

**Draft Regulatory Impact Analysis:
Control of Emissions from
Compression-Ignition Marine Engines**



**U.S. Environmental Protection Agency
Office of Air and Radiation
Office of Mobile Sources
Engine Programs and Compliance Division**

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CHAPTER 1: INTRODUCTION

EPA is proposing new standards for emissions of oxides of nitrogen (NO_x), hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) from diesel-cycle engines with a gross power output at or above 37 kilowatts used in marine engines.¹ This Draft Regulatory Impact Analysis (Draft RIA) provides technical, economic, and environmental analyses of the proposed emission standards for the affected engines. The anticipated emission reductions would translate into significant, long-term improvements in air quality in many areas of the U.S. In 2020, the proposed standards are projected to result in reductions of 9 percent HC, 28 percent NO_x, 12 percent PM, and 3 percent CO from marine diesel engines used in the U.S. The NO_x reduction would be in addition to a 7 percent reduction in 2020 that will be achieved by adopting international standards for U.S. flagged vessels. Overall, the proposed requirements would provide much needed assistance to states and regions facing ozone and particulate air quality problems that are causing a range of adverse health effects, especially in terms of respiratory impairment and related illnesses.

Chapter 2 contains an overview of the manufacturers, including a brief description of the engines or vessels, that would be affected by the proposed rule. Chapter 3 provides a description of the range of technologies being considered for improving emission control from these engines, including detailed projections of a possible set of compliance technologies. Chapter 4 applies cost estimates to the projected technologies for several different power categories and describes the potential impacts on small businesses. These costs are summarized in Table 1-3. Chapter 5 provides an overview of the health and welfare issues involved and presents the calculated reduction in emission levels resulting from the proposed standards. Chapter 6 compares the costs and the emission reductions to estimate the cost-effectiveness of the rulemaking.

EPA has created these categories to define the three distinctive types of marine diesel engines. Category 1 includes engines greater than 37 kW but with a per cylinder displacement of less than or equal to 5 liters/cylinder. Category 2 includes engines with 5 to 20 liters/cylinder, and Category 3 includes the remaining, very large, engines.

Beginning in 2000, marine diesel engines greater than or equal than 130 kW will be subject to an international NO_x emissions standard developed by International Maritime Organization (IMO). This standard is considered to be the baseline case (or “Tier 1”) for determining the benefits of the proposed EPA standards. The IMO NO_x standard is presented in Table 1-1.

¹ Diesel-cycle engines, referred to simply as “diesel engines” in this analysis, may also be referred to as compression-ignition (or CI) engines. These engines typically operate on diesel fuel, but other fuels may be also be used. This contrasts with Otto-cycle engines (also called spark-ignition or SI engines), which typically operate on gasoline.

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Table 1-1
IMO Marine Diesel Engine NO_x Standard

Effective Date	rated speed (n)	NO _x [g/kW-hr]
2000	n > 2000 rpm	9.8
	130 ≤ n ≤ 2000 rpm	45 × n ^{-0.2}
	n < 130 rpm	17

EPA is proposing two additional levels (Tier 2 and Tier 3) of standards for Category 1 and Category 2 marine diesel engines. Table 1-1 lists the proposed standards and the affected model years for marine diesel engines greater than 37 kW. Levels for the Tier 3 particulate standards are not being proposed at this time. EPA will investigate appropriate levels for the Tier 3 PM standard as a part of a feasibility review of the proposed marine Tier 3 standards.

Table 1-2
Proposed Engine Emissions Standards

Subcategory liters/cylinder	Tier	Effective Date	HC+NO _x g/kW-hr	CO g/kW-hr	PM g/kW-hr
power ≥ 37 kW 0.5 ≤ disp. < 0.9	2	2004	7.2	5.0	0.40
	3	2008	4.0	5.0	subject to review
0.9 ≤ disp. < 1.2	2	2004	7.2	5.0	0.30
	3	2008	4.0	5.0	subject to review
1.2 ≤ disp. < 1.5	2	2004	7.2	3.5	0.20
	3	2008	4.0	3.5	subject to review
1.5 ≤ disp. < 2.0	2	2004	7.2	3.5	0.20
	3	2008	4.0	3.5	subject to review
2.0 ≤ disp. < 2.5	2	2004	7.2	3.5	0.20
	3	2008	4.0	3.5	subject to review
2.5 ≤ disp. < 5.0	2	2006	7.2	3.5	0.20
	3	2010	5.0	3.5	subject to review
5.0 ≤ disp. < 20	2	2006	7.2	2.0	0.27
	3	2010	5.0	2.0	subject to review

This document presents an analysis of the projected regulatory impacts of the proposed rule. Included in these impacts are engine and operating costs, emissions benefits, and the associated cost-effectiveness of the rule. Table 1-3 presents these impacts on a per-engine basis for five different engine sizes. The listed engine costs reflect the full anticipated price increment resulting from the proposed emission standards. These costs are adjusted in the cost-effectiveness calculation to take into account the value of non-emission benefits (such as improved performance). The operating costs presented here are the net present value of the lifetime operating costs using a seven percent rate. Because the focus of this proposed rule is on ground-level ozone, all of the costs are applied to HC+NOx benefits. The benefits are discounted at a rate of seven percent to the year that the engine is introduced into commerce. All of the costs for the proposed Tier 2 standards are with respect to baseline. The benefits are incremental compared to the IMO requirements. Both the costs and benefits presented here for the proposed Tier 3 standards are incremental to Tier 2.

Table 1-3
Projected Discounted Incremental Costs and Benefits by Power Rating (kW)

Power Rating	Tier	Engine Cost*	Operating Costs	HC+NOx Benefits	Cost-Effectiveness
37-225	Tier 2	\$2,577	\$737	4.3	\$449
	Tier 3 (years 1-5)	\$5,303	\$829	4.2	\$1,155
	Tier 3 (years 6 +)	\$1,112			\$279
225-560	Tier 2	\$4,249	\$1,128	26	\$116
	Tier 3 (years 1-5)	\$6,210	\$1,119	30	\$196
	Tier 3 (years 6 +)	\$1,829			\$58
560-1000	Tier 2	\$25,319	\$207	80	\$283
	Tier 3 (years 1-5)	\$25,507	\$2,647	77	\$308
	Tier 3 (year 6 +)	\$6,601			\$62
1000-2000	Tier 2	\$22,725	\$635	267	\$76
	Tier 3 (years 1-5)	\$26,537	\$4,519	136	\$178
	Tier 3 (year 6 +)	\$10,659			\$62
2000-5000	Tier 2	\$54,103	\$12,430	829	\$58
	Tier 3 (years 1-5)	\$44,583	\$2,874	290	\$127
	Tier 3 (year 6 +)	\$3,169			\$16

CHAPTER 2: INDUSTRY CHARACTERIZATION

I. Introduction

To help assess the potential impact of the proposed emission control program, it is important to understand the nature of the affected industries. This chapter describes the marine diesel and vessel industries along several dimensions, including the variety of engines produced for this market, the ways in which they are produced, the types of companies that produce these engines, and the types of companies that manufacture the vessels on which they are installed. The picture that emerges is one of a complex industry, both in terms of products made and the markets in which they are sold.

II. Variety of Marine Diesel Engines

A. Broad Engine Categories

The proposed emission control program is intended to cover all marine diesel engines at or above 37 kW introduced into commerce in the United States. Thus, the rule encompasses a wide range of engines, from an auxiliary engine used on a small fishing vessel to a propulsion engine installed on an ocean-going vessel. Because of the differences among these engines, it is not possible to design one set of emission limits that would apply to all of them. Therefore, as discussed in the Notice of Proposed Rulemaking (NPRM), EPA is proposing to divide marine diesel engines into three subcategories. These engine groups are intended to reflect the similarities between the marine diesel engines in each group and their land-based counterparts.

Category 1 engines are proposed to be engines with rated power at or above 37 kW but with a specific displacement of less than 5 liters per cylinder. These engines are similar to land-based nonroad diesel engines that are used in applications ranging from skid-steer loaders to large earth moving machines. Category 2 engines are proposed to be engines with a specific displacement at or above 5 liters to 20 liters per cylinder. These are similar to locomotive engines. Category 1 and Category 2 marine diesel engines are often derived from or use the same technologies as their land-based counterparts. Consequently, EPA believes that most of the technology being developed to enable the land-based counterparts to achieve recently finalized emission control programs can be applied to these marine diesel engines.^{1,2} Already, limited experience with the application of land-based nonroad Tier 2 control technologies to marine engines, as part of low-emission demonstration programs, shows that Category 1 marine diesel engines can achieve emission levels comparable to the proposed Tier 2 standards for nonroad diesel engines. It is anticipated that this will also be the case when locomotive Tier 2 technologies are applied to Category 2 engines. These technologies and their application to marine diesel engines are discussed in greater detail in Chapter 3.

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Category 3 engines are very large engines, at or above 20 liters per cylinder. These are the largest mobile source engines addressed by EPA. They are similar in size to land-based power plant generators, and are used primarily for propulsion in ocean-going vessels. Because they are currently designed for maximum fuel efficiency and performance without consideration of the impacts on NOx emissions, these engines can have very high NOx emissions. In general, Category 3 marine engines are maintained by crews whose job is to optimize adjustable parameters on the engines to reflect ambient conditions. These engines are already using advanced controls of charge air temperature and pressure which are considered to be emission control strategies for smaller engines. However, NOx reductions can still be achieved through fuel injection control strategies such as rate shaping. Therefore, the NOx standards developed by the International Maritime Organization are appropriate for Category 3 engines.

Table 2-1
Engine Category Definitions

Category	Displacement per Cylinder	Basic Engine Type
1	disp. < 5 liters (and power \leq 37 kW)	Nonroad
2	$5 \leq$ disp. < 20 liters	Locomotive
3	disp. \geq 20 liters	Unique, "Cathedral"

B. Category 1 Engine Subgroups

EPA is further proposing to divide Category 1 engines into several subgroups. These subgroups are similar to the land-based nonroad diesel engine subgroups, with one significant change: EPA is proposing to base the marine subgroups on engine displacement rather than engine power. EPA believes this is a more appropriate scheme for two reasons. First, manufacturers sometimes offer different engine models that are the same except for the number of cylinders. These engines may fall into different power groupings by virtue of the added power from adding cylinders. Second, marine engines are often available in a wider range of power than their land-based counterparts. While it may be possible to define wider power bands for marine diesel engine subgroups, it may not be possible to do so without creating phase-in disadvantages for particular companies, especially in comparison to their land-based phase-in schedule. A displacement scheme should minimize these inequities. Consequently, EPA is proposing a displacement approach to defining engine groups, as described in Table 2-2.

In selecting the displacement values corresponding with the nonroad power ranges, EPA examined the engine displacement and power characteristics of a wide range of existing engines, as shown in Table 2-2. The listed displacement values were selected to provide the greatest degree of consistency with the established land-based nonroad engine power groups. The wide range in power ratings for engines with a given per-cylinder displacement, however, led to a high degree of overlap in the attempted correlation between displacement and power rating. As a result, some nonroad

engine models that were spread across different power groupings are brought together under a single displacement grouping. This has the potential to move an engine model into a group with somewhat more or less stringent requirements, but in almost all cases there was sufficient overlap to avoid moving a family of engines into an entirely new grouping. The observed overlap highlights the benefit of relying on displacement for a simplified approach. This should give manufacturers opportunity to more sensibly plan an R&D effort to a family of engines that must meet a single set of requirements with a common implementation date.

The most important aspect of defining sub-groups relates to which engines are treated like nonroad diesel engines rated above 560 kW. Emission limits and implementation dates for smaller marine engines are relatively uniform; however, the biggest group of Category 1 engines are subject to less stringent emission limits (for Tier 3) and have more lead time. Investigation of engine models led to three key observations. First, of the engines lines with per-cylinder displacement between 2.5 and 5.0 liter, all had configurations with available power ratings above 560 kW. Several of these were much greater than 560 kW. Second, except for one instance, all engines with displacements less than 2.5 liter had configurations with available power ratings below 560 kW; this means that the manufacturers of these engines would have to meet the more aggressive requirements for some of those engines. The only exception is the DDC 149 series engines, which is being replaced with a new engine model. Third, the common practice of bolting two marine engines together could in many cases move the combined engine artificially into the less stringent regime. For example, with respect to emissions and performance, two six-cylinder 300 kW engines bolted together would operate the same as each individual engine. Yet, by doubling the power at the crankshaft, the engine would be subject to less challenging requirements.

The net effect of changing to a displacement-based grouping is hard to quantify. Somewhat greater emission reductions would likely result for the reasons described above, though it is difficult to identify the relative sales volumes of engines that would fall above and below the threshold under both scenarios. The effect on costs is expected to be small. As described above, no engines would be subject to the more stringent standards that would not have a subset of the engine line subject to those same standards under a power-based grouping arrangement. As a result, there should be no increase in R&D. Variable costs would be incurred for a greater number of engines, but the costs analysis in Chapter 4 makes clear that fixed costs dominate the overall cost impact of emission requirements.

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Table 2-2
Nonroad Power Categories and Selected Engine Models
Corresponding to Per-Cylinder Displacement Ranges

Engine Power	Displacement, liters/cylinder	Selected Engine Models
37≤kW<75 (50≤hp<100)	displ.<0.9	Cat 3046 DDC 3-53 GM 6.5L Kubota D1703, V2203 Wis-Con TMD20, 27
75≤kW<130 (100≤hp<175)	0.9≤displ.<1.2	Cat 3054, 3064, 3066, 3056, 3114, 3116 Cummins B3.9, B5.9 Deere 3029, 4039, 4045, 6059, 6068 DDC 6/12/16V-71
130≤kW<225 (175≤hp<300)	1.2≤displ.<1.5	Cummins C8.3 Deere 6076, 6081
225≤kW<450 (300≤hp<600)	1.5≤displ.<2	Cat 3176, 3304, 3306 Cummins L-10, M11, VTA-903 Deere 6101, 6105 DDC 6/8/12/16V-92
450≤kW<560 (600≤hp<750)	2.0≤displ.<2.5	Cat 3406, 3408, 3412 Cummins NT-855, VT-28 DDC 8/12/16V-149
kW≥560 (hp≥750)	2.5≤displ.<5.0	Cat 3508, 3512, 3516 Cummins KTA-19, 38, 50, QSK19, QSK30

C. Auxiliary and Propulsion Engines

Category 1, 2, and 3 marine diesel engines can further be distinguished as to whether they are used for auxiliary or propulsion purposes. As described in Chapter 3, this will have an impact on the duty cycle used to measure emissions from the engine. Especially on larger vessels, one or more auxiliary engines may be added to a vessel to generate electricity for navigational and crew services, or to operate special shipboard equipment such as cargo cranes. Propulsion engines are used to move the vessel through the water. Large ocean-going ships may have small secondary propulsion engines known as “bow-thrusters” to help the vessel maneuver in ports.

D. Recreational and Commercial

Marine diesel engines can also be distinguished according to whether they are used on recreational or commercial vessels. This distinction is important because these engines are not identical.

Commercial vessels are typically displacement vessels, which means the engine pushes the vessel through the water. Optimal operation is more a function of hull characteristics, which are designed to reduce drag, than engine size. The power ratings of the engines used in these vessels are analogous to those used in land-based applications. Commercial vessels are typically heavily used, and their engines are designed to operate for as many as 2,000 to 5,000 hours a year at the higher engine loads needed to push the vessel and its cargo through the water. Commercial vessels are generally not serially produced. Instead, they are designed for a specific user, and many characteristics, including the choice of engines, are set by the purchaser.

The operation and design characteristics of recreational vessels are very different from commercial vessels. Recreational vessels are designed for speed and therefore typically operate in a planing mode. To enable the vessel to be pushed onto the surface of the water where it will subsequently operate, recreational vessels are constructed of lighter materials and use engines with high power density (power/weight). The tradeoff on the engine side is less durability, and these engines are typically warranted for fewer hours of operation. Fortunately, this limitation typically corresponds with actual recreational vessel use. With regard to design, these vessels are more likely to be serially produced. They are generally made out of light-weight fiberglass. This material, however, minimizes the ability to incorporate purchaser preferences, not only because many features are designed into the fiberglass molds, but also because these vessels are very sensitive to any changes in their vertical or horizontal centers of gravity. Consequently, optional features are generally confined to details in the living quarters, and engine choice is very limited or is not offered at all.

III. Marine Engine Production

Reflecting differences in their size and base engines, different marine diesel engines are produced in different ways. Not surprisingly, the largest of these engines, Category 3 engines, have perhaps the most complicated production process. These engines are generally uniquely built and designed for a particular vessel used in a particular application. Although their design may draw on technologies used in stationary source applications, Category 3 engines are not typically derived from a pre-developed land-based application. In addition, because they are so large, the engine often becomes part of the structure of the vessel.

Category 1 and 2 marine diesel engines, on the other hand, are often derived from land-based engines. Because of this, their production is often referred to as marinization, meaning the land-based engine is modified for use in the marine environment. Marinization can be very complex or relatively simple. Depending on the degree of change to the base engine, marinization can

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significantly affect the emission characteristics of an engine. This will often be the case if the engine fuel system or cooling systems are modified.

Some of the more complex changes associated with marinization are performed by large engine manufacturers such as Caterpillar, Cummins, and Detroit Diesel. For these companies, marinization may involve a significant redesign of their land-based product, including pistons, fuel systems, cooling systems, and electronic controls. Actual production of marine engines often begins on the same assembly line as the land-based counterparts. However, at some stage of the production process the marine engine may be moved to a different assembly line or area, where production is completed using parts and processes specifically designed for the marine derivative engine.

Post-manufacture marinizers will often make significant changes to base engines as part of the marinization process. These companies purchase a complete or semi-complete land-based engine from an engine manufacturer and finish or modify it using specially designed parts. The process is often less complex, although fuel and cooling systems may be extensively modified. The finished engine is often intended for niche applications.

A third type of marinization is performed by companies who purchase a completed engine from an engine manufacturer and who modify it to make it compatible for installation on a marine vessel without changing its underlying design characteristics or engine calibrations. These modifications may involve changes to engine mountings, electronic instrumentation and alarm systems. These companies, referred to here as engine dressers, may also add marine gears and couplings, in the case of propulsion engines, or a generator in the case of auxiliary engines. In contrast to the other marinization processes, these changes will not typically affect the emission characteristics of the engine.

IV. Description of Engine Manufacturers

The companies that are most immediately affected by the proposed emission control program are those that manufacture diesel marine engines. This section describes some of the main features of these companies, with regard to their overall size and marine engine production volumes. Manufacturers of each category of engines will be examined separately.

A. Sources of Information

The goal of an industry characterization is to describe the basic features of a particular engine market segment as a whole, focusing on those features that may be helpful for or may become potential obstacles to implementation of the proposed emission control program. In other diesel engine rules, both on-highway and nonroad, EPA based its engine industry characterizations in large part on information collected by Power Systems Research (PSR). This characterization of the marine diesel engine industry also relies on PSR databases. However, for reasons described below, the PSR databases are less helpful for describing this industrial segment. Therefore, EPA has augmented the

PSR data with information obtained through other sources, including trade journals and discussions with various engine manufacturers.

The two PSR databases used by EPA in this industry characterization are the OE Link database and the Parts Link database. Both of these depend on information provided to PSR by the engine manufacturers. This can be an important drawback for relying on these databases when developing a picture of the marine diesel engine market. Specifically, because they rely on self-reporting, very small engine manufacturers may not be present in the databases.

Each of the two databases have additional weaknesses that affect EPA's ability to describe this industry with a great deal of precision. The OE Link database contains data on U.S. engine production for the years 1980 to 1997. While the overall production information is useful in obtaining a picture of the potential impacts of the rulemaking on this industry, several features of this database should be kept in mind. First, it includes only those companies that produce engines in the United States. This is important because it means that engines that are imported into this country, and that must be certified to the proposed emission limits, are not included. Second, it includes all U.S. production, without differentiating between the engines that will be sold in this country, and that must meet the proposed emission limits, and those that will be exported. Consequently, relying on OE Link to paint a picture of the companies that may be affected by the proposed program may result in an overestimate or underestimate of the magnitude of the potential impact of the rule.

The Parts Link database, on the other hand, contains information about the annual population of marine diesel engines in the United States for the years 1990 to 1997. This database is useful because it provides the names of all engine manufacturers, domestic and foreign, who have sold engines into the U.S. fleet. The primary weakness of this database is that it does not yield annual sales into the market for a given manufacturer. Instead, the annual information for each manufacturer includes the cumulative engine sales over many years, with some internal accounting for scrappage. Consequently, it does not help EPA determine which foreign manufactures are active in the U.S. market at this time.

B. Category 1 Engines

1. Category 1 Engine Manufacturers

a) Identification of Domestic Producers

Using the PSR OE Link database, EPA assembled a list of companies who produce marine diesel engines in the United States. These manufacturers, listed in Table 2-1, are grouped into four categories. Domestic engine manufacturers (DEM) are companies who make fully-complete marine engines. As described in the marinization discussion in Section III above, these marine engines are likely to be derived from one of the manufacturer's own land-based nonroad or on-highway engines. Foreign engine manufacturers (FEM) are similar companies, but are owned by foreign companies. Post-manufacturer marinizers (PMM) are companies that purchase a finished or semi-complete engine from another engine manufacture and modify it for use in the marine environment. These

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Figure 2-1

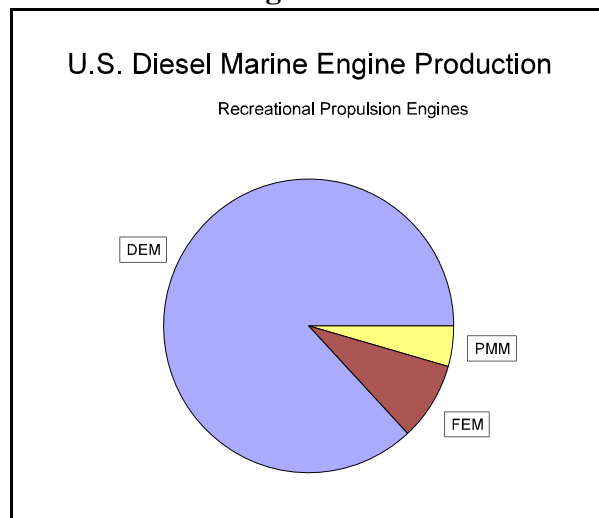
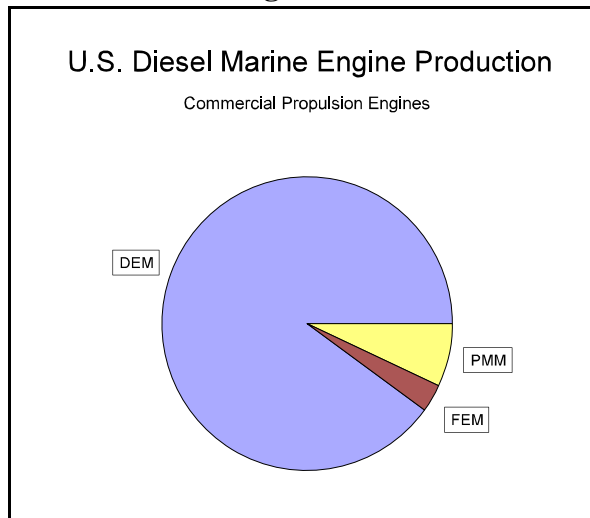


Figure 2-2



companies are broken down as to whether they make only an auxiliary engine or not, since those who make only auxiliary engines are more likely to be engine dressers and therefore not required to recertify their product to the proposed marine emission limits (see Section III.B.2 of the NPRM).

Table 2-1
Category 1 Engine Manufacturers
Source: PSR OE Link - U.S. Production Data

Domestic Engine Manufacturers	Foreign Engine Manufacturers	Post-Manufacture Marinizers - Propulsion and Auxiliary	Post-Manufacture Marinizers - Auxiliary only
Caterpillar Cummins Deere Detroit Diesel	Isuzu Yanmar	Alaska Diesel Daytona Marine Marine Corp. of Amer. Marine Power Onan Outboard Marine Peninsular Diesel Trinity Marine Westerbeke	Kohler M&L Industries R.A. Mitchell Co. Star Power Services Stewart & Stevenson York

It should be noted that engine dressers are not specifically identified as such in the PSR database, even though they are ostensibly producing marine diesel engines. Through contacts with various engine manufacturers and its own efforts, EPA identified several of these companies. Because of the special nature of their business, it is hard to precisely identify engine dressers; there may therefore be tens if not hundreds of others. While an exact profile of the engine dressing

Chapter 2: Industry Characterization

industry would be interesting, EPA believes it would be of limited value in this industry characterization since provisions are being proposed that would exempt them from certification requirements within certain constraints.

