore
7. stroke
8. number of cylinders (engines with aftertreatment devices only)
9. cylinder arrangement (engines with aftertreatment devices only)

EPA's second estimate of the number of nonroad compression-ignition engine families as categorized by the above criteria is shown in Table D.01. These engine families have applications above 37kW (50 hp) including equipment used in construction, industrial, agricultural, mining, forestry, pumps, compressors, welders, and generators. This does not include engines used in locomotives, stationary sources, recreational equipment, or marine applications. The cost analysis for this rulemaking assumes that all engine families will certify using the new definition.

Table D-01

Estimated Number of Nonroad Engine Families		
Manufacturer	Current Definition	New Definition
Caterpillar	21	13
Cummins	56	22
Deere	24	11
Detroit Diesel	48	15
Duetz	34	15
Ford New Holland	28	14
Ford Power Products	9	7
Hatz	5	3
Hercules	10	5
Hino	12	11
Isuzu	10	8
Kubota	3	2
Lister-Petter	8	4
Lombardini	10	4
MAN	1	1
Mitsubishi	5	3
MTU	20	10
MWM	3	2
Navistar	1	1
Perkins	21	16
Peugeot	13	7
Scania	10	10
Teledyne	4	2
Toyota	5	3
VM	26	10
Volkswagen	5	3
Volvo-Penta	11	8
Yanmar	3	3
TOTAL	406	213

Appendix E: Hourly Test Length Estimate

The test procedures adopted in this rulemaking are based on the ISO-8178 8-mode procedures. However, the test procedures are modified. EPA modifications to ISO 8178 include tightening of testing and measuring equipment specifications and calibration requirements, changes to the order of the test modes, and the inclusion of raw exhaust and full dilution exhaust sampling options. The modifications to ISO 8178 are intended to ensure greater uniformity in practices and results among manufacturers for gaseous emission measurement. This is an explanation of the time estimate derived for the modified test procedures.

There are two test time estimate categories. One is the "set up" time and the other is the "test" run time.

The set up time will depend on whether the test has previously been run on a particular engine block. If the test has been run on the particular engine block, then less time will be required to set up the test than if no test had been run.

If the test has been run before on the engine block in question, then the following 3 steps must be done.

1. make engine adapters for the dyno
2. make flywheel adapters for the dyno
3. make both inlet and exhaust system hook ups to your measurement system (This involves setting the measurement system up with the correct back pressure and inlet depression.)

These are time consuming tasks. This estimate represents the minimum time required. It is assumed that these three steps are performed once per engine family. However, it is likely to be several times per engine family because the boring holes for screws may be different for each flywheel. Further, the range of cylinders in the engine family may necessitate different inlet and exhaust pipes. There may be other changes between models in the same engine family as well. Ignoring these differences, the "first time set up" estimate is four 8-hour days (i.e., 32 hours).

If an emission test has been run on the engine block in question, then the first time set up work is complete. The necessary equipment can be retrieved and re-assembled for another test. The set up in this case is termed the "yearly set up" because it would be the set up done to perform a certification test after the first model year in which an engine family is certified. The yearly set up includes connecting the

- throttle linkage,
- wiring,
- pressure transducers, and
- fuel line hookup.

EPA estimates 8 hours to do the yearly set up. In addition, a selective enforcement audit test would require this yearly set up.

Therefore, the estimated total set up time required for the first time the test is performed is 32 hours plus 8 hours (i.e., 40 hours). Each yearly test would only require 8 hours for set up.

"Running the test" and gathering emissions involves the following five steps.

1. Setting the inlet and exhaust restrictions. Minimal time is required for this.
2. Testing performed to stabilize the test conditions. Full emissions are not taken. This takes about 4 hours.
3. Testing done with full emissions measurement. This takes 3 hours.
4. Documentation of the test. This takes about 2 hours.
5. Taking the engine out of the test cell. This takes about 2 hours.

Therefore, it is estimated that about 11 hours are required to run the test.

The Table E-01 summarizes the hourly test estimates.

Table E-01
Hourly Test Estimates

category	first test performed	yearly tests or SEA tests
first time set up	32	0
yearly set up	8	8
running the test	11	11
TOTAL	51	19