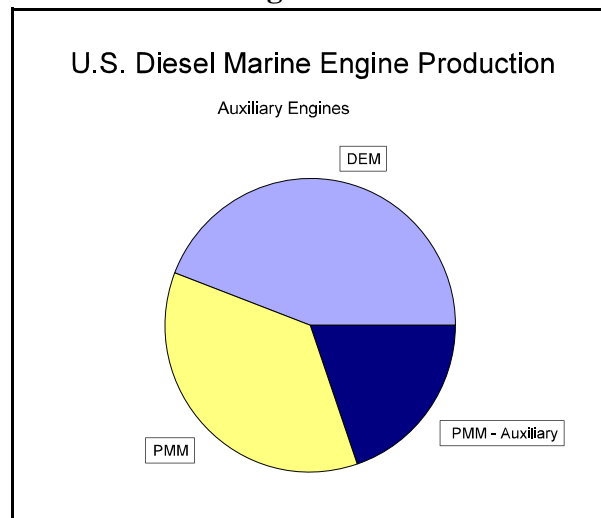
An interesting aspect of this industry revealed by the PSR data is that, although PMMs outnumber EMs numerically, their production of propulsion engines is much smaller. Using data on production volumes as reported in OE Link, it is possible to make several observations about the production of marine engines. It should be remembered that these reflect total production, and not just production intended for sale in the United States. However, these figures are nevertheless an indicator of the basic make-up of the industry.

As illustrated in Figures 2-1 and 2-2, the majority of propulsion engines produced in the U.S. are made by domestic engine manufacturers, even though the number of PMM companies exceeds the number of large engine manufacturers. This is true for both commercial and recreational propulsion engines.

In addition to producing more propulsion marine diesel engines, DEMs are also generally much larger companies than PMMs. This is to be expected since PMM generally do not produce base engines or serve markets outside of marine applications. The size difference between DEMs and PMMs is confirmed by a financial analysis performed by ICF Incorporated using Dunn and Bradstreet information. Of the eight large companies examined, five were DEMs and three were PMMs. According to this analysis, the median large company has approximately 23,000 employees and annual sales of \$3.2 billion. All of the small companies observed were PMMs, and the median small company has approximately 60 employees and annual sales of \$19 million. Conversations with various engine manufacturers also confirm the observation that PMMs are small companies. Several, such as Peninsular, Alaska Diesel, and Daytona are family-owned business that operate on a scale much smaller than the large engine manufacturers.

When auxiliary engines are considered, however, the relationship between output and engine sized is reversed. Specifically, PMMs appear to produce more marine auxiliary marine diesel engines than DEMs. In addition, as illustrated in Figure 2-3, a large number of auxiliary marine engines seem to be produced by companies who specialize in auxiliary engines. This, in turn, suggests that many of these engines are assembled by engine dressers. There are at least two explanations for this observation. It could be the case that large engine manufacturers do not get involved in the dressing process, preferring to leave this to smaller companies who can tailor their product to the special needs of marine customers. Alternatively, it could be the

Figure 2-3



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case that the data on auxiliary engine productions for DEMs and FEMs is included in their land-based nonroad figures instead of their marine figures.

b) Identification of Foreign Manufacturers

As indicated above, the PSR OE Link database contains information only on domestic producers of marine diesel engines. Yet, foreign companies that sell engines in the United States may also be affected by the proposed rule, and it is therefore important to identify them and estimate their share of the domestic market. PSR Parts Link population database contains a list of all the companies that have engines in the current U.S. fleet. A list of those companies is contained in Table 2-2. Note that, with regard to domestic engine manufacturers, Table 2-2 lists only the manufacturer of the base engines. Thus, Navistar and GM are on the list from the population database (Parts Link) but not on the production database (OE Link), since they do not produce a finished marine diesel engine. This may be the case for some of the foreign engine manufacturers as well. It should also be noted that the PSR Parts link database reflects manufacturers of engines that have been sold into the U.S. market, and does not permit distinguishing between those that are still active in the market and those that are not. The list also does not reflect those companies who seek to sell into the U.S. market, and that will also be affected by the proposed emission control program.

Table 2-2
Category 1 Engine Manufacturers
Source: PSR Parts Link - U.S. Population Data

Domestic Engine Manufacturers	Foreign Engine Manufacturers	
Allis-Chalmers	Bedford/AWD	Mitsubishi HVY
Caterpillar	Deutz-MWM	MTU
Cummins (including Consolidated Diesel)	Hino	New Holland
Deere	Isotta Fraschini	Perkins
Detroit Diesel	Isuzu	PSA
Ford	Komatsu	Renault
GM (Chev/Pont/Can)	Kubota	Rover Cars
Navistar	Leyland	SACM
Waukesha	Lister-Petter	Scania
	Mack	Steyr
	MAN	Toyota
	Mazda	VM
	Mercedes Benz	Volvo
	MIT Motors	Yanmar

Figure 2-4

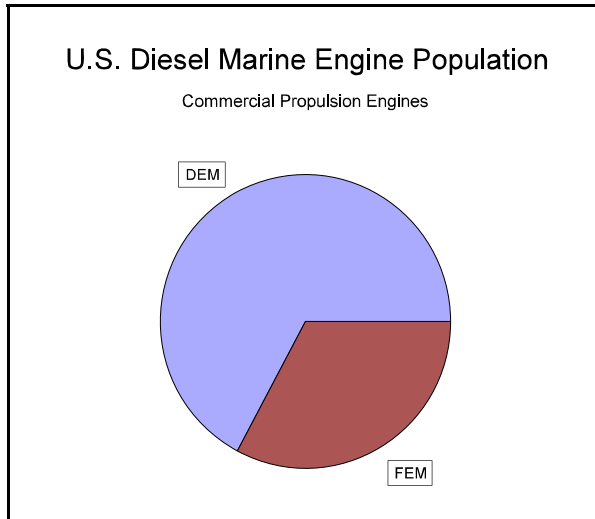


Figure 2-5

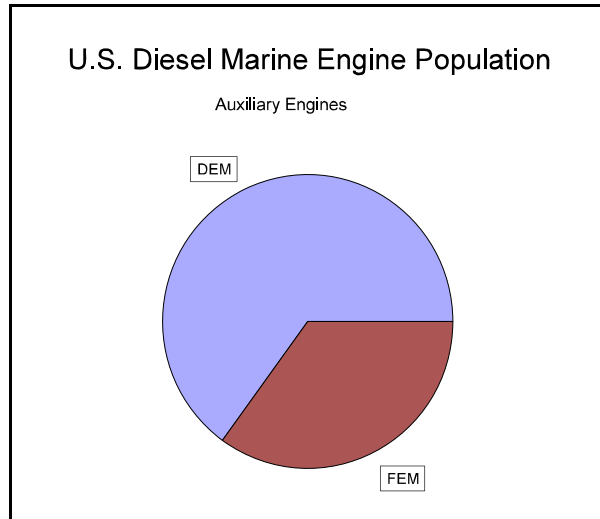


Figure 2-6

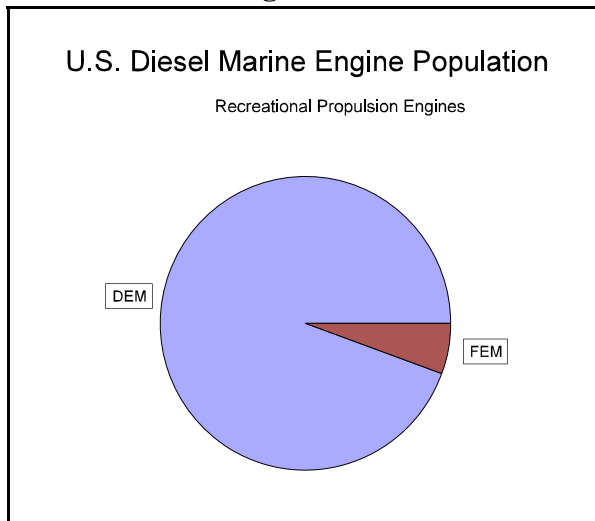
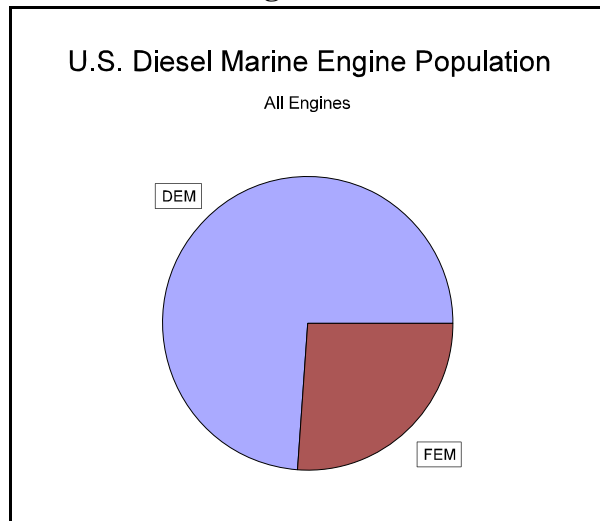


Figure 2-7



The PSR Parts Link database suggests that the majority of Category 1 engines sold into the U.S. domestic market, approximately 74 percent, were manufactured by domestic companies. The remaining 26 percent were manufactured by foreign companies. This suggests that foreign companies may have a considerable presence in the Category 1 engine market. When broken down by engine category, this data suggests that the domination of DEMs is strongest in the recreational category. These statements are illustrated in Figures 2-4 through 2-7 above. This data supports the above observation suggested by the PSR OE Link database, that U.S. manufacturers have the majority of the domestic diesel marine market.

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c) Other Marine Diesel Engine Manufacturers

Finally, there are at least four other diesel marine engine manufacturers identified by EPA that do not appear in the PSR databases. These are American Diesel, Mercury Marine, Norpro, and Regan Equipment. It is EPA's understanding that each of these are PMMs, and therefore their omission will not greatly affect the above observations about the characteristics of the marine diesel engine market.

d) Conclusion

The above information suggests that the U.S. diesel engine industry is dominated by U.S. manufacturers and that the large engine manufacturers produce the majority of the engines. PMMs play a significant role in this market, although more so in the auxiliary engine market than in the propulsion market. Foreign manufacturers are a smaller presence in the market, though they play a larger role in commercial than in recreational applications.

2. Category 1 Engine Applications

With regard to the numbers of engines produced, the PSR OE Link database indicates total annual production has varied over the past 17 years, from a low of 10,000 units in 1980 to a high of nearly 20,000 units in 1988. Figure 2-8 illustrates that growth in this industry was interrupted in the late 1980s and early 1990s. This may have been due to the economic recession in those years or changes in the tax code, particularly from additional taxes on luxury goods.

Figure 2-8

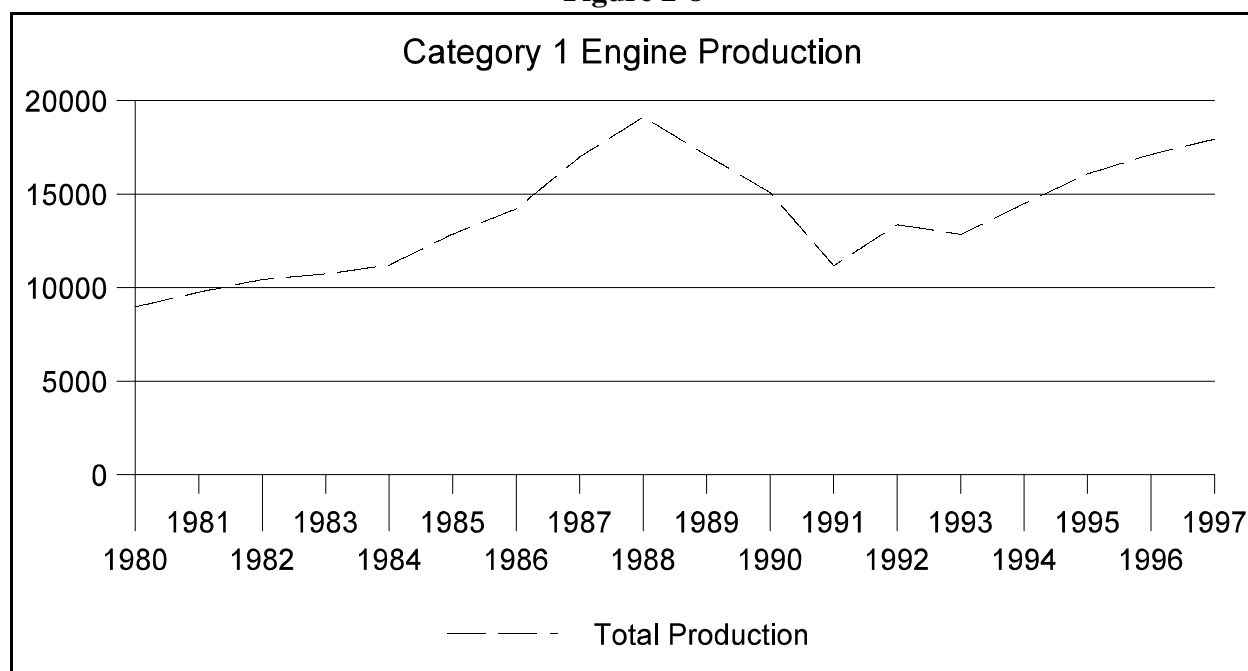
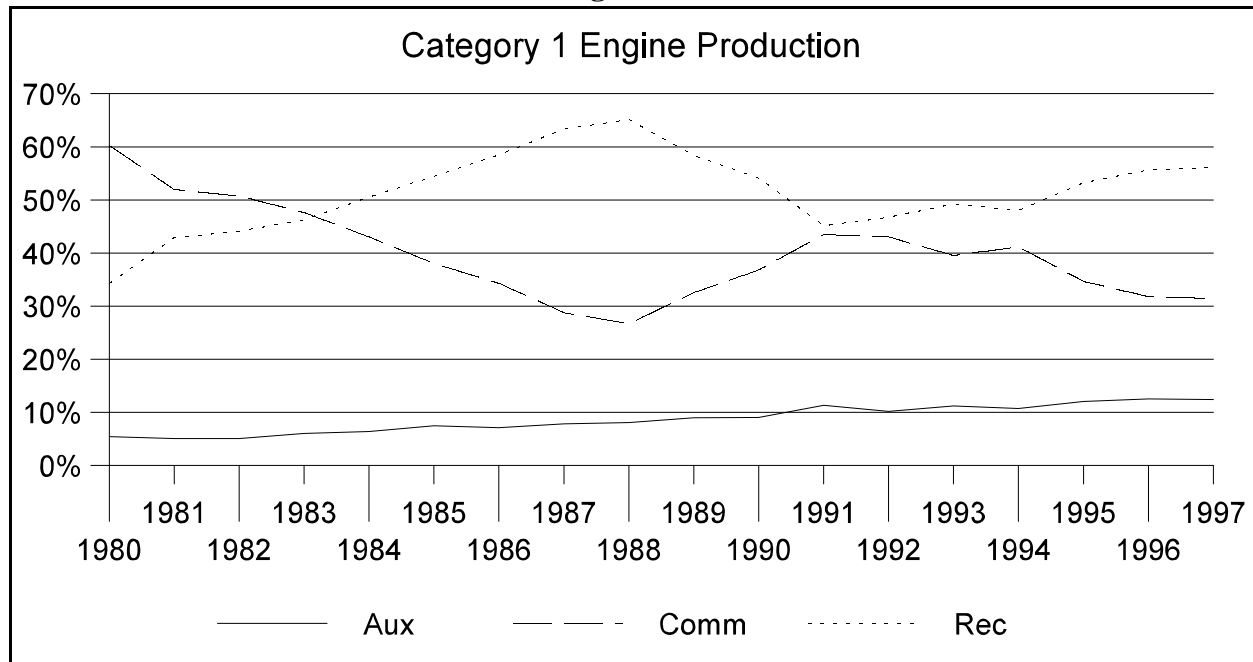


Figure 2-9 illustrates the portion of production for each segment of the industry, commercial propulsion engines, recreational propulsion engines, and auxiliary engines. According to this chart, auxiliary engines have had a fairly constant share of total production, increasing from about 7 percent at the beginning of the period to about 12 percent at the end. The more important feature of the shares of production concern propulsion engines. In the early 1980s, recreational engines replaced commercial engines as the largest segment of production. This has been the case since then, although production of these two types of propulsion engines was almost the same in the early 1990s.

Figure 2-9



C. Category 2 Engine Manufacturers

The greater mass and slower operating speeds of Category 2 engines generally corresponds with better brake-specific fuel efficiency and longer total engine lifetime. Because of the large capital requirements and the need to supply replacement parts over many years, companies with a long history of supplying marine engines have a distinct advantage in the marketplace. Also, because of the relatively low sales volume of these engines, producing engines for locomotives and for the international marine market is also very important for broadening the sales base for distributing fixed costs. Category 2 engine sales are therefore dominated by a small number of manufacturers.

General Motors Electromotive Division (EMD) has the longest history of supplying Category 2 marine engines and therefore produces the majority of these engines introduced into the U.S. Caterpillar is also actively pursuing sales of Category 2 engines with a relatively new engine product. Several other companies have engines available, but do not focus on the marine market. General Electric sells the large majority of its engines only for locomotives, though some of these engines

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find their way into marine vessels. Fairbanks Morse has long produced Category 2 marine engines, but has shifted its focus to supplying engines into military applications, rather than the commercial applications that would be most affected by the proposed standards. Several foreign companies produce engines that could be sold into the U.S. market, though companies buying new vessels have consistently specified U.S.-made engine models. This may change somewhat in the future, especially considering the ongoing developments in joint ventures and other business arrangements. Wartsila, MaK, MTU, Deutz, and Yanmar are some of the leading candidates for supplying engines into the U.S.-flagged marine vessels.

Post-manufacture marinizers play an important role in producing Category 2 marine engines. In the case of EMD engines, three authorized distributors take on the responsibility of marinizing the engine, overseeing sales distribution, and managing installation and service as needed. Stewart and Stevenson sells engines primarily into East Coast and Gulf states, while Valley Detroit Diesel is responsible for West Coast sales. Inland sells Category 2 engines for states with Great Lakes and inland river marine traffic.

Tugboats and towboats are the principal use of Category 2 marine engines. While tugboats with total propulsive power up to about 2000 kW use multiple Category 1 engines, larger models rely on one or two Category 2 engines. Similarly, the largest fishing vessels, ferries, and workboats use these larger engines. These high-powered engines are used for carrying greater loads and, in many cases, for more intensive operations. It is common for companies to own and operate small fleets of these vessels. In addition, multiple Category 2 engines are commonly used for auxiliary power on an ocean-going vessel.

With prices approaching \$1 million for a new engine, there is a strong dependence on maintaining and remanufacturing engines in the field. A strong preventive maintenance program is the norm, often including extensive ongoing diagnostics for oil quality, fuel consumption, and other engine performance parameters. Standard industry practice is to completely remanufacture the engines every five years. Procedures have improved to the point that engine durability on remanufactured engines is no different than on new engines. Since engine remanufacturing costs only 20 to 30 percent as much as buying a new engine, even twenty- or thirty-year-old engines are frequently overhauled to provide dependable power. The quality of remanufactured engines is so good, and the price savings so great that it is even common practice to install remanufactured engines into new marine vessels.

Another consequence of the prevalence of engine remanufacturing is the practice of reviving retired locomotive engines for installation in new or used marine vessels. Since locomotive operators have a higher sensitivity to achieving optimum performance and avoiding any downtime resulting from repairs, engines no longer suitable for locomotive application can continue to serve very well in several marine applications. Marine operations are generally less susceptible to competitive pressures and can therefore maintain profitable operations with somewhat older technology engines. Also, with predominantly local operation and an engineer onboard at all times, there is less concern for expensive downtime due to part failures.

D. Category 3 Engine Manufacturers

There are currently no U.S. manufacturers of Category 3 marine engines for commercial purposes. The Agency, however, has identified 22 foreign manufacturers of these engines, a large fraction of which are located in Germany and Japan. Due to the competitive nature of this industry, the number of manufacturers has changed over time due to mergers between companies. In addition, of the Category 3 engine manufacturers identified, only 12 produce engines of their own design. The remainder of the manufacturers produce engines under licensing agreements with other companies that control engine design. Table 2-3 presents the Category 3 engine manufacturers identified by EPA. These manufacturers are divided by those that produce their own designs and those that solely produce licensed designs. In many cases, the manufacturer names are hyphenated which generally is the result of a merger between two or more companies.

Table 2-3
Manufacturers of Category 3 Marine Diesel Engines

Produce Own Designs	Produce Engines Using Licensed Designs
Akasaka	Bazan
Allen Diesel	Cegielski
Daihatsu	Coltec Industries
Deutz-MWM	Dieselmotorenwerk Vulcan GMBH
Fincantier Group/GMT	Jadranbrod ULJANK
Hanshin	Kawasaki Heavy Ind.
MAN-B&W	Kirloskar Oil Engines Ltd.
MaK	Koloma Plant Joint Stock
Matsui Iron Works	Maschinenbau Halberstadt
Mitsubishi Heavy Ind. LTD	Niigata
SEMT-Pielstick	
Wartsila-NSD	

V. Recreational Boat Builders

A. Introduction

The second set of companies that is potentially affected by the proposed controls on diesel marine engines is the group of companies that manufacture marine vessels. In general, the companies that manufacture vessels would not be directly responsible for ensuring that the engines they install meet the proposed emission control requirements. However, they are potentially affected by the proposed rule to the extent that physical changes to the engines require changes to their vessel designs.

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This section contains a brief description of the recreational vessel market. Since the Agency is not proposing regulations for this sector of the industry at this time, the following discussion is provided to support the decision to defer requirements for recreational engines until a subsequent rulemaking. This description of this industry segment focuses on the number and location of recreational vessel builders, industry sales information, the types of vessels made by these companies, and the types of engines they use. The commercial vessel market is described in the following section.

B. Identification and Location of Builders

EPA considered several sources, including trade associations and Internet Web sites when identifying entities that build and/or sell recreational vessels. This resulted in a list of 165 manufacturers that build and/or sell recreational vessels. However, not all of these companies offer a version of their product using a diesel engine. Discussions with industry representative narrowed this list down to 73 companies that offer a diesel engines in their product lines. Overall, diesel engines do not constitute the majority of product offerings for the 73 companies. While, for some, diesels account for a majority of sales, others may sell as few as one per year or may sell a diesel version once every several years. This implies that this regulation will not affect all companies in the same way. Not surprisingly, the analysis shows that recreational vessel building is concentrated in coastal states with the largest presence in the state of Florida.

C. Sales and Employment Figures

To gain a better understanding of the nature of companies that participate in this industry, EPA was able to obtain financial and employment information for 51 of the 73 companies from Dunn & Bradstreet and through contact with individual companies. D&B data was not available for the remaining 22 companies. Of the recreational boat builders installing CI marine engines evaluated by the Agency, four companies reported annual sales of their products ranging from 95 million to 3.0 billion dollars. The next group of companies reported annual sales ranging from 10 million to 70 million dollars. The last range of companies reported annual sales ranging from 1.5 million to 8 million dollars. The lower range of companies reported annual sales of around 100,000 dollars.

The largest company employs 21,000. The next highest range of companies employ 8,000 and 5,000, but a majority of the companies identified in our sample employ less than 500, with average being around 130. Of the 51 companies for which the Agency has information, 47 companies employed less than 500. The Small Business Administration (SBA) has developed standards by which to define a small business. According to the SBA, for the boat building and repairing industry, a company is defined as small if it employees less than 500. Using this definition, 92 percent of the companies researched by the Agency would be considered small business.

Table 2-4
Sales and Employment Data for
Recreational Boat Builders Using Diesel Engines

Number of Companies	Annual Sales	Number of Employees
15	\$93,300 - \$890,000	1-12
13	\$1.3 million - \$9.6 million	12-60
19	\$10 million - \$70 million	60-500
4	\$95 million - \$3.0 billion	1000-21000

D. Production Practices

Based on information supplied by a variety of recreational boat builders, the following discussion provides a description of the general production practices used in this sector of the marine industry.

Engines are usually purchased from factory authorized distribution centers. The boat builder provides the specifications to the distributor who helps match an engine for a particular application. It is the boat builders responsibility to fit the engine into their vessel design. The reason for this is that sales to boat builders are a very small part of engine manufacturers' total engine sales. These engines are not generally interchangeable from one design to the next. Each recreational boat builder has their own designs. In general, a boat builder will design one or two molds that are intended to last 5-8 years. Very few changes are tolerated in the molds because of the costs of building and retooling these molds.

E. Gasoline Engine vs. Diesel Engine Installation in Recreational Vessels in the U.S.

Based on information obtained from the National Marine Manufacturers Association, the largest majority of engines used for recreational marine purchases are gasoline powered engines. Of the 75 companies submitting data for their 1996 annual survey of the recreational marine industry, 65,653 gasoline engines were installed vs. 1,381 diesel engines. Of the 1,381 diesel engines installed, 53 percent of these engines were installed in boats over 41 feet long. Of the 90 companies that submitted data for the 1997 survey, 80,339 gasoline engines were installed compared to 1,752 diesel engines. Of the 1,752 diesel engines, 57 percent were installed in boats over 41 feet long.

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Table 2-5
1996 and 1997 U.S. Sales of Gasoline and Diesel Recreational Engines

Length	Gasoline		Diesel	
	1996	1997	1996	1997
25' & Under	53,844	71,304	5	12
26' - 30'11"	7,836	4,905	90	125
31' - 35'11"	2,899	2,919	223	237
36' - 40'11"	875	805	330	378
41' & over	199	406	733	1,000
Totals	65,653	80,339	1,381	1,752

Overall, diesel engines comprise a relatively small portion of the engines installed and used for recreational purposes.

VI. Commercial Vessel Builders

A. Introduction

The industry characterization for the commercial marine vessel industry was developed by ICF Incorporated under contract for EPA. Following is a summary of their findings. A complete copy of this report is available from EPA Air Docket A-97-50.

There are three main parts to this report. Parts one and two establish the location, number, size, and relevant factors associated with shipbuilding and boat building. Part three covers production practices commonly employed by shipbuilders and boat builders.

B. Vessel Types

The report makes a distinction between two broad groups of commercial vessels, "ships" and "boats," based on a vessel's basic dimensions, mission and area of operation.

- Commercial Ships - this category is comprised of larger merchant vessels, usually exceeding 400 feet in length, that engage in waterborne trade and/or passenger transport. These ships tend to operate in Great Lakes, coastwise, inter-coastal, non-contiguous, and/or transoceanic routes. Principle commercial ship types are dry cargo ships, tankers, bulk carriers and passenger ships. Passenger ships include cruise ships and larger ferries.

- Commercial Boats - This category is comprised of smaller service and industrial vessels less than 400 feet in length that provide service to commercial ships, industrial vessels, and/or barges that perform specialized marine functions. Commercial boats are found mainly in inland and coastal waters. Principle commercial boat types are tugboats, towboats, offshore supply boats, fishing and fisheries vessels, passenger boats, and industrial boats. Passenger boats include crewboats, excursion boats, and smaller ferries.

C. Shipbuilders

1. Production Information and Industry Drivers

The vast majority of commercial ships are foreign built. Currently, the U.S. holds less than one half of one percent of the world market share of commercial shipbuilding and repair. The late 1970s and early 1980s reflect a worldwide boom in shipbuilding, particularly in energy-related vessels such as oil drill rigs and tankers. With falling oil prices in the 1980's, there was a substantial decline in commercial vessel orders throughout the world. No commercial orders were placed at U.S. shipyards for 1987 through 1989. In the 1990s, however, the rate of orders has slowly increased to the current rate of approximately 16 ships per year.

2. Location and Number of Builders

There are currently only 18 major shipbuilding facilities in the United States. Most of the facilities are located on the East and Gulf Coasts. The Gulf Coast is a particularly attractive location for shipbuilders due to the relatively low labor costs for the region. New Orleans and Houston lead the U.S. in international trade tonnage.

3. Size and Sales Profile

The six largest companies in the shipbuilding industry in terms of employment and sales revenue are represented by The American Shipbuilding Association (ASA). Almost all commercial ships currently manufactured in the U.S. constructed at an ASA yard. These six companies employ nearly 55,000 people, representing 90 percent of new ship construction employment in the U.S. Additionally, five of the yards are the largest employers in their states. Sales revenue for these six companies is estimated at approximately \$5.2 billion dollars annually.

4. Outlook

Worldwide, the demand for ships is expected to increase during the next decade. Chartering companies and class societies are tightening their requirements. Insurance will become increasingly expensive for older tonnage. Tighter safety regulations will force single-hulled and 30-year old oil tankers out of the market. These collective forces are expected to create a market momentum in which new vessels may be more attractive.

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In sum, the gains due to the anticipated U.S. market growth in commercial shipbuilding are expected to be modest. During the next decade, U.S. shipyards are projected to lose 28,000 jobs as a result of the cut in military orders. This shift in the government market may result in U.S. Shipyard closings or conversions to repair facilities or even non-shipbuilding projects as they have during the lean years. Recent reports by market analysts also suggest a tempered shipbuilding outlook due to the financial crisis in Asia. Any increases in U.S. shipbuilding is likely to be modest.

D. Boat Builders

1. Production and Industry Drivers

Because of Jones Act requirements, the vast majority of boats used in the U.S. are U.S. made. According to WorkBoat Magazine's annual construction survey, 569 commercial boats were ordered in 1997, approximately 100 more than were reported in both 1995 and 1996. While these estimates rely upon survey responses, WorkBoat Magazine's 1995 estimates closely compare with another industry journal, Seatrade Review.

The U.S. boatbuilding industry is currently influence by four key factors: increasing demand for T class vessels, increasing demand for offshore supply vessels, increasing demand for oil, and the expansion of demand for casino boats. For further analyses of these factors, see section 3.1 of the ICF report.

2. Boat Types and Customers

U.S. boatbuilders construct a wide variety of commercial boats less than 400 feet in length. Most of these yards are small and manufacture small and/or less complex boat designs. A few of the yards have the capacity to build more advanced boats, and some also have the capacity to build small ships. U.S. Boatyards build boats primarily used on inland and coastal waterways between U.S. ports. Such vessels must satisfy Jones Act requirements and, therefore, be built in the United States. For this reason, the U.S. boat building industry has a protected local market and does not face the intense foreign competition that U.S. shipbuilders do.

3. Location and Number of Builders

In contrast to the highly concentrated shipbuilding industry, there are several hundred yards that build many different types of boats. Using various sources of information including Duns and Bradstreet databases, industry magazines, and Internet searches, ICF estimated that there are approximately 430 firms that engage in boat building. A majority of the boat builders are located in the Gulf Coast, the Northeast, and the West Coast. The number of boatbuilders in these three regions account for approximately 30 percent, 26 percent and 25 percent of the boat building industry, respectively.

4. Size and Sale Profile

Given the large number of companies in the Boatbuilder Database, it was not possible to contact each one to gather size and sales information. Therefore, two boatbuilders were contacted from the top, middle, and bottom third of the boatbuilder database based on the total employment for the company, including subsidiaries. For specific information on the size and sales of boatbuilders, see section 3.4 of the ICF report as referenced in the introduction of this section.

5. Applications by Geographic Location

A majority of boatbuilders are located in the Gulf Coast, the Northeast, and the West Coast. Collectively, these three regions represent 345 boatbuilders, or 80 percent of all companies in the Boatbuilder Database.

The Gulf Coast is currently the leader in boat production, outperforming the east and west coasts due to advantages in weather, production automation, favorable labor rates and relatively inexpensive real estate. Approximately 30 percent of all boatbuilders are located in the Gulf Coast. Overall, roughly 35 percent of the yards that build industrial boats, tugboats, ferries and passenger boats are located in this region.

The Northeast comprises about 25 percent of the firms in the database. Compared with yards located in the Gulf Coast and the South Atlantic, a boatbuilder in the north is 20 to 25 percent more expensive, taking into account both labor and operating costs. Few of these Northeastern yards build industrial boats, tugboats, ferries, and passenger boats. However, nearly 70 percent of the yards that build fishing boats are located in this region.

The West is primarily dedicated to highly specialized boat yards. For example, boatbuilder in this region construct vessels such as processor catchers, tuna clippers, and small aluminum brine shrimp boats. About 25 percent of the firms in the database are located in the West, including 30 percent of all firms that build fishing boats and nearly 42 percent of the firms that build industrial boats, tugboats, ferries, and passenger boats.

ICF also identified 156 small boat builders that employ fewer than 20 workers, based on total company employment. These yards primarily repair and build small boats less than 55 feet in length which are used in fishing applications such as lobster, oyster, and crab boats.

6. Very Small Boat Builders

ICF identified 182 small boatbuilders that employ fewer than 20 workers, based on total company employment. These yards primarily repair and build small boats less than 55 feet in length, which are used in numerous fishing applications. Such applications include lobster, oyster, and crab boats. Production of these vessels requires smaller facilities and fewer employees. Vessel production at these yards is cyclical, which in part explains why the primary source of revenue for most small yards is repair services.

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According to ICF, little data exists on how many of these small vessels are manufactured annually. However, the production of small fishing vessels is extremely regional. Generally, local demand looks to local builders for vessel production.

Additionally, some small yards do assemble tugs, particularly for inland use. Tugs are technically less difficult to develop than other types of boats and their designs have not changed much over time.

7. Outlook

Decisions by leading boatbuilders to reopen facilities and expand their labor forces are strong indications that market growth for commercial boatbuilding is expected to be considerable. The extent that smaller boatbuilders realize the same level of growth is uncertain. If the commercial boatbuilding industry continues to grow at approximately the same pace maintained over the last decade, the overall demand for new boats may mean more business for even the smallest yards.

Demands for new boats in the U.S. will likely be in “hot markets” such as T class vessels, offshore supply vessels, drillships and semisubmersible rigs, and casino boats. For this reason, the projected increase in demand for new boats will more business for the U.S. boating industry, as foreign builders are ineligible to build for this market.

In sum, U.S. boatbuilders are expected to continue to be a major consumer of marine diesel engines. If market increases are realized, the number of marine diesel units used in the boatbuilding industry may increase substantially.

Chapter 2 References

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CHAPTER 3: TECHNOLOGICAL FEASIBILITY

I. Introduction

The purpose of this chapter is to discuss the feasibility of achieving significant reductions in exhaust emissions from marine diesel engines. Because marine diesel engines are often derived from or use the same technologies as land-based engines, EPA believes that the marine industry will be able to capitalize on the technological improvements being made to land-based diesel engines and achieve similar emission reductions.

This chapter covers a wide range of areas that affect the technological feasibility of this rule. It begins with a rudimentary description of the classifications and applications of marine engines as well as the marinization process. This is followed by an overview of emission formation from diesel engines. Then, established diesel emission control technologies will be described, which EPA believes can be used on marine diesel engines to meet the proposed standards. Next, the proposed emission test procedures that will be used to measure and assess the impacts of the proposed emission levels will be discussed. This will be followed by a description of baseline technologies currently used on marine diesel engines and a discussion of developing emission control strategies and results achieved from various low-emission marine engine designs. Finally, this chapter presents the most likely technology mix that EPA believes would result from putting the proposed Tier 2 and Tier 3 standards into place for marine diesel engines.

II. Marine Diesel Engine Design Ratings

Broadly speaking, the rating of an engine refers to the type of operating conditions the engine is designed to handle. For marine diesel engines, engine ratings also roughly correspond to how the engine is intended to be used, for primarily recreational or some type of commercial application. These are described in greater detail below.

A. High Performance Ratings: Recreational Marine Engines

High performance engines are generally intended for light-use recreational marine purposes. The high performance rating varies by manufacturer but generally means that the engines are designed to maximize the power-to-weight ratio. In other words, they are designed for maximum performance while minimizing the space needed on the boat for the engine and minimizing the added weight of the engine. Because the purpose of these engines is to get high power from a small engine, they are not built to withstand long periods of operation at rated power. For planing vessels, the engine only needs the high power until the vessel is raised to the surface of the water, then a much lower power is used for cruising. Marine engines with a high performance rating are generally designed to be operated a maximum of 200 to 1000 hours per year. They are intended for variable

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load applications where the engine operates at full power no more than 15 minutes at a time and where the engine would only spend one out of every eight to twelve hours at full load. These engines are typically Category 1 engines.

B. Other Ratings: Commercial Marine Engines

Light duty commercial engines have many of the same characteristics as the recreational engines, except that they are designed to be more durable and thus more attractive for commercial applications. Greater durability is achieved by using a heavier engine design for a given power rating. Although these engines are still only designed to be operated one hour out of every six to eight hours at high power, they are intended to be used anywhere from 750 to 3000 hours per year, for active seasonal to annual use. Light duty commercial engines are usually used in boats with planing hulls such as, seasonal fishing vessels and emergency rescue boats, or to power bow thrusters on larger vessels. While they can also be used in recreational applications, this is typically on larger vessels that need more power to achieve planing or are intended to be used more than just occasionally. These engines are typically Category 1 engines.

Intermittent duty commercial rated engines are intended for use in boats with either planing or displacement hulls that are used under variable speeds and loads. These engines are designed to operate at full load no more than half of the time for 2000 to 4000 hours per year. Typical applications for intermittent duty engines would be commercial fishing boats, ferries, and coastal freighters. In addition, most auxiliary marine engines would fall into this category. Again, the use of these engines is not exclusively commercial, and they can be used on large displacement hull yachts. Intermittent duty engines are typically Category 1 engines, but may include some Category 2 engines.

Marine engines with a medium continuous rating are designed to operate a large number of hours at fairly constant speeds and loads on vessels with displacement hulls. These engines are recommended for applications where the engine would be operated from 3000 to 5000 hours per year (60-100 hours per week), but spend no more than about 80 percent of the time at full load. The advantages of this design are good durability and fuel consumption while still maintaining some performance benefits. These engines may be found in applications such as crew and supply boats, trawlers, and tow boats. Large auxiliary engines generally would fall into this rating as well. This rating would include mostly Category 2 engines with some Category 1 engines.

Marine engines with a continuous rating are designed to operate under full load 24 hours per day and generally are operated more than 5000 hours per year. These engines are designed to maximize durability and fuel efficiency which results in low operating costs. Typical applications for marine engines with a continuous rating range from tug boats to ocean-going vessels. Tug boat applications would still likely use Category 2 engines, but the majority of the ocean-going vessels would use Category 3 engines.

III. The Marinization Process

As noted in the previous chapter, marine engines are not generally built from the ground up as marine engines. Instead, they are often marinized land-based engines. The following is a brief discussion of the marinization process, as it is performed by either engine manufacturers or post-manufacture marinizers (PMM).

The most obvious changes made to a land-based engine as part of the marinization process concern the engine's cooling system. Marine engines generally operate in closed compartments without much air flow for cooling. This restriction can lead to engine performance and safety problems. To address engine performance problems, these engines make use of the ambient water to draw the heat out of the engine coolant. To address safety problems, marine engines are designed to minimize hot surfaces. One method of ensuring this, used mostly on recreational or light duty commercial engines, is to run cooling water through a jacket around the exhaust system and the turbocharger. Larger engines generally use a thick insulation around the exhaust pipes. Hardware changes associated with these cooling system changes often include water jacketed turbochargers, water cooled exhaust manifolds, heat exchangers, sea water pumps with connections and filters, and marine gear oil coolers. In addition, because of the greater cooling involved, it is often necessary to change to a single-chamber turbocharger, to avoid the cracking that can result from a cool outer wall and a hot chamber divider.

Other important design changes are related to engine performance. Especially for planing hull vessels used in recreational and light duty commercial marine applications, manufacturers strive to maximize the power-to-weight ratio of their marine engines, typically by increasing the power from a given cylinder displacement. The most significant tool to accomplish this is the fuel injection system: the most direct way to increase power is to inject more fuel. This can require changes to the camshaft, cylinder head, and the injection timing and pressure. Currently, the design limits for increased fuel to the cylinder are smoke and durability. Modifications made to the cooling system also help enhance performance. By cooling the charge, more air can be forced into the cylinder. As a result, more fuel can be injected and burned efficiently due to the increase in available oxygen. In addition, changes are often made to the pistons, cylinder head components, and the lubrication system. For instance, aluminum piston skirts may be used to reduce the weight of the pistons. Cylinder head changes include changing valve timing to optimize engine breathing characteristics. Increased oil quantity and flow may be used to enhance the durability of the engine.

Marinization may also involve replacing engine components with similar components that are made of materials that are more carefully adapted to the marine environment. Material changes include more use of chrome and brass including changes to electronic fittings to resist water induced corrosion. Zinc anodes are often used to prevent engine components, such as raw-water heat exchangers, from being damaged by electrolysis.

Depending on the stage of production and the types of changes made, the marinization process can have an impact on the base engine's emission characteristics. In other words, land-based engine that meets a particular set of emission limits may no longer meet these limits after it is marinized.

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This can be the case, for example, if the fuel system is changed to enhance engine power or if the cooling system no longer achieves the same degree of engine cooling as that of the base engine. Because marine diesel engines are currently unregulated, engine manufacturers have been able to design their marine engines to maximize performance, often obtaining power/weight ratios much higher than land-based applications. The challenge presented by the proposed emission control program will be to achieve the emission limits while maintaining these favorable performance characteristics.

IV. Background on Diesel Emission Formation

In a diesel engine, the liquid fuel is injected into the combustion chamber after the air has been heated by compression (direct injection), or the fuel is injected into a prechamber, where combustion initiates before spreading to the rest of the combustion chamber (indirect injection). The fuel is injected in the form of a mist of fine droplets or vapor that mix with the air. Power output is controlled by regulating the amount of fuel injected into the combustion chamber, without throttling (limiting) the amount of air entering the engine. The compressed air heats the injected fuel droplets, causing the fuel to evaporate and mix with the available oxygen. At several sites where the fuel mixes with the oxygen, the fuel auto-ignites and the multiple flame fronts spread through the combustion chamber.

NO_x and PM are the emission components of most concern from diesel engines. Incomplete evaporation and burning of the fine fuel droplets or vapor result in emissions of the very small particles of PM. Small amounts of lubricating oil that escape into the combustion chamber can also contribute to PM. Although the air/fuel ratio in a diesel cylinder is very lean, the air and fuel are not a homogeneous charge as in a gasoline engine. As the fuel is injected, the combustion takes place at the flame-front where the air/fuel ratio is near stoichiometry. At localized areas, or in cases where light-ends have vaporized and burned, molecules of carbon remain when temperatures and pressures in the cylinder become too low to sustain combustion as the piston reaches bottom dead center. Therefore, these heavy products of incomplete combustion are exhausted as PM.

High temperatures and excess oxygen are necessary for the formation of NO_x. These conditions are found in a diesel engine. Therefore, the diesel combustion process can cause the nitrogen in the air to combine with available oxygen to form NO_x. High peak temperatures can be seen in typical unregulated diesel engine designs. This is because the fuel is injected early to help lead to more complete combustion, therefore, higher fuel efficiency. If fuel is injected too early, significantly more fuel will mix with air prior to combustion. Once combustion begins, the premixed fuel will burn at once leading to a very high temperature spike. This high temperature spike, in turn, leads to a high rate of NO_x formation. Once combustion begins, diffusion burning occurs while the fuel is being injected which leads to a more constant, lower temperature, combustion process.

Because of the presence of excess oxygen, hydrocarbons evaporating in the combustion chamber tend to be completely burned and HC and CO are not emitted at high levels. Evaporative emissions from diesel engines are insignificant due to the low evaporation rate of diesel fuel.

Controlling both NO_x and PM emissions requires different, sometimes opposing strategies. The key to controlling NO_x emissions is reducing peak combustion temperatures since NO_x forms at high temperatures. In contrast, the key to controlling PM is higher temperatures in the combustion chamber or faster burning. This reduces PM by decreasing the formation of particulates and by oxidizing those particulates that have formed. To control both NO_x and PM, manufacturers need to combine approaches using many different design variables to achieve optimum performance. These design variables are discussed below.

V. General Description of Emission Control Strategies

EPA believes that the proposed standards for diesel marine engines can be met using technology that has been developed for and used on locomotive, land-based nonroad, and on-highway engines. This section discusses technology used successfully on diesel engines to reduce exhaust emissions, including combustion optimization, better fuel control, improved charge air characteristics, exhaust gas recirculation, and aftertreatment. A more detailed analysis of the application of several of these technologies to marine engines is discussed later in this chapter. The costs associated with applying these systems to marine engines are considered in the next chapter.

A. Combustion Optimization

Several parameters in the combustion chamber of a heavy-duty diesel engine affect its efficiency and emissions. These engine parameters include injection timing, combustion chamber geometry, compression ratio, valve timing, turbulence, injection pressure, fuel spray geometry and rate, peak cylinder temperature and pressure, and charge (or intake) air temperature and pressure. Many technologies that are designed to control the engine parameters listed above have been investigated. As mentioned previously, however, a positive influence on one pollutant may have a negative influence on another. For example, charge air cooling reduces NO_x emissions, but increases PM. Manufacturers will need to integrate all of these variables into optimized systems to meet the proposed standards.

1. Timing retard

The effect of injection timing on emissions and performance is well established.^{1,2,3,4} Retarded timing will most likely be used at cruising speeds where propulsion marine engines spend most of their operating time. NO_x is reduced because the premixed burning phase is shortened and because cylinder temperature and pressure are lowered. Timing retard increases HC, CO, PM, and fuel consumption, however, because the end of injection comes later in the combustion stroke where the time for extracting energy from fuel combustion is shortened and the cylinder temperature and pressure are too low for more complete oxidation of PM. One technology that can offset this trend is higher injection pressure, which is discussed further below.

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2. Combustion chamber geometry

While manufacturers are already achieving emission reductions through modifications to the combustion chamber, EPA believes there are additional changes that may provide further improvements in emission control. The parameters being investigated include (1) the shape of the chamber and the location of injection; (2) reduced crevice volumes; and (3) compression ratio. These parameters have been thoroughly explored for highway engines and should be readily adaptable to nonroad and marine engines.

Efforts to redesign the shape of the combustion chamber and the location of the fuel injector for highway and nonroad engines have been primarily focused on optimizing the relative motion of air and injected fuel to simultaneously limit the formation of both NO_x and PM. Piston crown design must be carefully matched with injector spray pattern and pressure for optimal emission behavior.⁵ One strategy, reentrant piston bowl design, focuses on optimizing the radius of the combustion bowl, the angle of the reentrant lip, and the ratio of the bowl diameter to bowl depth to optimize air motion. An alternative is the use of higher pressure injection systems that decrease the need for turbulent in-cylinder charge air motion. While higher pressure systems raise concerns of durability, there has been a significant amount of progress in this area and it is expected that manufacturers will be able to develop a durable system.⁶

The second parameter being investigated is reducing crevice volumes by moving the location of the top piston ring relative to the top of the piston.⁷ A reduced crevice volume can result in reduced HC emissions and, to a lesser extent, reduced PM emissions. Costs associated with the relocation of the top ring can be substantial because raising the top of the piston ring requires modified routing of the engine coolant through the engine block and lube oil routing under the piston to prevent the raised ring from overheating. It is also important to design a system that retains the durability and structural integrity of the piston and piston ring assembly, which requires very precise tolerances to avoid compromising engine lubrication.

Compression ratio is another engine design parameter that impacts emission control. In general, higher compression ratios cause a reduction of cold start PM and improved fuel economy, but can also increase NO_x. Several methods can be employed to increase the compression ratio in an existing diesel engine. Redesign of the piston crown or increasing the length of the connecting rod or piston pin-to-crown length will raise the compression ratio by reducing the clearance volume.⁸ There is a limit to the benefit of higher compression ratios because of increased engine weight (for durability) and frictional losses, which could somewhat limit fuel economy improvements.

3. Swirl

Increasing the turbulence of the intake air entering the combustion chamber (i.e., inducing swirl) can reduce PM by improving the mixing of air and fuel in the combustion chamber. Historically, swirl was induced by routing the intake air to achieve a circular motion in the cylinder. Manufacturers are, however, increasingly using "reentrant" piston designs in which the top surface of the piston is cut out to allow fuel injection and air motion in a smaller cavity in the piston to

induce additional turbulence. Manufacturers are also changing to four valves per cylinder, which reduces pumping losses and can also allow for intake air charge motion. The effect of swirl is often engine-specific, but some general effects may be discussed.

At low loads, increased swirl reduces HC, PM, and smoke emissions and lowers fuel consumption due to enhanced mixing of air and fuel. NO_x emissions might increase slightly at low loads as swirl increases. At high loads, swirl causes slight decreases in PM emissions and fuel consumption, but NO_x may increase because of the higher temperatures associated with enhanced mixing and reduced wall impingement.⁹ A higher pressure fuel system can be used to offset some of the negative effects of swirl, such as increased NO_x, while enhancing the positive effects such as a reduction in PM.¹⁰

B. Advanced Fuel Injection Controls

Control of the many variables involved in fuel injection is central to any strategy to reduce diesel engine emissions. The principal variables being investigated are injection pressure, nozzle geometry (e.g., number of holes, hole size and shape, and fuel spray angle), the timing of the start of injection, and the rate of injection throughout the combustion process (e.g., rate shaping).

Manufacturers continue to investigate new injector configurations for nozzle geometry and higher injection pressure (in excess of 2300 bar (34,000 psi)).^{11,12} Increasing injection pressure achieves better atomization of the fuel droplets and enhances mixing of the fuel with the intake air to achieve more complete combustion. Though HC and PM are reduced, higher cylinder pressures can lead to increased NO_x formation.¹³ However, in conjunction with retarding the start of fuel injection, higher fuel injection pressures can lead to reduced NO_x because of lower combustion temperatures. HC, PM, or fuel economy penalties from this strategy can be avoided because the termination of fuel injection need not be delayed. Nozzle geometry is used to optimize the fuel spray pattern for a given combustion chamber design in order to improve mixing with the intake air and to minimize fuel condensation on the combustion chamber surfaces.¹⁴ Minimizing the leakage of fuel droplets is critical for reducing HC emissions. Valve-closed orifice (VCO) tips are more effective than sac-type nozzles, because they eliminate any droplets remaining after injection, which would increase HC emissions. Although VCO tips are subject to very high pressures, EPA believes progress will continue in developing a durable injector tip prior to implementation of these standards.

The most recent advances in fuel injection technology are the systems that use rate shaping or multiple injections to vary the delivery of fuel over the course of a single injection. Igniting a small quantity of fuel initially limits the characteristic rapid increase in pressure and temperature that leads to high levels of NO_x formation. Injecting most of the fuel into an established flame then allows for a steady burn that limits NO_x emissions without increasing PM emissions. Rate shaping may be done either mechanically or electronically. Rate shaping has been shown to reduce NO_x emissions by up to 20 percent.¹⁵

For electronically controlled engines, multiple injections may be used to shape the rate of fuel injection into the combustion chamber. Recent advances in fuel system technology allow high-

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pressure multiple injections to be used to reduce NO_x by 50 percent with no significant penalty in PM. Two or three bursts of fuel can come from a single injector during the injection event. The most important variables for achieving maximum emission reductions with optimal fuel economy using multiple injections are the delay preceding the final pulse and the duration of the final pulse.¹⁶ This strategy is most effective in conjunction with retarded timing, which leads to reduced NO_x emissions without the attendant increase in PM.

A promising fuel injection design is that developed by Caterpillar and Navistar, the Hydraulically actuated Electronically controlled Unit Injection (HEUI) system.^{17,18} The HEUI system utilizes a common rail of pressurized oil to provide high injection pressures of 175 MPa (25,000 psi) throughout an engine's operating range. The HEUI system provides full electronic control of injection timing and duration, along with the possibility for rate shaping. The most attractive aspect of this system is that it operates largely independent of engine speed so that the engine can be optimized over a larger range of operation. Some marine engine manufacturers are already utilizing this system on production engines. It is expected that manufacturers will be able to develop and produce a full-authority electronic fuel injection system for a reasonable cost in time for these standards. For larger engines (>1.5 liters/cylinder), Caterpillar has designed a Mechanically actuated Electronically controlled Unit Injection (MEUI) system. MEUI is similar to HEUI in that it can control injection pressure, timing and rate shaping independent of engine speed. Caterpillar has reported injection pressures as high as 200 MPa (30,000 psi) with the MEUI system.

Common rail fuel systems may be used to gain fuel injection improvements over distributor pump type systems. Fuel is pressurized in the fuel rails which allows high pressures independent of engine speed. Cummins has recently developed an alternative technology known as the Cummins Accumulator Pump (CAP) fuel system.^{19,20} The CAP system uses an accumulator between the high pressure fuel injection pump and the distributor to achieve high pressure fuel injection of 145 MPa (21,000 psi) and control timing independent of engine speed. This system offers a low cost alternative to common rail fuel injection.

C. Improving Charge Air Characteristics

Charge air compression (turbocharging) is primarily used to increase power output and reduce fuel consumption from a given displacement engine. At rated power, a typical diesel engine loses about 30 percent of its energy through the exhaust. A turbocharger uses the waste energy in the exhaust gas to drive a turbine linked to a centrifugal compressor, which then boosts the intake air pressure. By forcing more air into the cylinder, more fuel can also be added at the same air-fuel ratio, resulting in higher power and better fuel consumption while controlling smoke and particulate formation.

In most recreational and light duty commercial marine applications, the exhaust system and turbocharger are generally water-jacketed to keep surface temperatures low. In addition, raw water is actually mixed with the exhaust for cooling and tuning reasons. Because the exhaust is dumped directly into the surrounding water, the more gradual cooling from mixing water with the exhaust prevents a large pressure spike which could affect the exhaust tuning. The water jacketing causes

some of the reclaimed energy in the turbocharger to be lost to the cooling water. This energy loss is not large and could be reduced further by insulating the turbine from the water jacket. For larger marine engines, insulation rather than water jacketing is generally used to keep surface temperatures down. For these engines, dry exhaust is directly emitted into the atmosphere.

Aftercooling is often used to reduce NO_x by reducing the temperature of the charge air after it has been heated during compression. Reducing the charge air temperature directly reduces the peak cylinder temperature during combustion which is where NO_x is formed. This technology was initially developed to improve the specific power output of an engine by increasing the density of air entering the combustion chamber. Water-to-air and air-to-air aftercooling are well established for land-based engine applications. For engines in marine vessels, there are two different types of aftercooling strategies used: jacket-water, and raw-water aftercooling. Because of the access that marine engines have to a large cooling medium (i.e. oceans and lakes), EPA anticipates aftercooling will play an important role in gaining significant NO_x reductions from marine diesel engines.

1. Jacket-water aftercooling

Marine engines use jacket water systems to pull heat from the engine coolant. Raw water is pumped into a heat exchanger which is used to cool the engine coolant. For most recreational and light commercial applications, the raw water is then used to cool the exhaust. If jacket-water aftercooling is applied, the coolant coming from the heat exchanger passes through the aftercooler before entering the engine. Through the use of jacket-water aftercooling, boost air may be cooled to approximately 95-105°C. Another 40 to 50°C reduction in boost air temperature can be gained by using a completely separate cooling circuit for the aftercooler.

The heat exchanger is designed to resist the difficulties associated with operating in a sea-water environment. Water is pumped through the heat exchanger at a high velocity to help prevent barnacle growth and to keep the passages clean. In addition, copper is a poison to barnacles and the heat exchangers are generally made of a copper-nickel alloy. To prevent sea water from causing the metal in the heat exchanger to decay due to electrolysis, zinc anodes are used.

In commercial applications where the water temperature is expected to be near freezing or very dirty, keelcooling may be used. In a keelcooled system, the engine coolant is passed through many long tubes along the bottom of the boat which act as a heat exchanger. Therefore, no ambient water is brought into the vessel or cooling system. This avoids problems that could be associated with contaminants such as mud, chemicals, or ice. In displacement hull vessels keelcooling can be as effective as a standard heat exchanger and is often used on commercial vessels. One disadvantage of keel cooling is that it is a more complex and costly system than a standard shell and tube heat exchanger. Also, keelcooling is less effective on a planing vessel, and is not often used for recreational vessels.

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2. Raw-water aftercooling

Raw-water aftercooling means that outside water is pumped through the aftercooler rather than engine coolant. Depending on the temperature of the water and the size of the aftercooler, raw-water aftercooling can be used to cool the boost air to approximately 45-55°C. Because of the cooler intake air temperatures associated with this technology, it can be used to achieve lower NO_x levels from a marine engine. The same strategies used to protect the jacket water heat exchanger from the corrosive effects of sea water can also be used to protect a raw-water aftercooler. Currently, this aftercooling strategy is only used in recreational and light commercial applications. While introducing raw-water aftercooling may require additional maintenance (replacing anodes), the benefits of improved fuel efficiency, greater engine durability, and better control of NO_x emissions make a compelling case for its widespread use in the long term.

D. Electronic Control

Various electronic control systems are in use or under development for nonroad, locomotive, highway, and marine diesel engines. Use of electronic controls enables designers to implement much more precise control of the fuel injection system and is necessary for advanced concepts such as rate shaping. Through this precise control, trade-offs between various control strategies can be minimized. In addition, electronic controls can be used to sense ambient conditions and engine operation to maximize performance and minimize emissions over a wide range of conditions such as transient operation of the engine. Electronic control is already used in limited marine applications and has shown its ability to endure the marine environment. These same controls used today could be used to optimize for emissions as well as performance.

E. Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is the most recent development in diesel engine control technology for obtaining significant NO_x reductions. EGR reduces peak combustion chamber temperatures by slowing reaction rates and absorbing some of the heat generated from combustion. While NO_x emissions are reduced, PM and fuel consumption can be increased, especially at high loads, because of the reduced oxygen available during combustion.^{21,22} One method of minimizing PM increases is to reduce the flow of recirculated gases during high load operation, which would also prevent a loss in total power output from the engine. Recent experimental work showed NO_x reductions of about 50 percent, with little impact on PM emissions, using just six percent EGR in conjunction with a strategy of multiple injections.²³

1. EGR cooling

There are several methods of controlling any increase in PM emissions attributed to EGR. One method is to cool the exhaust gas recirculated to the intake manifold. By cooling the recirculated gas, it takes up less volume allowing more room for fresh intake air. With EGR cooling, a much higher amount of exhaust gas can be added to the intake charge. At light loads, there can be a small NO_x penalty due to increased ignition delay, but at high loads, some additional NO_x reduction may

result from EGR cooling.²⁴ Another method to offset the negative impacts of EGR on PM is through the use of high intake air boost pressures. By turbocharging the intake air, exhaust gas can be added to the charge without reducing the supply of fresh air into the cylinder.²⁵

2. Soot removal

Another challenge facing manufacturers is the potential negative effects of soot from the recirculated exhaust being routed into the intake stream. Soot may form deposits in the intake system, which could cause wear on the turbocharger or decrease the efficiency of the aftercooler. As the amount of soot in the cylinder increases, so does the amount of soot that works its way past the piston rings into the lubricating oil, which can lead to increased engine wear. One thing that has been developed to reduce soot in the recirculated exhaust gas is a low-voltage soot removal device.²⁶ Engine wear was shown to be greatly reduced as a result of this device. Another strategy is to recirculate the exhaust gas after it has passed through a particulate trap or filter. Demonstrations have shown that some prototype traps can remove more than 90 percent of particulate matter.²⁷

One study discusses a technology package designed to solve the problems of minimizing the amount of intake charge displaced by exhaust gas and of fouling of the turbocharger and aftercooler.²⁸ This technology package uses a variable geometry turbocharger, an EGR control valve, and a venturi mixer to introduce the recirculated gas into the inlet stream after the intake air is charged and cooled. The variable geometry turbocharger is used to build up pressure in the exhaust stream. Once the pressure is high enough, the EGR control valve is opened and the recirculated gas is mixed into the high pressure inlet stream in a venturi mixer. Although the recirculated gas is cooled, this cooling is minimal to prevent both fouling in the cooler (due to condensation) and a large pressure drop across the cooler.

Several bypass filtration designs exist to filter smaller particles out of engine oil.²⁹ With bypass filtration, a portion of the oil is run through a secondary unit which results in well filtered oil. This type of filtration system could be used to minimize negative effects of soot in the oil that are associated with high levels of EGR. At least one design claims efficiencies of up to 99 percent in capturing 1-micron particles. Another design is capable of removing water as well as particles less than 1 micron in size. To accelerate vaporization of impurities and to maintain oil viscosity, a heated diffuser plate is used in a third design.

F. Exhaust Aftertreatment Devices

Researchers in industry and academia have explored various technologies for treating engine-out exhaust emissions. In general, EPA does not expect that marine engine manufacturers will need to utilize exhaust aftertreatment to meet the proposed standards; however, further work on these technologies may lead to development of an approach that provides effective control at a lower cost than today's anticipate technologies. One technical difficulty that would have to be investigated is the concern of catalyst poisoning in a salt-water environment.

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1. Oxidation catalysts

The flow-through oxidation catalyst provides relatively moderate PM reductions by oxidizing both gaseous hydrocarbons and the portion of PM known as the soluble organic fraction (SOF). The SOF consists of hydrocarbons adsorbed to the carbonaceous solid particles and may also include hydrocarbons that have condensed into droplets of liquid.³⁴ The carbon portion of the PM remains largely unaffected by the catalyst. Although recent combustion chamber modifications have reduced SOF emissions, the SOF still comprises between 30 and 60 percent of the total mass of PM. Catalyst efficiency for SOF varies with exhaust temperature, ranging from about 50 percent at 150°C to more than 90 percent above 350°C.³⁰

Another challenge facing catalyst manufacturers is the formation of sulfates in the exhaust. This is especially true for marine engines which tend to use fuels with higher sulfur levels than land-based engines. At higher exhaust temperatures, catalysts have a greater tendency to oxidize sulfur dioxide to form sulfates, which contribute to total PM emissions. For highway applications, this is helped by the introduction of low-sulfur fuel. In addition, catalyst manufacturers have been successful in developing catalyst formulations that minimize sulfate formation.³¹ Catalyst manufacturers have also adjusted the placement of the catalyst to a position where the needed SOF reduction is achieved, but sulfate formation is minimized.³² Marine fuel with sulfur concentrations higher than 0.05 weight percent may prevent the use of more active oxidation catalysts with higher conversion efficiencies.

2. Particulate traps

Use of a particulate trap is a very effective way of reducing particulate emissions, including the carbon portion. Particulate traps have been extensively developed for highway applications, though very few engines have been sold equipped with traps, primarily because of the complexity of the systems needed to remove the collected particulate matter. Continued efforts in this area may lead to simpler, more durable designs that control emissions cost-effectively. Research in this area is focused on developing new filter materials and regeneration methods. Some designs rely on an additive acting as a catalyst to promote spontaneous oxidation for regeneration, while other designs aim to improve an active regeneration strategy with microwave or other burner technology.

3. Selective Catalytic Reduction

Selective catalytic reduction (SCR) is one of the most effective, but also most complex and expensive, means of reducing NO_x from large diesel engines. Emission reductions in excess of 90 percent can be achieved using SCR.³³ In SCR systems, a reducing agent, such as ammonia, is injected into the exhaust and both are channeled through a catalyst where NO_x emissions are reduced. These systems are being successfully used for large stationary source applications which operate under constant, high load conditions.

A number of disadvantages are apparent for the use of current technology SCR systems on ships. The SCR system is effective only over a narrow range of exhaust temperatures. The effectiveness of the system is decreased at reduced temperatures exhibited during engine operation

at partial loads. Also, excess ammonia in the exhaust can occur during transient operation, where control of optimum ammonia injection is difficult. However, because marine engines (especially larger engines) operate under fairly steady-state conditions, this “ammonia slip” would be less of a problem.

G. Water Emulsification

Water emulsification of the fuel is a technique which also lowers maximum combustion temperature without an increase in fuel consumption. Water has a high heat capacity, which allows it to absorb enough of the energy in the cylinder to reduce peak combustion temperatures. There are at least two ways to accomplish the emulsification during combustion: in the combustion chamber or in the fuel tank. Testing on a diesel engine has shown a 40 percent reduction in NO_x with a water-fuel ratio of 0.5 with only a slight increase in smoke.³⁴ Water dilution does have significant challenges. Combining water and fuel for the first time in the chamber requires significant changes to the cylinder head to add an injector. Using a single injector with stratified water and fuel adds complexity to the injection system. Combining water with fuel in the tank may introduce combustion problems due to unstable emulsion. Also, this technique requires a significantly redesigned fuel handling system to overcome the potential risk of corrosion and to maintain power output. However, these problems may be overcome in the future as the strategy is refined. In any event, extra liquid storage availability is necessary to retain similar range.

VI. Emission Measurement

In any program designed to achieve emissions reductions from internal combustion engines, the test procedures that are used to determine emissions levels are as important as the emissions standards that are implemented. Five duty cycles were investigated for use in this rule: three designed for propulsion marine diesel engines, one used for land-based nonroad diesel engines, and one intended for constant-speed auxiliary diesel engines. These cycles are designated by the International Standards Organization (ISO) as E2, E3, E5, C1, and D2, respectively.³⁵ This section discusses the duty cycles proposed for this rule as well as other testing issues specific to marine diesel engines.

A. Certification Duty Cycles

The E3 duty cycle is proposed to be used for measuring emissions from propulsion marine diesel engines operating on a propeller curve. Both the E3 and the E5 are designed to represent marine diesel engines, and both cycles focus on operational modes which lie on a propeller curve. However, the E3 is intended to represent heavy-duty diesel marine engine operation while the E5 is intended to represent diesel marine engine operation on vessels less than 24 meters in length. In addition, the E3 operates at a higher average power than the E5. These two facts imply that the E3 is probably more representative for commercial while the E5 is probably more representative for recreational marine diesel engines. Since most of the combined HC and NO_x emissions from marine diesel emissions come from commercial applications, the use the E3 cycle for all marine propulsion diesel engines operating on a propeller curve is acceptable. Using single cycle to represent all

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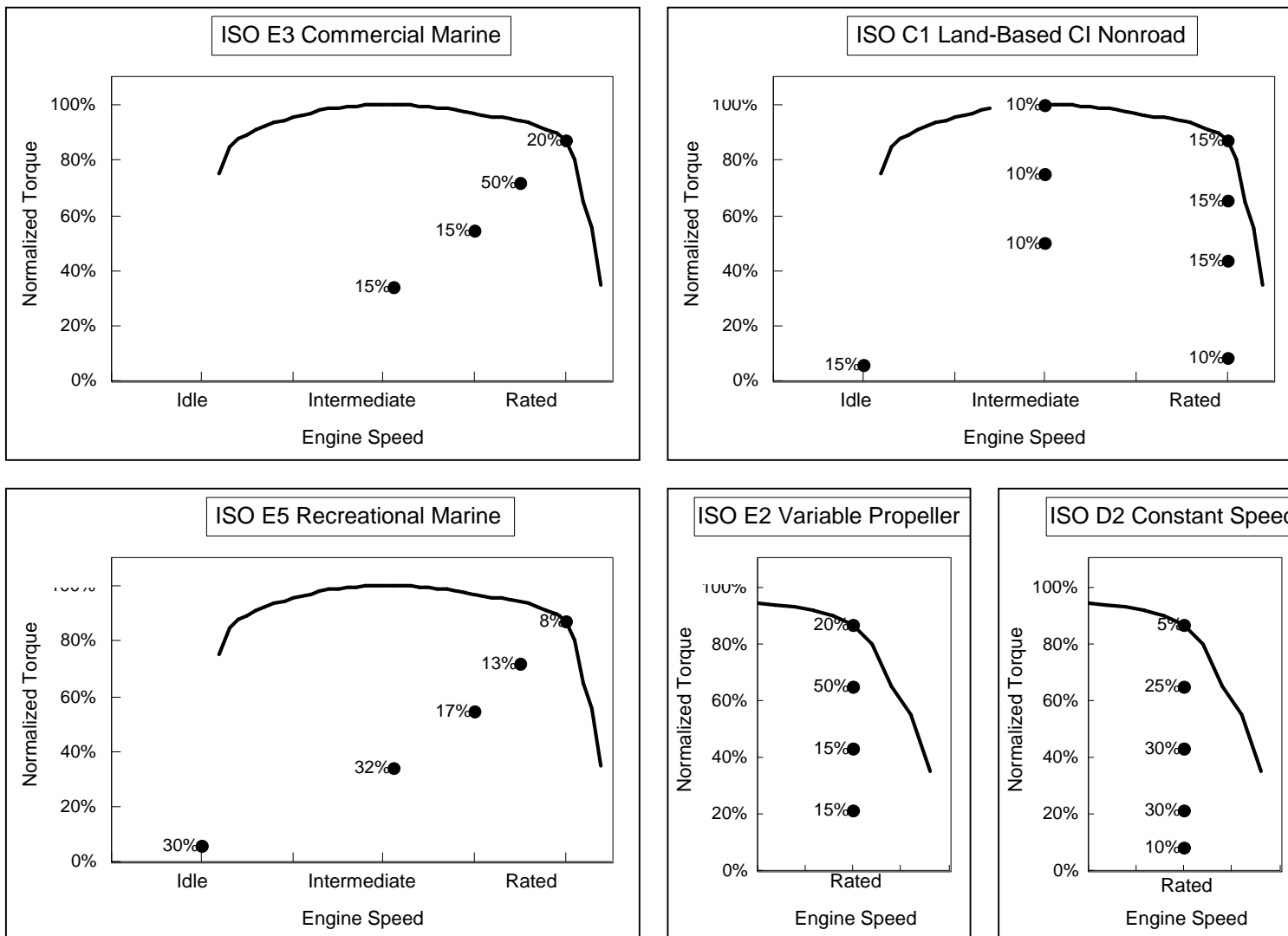
propeller-curve marine diesel engines should reduce certification burdens for marine engines that are used in both vessels under and over 24 meters in length. More detail on this issue may be found in the docket.³⁶

For auxiliary marine diesel engines, ISO provides the C1 and D2 duty cycles. Auxiliary marine engines would include any engines used on a marine vessel which are not primarily used for propulsion. The C1 duty cycle was developed for nonroad diesel engines and applies to variable-speed engines while the D2 applies to constant speed engines. The D2 duty cycle is a five-mode cycle at a constant speed which is intended for generator sets with an intermittent load and is currently allowed as an option for the certification of land-based constant speed engines.

Many larger propulsion marine engines do not operate on a propeller curve. These engines run at a constant speed and use a variable pitched propeller to control vessel speed. EPA proposes that the E2 constant speed propulsion marine duty cycle be used for these engines. Figure 3-1 presents the five duty cycles discussed above.

There is another class of propulsion engines that run at variable speed and use a variable pitched propeller. These engines are designed to operate near the power curve for the engine in order to maximize fuel efficiency. In general, these engines will operate at a constant speed except when maneuvering in port. Because of the expense of the system, variable speed engines are rarely used with variable pitched propellers. ISO does not have a test duty cycle specifically designed for these engines. However, because most of their operation is at constant speed, EPA is proposing that these engines certify to the E2 duty cycle. It should be noted that the speed setting for testing should coincide with the speed setting at which the engine would spend most of its time in use.

Figure 3-1: CI Marine Test Duty Cycles Plotted Under the Full Load Torque Curve
 (percentages are modal weightings used to calculate a composite emissions level)



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B. Relative Stringency of Duty Cycles

In general, emissions levels are sensitive to the duty cycle used to generate them. For instance, if emissions from a given engine were lower on the marine cycle than on the land-based nonroad duty cycle, it would suggest that lower standards would be necessary to ensure the same level of control from marine engines as will be achieved from nonroad land-based diesel engines. However, according to EPA's analysis in the case of C1 versus E3 and the locomotive line-haul cycle versus E2, emissions tend to be roughly equivalent. This analysis is described below.

1. Category 1 marine vs. land-based test procedure

Test data on five uncontrolled Category 1 marine diesel engines^{37,38} show that HC+NOx emissions are approximately the same when measured on the C1 or E3 duty cycle. This would suggest that emission levels determined using the C1 cycle would be roughly equivalent to those determined using the E3 cycle. Although there is more variation between the E3 and the D2 results, it seems reasonable to consider the same standard levels based on both duty cycles. However, data on the same engines show that HC+NOx emissions measured on the E5 duty cycle is somewhat higher. Table 3-1 presents HC+NOx results for these five engines based on the E3, C1, D2, and E5 cycles. For controlled marine diesel engines, EPA anticipates that it will be somewhat easier to demonstrate compliance on the E3 cycle than the C1 cycle since the E3 only has half as many test modes and does not include the peak torque mode that drives many nonroad diesel engine emission control designs.

Table 3-1
HC+NOx Results by Duty Cycle for Five Uncontrolled Marine Diesel Engines

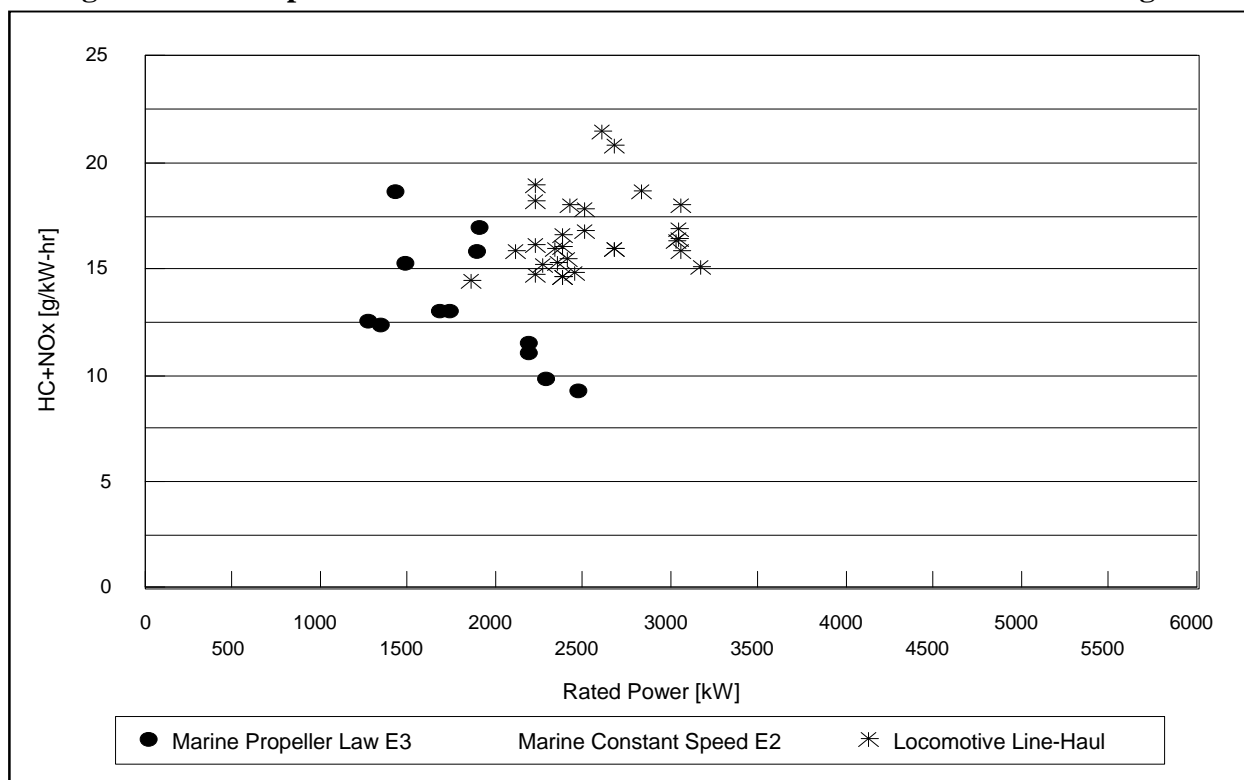
Duty Cycle	Rated Power (kW)				
	20	265	336	447	895
E3 (g/kW-hr)	6.9	9.8	7.1	10.2	10.0
C1 (g/kW-hr)	6.7	9.9	6.6	9.5	10.1
C1 (% difference)	-2%	2%	-8%	-7%	1%
D2 (g/kW-hr)	8.3	8.7	6.9	8.2	8.1
D2 (% difference)	21%	-11%	-3%	-20%	-19%
E5 (g/kW-hr)	9.6	11.4	8.1	12.6	10.8
E5 (% difference)	39%	17%	15%	23%	9%

2. Category 2 marine vs. locomotive line-haul

The proposed standards for Category 2 marine diesel engines are based on the line-haul standards for locomotive engines. Although locomotive engines must certify to two duty cycles with separate standards, EPA focused on the line-haul standard as being more applicable to marine engines. This is because the line-haul duty cycle has a high average power similar to the commercial marine diesel duty cycles. Another similarity between the locomotive and marine duty cycles is that they are based on a path of operation under the torque curve rather than over the whole torque curve. Locomotive engines run at eight distinct operating points or “notches” in real world use while marine engines either operate over a propeller curve or at constant speed.

To compare the relative stringency of the marine E2 and E3 and the locomotive line-haul duty cycles, EPA looked at baseline emission data based on these cycles. Data on thirteen locomotive engines³⁹ and twenty-one marine engines^{40,41,42} are presented in Figure 3-2. This data clearly shows that combined HC and NOx baseline emissions from engines tested on the three duty cycles are at about the same levels.

Figure 3-2: Comparison of HC+NOx Emissions for Marine and Locomotive Engines



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C. Emission Control of Typical In-Use Operation

EPA is concerned that if a marine engine is designed for low emissions on average over a low number of discrete test points, it may not necessarily operate with low emissions in-use. This is due to a range of speed and load combinations that can occur on a vessel which do not necessarily lie on the test duty cycles. For instance, the test modes for the E3 cycle lie on an average propeller curve. However, a propulsion marine engine may never be fitted with an “average propeller.” In addition, a light vessel with a planing hull may operate at lower torques than average while the same engine operated on a heavy vessel with a deep displacement hull may operate at higher torques than average. In addition, a planing hull vessel can operate at high torques at low speed prior to planing.

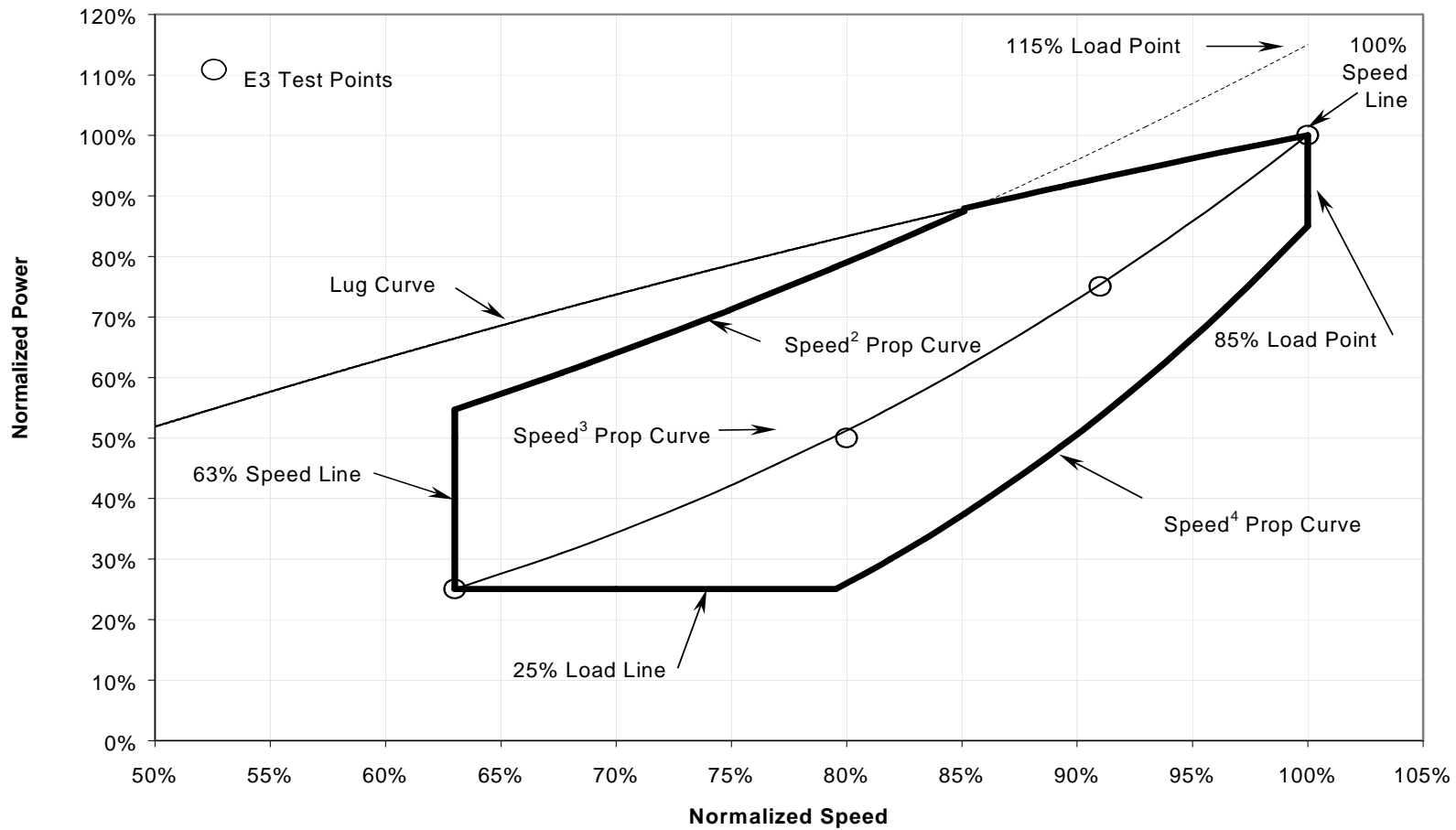
It is EPA’s intent that an engine would operate clean under all in-use speed and load combinations that can occur on a vessel rather than just at the discrete test modes in the proposed duty cycles. To ensure this, EPA is proposing to establish requirements extending to typical in-use operation. For propulsion marine engines certified to the E3 duty cycle, EPA proposes to apply a “not to exceed” (NTE) zone based on the maximum power curve of the engine. Under this provision, the manufacturers would be required to design their engines to comply to a not to exceed limit, tied to the standard, for all of the regulated pollutants within the NTE zone. In cases where the engine is included in averaging, banking, or trading of credits, the not to exceed limits would be tied to the family emission limits. EPA would reserve the right to test an engine in a lab or installed on a vessel to confirm compliance to this requirement.

When testing the engine within the NTE zone, the engine could be operated in any manner that could reasonably be expected to be seen by that engine in use. Examples of transience that would be included are bringing a vessel to plane or changing engine speeds. Because most of the time marine engines operate under fairly steady speeds and loads, EPA believes that it is reasonable to average out any emissions spikes due transience over a short period of time. To ensure that a short transient does not unfairly give high results, EPA proposes that the emissions sampling must be at least over a 30 second time period. This 30 second sampling period should be long enough to allow an emissions spike to be averaged out while still retaining a short enough period to look at a specific type of operation. Regardless of the shape of the NTE zone, an acceleration associated with bringing a vessel to plane would be considered by EPA to be acceptable to be included for NTE type testing. Any transient operation tested under the NTE provisions would have to be representative of what an application using that engine could see in-use.

For engines certified on the E3 cycle, the NTE zone is proposed to be defined by the maximum power curve, actual propeller curves, and speed and load limits. The E3 duty cycle itself is based on a cubic relationship between speed and power which intersects the rated power point of the engine. For the NTE zone, the upper boundary would be based on a speed squared propeller curve passing through the 115 percent load point at rated speed and the lower boundary would be based on a speed to the fourth propeller curve passing through the 85 percent load point at rated speed. These propeller curves are believed to represent the full range of propeller curves seen in use.⁴³ To prevent imposing an unrealistic cap on a brake-specific basis, EPA proposes to limit this region to power at or above 25 percent of rated power and speeds at or above 63 percent of rated speed. These

limits are consistent with mode 4 in the E3 duty cycle. The proposed NTE zone is illustrated in Figure 3-3. For engines operating in applications in which the in-use operation differs significantly from the NTE zone in Figure 3-3, manufacturers would be able to petition for adjustments to the NTE zone for a given engine design.

Figure 3-3: Illustration of "Not to Exceed" Zone



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For constant speed propulsion engines certified to the E2 duty cycle, EPA proposes a similar approach to ensuring that emissions measured on the duty cycle are representative of emissions generated in-use. Because these engines operate at a constant speed, the NTE zone is easier to define than for the E3 duty cycle. The not to exceed limits would apply to the speed that the engine is designed to operate at for all loads greater than or equal to 25 percent of maximum load at that speed. Below 25 percent load, EPA is not proposing a NTE cap because brake-specific emissions become large at low loads due to a small power level in the denominator which would make it technically difficult to adhere to a single cap throughout the zone. In addition, these engines generally do not spend much time operating at low loads.

Ambient air conditions would likely have a significant effect on emissions from marine engines in use. Such ambient air conditions include temperature and humidity. To ensure real world emissions control, the NTE zone testing should include a wide range of ambient air conditions representative of real world conditions. EPA believes that the appropriate ranges should be 13-35°C (55-95°F) for air temperature and 7.1-10.7 grams water per kilogram of dry air (50-75 grains/pound of dry air) for air humidity. The air temperature and humidity ranges are consistent with those developed for NTE testing of on-highway heavy-duty diesel engines. The air temperature ranges were based on temperatures seen during ozone exceedences.⁴⁴ For NTE testing in which the air temperature or humidity is outside of the range, the emissions shall be corrected back to the air temperature or humidity range. These corrections shall be consistent with the equations in 40 CFR Part 89 Subpart E. These equations correct to 25°C and 10.7 grams per kilogram of dry air. However, corrections associated with the NTE testing shall be to the nearest outside edge of the specified ranges. For instance, if the temperature were higher than 35°C, a temperature correction factor would be applied to the emissions results to determine what the emissions would have been at 35°C.

Ambient water temperature also may affect emissions due to its impact on engine and charge air cooling. For this reason, NTE testing would include a range of ambient water temperatures from 5-32°C (41-90°F). The water temperature range is based on temperatures that marine engines experience in the U.S. in use. It is EPA's understanding that marine engine manufacturers currently design their cooling systems for the worst case condition of 32°C water temperatures. Although marine engines experience water temperatures near freezing, EPA does not believe that additional emission control will be gained by lowering the minimum water temperature below 5°C. At this time, EPA is not aware of an established correction factor for ambient water temperature. For this reason NTE zone testing must be within the specified ambient water temperature range.

EPA is aware that many marine engines are designed for operation in a given climate. For instance, an engine in a fishing vessel designed to operate in Alaska would not need to be designed for 32°C water temperatures. For situations such as this, manufacturers would be able petition for the appropriate temperature ranges associated with the NTE zone for a specific engine design. In addition, EPA understands that there are times when emission control needs to be compromised for startability or safety. Manufacturers would not be responsible for the NTE requirements under start up conditions. In addition, manufacturers could petition to be exempt from emissions control under

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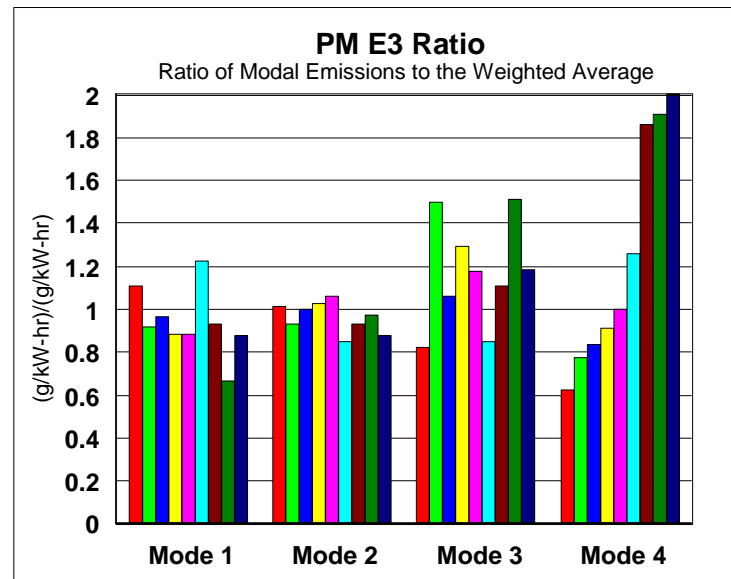
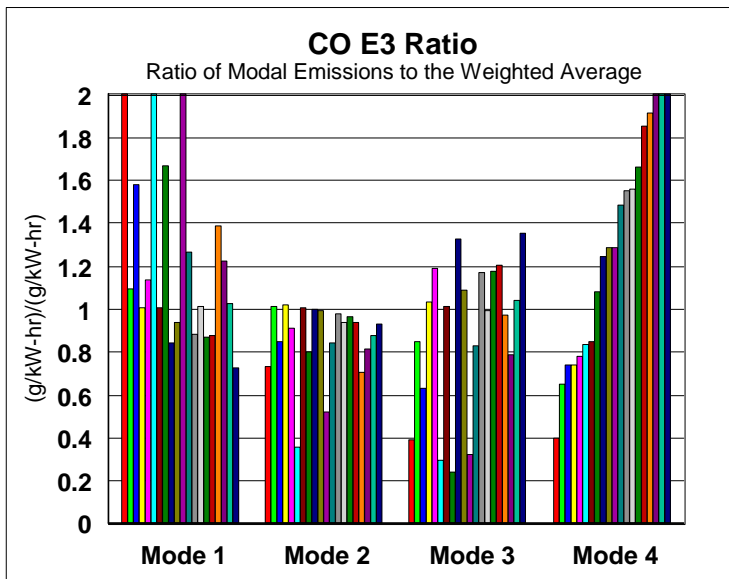
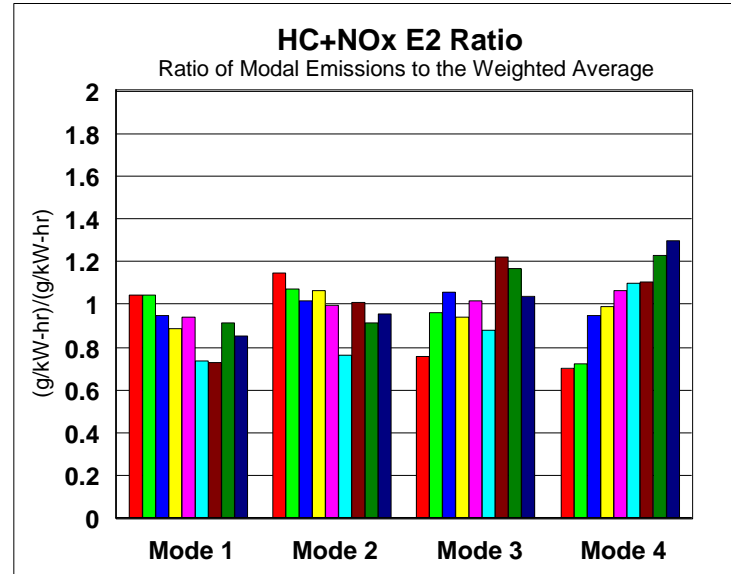
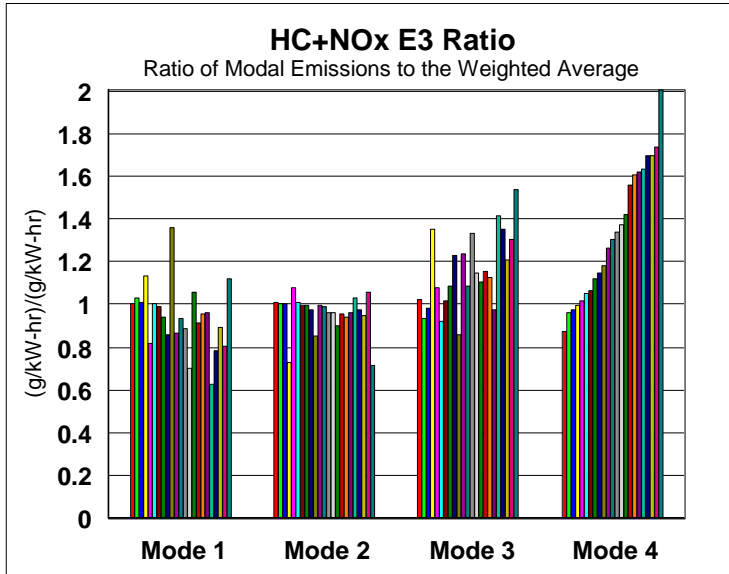
specified extreme conditions such as engine overheating where emissions may increase under the engine protection strategy.

EPA is proposing a single cap for the entire NTE zone. Although ideally the engine should meet the proposed standard under any operation, EPA understands that a cap of 1.0 times the standard would not be reasonable because there is inevitably some variation in emissions over the range of engine operation. This is consistent with the concept of a weighted modal emission test such as the steady-state tests proposed in this rule.

For engines certified to the E2 and E3 duty cycles, EPA believes that a not to exceed limit of 1.25 times the emissions standard (or FEL) is appropriate. EPA's decision not to apply a tighter cap for marine engines is based on all of the emissions data in this chapter for which individual modal results were available to EPA. Figure 3-4 presents the ratio of the modal emissions to the cycle weighted emissions and includes both Category 1 and Category 2 marine diesel engines. This data shows that a 1.25 limit is easily achievable for HC+NO_x on constant speed engines, but may be more challenging for variable speed engines, especially at low speeds and powers (mode 4). However, several of the engines are below 1.25 times their cycle weighted average, and EPA believes that all marine diesel engines can be optimized to meet a 1.25 limit, particularly as the marine engine market shifts more towards electronically controlled engines. EPA only had modal data for CO and PM on the E3 duty cycle. Meeting a 1.25 limit for PM appears to be equally as challenging as for HC+NO_x, but feasible as about half of the engines already meet this limit. It should be noted that the CO emissions data presented here were well below the proposed standards, so CO should not be a limiting factor.

This NTE zone and cap is consistent with the recent guidance for on-highway engines.⁴⁵ However, on-highway engines have a much larger NTE zone which covers a full range of possible engine operation. In addition, on-highway engines have the additional requirement of a second cap shaped by the emission results from the 13 mode EURO test. For marine engines, the NTE zone is much smaller and does not include peak torque or high-speed/low power operation. In addition, marine engines characteristically see much less transient operation than heavy-duty diesel on-highway engines in use. This reduced transient in use operation would translate into less transient operation during NTE testing.

Figure 3-4: Ratio of Modal Emissions to Cycle Weighted Emissions



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EPA is interested in low emissions regardless of engine operation, but would consider dividing the NTE zone into subzones with different caps if the single zone was shown to not be feasible. The purpose of this is to account for differing brake-specific emissions at different operating points. In general, marine engines have lower brake-specific emissions at high speeds and loads than at low speeds and loads. However, EPA believes that the 1.25 limit is reasonable for the entire NTE zones as defined above. If the NTE zone was broken into more than one subzone, it may be feasible to have a lower cap in the high speed/high power range, and a higher cap at the low power/low speed range. While more complicated than the single zone proposed, it would nevertheless appear to be feasible based on the data in Figure 3-4. If a zone was divided into subzones, it would not be reasonable to allow too much variation in the caps since it is important that the engines cannot be designed only to operate at low emissions at certain modes. This is especially true for engines used in applications whose operation is significantly different from the E3 duty cycle. In addition, having different subzones with different caps would increase the complexity of the NTE provision, especially for transient operation that reaches into more than one subzone.

The use of electronic controls should give marine engine manufactures more flexibility in how they meet the proposed cap under all operation than they would have with mechanically controlled engines with fixed injection timing. EPA is concerned, however, that electronic controls (or any other Auxiliary Emission Control Devices) not be used in such a way as to result in higher emissions from marine engines in-use than would be seen during testing. EPA believes that the best way of ensuring this is the use of the NTE provisions. In addition, however, EPA believes that it is appropriate to require that the manufacturers provide information such as message or parameter identification, scaling, limit, offset, and transfer function information required to interpret all messages and parameters broadcast on an engine's controller area network. In addition, requiring that electronically controlled engines broadcast their engine speeds and loads on the controller area networks would help facilitate in-use testing.

EPA recognizes the difficulties of complying to a single cap over an NTE zone with a mechanical engine due to the restriction of a fixed injection timing. Nevertheless, the requirement for effective in-use emission performance over the broad range of in-use operation should not be restricted to electronically controlled engines. Even with mechanical controls, EPA believes that it is feasible for marine engines to meet the proposed requirements through optimization of the engine calibration. However, EPA is concerned that this would cause an unnecessary increase in emissions at higher speeds and loads where marine engines spend most of their time. Therefore, EPA would consider options for mechanical engines such as subzones, smaller zone, or phase in of requirements if there were no significant loss to the environment or market advantage to mechanical engines created.

EPA is not proposing any NTE provisions for auxiliary marine engines certified using the D2 and C1 duty cycles. At this time, EPA does not have enough information on the operation and design of these engines. However, EPA will investigate typical emissions from auxiliary marine engines off of the D2 and C1 duty cycles and act appropriately. Finally, because the impact of NTE is not fully understood for very large propulsion engines and to be consistent with the IMO

requirements, EPA does not believe that it is appropriate to extend the NTE concept to Category 3 engines at the present time.

D. Emissions Sampling

Aside from the duty cycle, the test procedures for CI marine engines are proposed to be similar to those for land-based nonroad diesel engines. However, there are a few other aspects of marine diesel engine testing that need to be considered. Many recreational, auxiliary, and light-commercial marine engines mix cooling water into the exhaust. This exhaust cooling is generally done to keep surface temperatures low for safety reasons and to tune the exhaust for performance and noise. Since the exhaust must be dry for dilute emission sampling, the cooling water must be routed away from the exhaust in a test engine.

Even though many marine engines exhaust their emissions directly into the water, EPA is proposing to base its test procedures and associated standards on the emissions levels in the “dry” exhaust. Relatively little is known about water scrubbing of emissions. EPA must therefore consider all pollutants out of the engine to be a risk to public health. Additionally, EPA is not aware of a repeatable laboratory test procedure for measuring “wet” emissions. This sort of testing would be nearly impossible from a vessel in-use. Finally, a large share of the emissions from this category come from large engines which emit their exhaust directly to the atmosphere.

The established method for sampling transient emissions is through the use of full dilution sampling. However, for larger engines the exhaust flows become so large that conventional dilute testing would require a very large and costly dilution tunnel. One option for these engines is to use a partial dilute sampling method in which only a portion of the exhaust is sampled. It is important that the partial sample be representative of the total exhaust flow. The total flow of exhaust can be determined by measuring fuel flow and balancing the carbon atoms in and out of the engine. For guidance on shipboard testing, IMO NO_x Technical Code specifies analytical instruments, test procedures, and data reduction techniques for performing test-bed and in-use emission measurements.⁴⁶ Partial dilution sampling methods can provide accurate steady-state measurements and show great promise for measuring transient emissions in the near future. EPA intends to pursue development of this method and put it in place prior to the date that the standards in today’s proposal become enforceable.

Because marine engines often become an integral part of a vessel and cannot easily be removed, EPA proposes the option for in-use testing to be performed on the vessel. There are several portable sampling systems on the market that, if used carefully, can give fairly accurate results. For Category 3 engines, and some Category 2 engines, it may not be feasible to test the engines on a dynamometer. When this is the case, it may be more appropriate to test the engine aboard the vessel. For these vessels, there should be enough space to bring an electro-chemical sampler aboard similar to those used for stationary source testing. Engine speed can be monitored directly, but load may have to be determined indirectly. For constant speed engines, it should be relatively easy to set the engine to the points specified in the duty cycles.

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VII. Baseline Technology Mix

A. Category 1 Marine Diesel Engines

EPA developed estimates of the current mix of technology for Category 1 marine diesel engines based on data from the 1997 Power Systems Research (PSR) OE Link database and from conversations with marine manufacturers. Based on this information, EPA estimates that 70 percent of new marine engines are turbocharged, and 70 percent of these turbocharged engines use aftercooling. The majority of these engines are four-strokes, but about 20 percent of Category 1 engines are two-strokes. Although indirect injection (IDI) is mostly used with smaller diesels, engines with IDI account for about 10 percent of total CI sales for the past five years. Electronic controls have only recently been introduced into the marine market place; however, EPA anticipates that their use will increase as customers realize the performance benefits associated with electronic controls and as the natural migration of technology from on-highway to nonroad to marine occurs. Table 3-2 provides more detail on the baseline technology mix.

Table 3-2
Baseline Technology Mix of Category 1 Marine Diesel Engines

Technology	Auxiliary	Recreational	Commercial	Aggregate
natural aspiration	47%	29%	31%	30%
turbocharger	53%	71%	69%	70%
no aftercooler	70%	48%	53%	50%
jacket-water aftercooler	21%	46%	41%	44%
raw-water aftercooler	9%	6%	6%	6%
direct injection	78%	90%	96%	91%
indirect injection	22%	10%	4%	9%
mechanical control	97%	99%	100%	99%
electronic control	3%	1%	0%	1%

With regard to baseline emissions, data from eight high-speed marine diesel engines^{47,48,49} are presented in Table 3-3 and compared to the proposed standards. For the seven propulsion marine engines, the results are based on the E3 test cycle; the D2 test cycle was used for the auxiliary marine engine. PM emissions were not sampled from all of the engines. This data shows to what extent emissions need to be reduced from today's Category 1 marine diesel engines to meet the proposed standards. On average, EPA is requiring significant reductions in HC+NOx and PM; however, the proposed CO standards will just act as a cap.

Table 3-3
Emissions Data from Baseline Category 1 Marine Diesel Engines

Rated Power (kW)	Technology Mix	Emissions Data g/kW-hr				Proposed Standards		
		HC	NO _x	CO	PM	HC+NO _x	CO	PM
20	naturally aspirated indirect injection	0.27	6.6	2.8	0.99	—	—	—
71*	naturally aspirated	3.45	8.3	11.5	1.17	7.8/4.0	5.0	0.4
237	turbocharged	0.03	9.1	1.4	—	7.8/4.0	3.5	0.2
262	turbocharged raw-water aftercooled	0.37	7.8	0.7	—			
265	turbocharged jacket-water aftercooled	0.35	9.4	0.6	—			
336	turbocharged	0.09	7.0	1.6	0.17			
447	turbocharged jacket-water aftercooled	0.52	9.7	1.7	0.17			
895	turbocharged jacket-water aftercooled	0.27	9.7	1.3	—	7.8/5.0	2.0	0.27

* Because this is an auxiliary marine engine, this data is based on the D2 test cycle.

B. Category 2 Marine Diesel Engines

Category 2 marine engines are essentially maritized locomotive two and four-stroke engines. Two-stroke engines currently make up the vast majority of the fleet; however, four-stroke engines are expected to gain market share as locomotives go to four-stroke to meet the recently finalized standards for locomotive engines. Like locomotive engines, almost all Category 2 marine diesel engines use turbochargers to increase their power to weight ratios. About 90 percent of Category 2 marine diesel engines are turbocharged and jacket water aftercooled. A small fraction of these aftercoolers are on a separate circuit from the engine cooling system. Electronic controls have not really made any inroads into this class of engines.

Baseline emission data is drawn from five Category 2 marine diesel engine pairs that were emission tested for the U.S. Coast Guard.⁵⁰ The E3 weighted emission results from these engines are presented in Table 3-4. Of these five engine pairs, two have emissions levels below the Tier 0 locomotive engine standards and a third has emission levels below the Tier 1 locomotive engine emission standard. These marine engines probably have somewhat lower baseline emissions than locomotive engines because locomotive engines are severely constrained in their heat rejection

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capabilities while marine engines have the advantage of being able use to the oceans, rivers, and lakes as a large heat sink. Additional testing of Category 2 engines by Lloyd’s Register confirms that Category 2 marine engines have lower emissions than baseline locomotive engines.^{51,52} This data was included in Figure 3-2. The Lloyd’s data is particularly interesting because it measures emissions from commercial vessels in-use.

Table 3-4
Emissions Data from Baseline Category 2 Marine Diesel Engines

Rated Power (kW)	Technology Mix	Emissions g/kW-hr				Proposed Standards		
		HC	NOx	CO	PM	HC+NOx	CO	PM
1460*	turbocharged	0.50	16.5	1.1	0.52	7.8/5.0	2.0	0.27
1710*	turbocharged	0.03	13.1	1.4	0.17			
1900*	turbocharged, aftercooled	0.03	16.4	4.1	0.27			
2190*	turbocharged	0.00	11.3	4.9	0.32			
2380*	turbocharged, two-stroke opposed piston	0.11	9.5	0.9	—			

* The emissions results reported here are averages of engine pairs.

C. Category 3 Marine Diesel Engines

Category 3 engines are significantly different from Category 1 and 2 engines in several ways that can affect the technologies used and the baseline emissions. First these engines are intended for a different sort of operation. Category 3 engines are typically used for propulsion on large ocean-going commercial vessels whose service is characterized by principally by cruising operations. Typically, the engine is coupled directly to a fixed pitch propeller, and maneuvering and reverse propulsion is accomplished by reversing the entire engine. Category 3 engines are also used to a lesser extent on coast-wise commercial vessels. For maneuverability in coast-wise applications, variable pitch propellers are used to allow the engine to operate in one direction at a constant speed. Occasionally, smaller Category 3 engines may be used for auxiliary service on ocean-going vessels.

Consequently, Category 3 engines have a characteristic operation profile that can be different from Category 2 and Category 1 marine engines. Because of Category 3 engines’ high power (3,000-60,000 kW) and relatively continuous use, fuel is the most significant cost in a vessel’s operation. Therefore, Category 3 engines are designed and operated at the lowest brake specific fuel consumption (BSFC) of any combustion system (as low as 0.176 kg/kW-hr).^{53,54} To achieve this they are operated at maximum brake mean effective pressures (BMEP) (~1500-2200 kPa) to maximize thermal efficiency and minimum mean piston speed (7-9 m/s) to maximize mechanical and propeller efficiency.⁵⁵ Power density (rated engine power/engine weight) is sacrificed to operate at maximum

efficiency rather than maximum output. In comparison, commercial Category 2 and 1 marine engines are often designed and operated at maximum output rather than maximum efficiency due to economies gained in high average-trip speeds.

This operation profile has an effect on total oxides of nitrogen (NO_x) and particulate matter (PM) emissions. For diesel engines there is an exponential relationship between NO_x emissions and peak combustion temperatures, which occur at peak combustion pressures. Keeping in mind that BSFC is minimized if BMEP is maximized at a given speed, Category 3 engines are unfortunately designed for and most economically operated at peak NO_x formation conditions. However, these conditions do provide for a high 95%-burn combustion temperature, which minimizes non-volatile carbon PM emissions.⁵⁶ In addition, the use of bunker fuel can result in higher NO_x from Category 3 engines than for other diesel engines for two reasons: 1) nitrogen in the fuel, and 2) poor ignition qualities leading to increased ignition delay and higher peak temperatures. Marine fuels are discussed in more detail later in this chapter.

In general, Category 3 marine diesel engines are two-stroke cycle engines using a crosshead piston design. This means that an additional linkage is used in the piston-crank assembly to allow for long strokes. Charge air is generally compressed using a supercharger driven by the crankshaft at low loads and using a turbocharger under cruising and high loads. To reduce pumping losses, the down stroke of one piston may be used to help push intake air into the next cylinder. This charge air is heavily cooled. Typically, large Category 3 engines will use a two stage aftercooler where the first stage is cooled by jacket water and the second stage is cooled by raw water. Each cylinder typically will have its own fuel injection pump so that each cylinder may be independently optimized for peak performance.

Lloyd's has collected baseline emission data on many marine diesel engines.⁵⁷ However, from this data, EPA was only able to determine E2 emissions from five Category 3 engines since the modes tested did not generally line up with the proposed test procedure. This data is presented in Table 3-5. To generate the E2 weighted results, the raw Lloyd's data was converted to mass rates by converting all NO_x reported volume concentrations to NO₂ mass concentrations and then multiplying by exhaust flow rates calculated by carbon balance. Power was based on reported data. Because the emission standards are based on distillate fuel and the emission data was based on residual fuel, an adjustment of the standard to reflect residual fuel use is provided. This adjustment of 10 percent was based on comparing Lloyd's data on distillate and residual fuel and is consistent with the allowance provided by IMO. EPA recognizes that the small ship population sampled is a source of significant uncertainty; however, these results do indicate that an emissions benefit exists for Category 3 engines.

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Table 3-5: Emission Data from Baseline Category 3 Marine Diesel Engines

Rated Power [kW]	Rated Speed [rpm]	Measured NOx [g/kW-hr]	IMO NOx Standard [g/kW-hr]	Standard Adjusted for Bunker Fuel*
4246	570	12.7	11.2	12.3
4780	520	16.2	11.9	13.2
4780	512	17.7	12.6	13.9
6545	510	19.5	12.9	14.2
7700	510	16.2	12.9	14.2

* This is a rough adjustment for comparison purposes only.

VIII. Low Emission Category 1 Marine Engines

In an effort to achieve significant and timely emission reductions from marine engines in California, many vessels have been repowered with low-emission marine engines as part of various demonstration programs. These repower (completed and planned) programs are the result of efforts by local agencies such as the Santa Barbara County Air Pollution Control District and the South Coast Air Quality Management District as well as EPA's Region 9, the Port of Los Angeles, and others. The low-emission marine engines have been specially produced for the marine repower programs by a number of manufacturers including Cummins, Detroit Diesel, Mercruiser, Marine Corporation of America, and Yanmar. At this time, more than 75 low-emission high-speed marine engines have been installed and are still operating in a wide variety of applications, and more replacements are planned.

The emission control strategies used on these demonstration engines were targeted on achieving low NOx. For the majority of these engines, timing was retarded at cruise and full load operating conditions using either electronic or mechanical engine control. Another technology which achieved low NOx emissions was indirect injection (IDI). All of the engines used raw-water aftercooling. Vessel owners reported positively on the performance and fuel efficiency of these engines. Apart from a problem with the calibration of electronic controls on one engine type, which has subsequently been resolved, no significant problems have arisen as a result of the low-emission technology.² Table 3-6 presents emissions data from several low-emission marine engines based on the E3 marine test cycle.^{58,59,60,61,62} Figure 3-5 compares the emission results from the baseline and low-emission high-speed marine engines presented in this chapter to the proposed standards. The emission levels of these demonstration engines compare favorably to the proposed standards.

² The only problem that was reported was due to the calibration of the electronic controls on one engine type. This problem has been resolved.

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Table 3-6: Emissions Data from Low-Emission Category 1 Marine Diesel Engines

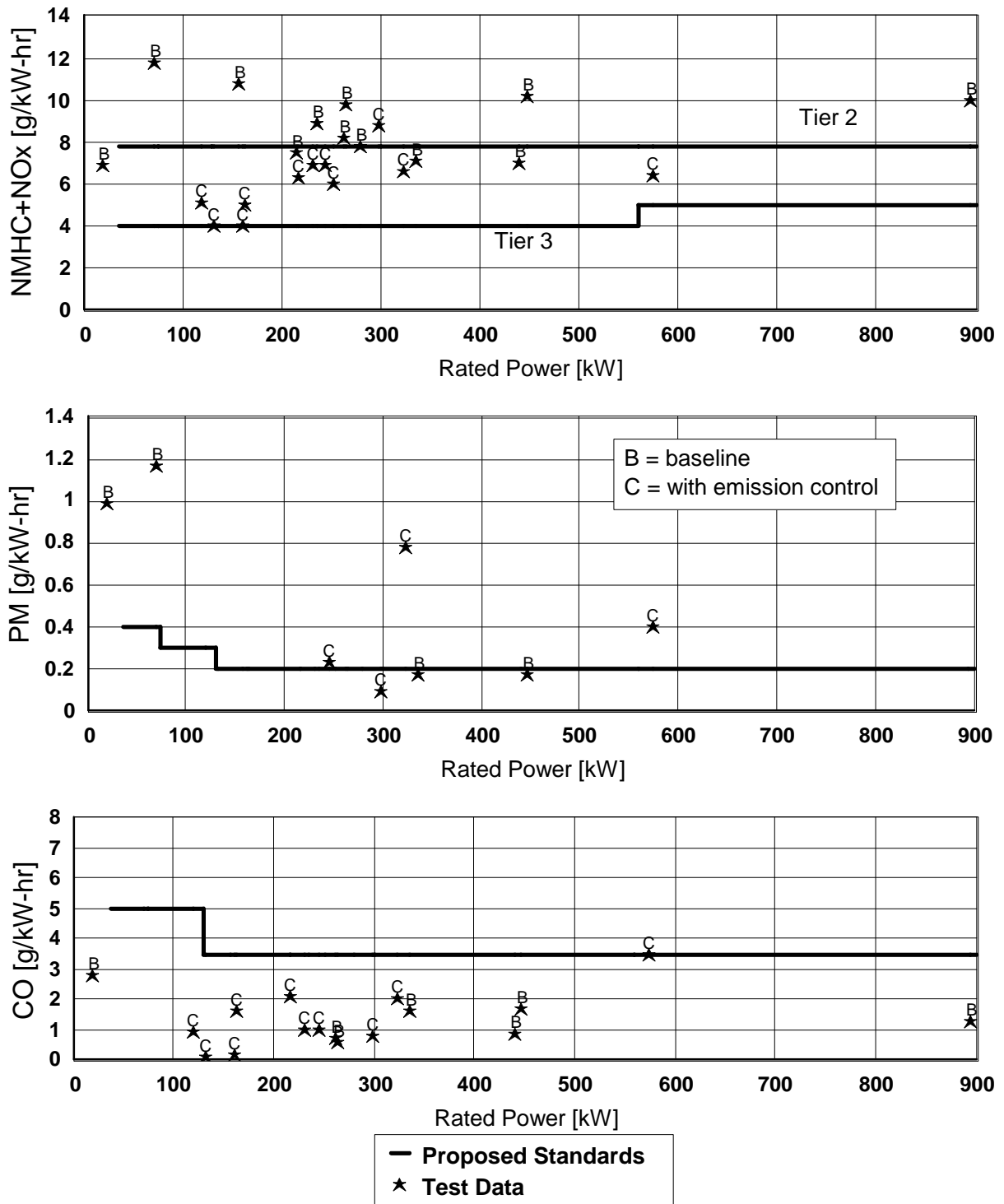
Rated Power (kW)	Technology Mix	Emissions g/kW-hr				Proposed Standards		
		HC	NO _x	CO	PM	HC+NO _x	CO	PM
120	turbocharged, raw-water aftercooled, electronic control	0.09	5.0	0.96	—	7.8/4.0	5.0	0.3
132	turbocharged, raw-water aftercooled, IDI	0.05	4.0	0.13	**	7.8/4.0	3.5	0.2
162	turbocharged, raw-water aftercooled, IDI	0.07	3.9	0.17	**			
164	turbocharged, raw-water aftercooled, electronic control	0.31	4.7	1.6	—			
217	turbocharged, raw-water aftercooled, electronic control	0.14	6.1	2.1	—			
232	turbocharged, raw-water aftercooled	0.45	6.5	0.99	—			
245*	turbo, raw-water aftercooled, electronic ctrl, 2-stroke	0.4	6.5	1.0	0.23			
252	turbocharged, raw-water aftercooled	—	5.5	—	—			
298*	turbocharged, raw-water aftercooled, electronic control	0.13	8.7	0.78	0.09			
324	turbocharged, jacket-water aftercooled	0.11	6.5	2.0	0.78			
575*	turbo, raw-water aftercooled, electronic ctrl, 2-stroke	0.3	6.1	3.5	0.40			

* This data is based on C1 test cycle.

** No PM data was collected, but the manufacturer reported that there was no visible smoke.

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Figure 3-5: Diesel Marine Engine Emissions Compared to the Proposed Standards



IX. Anticipated Technology Mix

As discussed above, marine engines are generally derived from land-based nonroad, locomotive, and to some extent highway engines. This allows marine engines, which generally have lower sales volumes than other nonroad engines, to be produced more cost-effectively. Because the marine designs are derived from land-based engines, EPA believes that many of the emission-control technologies which are likely to be applied to nonroad engines to meet their Tier 2 and 3 emission standards and to locomotives to meet their Tier 2 emissions standards will be applicable to marine engines.

EPA believes that the technology listed below will be sufficient for meeting both the proposed standards and the NTE requirements. While the transient portion of the NTE requirements may have some effect on PM emissions, no additional hardware should be required to meet the proposed limits. Some additional design time may be required to optimize the engine under transient conditions. However, marine operations typically have only limited transience, and the 30 second averaging period in the NTE testing should prevent short emissions spikes from defining maximum emissions thereby lessening the effects of transience on NTE test results.

A. Category 1 Marine Diesel Engines

Due to the emissions standards proposed, EPA anticipates that timing retard will likely be used in most Category 1 marine diesel applications, especially at cruising speeds, to gain NO_x reductions. The negative impacts of timing retard on HC, PM and fuel consumption can be offset with advanced fuel injection systems with higher fuel injection pressures, optimized nozzle geometry, and potentially through rate shaping. EPA does not expect marine engine manufacturers to convert from direct injection to indirect injection due to these standards.

Regardless of environmental regulations, EPA believes that Category 1 engine manufacturers would make more use of electronic engine management controls in the future to satisfy customer demands of increased power and fuel economy. Through the use of electronic controls, additional reductions in HC, CO, NO_x, and PM can be achieved. Electronics may be used to optimize engine calibrations under a wider range of operation. Most of the significant research and development for the improved fuel injection and engine management systems should be accomplished for land-based nonroad diesel engines which are being designed to meet Tier 2 and Tier 3 standards. Common rail should prove to be a useful technology for meeting Tier 3, especially for smaller engines. Thus, the challenge for this control program will be transferring land-based techniques to marine engines.

EPA projects that, under the proposed standards, all Category 1 marine diesel engines will be turbocharged and most will be aftercooled. Aftercooling strategies will likely be mostly jacket-water charge air cooling, and especially for Tier 3, EPA believes that separate cooling circuits for the aftercooling will be widely used. EPA expects a significant increase in the use of raw-water charge air cooling for engines with specific displacements under 2.5 liters per cylinder. The raw-water aftercooling systems will have to be designed specifically for marine engines; however, since they

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are currently in use in some applications, most of the significant developmental work for these cooling strategies is assumed to be completed.

EPA believes that manufactures will need to use EGR to meet the Tier 3 standards. For engines with less than 2.5 liters per cylinder, manufacturers will likely need to cool the recirculated exhaust gas to achieve the proposed Tier 3 standards while maintaining performance and durability. Because of the less stringent standards for the lower production volumes of engines with 2.5 liters per cylinder or more, hot EGR should be sufficient to meet the proposed Tier 3 standards. Chapter 4 presents one possible scenario of how these technologies could be used on Category 1 marine diesel engines to meet the proposed Tier 2 and Tier 3 standards.

By proposing standards with implementation dates that extend well into the next decade, EPA is providing engine manufacturers with substantial lead time for developing, testing, and implementing emission control technologies. This lead time and the coordination of standards with those for nonroad engines allows for a comprehensive program to integrate the most effective emission control approaches into the manufacturers' overall design goals related to performance, durability, reliability, and fuel consumption.

B. Category 2 Marine Diesel Engines

EPA anticipates that Category 2 marine diesel engines will use the same control strategies as Category 1 engines. As a result of the proposed Tier 2 regulations, EPA projects that the majority of these engines will continue to be turbocharged and aftercooled. Due to changes in locomotive engine design and the requirements of the proposed standard, EPA expects that most new Category 2 engines will be four-strokes. EPA believes that separate circuit aftercooling will most likely be considered more attractive than single circuit aftercooling for most applications. These control strategies are similar to those that are likely to be used on locomotive engines, except that the cooling strategies on marine engines are expected to be more effective.

EPA believes that marine engines should be able to achieve lower emissions than locomotives with the same emission controls due to the greater potential for cooling and because high altitude conditions do not need to be considered in their designs. However, EPA does not consider this advantage to be enough for Category 2 marine engines to achieve the proposed Tier 3 standards using only the technology expected to be used on Tier 2 locomotive engines. EPA believes that the key technologies to meeting the proposed Tier 3 levels will be common rail fuel injection systems and exhaust gas recirculation. Chapter 4 presents one possible scenario of how the technologies discussed in this chapter could be used on Category 2 marine diesel engines to meet the proposed standards.

C. Category 3 Marine Diesel Engines

EPA anticipates that Category 3 engines will be able to achieve the IMO NO_x limit without significant engine redesign. Typically, the same strategies that have been used over time to reduce fuel consumption have generally resulted in an increase in NO_x emissions. Reducing NO_x with the

technology used today basically means calibrating the engines with a focus on emissions as well as fuel consumption. For instance, rate shaping may be used to inject a small amount of fuel early followed by the remaining charge so that the majority of the fuel may undergo diffusion burning. This would reduce NO_x by reducing peak cylinder temperatures associated with the burning of fuel that is premixed with air prior to the start of combustion. Negative impacts on fuel consumption can also be minimized through fuel injection strategies, including increasing injection pressures and through optimizing nozzle geometry. Wartsila NSD, a market leader in Category 3 engine production, has demonstrated a combination of engine technologies that meets the IMO/Annex VI emission standard. Wartsila NSD has utilized a combination of late fuel injection rate shaping, higher cylinder compression ratio, higher fuel injection pressure and an optimized combustion chamber to achieve a 25-35 percent reduction in emissions.⁶³ Furthermore, the combination of these technologies has no negative effect on BSFC.

X. Test Fuel Specifications

A. Category 1 and 2 Marine Diesel Engines

EPA is proposing that the recently finalized test fuel specifications for nonroad diesel engines be applied to Category 1 and 2 marine diesel engines, with a change in the sulfur content upper limit from 0.4 to 0.8 weight-percent (wt%). EPA believes that this will simplify development and certification burdens for marine engines that are developed from land-based counterparts. This proposed test fuel has a sulfur specification range of 0.03 to 0.80 wt%, which covers the range of sulfur levels observed for most in-use fuels. Manufacturers will be able to test using any fuel within this range for the purposes of certification. Thus, they will be able to harmonize their marine test fuel with U.S. highway (<0.05 wt%) and nonroad (0.03 to 0.40 wt%), and European testing (0.1 to 0.2 wt%).

The intent of these test fuel specifications is to ensure that engine manufacturers design their engines for the full range of typical fuels used by Category 1 marine engines in use. Because the technological feasibility of the proposed standards are based on fuel with up to 0.4 wt% sulfur, any testing done using fuel with a sulfur content above 0.4 wt% would be done with an allowance to adjust the measured PM emissions to the level they would be if the fuel used were 0.4 wt% sulfur. The full range of proposed test fuel specifications are presented in Table 3-7. Because testing conducted by EPA would be limited to the test fuel specifications, it is important that the test fuel be representative of in-use fuels.

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Table 3-7
Proposed Category 1 and Category 2 Test Fuel Specifications

Item	Procedure (ASTM)	Value (Type 2-D)
Cetane	D613-86	40-48
Initial Boiling Point, °C	D86-90	171-204
10% point, °C	D86-90	204-238
50% point, °C	D86-90	243-282
90% point, °C	D86-90	293-332
End Point, °C	D86-90	321-366
Gravity, API	D287-92	32-37
Total Sulfur, % mass	D129-21 or D2622-92	0.03-0.80
Aromatics, % volume	D1319-89 or D5186-91	10 minimum
Parafins, Napthenes, Olefins	D1319-89	remainder
Flashpoint, °C	D93-90	54 minimum
Viscosity @ 38 °C, centistokes	D445-88	2.0-3.2

B. Category 3 Marine Diesel Engines

Category 3 engines typically burn residual fuel, which is the by-product of distilling crude oil to produce lighter petroleum products such as gasoline, diesel fuel and kerosene. Residual fuel possesses a high viscosity and density, and it typically has high ash, sulfur and nitrogen content in comparison to marine distillate fuels. Some Category 3 engines can burn straight residual fuel, but many burn a blend of residual and distillate, which is called intermediate fuel (IF). The two most common IF blends burned in Category 3 engines are IF 180, which contains about 88 percent residual fuel and IF 380 which contains about 98 percent residual fuel.⁶⁴ Table 3-8 summarizes current ASTM standards for a marine distillate oil, residual fuel, and the two most common IF blends.

The use of residual fuel has two important consequences. First, it is more difficult to handle. Because of its high viscosity and high impurities, the fuel must be heated and filtered before it can be passed to the engine. This requires additional equipment and space. Bunker fuel is kept in a main fuel tank where it is kept heated, generally using steam coils, to just above its pour point. Prior to use, this fuel is pumped into a settling tank, where the heavier portions settle to the bottom. Fuel is pumped from the top of the settling tank through heaters, centrifugal separators, and filters before entering the fuel metering pump. The centrifugal separators and filters remove water and remaining

sludge from the fuel. The sludge is then routed to a sludge tank. In addition, a separate fuel tank is usually necessary to store a lighter fuel which is used to start a cold engine.

Table 3-8
Comparison of ASTM Fuel Specifications⁶⁵

	Units	Distillate fuel	IF 180	IF 380	Residual fuel
ISO-F symbol		DMA	RMF-25	RMH-35	RML-55
Density @ 15C, max	kg/m ³	890	991	991	no max
Viscosity @ 40C	cSt	1.5-6.0	316	~710	—
Viscosity @ 50C	cSt	—	180	380	—
Viscosity @ 100C	cSt	—	25	35	55
Carbon Residue, max	wt%	0.20*	20**	22**	no max
Ash, max	wt%	0.01	0.15	0.20	0.20
Sulfur, max	wt%	1.5	5.0	5.0	5.0

* Ramsbottom test

** Conradson test

Second, residual fuels can have detrimental effects on engine emissions. These fuels may contain between 0.6-2.15 percent nitrogen by weight, and fuel-bound nitrogen is almost completely converted to NO in diesel engines.⁶⁶ It is estimated that fuel-bound nitrogen contributes 0.35 g/kW-hr per 0.1 percent nitrogen, however test results indicate that fuel ignition quality also has a detrimental effect on NOx emissions.⁶⁷ For example ISO E3 test results on a Category 3 engine indicate a 22 percent increase in ISO weighted NOx when residual fuel was substituted for distillate fuel, but the fuel-bound nitrogen (0.4 percent) only accounted for 9 percent of this increase. The remainder of the NOx increase was attributed to the fuel's poor ignition quality, which caused excessive ignition delay at part load. At 25 percent load on residual fuel, the engine produced 50 percent more NOx than on distillate, while at full load it produced only 25 percent more than on distillate.⁶⁸

Residual fuel also has a detrimental effect on particulate matter (PM) emissions. One Category 3-engine study⁶⁹ indicated that on residual fuel, PM increased on average by a factor of 10 in comparison to distillate. Furthermore, lab-to-lab comparisons showed ±25 percent variability in PM results when residual fuel was tested. This unacceptable test variability has been attributed to the effect of high sulfate concentrations on the dilute sampling method specified by the International Standards Organization (ISO). These results have led to a remark in ISO 8178 stating that the method has not been validated with fuel containing more than 0.8 percent sulfur by-weight. Since

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even the lowest international marine distillate fuel sulfur specification is 1.5 percent, Category 3 engines operate on fuels for which no PM test method has been developed.

XI. Impact on Noise, Energy, and Safety

The Clean Air Act requires EPA to consider potential impacts on noise, energy, and safety when establishing the feasibility of emission standards for marine diesel engines. One important source of noise in diesel combustion is the sound associated with the combustion event itself. When a premixed charge of fuel and air ignites, the very rapid combustion leads to a sharp increase in pressure, which is easily heard and recognized as the characteristic sound of a diesel engine. The conditions that lead to high noise levels also cause high levels of NO_x formation. Fuel injection changes and other NO_x control strategies therefore typically reduce engine noise, sometimes dramatically.

The impact of the proposed standards on energy is measured by the effect on fuel consumption from complying engines. Many of the marine engine manufacturers are expected to retard engine timing which increases fuel consumption somewhat. Most of the technology changes anticipated in response to the proposed standards, however, have the potential to reduce fuel consumption as well as emissions. Redesigning combustion chambers, incorporating improved fuel injection systems, and introducing electronic controls provide the engine designer with powerful tools for improving fuel efficiency while simultaneously controlling emission formation. To the extent that manufacturers add aftercooling to non aftercooled engines and shift from jacket-water aftercooling to raw-water aftercooling, there will be a marked improvement in fuel-efficiency. Manufacturers of highway diesel engines have been able to steadily improve fuel efficiency even as new emission standards required significantly reduced emissions.

There are no apparent safety issues associated with the proposed standards. Marine engine manufacturers will likely use only proven technology that is currently used in other engines such as nonroad land-based diesel applications, locomotives, and diesel trucks.

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CHAPTER 4: ECONOMIC IMPACT

EPA expects that in almost all cases, manufacturers will produce a complying marine engine by adapting an engine that has been designed and certified to meet highway or nonroad emission standards. This analysis considers the cost of these upgrades to the base engines as part of the impact of new marine emission standards; variable costs are applied directly, with an additional fixed cost added to apply the technologies to marine engines. The analysis arrives at the full cost impact by considering changes to turbocharging and aftercooling applicable to marine engines.

This chapter describes EPA's approach to estimating the cost of complying with the new standards. Both engine and vessel design are considered in determining a total cost impact. The estimated aggregate cost to society is also considered, followed by an analysis of the impact on small businesses.

I. Methodology

EPA has estimated a mix of current and projected technologies for complying with the proposed emission standards. The costs of individual technologies are developed in considerable detail and then combined according to the projections of technology changes for successive tiers of emission standards. EPA developed the costs for individual technologies in cooperation with ICF, Incorporated and Geraghty & Miller in a series of reports related to diesel engine emission controls.^{1,2,3}

To simplify the analyses, costs were examined for five types of engines representing five power ranges. The five cases, shown in Table 4-1, cover four Category 1 engines and one Category 2 engine. The selected power ratings are intended to correspond with the displacement values used to differentiate among the standards. The maximum listed value of 5,000 kW is intended merely to reflect the upper end of the range of Category 2 engines.

Costs of control include variable costs (for incremental hardware costs, assembly costs, and associated markups) and fixed costs (for tooling, R&D, and certification). Variable costs are marked up at a rate of 29 percent to account for manufacturers' overhead and profit.⁴ For technologies sold by a supplier to the engine manufacturers, an additional 29 percent markup is included for the supplier's overhead and profit. The analysis also includes consideration of lifetime operating costs where applicable. The result is a total estimated incremental cost for individual engines of various sizes.

Table 4-1 also includes information on current product offerings and sales volumes, which is needed to calculate amortized fixed costs for individual engines. Estimated sales and product offerings were compiled from the PSR database based on historical 1997 information. For the largest

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engines, some sales volumes were modified slightly to take into account recent data related to vessel populations.

Table 4-1
Power Ranges and Nominal Power for Estimating Costs (kW)

Engine Power Ranges	Nominal Engine Power	Models	Annual Sales*	Average Sales per Model
37 - 225	100	26	3,284	126
225 - 560	400	15	1,579	105
560 - 1000	750	10	142	14
1000 - 2000	1500	8	130	16
2000 - 5000	3000	5	68	14

*Excluding recreational.

Even though the analysis does not reflect all the possible technology variations and options that are available to manufacturers, EPA believes that the projections presented here provide a cost estimate representative of the different approaches manufacturers may ultimately take.

II. Overview of Technologies

The land-based engines that often serve as the base engines for marine diesel applications will be changing as a result of new emission standards adopted for nonroad and locomotive engines. Most new nonroad and locomotive engines rated over 37 kW will be subject to two new tiers of standards spanning the next ten years. These engines will be designed, manufactured, and certified to have reduced emissions. The technological challenge for developing compliant marine engines is therefore to make the necessary modifications to the land-based engines for their use in the marine environment without significantly increasing emission levels.

In the absence of emission standards for marine engines, manufacturers would have to decide whether it would be more effective to marinize their low-emitting Tier 2 land-based engines, thus maintaining a single base engine, or to continue to marinize unregulated or Tier 1 land-based engines, thus maintaining separate production of older-technology engines for marine application. This analysis is based on engine manufacturers choosing the latter, and accordingly assesses the previously estimated variable costs of the land-based programs as an impact of the marine emission standards. To the extent that manufacturers would simplify production by using their low-emitting models anyway, the cost estimates developed in this analysis would overstate the actual impact of the emission standards.

As discussed in Chapter 3, manufacturers of Category 1 engines are expected to comply with the proposed emission standards by conducting basic engine modifications, upgrading fuel systems, adding some degree of electronic controls, and improving aftercooling systems. Manufacturers of Category 2 engines are expected to redesign combustion chambers, improve high-pressure electronic fuel injection systems, and upgrade or add turbocharging and aftercooling.

Except for the aftercooling changes, hardware improvements for nonroad and locomotive engines should be transferrable to marine engines, in many cases with some degree of adaptation. The analysis includes a substantial degree of development work to make adjustments for turbocharger matching, reprogramming electronic control software, and other changes that may be needed to prepare an engine for marine applications. Also, because manufacturers will in many cases be producing new engine designs outside the normal product development cycle, extensive development costs are included to design a marine version of a base engine, taking into account not only direct expenses for controlling emissions, but also considering some need for re-optimizing performance. Finally, marine engines rely on seawater (through a heat exchanger), not the ambient air, for rejecting heat from the engine and aftercooler. The cost of adding these systems are therefore presented separately in this chapter for different sizes of marine engines.

The first step in estimating the incremental cost of new emission standards is to establish the baseline technology package from which changes will be made. As described above, most of the technologies included in the analysis of costs for the land-based rules are carried directly into the analysis of costs for marine engines. Including these sets of technologies as a package defines both baseline and projection scenarios. A more detailed assessment is required for turbocharging and aftercooling. The PSR database provides information on sales and engine data for engine models available for auxiliary and propulsion marine applications. Table 4-2 summarizes the sales-weighted figures showing how many current engine sales include the various turbocharging and aftercooling options. Table 3-2 provides similar information without breaking engines into different size ranges. The predominance of naturally aspirated engines rated under 130 kW is contrasted with the nearly universal use of turbocharging for bigger engines. The table also shows that most turbocharged engines are equipped with jacket-water (or “single-circuit”) aftercoolers, though a small number of turbocharged engines in certain size ranges have either no aftercooling or the more sophisticated separate-circuit aftercooling.

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Table 4-2
Baseline Technologies for Marine Engines*

Engine Power (kW)	Naturally Aspirated	Turbocharged	Jacket-water Aftercooling	Separate-circuit Aftercooling
100	65%	35%	15%	0%
400	0%	100%	55%	15%
750	0%	100%	100%	0%
1500	0%	100%	100%	0%
3000	10%	90%	80%	10%

source: PSR Database.

*All numbers rounded to the nearest 5 percent.

As described in the cost analysis for the land-based nonroad engine rulemaking, manufacturers are expected to develop engine technologies not only to reduce emissions, but also to improve engine performance. While it is difficult to take into account the effect of ongoing technology development, EPA is concerned that assessing the full cost of the anticipated technologies as an impact of new emission standards would inappropriately exclude from consideration the expected benefits for engine performance, fuel consumption, and durability.³ Short of having sufficient data to predict the future with a reasonable degree of confidence, EPA faces the need to devise an alternate approach to quantifying the true impact of the new emission standards. EPA requests comment on the most appropriate way of accounting for these non-emission benefits.

III. Technology Costs

The total estimated cost impact of new emission standards is developed by considering the cost of each of the anticipated technologies. The following paragraphs describe these technologies and their application to marine engines. The analysis then combines these itemized costs into a composite cost estimate for the range of marine engines affected by the rulemaking.

Cost estimates for electronic controls, fuel injection upgrades, and exhaust gas recirculation are derived from estimates for nonroad engines. Variable costs for these technologies are carried into this analysis. In some cases, cost figures represent an average across a broader power range or an extrapolation to a bigger engine. Estimated R&D expenditures for these technologies and other engine modifications are also considered. The anticipated R&D effort should be focused primarily

³While EPA does not anticipate widespread, marked improvements in fuel consumption, small improvements on some engines may occur.

on transferring established engine technologies to marine engines. Projected fixed costs are therefore reduced from the levels anticipated for redesigning nonroad engines. EPA’s general expectation is that one-third of the previously anticipated level of R&D would be needed to successfully implement the changes for marine engines.

Estimated levels of R&D in the analysis are developed for individual technologies to show the incremental effect of combining different levels of emission control. Engine design in practice, however, is much more integrated. Table 4-3 shows a weighted total of the combined R&D costs calculated for each size engine to integrate the projected package of technologies for each tier of emission limits. To put these large capital expenditures in context, the analysis is based on each \$1 million of R&D consisting of about three engineer-years and four technician-years of effort, plus nearly \$500,000 for testing-related expenses.

Table 4-3
Total Estimated R&D Expenditures per Engine Family

	100 kW	400 kW	750 kW	1500 kW	3000 kW
Tier 2	\$600,000	\$610,000	\$1,400,000	\$1,400,000	\$1,870,000
Tier 3	\$1,060,000	\$1,100,000	\$1,890,000	\$2,250,000	\$2,250,000

As described in the notice of proposed rulemaking, EPA intends to require that manufacturers comply with emission limits at any speed and load that can occur on a vessel. While these so-called off-cycle requirements may increase the difficulty of meeting the emission limits, EPA believes it is not appropriate to consider additional costs for manufacturers to comply with them. This is because managing engine operation to avoid unacceptable variation in emission levels is expected to be achievable by more effective utilization of the technologies that will be used to meet the emission limits more broadly, rather than by use of additional hardware. For example, electronically controlled common rail fuel systems can be reprogrammed to adjust a wide range of injection variables under certain operating conditions to avoid excessive emissions. This approach would involve no additional variable cost. The estimated R&D expenditures are intended to reflect the time needed to address this. It is possible that manufacturers will need to retard injection timing for some engines, which would result in a cost penalty for increased fuel consumption. This scenario is considered as a sensitivity analysis in Section III.J. below.

A. Electronic Controls

EPA anticipates that electronic controls will be an essential design element as emission limits increase in stringency. Almost all engines rated over 560 kW are already equipped with electronic controls, because of the associated performance improvements. Engines rated between 37 and 560 kW will need to add electronic controls to meet the proposed emission limits.

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The analysis reaches an estimated cost for applying electronic controls in several steps, as summarized in Table 4-4. First, the hardware is expected to be the same as that used for nonroad engines, so costs are transferred directly from previous estimates. Second, an additional cost is assessed to account for preventing corrosion in the wiring, connections, and the electronic controller and to meet explosion-proof specifications or other marine-specific requirements. The increasing use of electronic systems for navigation, communication, and inventory purposes has led to better, lower cost approaches to producing more durable and reliable systems. These marine improvements consist primarily of additional material to seal metal parts and joints and stronger materials or better fasteners for some components. Third, the R&D cost for programming the electronics for all the applications of a single engine model is treated the same as adding two new calibrations to the base engine.

Table 4-4
Electronic Controls

	100 kW	400 kW
Component costs	\$454	\$650
Marine upgrade	\$50	\$75
Assembly, markup, and warranty	\$219	\$307
Hardware cost per engine	\$723	\$1,032
Total fixed costs	\$150,000	\$150,000
Fixed cost per engine	\$290	\$348
Composite Unit Cost	\$1,012	\$1,380

B. Fuel Injection Improvements

All engines are expected to see significant improvements in their fuel injection systems. Some engines are expected to make incremental improvements to existing unit injector designs (see Table 4-5). Better control of injection timing and increased injection pressure contribute to reduced emissions.

The rapidly growing demand for common rail fuel injection across engine sizes and applications supports a projection of long-term use of common rail for all engines.⁵ The principal benefit of common rail technology is that injection pressure is no longer dependent on engine speed, which, in conjunction with electronic controls, greatly increases the flexibility of tailoring the injection timing and profile to varying modes of operation. Though the technology development originated with highway diesel engines, common rail designs have been tailored for application in much larger engines.⁶ Cost estimates for common rail systems are summarized in Table 4-6.

Table 4-5
Unit Injection Improvements

	100 kW	400 kW	3000kW
Component costs	\$63	\$98	\$4,000
Assembly, markup, and warranty	\$32	\$46	\$1,882
Hardware cost per engine	\$95	\$144	\$5,882
Total fixed costs	\$45,000	\$100,000	*
Fixed cost per engine	\$87	\$232	*
Composite Unit Cost	\$182	\$375	\$5,882

*Fixed costs for developing unit injectors are included under Engine Modifications.

Table 4-6
Common Rail Fuel Injection

	100 kW	400 kW	750 kW	1500kW	3000kW
Component costs	\$80	\$116	\$205	\$630	\$1,500
Assembly, markup, and warranty	\$23	\$34	\$59	\$183	\$435
Hardware cost per engine	\$103	\$150	\$264	\$813	\$1,935
Total fixed costs	\$100,000	\$100,000	\$300,000	\$300,000	\$1,000,000
Fixed cost per engine	\$193	\$232	\$5,153	\$4,503	\$17,933
Composite Unit Cost	\$296	\$381	\$5,417	\$5,315	\$19,868

C. Engine Modifications

Manufacturers have continued to pursue improvements in basic engine technology in an effort to improve operating performance while controlling emissions. Such variables include routing of the intake air, piston crown geometry, and placement and orientation of injectors and valves. Most of these variables affect the mixing of air and fuel in the combustion chamber. Small changes in injection timing are also considered in this set of modifications. EPA expects that the base engines from which the marine engines are derived will have been extensively redesigned for operation at Tier 2 emission levels. Remaining engine modifications would then reflect the need to adapt these

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engines for complying with marine emission limits, including requirements to maintain control of emissions over the whole range of marine engine operation.

Because no performance improvements beyond those already achieved for nonroad engines are anticipated, no discount for non-emission benefits are applied. Accounting for the full cost of engine modifications as an impact of new emission standards also reflects the extensive effort needed to conduct an overall recalibration and reoptimization of the engine according to the schedule dictated by the implementation of Tier 2 emission limits. On the other hand, no fuel economy penalty for retarded injection timing is included. EPA believes that manufacturers will either not need to retard timing, or at least will be able to optimize other variables such as injection pressure and aftercooling to overcome any effects of retarding timing. The possibility of a fuel penalty is considered in the sensitivity analysis described in Section V below.

As described in the cost analysis for the land-based nonroad engine rulemaking, engine modifications are expected to require extensive R&D and retooling, but no change in hardware costs. The hardware costs included in this analysis for Category 2 engines are based on the different technology projections for Tier 2 locomotive engines. Table 4-7 shows the estimated per-engine costs for these modifications.

Table 4-7
Engine Modifications

	100 kW	400 kW	750 kW	1500 kW	3000kW
Hardware cost per engine	—	—	—	—	\$800
Total fixed costs	\$200,000	\$200,000	\$1,100,000	\$1,100,000	\$1,500,000
Fixed cost per engine	\$386	\$463	\$18,893	\$16,510	\$26,900
Composite Unit Cost	\$386	\$463	\$18,893	\$16,510	\$27,700

D. Turbocharging

EPA expects that turbocharging will be needed by all marine diesel engines rated over 37 kW to meet Tier 2 emission limits. As shown in Table 4-2, except for some engines rated below 225 kW or above 2000 kW, all marine diesel engines are already turbocharged. Turbocharger costs for the remaining engines were developed for EPA by Arcadis Geraghty and Miller.⁷ Since R&D costs were not developed separately for turbocharging, EPA conservatively estimated that one-fourth of the R&D required for a turbocharging and aftercooling system would be needed for adding turbocharging alone. Total turbocharger cost impacts are presented in Table 4-8.

Turbocharging can be used to increase power, which would involve higher costs for virtually all the powertrain components. This analysis, however, does not presume an increase in power or improved fuel economy resulting from turbocharging. Rather, turbocharging in the context of

emission controls is seen primarily as a technology that enables aftercooling, which has a great potential to control NOx emissions. Manufacturers may choose to exploit new turbochargers to improve performance, but EPA believes that such an approach would not be needed to comply with emission standards. As described earlier, these non-emission benefits support the analytical approach of assigning only half the cost of turbocharging as an impact of the proposed emission standards.

Table 4-8
Turbocharging

	100 kW	3000kW
Hardware cost per engine	\$208	\$2,133
Total fixed costs	\$100,000	\$300,000
Fixed cost per engine	\$193	\$5,380
Composite Unit Cost	\$401	\$7,513

E. Aftercooling

Cost estimates for adding or upgrading aftercooling systems were developed for EPA by Arcadis Geraghty and Miller.⁸ Separate costs were developed for adding jacket-water aftercooling and separate-circuit aftercooling (Tables 4-9 and 4-10, respectively). A third scenario of improving technology can be determined by calculating the net increase in cost for converting from jacket-water aftercooling to separate-circuit aftercooling (Table 4-11). The ample supply of cooling water and its greater convection coefficient relative to air support EPA’s belief that optimized separate-circuit aftercooling systems can match or exceed the cooling capability of air-to-air cooling in land-based engines.

Cost estimates were developed for separate-circuit aftercooling systems using tube-and-shell heat exchangers. An alternative design sometimes used on marine vessels is keel cooling, in which coolant is plumbed from the engine or aftercooler to the hull, where it is cooled by exposure to the seawater. Upgrading systems that rely on keel cooling would involve somewhat higher initial costs, but this cost premium is offset by lower operating costs for maintenance or rebuild. Costs related to keel cooling systems are not considered separately in this analysis.

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Table 4-9
Incremental Cost of Adding Jacket-Water Aftercooling

	100 kW	400kW
Component costs	\$237	\$899
Assembly, markup, and warranty	\$383	\$746
Hardware cost per engine	\$620	\$1,645
Total fixed costs	\$400,000	\$550,000
Fixed cost per engine	\$826	\$3,092
Composite Unit Cost	\$1,446	\$4,737

Table 4-10
Incremental Cost of Adding Separate-circuit Aftercooling

	100 kW	400kW	3000 kW
Component costs	\$596	\$1,800	\$20,492
Assembly, markup, and warranty	\$790	\$1,765	\$11,113
Hardware cost per engine	\$1,386	\$3,565	\$31,605
Total fixed costs	\$480,000	\$660,000	\$1,440,000
Fixed cost per engine	\$992	\$3,711	\$27,631
Composite Unit Cost	\$2,387	\$7,276	\$59,236

Table 4-11
Incremental Cost of Converting from Jacket-Water to Separate-circuit Aftercooling

	100 kW	400 kW	750 kW	1500 kW	3000kW
Component costs	\$359	\$901	\$1,701	\$3,151	\$5,964
Assembly, markup, and warranty	\$407	\$1,019	\$2,011	\$3,189	\$5,143
Hardware cost per engine	\$766	\$1,920	\$3,712	\$6,340	\$11,107
Total fixed costs	\$80,000	\$110,000	\$140,000	\$200,000	\$240,000
Fixed cost per engine	\$166	\$619	\$2,573	\$3,212	\$4,605
Composite Unit Cost	\$932	\$2,539	\$6,285	\$9,552	\$15,712

F. Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) reduces NO_x emissions by mixing a portion of the exhaust gases into the intake air. Adding an EGR cooler to a basic EGR system increases the effectiveness of controlling NO_x emissions by further suppressing temperatures in the combustion chamber. EGR has the advantage that it can be focused on the light-load modes of operation where NO_x emissions are most difficult to control. This also enables the designer to add moderate to extensive levels of EGR to control NO_x, with minimal negative effects on overall fuel economy, which is most important at high-load operation.

Proposed Tier 3 emission limits for engines with per-cylinder displacement less than 2.5 liters (roughly corresponding with 560 kW) are more stringent than for bigger engines (see Table 1-2). The more stringent standards will likely require cooled EGR systems. EPA believes that the design challenges associated with EGR cooling make this a less attractive design option for larger engines, whose low sales volumes make it more difficult to distribute high fixed costs. The less stringent emission limits for these engines reflect this difficulty. As described in a sensitivity analysis below, injection timing retard can be used as a supplemental measure if an engine with hot EGR is unable to sufficiently control NO_x emissions.

Estimated system costs for EGR are derived from the similar analyses for highway and nonroad engines. Applying these cost estimates to marine engines requires significant extrapolation to the high-power engines. While component costs can be considered approximate, the cost impact of adding EGR comes predominantly from amortizing R&D costs. The estimated level of \$500,000 for R&D and other fixed costs for 100 and 400 kW engines reflects the extensive development required to adapt cooled EGR systems expected in nonroad engines for the counterpart marine engines. For larger engines, the additional R&D needed to address unique engine issues is offset by the lower sophistication of the hot EGR systems. These costs are summarized in Table 4-12.

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One particular design challenge that engineers will have to address is the recirculation of particulate matter through the engine. The principal concern is for degradation of the lubricating oil as the oil absorbs significant amounts of particulate matter. In anticipation of EGR for highway engines, motor oil producers have developed a product that can absorb these levels of particulate matter without losing its lubricating properties. To account for the expense of higher-quality oils, the analysis adds an operating cost based on a 2 percent increase in the cost of oil. For companies that conduct oil sampling analysis in lieu of periodic oil changes, the listed life-cycle cost estimates overstate the effect of improved oils.

Table 4-12
Exhaust Gas Recirculation

	100 kW	400 kW	750 kW	1500 kW	3000kW
Electronic EGR valve	\$35	\$43	\$70	\$130	\$240
EGR tubing	\$9	\$22	\$45	\$90	\$180
EGR cooler	\$48	\$64	—	—	—
Component costs	\$92	\$129	\$115	\$220	\$420
Assembly, markup, and warranty	\$45	\$59	\$64	\$105	\$203
Hardware cost per engine	\$137	\$188	\$179	\$325	\$623
Total fixed costs	\$500,000	\$500,000	\$500,000	\$500,000	\$500,000
Fixed cost per engine	\$2,896	\$3,475	\$8,588	\$7,504	\$8,967
Composite Unit Cost	\$3,033	\$3,663	\$8,767	\$7,830	\$9,589
Life-cycle oil cost (npv)	\$20	\$56	\$167	\$311	\$715

G. Rebuild Costs

Operating data related to marine engines indicates that rebuild or remanufacture typically occurs multiple times for an engine, especially for larger engines. To the extent that manufacturers are adding new hardware to an engine to comply with emission requirements, there may be an increase in the cost of repair or replacement of parts over the life of an engine. This analysis includes an estimate of increased operating costs by projecting a schedule of parts replacement coinciding with periodic rebuilds. To calculate a total cost for each rebuild, the analysis provides for a rebuild rate of one-third of total long-term variable costs for each rebuild event. For some technologies, this represents a scenario of one-third of all engines replacing all the hardware in the system (such as turbochargers). For other technologies, this represents a scenario of all engines needing replacement of one-third of the value of new or improved components. For example, a rebuilder is not expected

to replace all the elements of an electronic control system at the point of rebuild; rather, after searching for defective or potentially defective parts, a rebuilder is expected to replace individual components on an as-needed basis. The value of replacement parts is calculated on a long-term basis, as described below, then marked up by a factor of three to account for the higher cost of aftermarket parts.

Turbocharging and aftercooling are the only technologies expected to require an increase in labor hours to rebuild an engine. Since these systems are virtually custom-built in commercial vessels, the analysis uses the same assembly times as were used to develop costs for new engines.

The rebuild schedule for Category 1 engines is based on a sixteen-year life, with two rebuilds occurring at the end of the fifth and tenth years. This represents median values for the fleet of engines, rather than incorporating scrappage rates and additional rebuilds on a subset of the fleet. Similarly, Category 2 engine rebuilds are based on a 23-year lifetime with three rebuilds occurring after years six, twelve, and eighteen. Lifetime costs are discounted to a net-present-value figure at the point of sale using a 7 percent discount rate. Rebuild costs are shown in Table 4-13.

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Table 4-13
Incremental Rebuild Costs

	100 kW	400 kW	750 kW	1500 kW	3000kW
Incremental hardware costs					
Electronic controls	\$323	\$464	—	—	—
Common rail	\$66	\$96	\$169	\$520	\$1,238
Unit injection	\$40	\$62	—	—	\$2,560
Turbocharger	\$133	—	—	—	\$1,365
Jacket-water aftercooling	\$152	\$575	—	—	—
Separate-circuit aftercooling	\$381	\$1,152	\$2,237	\$5,642	\$13,115
Aftercooling upgrade	\$230	\$577	\$1,089	\$2,017	\$3,817
Exhaust gas recirculation	\$59	\$82	\$74	\$141	\$269
Incremental labor hours:					
Turbocharger	1	—	—	—	6
Jacket-water aftercooling	5	5	—	—	—
Separate-circuit aftercooling	11	20	40	60	90
Aftercooling upgrade	6	15	30	45	68
Exhaust gas recirculation	1	1	1	1	1

H. Certification and Compliance

EPA has significantly reduced certification requirements in recent years, but manufacturers are nevertheless responsible for generating a minimum amount of test data and other information to demonstrate compliance with emission standards. Table 4-14 lists the expected costs for different sizes of engines, including the amortization of those costs over five years of engine sales. Estimated certification costs are based on two engine tests and \$20,000 worth of engineering and clerical effort to prepare and submit the required information.

Until engine designs are significantly changed, engine families can be recertified each year using carryover of the original test data. Since these engines are currently not subject to any emission requirements, the analysis includes a cost to recertify an upgraded engine model every five years.

Costs for production line testing (PLT) are summarized in Table 4-15. These costs are based on testing 1 percent of total estimated sales, then distributing costs over the fleet. Listed costs for engine testing presume no need to build new test facilities, since most or all manufacturers already have testing facilities available. The proposal also includes provisions to exclude the smallest companies from requirements to conduct production line testing.

Table 4-14
Certification

	100 kW	400 kW	750 kW	1500 kW	3000kW
Total fixed costs	\$40,000	\$40,000	\$50,000	\$50,000	\$60,000
Fixed cost per engine	\$77	\$93	\$859	\$750	\$1,076
Composite Unit Cost	\$77	\$93	\$859	\$750	\$1,076

Table 4-15
Costs for Production Line Testing

	100 kW	400 kW	750 kW	1500 kW	3000kW
Cost per test	\$10,000	\$10,000	\$15,000	\$15,000	\$20,000
Testing rate	1 %	1 %	1 %	1 %	1 %
Cost per engine	\$100	\$100	\$150	\$150	\$200

I. Total Engine Costs

These individual cost elements can be combined into a calculated total for each tier of new emission limits by assessing the degree to which the different technologies will be deployed. As described above, comparing the projected need for specific technologies can be compared to the technology baseline to determine the changes that will occur in the Tier 2 and Tier 3 time frames.

For Tier 2 emission limits, manufacturers are expected to rely on turbocharged engines with extensive modification to injection systems (including some additional use of electronic controls), and basic engine design. Some engines are expected to require new or improved aftercooling systems. In general, the projected utilization of each technology is expected to match that of land-based counterpart engines. With respect to aftercooling, jacket-water cooling systems are considered equivalent to air-to-water designs, and separate-circuit systems are considered equivalent to air-to-air designs. Since the Tier 2 emission limits for marine engines are in most cases less stringent than those finalized for the land-based counterpart engines, projecting the same degree of technology deployment represents a very conservative estimate of cost impacts. This approach is nevertheless

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used to estimate Tier 2 costs, because it accounts for the uncertainties associated with the marinization process and the effect of differing test cycles and compliance requirements.

To comply with Tier 2 emission limits, manufacturers are expected to take a variety of approaches to improve fuel systems, making incremental improvements to the various current designs. Unit injection systems can generally be further optimized for higher injection pressures and improved rate shaping capability. Nonroad engines with the highest sales volumes have begun converting to common rail fuel systems to take advantage of the step improvement in control of injection variables. EPA believes that these fuel systems will be used similarly for land-based and marine engines. Some engines will also likely use improved aftercooling technologies.

Projecting the mix of technologies for complying with Tier 3 emission limits necessarily involves a greater degree of uncertainty. Recent technology developments for highway and nonroad engines, however, has already done much to establish the emission-control potential of several of the anticipated technology improvements. In this analysis, EPA based the estimated Tier 3 costs on a scenario of universal deployment of common rail fuel injection, separate-circuit aftercooling, and exhaust gas recirculation. Most of the benefit of Tier 2 engine modifications will carry over to Tier 3 designs; however, an expected additional effort for improving and optimizing basic engine design is estimated to be half as much as that required to reach Tier 2 levels.

Injection timing retard is not part of the package of measures manufacturers are expected to take to comply with Tier 3 emission limits. Manufacturers may eventually choose to rely on timing retard, either to achieve an additional level of emission control or to avoid a more costly alternative technology. A sensitivity analysis, described in Section J below, evaluates the potential cost impacts of timing retard or other alternatives that may increase fuel consumption. In any case, EPA will review the feasibility and estimated cost of compliance with the Tier 3 emission limits in the 2003 Review.

Factoring in the degree of deployment and adding up the costs of the individual technologies results in a total estimated cost impact for engines designed and produced to meet emission limits. As shown in Table 4-16, estimated costs for complying with Tier 2 emission limits increase with increasing power ratings. Estimated price impacts range from \$2,600 for a 100 kW engine to \$54,000 for a 3,000 kW engine. Increased rebuild costs add to the total estimated impact, though to a much lesser degree than from the expected increase in new engine prices (Table 4-17). Similarly, cost increases for Tier 3 engines are shown in Table 4-18, with total costs ranging from \$5,300 to \$45,000. The percentages listed in the tables represent the anticipated change in the individual technologies and should not be confused with the total anticipated deployment of these technologies.

As described in the nonroad diesel rulemaking, long-term costs would be reduced by two principal factors. First, fixed costs are assessed for five years, after which they are fully amortized and are therefore no longer part of the cost calculation. Second, manufacturers are expected to learn over time to produce the engines with the new technologies at a lower cost. This should be especially true with marine engines. Because of the relatively low sales volumes, manufacturers are less likely

to put in the extra R&D effort for low-cost manufacturing. As production starts, assemblers and production engineers would then be expected to find significant improvements in fine-tuning these designs. To reflect this learning, variable costs are reduced by 20 percent beginning with the third year of production and an additional 20 percent beginning with the sixth year of production. Table 4-18 also lists the long-term cost estimates for these engines the sixth and subsequent years of production after incorporating these two changes. Reductions in long-term cost estimates ranging from 50 to 90 percent demonstrate the predominance of research and other fixed costs in the total estimated impact of the emission standards.

Characterizing these estimated costs in the context of their fraction of the total purchase price and life-cycle operating costs is helpful in gauging the economic impact of the new standards. Although the incremental cost projections increase dramatically with increasing power rating, they in fact represent a comparable price change relative to the total price of the engine. The estimated first-year cost increases for all engines are at most 3 percent of estimated vessel prices, with even lower long-term effects, as described above.

Table 4-16
Engine Costs—Tier 2

	100 kW		400 kW		750 kW		1500 kW		3000kW	
	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost
Electronic controls	75%	\$759	75%	\$1,035	0%	—	0%	—	0%	—
Common rail	0%	—	0%	—	100%	\$5,417	100%	\$5,315	0%	—
Unit injection upgrade	100%	\$182	100%	\$375	0%	—	0%	—	100%	\$5,882
Engine modifications	100%	\$386	100%	\$463	100%	\$18,893	100%	\$16,510	100%	\$27,700
Turbocharger	65%	\$261	0%	—	0%	—	0%	—	10%	\$751
Jacket-water aftercooling	30%	\$434	30%	\$1,421	0%	—	0%	—	0%	—
Separate-circuit aftercooling	10%	\$231	0%	—	0%	—	0%	—	10%	\$5,924
Upgrade to separate-circuit aftercooling	15%	\$140	30%	\$762	0%	—	0%	—	80%	\$12,570
Certification + PLT	100%	\$177	100%	\$193	100%	\$1,009	100%	\$900	100%	\$1,276
Total Engine Costs	0%	\$2,577	—	\$4,249	0%	\$25,319	—	\$22,725	0%	\$54,103

*"Fraction" denotes the percentage of engines estimated to require each of the new or improved technologies.

Table 4-17
Rebuild Costs—Tier 2

	100 kW		400 kW		750 kW		1500 kW		3000kW	
	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost
Incremental hardware costs:										
Electronic controls	75%	\$242	75%	\$348	0%	—	0%	—	0%	—
Common rail	0%	—	0%	—	100%	\$169	100%	\$520	0%	—
Unit injection upgrade	100%	\$40	100%	\$62	0%	—	0%	—	100%	\$2,560
Turbocharger	65%	\$87	0%	—	0%	—	0%	—	10%	\$137
Jacket-water aftercooling	30%	\$46	30%	\$173	0%	—	0%	—	0%	—
Separate-circuit aftercooling	10%	\$38	—	—	0%	—	0%	—	10%	\$1,311
Upgrade to separate-circuit aftercooling	15%	\$34	30%	\$173	0%	—	0%	—	80%	\$3,054
Hardware cost per engine	—	\$487	—	\$756	—	\$169	—	\$520	—	\$7,062
Incremental labor costs:	—	\$116	—	\$168	—	\$0	—	\$0	—	\$1,778
Total cost per rebuild	—	\$603	—	\$924	—	\$169	—	\$520	—	\$8,840
Total operating cost (npv)	—	\$603	—	\$924	—	\$169	—	\$520	—	\$8,840

*"Fraction" denotes the percentage of engines estimated to require each of the new or improved technologies.

Table 4-18
Engine Costs—Tier 3

	100 kW		400 kW		750 kW		1500 kW		3000kW	
	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost
Electronic controls	25%	\$253	25%	\$345	0%	—	0%	—	0%	—
Common rail	100%	\$296	100%	\$381	0%	—	0%	—	100%	\$19,868
Engine modifications	50%	\$193	50%	\$232	50%	\$9,446	50%	\$8,255	50%	\$13,850
Separate-circuit aftercooling	45%	\$1,070	0%	—	0%	—	0%	—	0%	—
Upgrade to separate-circuit aftercooling	30%	\$280	55%	\$1,396	100%	\$6,285	100%	\$9,552	0%	—
Exhaust gas recirculation	100%	\$3,033	100%	\$3,663	100%	\$8,767	100%	\$7,830	100%	\$9,589
Certification + PLT	100%	\$177	100%	\$193	100%	\$1,009	100%	\$900	100%	\$1,276
Total Engine Costs (yr. 1-5)	—	\$5,303	—	\$6,210	—	\$25,507	—	\$26,537	—	\$44,583
Total Engine Costs (yr. 6 and later)	—	\$1,112	—	\$1,829	—	\$5,601	—	\$10,659	—	\$3,169

*"Fraction" denotes the percentage of engines estimated to require each of the new or improved technologies.

Table 4-19
Rebuild Costs—Tier 3

	100 kW		400 kW		750 kW		1500 kW		3000kW	
	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost
Incremental hardware costs:										
Electronic controls	25%	\$81	25%	\$116	0%	—	0%	—	0%	—
Common rail	100%	\$66	100%	\$96	0%	—	0%	—	100%	\$1,238
Separate-circuit aftercooling	45%	\$172	0%	—	0%	—	0%	—	0%	—
Upgrade to separate-circuit aftercooling	30%	\$69	55%	\$317	100%	\$1,089	100%	\$2,017	0%	—
Eshhaust gas recirculation	100%	\$59	100%	\$82	100%	\$74	100%	\$141	100%	\$269
Hardware cost per engine	—	\$446	—	\$611	—	\$1,162	—	\$2,157	—	\$1,507
Incremental labor costs:	—	\$217	—	\$259	—	\$868	—	\$1,288	—	\$28
Total Cost per Rebuild	—	\$663	—	\$870	—	\$2,030	—	\$3,445	—	\$1,535
Total Engine Cost (npv)	—	\$810	—	\$1,063	—	\$2,480	—	\$4,208	—	\$2,159
Life-cycle oil cost (npv)	—	\$20	—	\$56	—	\$167	—	\$311	—	\$715
Total operating cost (npv)	—	\$829	—	\$1,119	—	\$2,647	—	\$4,519	—	\$2,874

*"Fraction" denotes the percentage of engines estimated to require each of the new or improved technologies.

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J. Sensitivity

There has been some concern expressed that the technologies used to meet emission requirements for land-based engines will be less effective at controlling emissions from marine engines. Some of the reasons suggested for needing a more aggressive approach include the change in duty cycle, the effects of “marinizing” an engine, and the need to comply with emission limits across not-to-exceed zones. Manufacturers could rely on injection timing retard as a technology option for achieving an additional measure of NO_x control. Also, manufacturers may choose, for example, to avoid the high R&D costs of implementing a new technology for an engine family with low sales volume by relying on timing retard as a lower-cost alternative. In addition, manufacturers using EGR may need to add exhaust gases during medium- and high-load operation to the point that there would be an increase in fuel consumption that cannot be offset by improvements such as better control of fuel injection. EPA therefore conducted a sensitivity analysis to show the costs associated with a fuel penalty resulting from relying on retarded timing or EGR.

Because the requirement to control emissions throughout an engine’s operating range poses the greatest challenge at low speeds and loads, EPA calculated the costs of increasing fuel consumption by one percent at modes 2 and 3 and by three percent at mode 4 (lightest load operation). Using the weightings for the composite duty cycle, increased life-cycle fuel consumption from this net 1.0 percent fuel penalty can be calculated and then discounted to the present at a 7 percent rate. The resulting estimated net-present-value cost increase ranges from \$400 for a 100 kW engine to \$19,000 for a 3000 kW engine. Considering the established effectiveness of timing retard as a strategy to control NO_x emissions, this may be considered a viable approach, either as a substitute or a supplemental technology.

IV. Aggregate costs

The above analysis presents unit cost estimates for each power category. These costs represent the total set of costs borne by engine manufacturers to comply with emission standards. With current data for engine and vessel sales for each category and projections for the future, these costs can be translated into projected direct costs to the nation for the new emission standards in any year. Aggregate costs are estimated at about \$19 million in the first year the new standards apply, increasing to a peak of about \$57 million in 2008 as increasing numbers of engines become subject to the new standards. The following years show a drop in aggregate costs as the per-unit cost of compliance decreases, resulting in aggregate costs of about \$14 million in 2015, followed by slowly growing costs due to increasing sales over time.

Chapter 4 References

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CHAPTER 5: ENVIRONMENTAL IMPACTS

Today's proposed regulations for compression-ignition marine engines focus on exhaust emission reductions of HC, NO_x, CO, and PM. The purpose of this chapter is to describe the expected environmental impacts of the proposed emission standards. Specifically, the first part of this chapter will discuss the health and welfare impacts of the pollutants covered by this proposal. The second part of this chapter estimates the total nationwide emissions inventory for marine diesel engines and projects future emissions and emission reductions associated with this proposed rule.

I. Health and Welfare Concerns

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

A. Ozone

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

Most of the recent controlled-exposure ozone studies have shown that respiratory effects similar to those found in the short-term exposure studies occur when human subjects are exposed to ozone concentrations as low as 0.08 ppm while engaging in intermittent, moderate exercise for six to eight hours. These effects occur even though ozone concentrations and levels of exertion are lower than

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in the earlier short-term exposure studies. They appear to build up over time, peaking in the six- to eight-hour time frame. Other effects, such as the presence of biochemical indicators of pulmonary inflammation and increased susceptibility to infection, have also been reported for prolonged exposures and, in some cases, for short-term exposures. Although the biological effects reported in laboratory animal studies can be extrapolated to human health effects only with great uncertainty, a large body of toxicological evidence exists which suggests that repeated exposures to ozone causes pulmonary inflammation similar to that found in humans and over periods of months to years can accelerate aging of the lungs and cause structural damage to the lungs.

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

B. Particulate Matter

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

Key EPA findings can be summarized as follows:

1. Health risks posed by inhaled particles are affected both by the penetration and deposition of particles in the various regions of the respiratory tract, and by the biological responses to these deposited materials.
2. The risks of adverse effects associated with deposition of ambient particles in the thorax (tracheobronchial and alveolar regions of the respiratory tract) are markedly greater than for deposition in the extrathoracic (head) region. Maximum particle penetration to the thoracic regions occurs during oronasal or mouth breathing.
3. The key health effects categories associated with PM include premature death; aggravation of respiratory and cardiovascular disease, as indicated by increased hospital admissions and emergency room visits, school absences, work loss days, and restricted activity days; changes in lung function and increased respiratory symptoms; changes to lung tissues and structure; and

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

4. Based on a qualitative assessment of the epidemiological evidence of effects associated with PM for populations that appear to be at greatest risk with respect to particular health endpoints, the EPA has concluded the following with respect to sensitive populations:
 - a. Individuals with respiratory disease (e.g., chronic obstructive pulmonary disease, acute bronchitis) and cardiovascular disease (e.g., ischemic heart disease) are at greater risk of premature mortality and hospitalization due to exposure to ambient PM.
 - b. Individuals with infectious respiratory disease (e.g., pneumonia) are at greater risk of premature mortality and morbidity (e.g., hospitalization, aggravation of respiratory symptoms) due to exposure to ambient PM. Also, exposure to PM may increase individuals' susceptibility to respiratory infections.
 - c. Elderly individuals are also at greater risk of premature mortality and hospitalization for cardiopulmonary problems due to exposure to ambient PM.
 - d. Children are at greater risk of increased respiratory symptoms and decreased lung function due to exposure to ambient PM.
 - e. Asthmatic individuals are at risk of exacerbation of symptoms associated with asthma, and increased need for medical attention, due to exposure to PM.
5. There are fundamental physical and chemical differences between fine and coarse fraction particles, and it is reasonable to expect that differences may exist between the two subclasses of PM-10 in both the nature of potential effects and the relative concentrations required to produce such effects. The specific components of PM that could be of concern to health include those typically within the fine fraction (e.g., acid aerosols, sulfates, nitrates, transition metals, diesel particles, and ultra fine particles), and those typically within the coarse fraction (e.g., silica and resuspended dust). While components of both fractions can produce health effects, in general, the fine fraction appears to contain more of the reactive substances potentially linked to the kinds of effects observed in the epidemiological studies. The fine fraction also contains the largest number of particles and a much larger aggregate surface area than the coarse fraction which enables the fine fraction to have a substantially greater potential for absorption and deposition in the thoracic region, as well as for dissolution or absorption of pollutant gases.

With respect to welfare or secondary effects, fine particles have been clearly associated with the impairment of visibility over urban areas and large multi-state regions. Fine particles, or major

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constituents thereof, also are implicated in materials damage, soiling and acid deposition. Coarse fraction particles contribute to soiling and materials damage.

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

C. Carbon Monoxide

Though carbon monoxide (CO) is not the primary focus of this rule, EPA is proposing new standards for CO. CO has long been known to have substantial adverse effects on human health and welfare, including toxic effects on blood and tissues, and effects on organ functions, and has been linked to fetal brain damage, increased risk for people with heart disease, and reduced visual perception, cognitive functions and aerobic capacity. Due to recent emission standards, the number of areas in nonattainment for CO has greatly diminished in the past decade. There are approximately 20 remaining serious or moderate CO nonattainment areas.

D. Smoke

Smoke from diesel engines has long been associated with adverse effects on human welfare, including considerable economic, visibility and aesthetic damage. The carbon particles that make up diesel smoke cause reduced visibility; soiling of urban buildings, homes, personal property, clothes, and skin; and are associated with increased odor, coughing, and eye irritation. In addition, the particles causing visible smoke are the same as those associated with the significant threats to human health described above for particulate matter.

II. Emission Reductions

For the purposes of this proposed regulation, EPA has divided marine diesel engines into three categories. Category 1 engines are smaller engines used in recreational and light commercial applications, Category 2 engines are medium sized engines such as those used in tugboats, and Category 3 engines are the large engines used primarily for propulsion in ocean-going vessels. Because of the distinctly different characteristics between the design and operation of the marine diesel engines in these three categories, the proposed regulations focus on each category separately. Also due to distinctions between the categories, different data sources and approaches were required to develop an inventory for the three categories. The remainder of this chapter will describe the inventory calculations for the categories separately then combine them to discuss the nationwide benefits.

A. Category 1

1. General Methodology

In the inventory calculations, Category 1 compression-ignition marine engines were divided into recreational, commercial, and auxiliary applications. The applications were further divided into power ranges which are consistent with the proposed standards. Each of the engine applications and power ranges were modeled with distinct annual hours of operation, load factors, and average engine lives. The basic equation for determining the emissions inventory, for a single year, from marine engines is shown below:

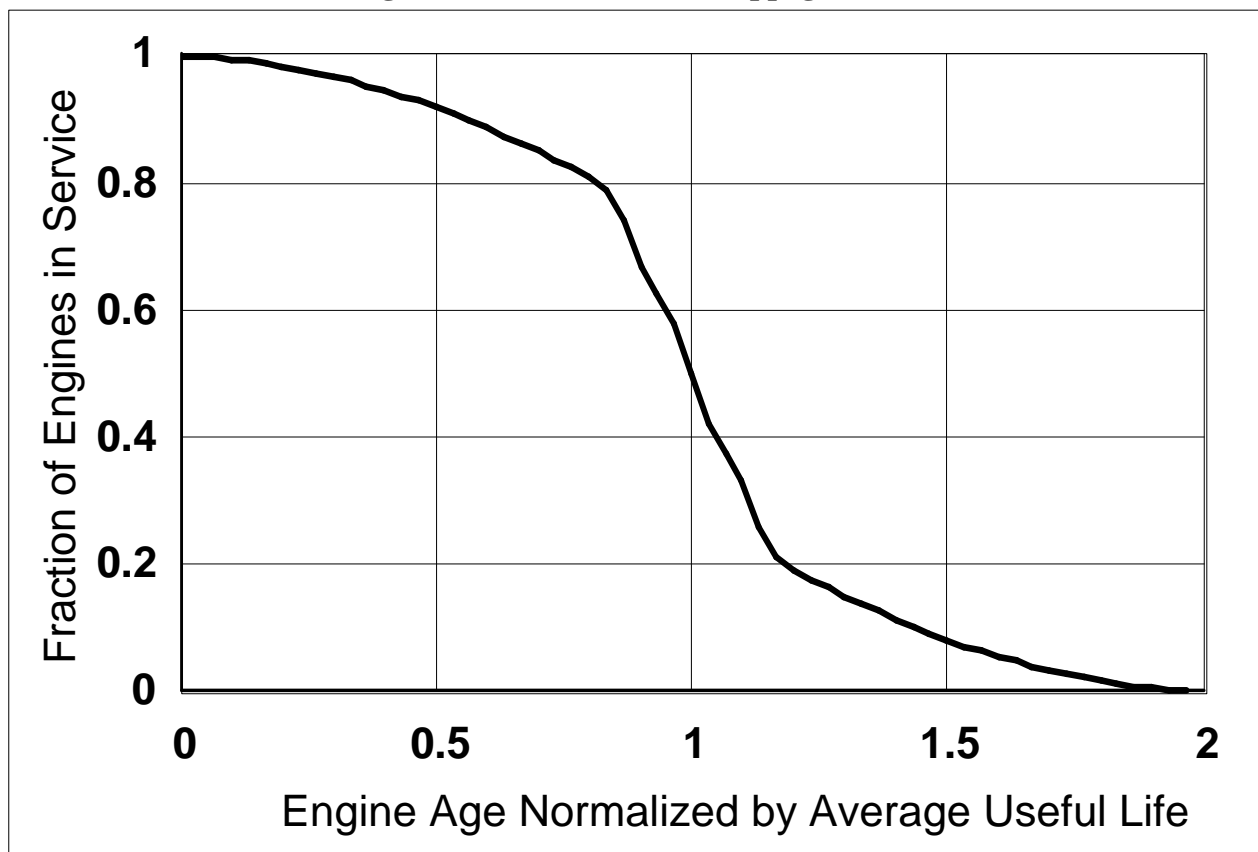
$$Emissions = \sum_{rec, com, aux} \left[\sum_{ranges} (population \times power \times load \times annual\ use \times emission\ factor) \right]$$

This equation sums the total emissions for each of the power ranges and applications. “Population” refers to the number of marine diesel engines greater than or equal to 37 kW but with a displacement per cylinder of five liters or less estimated to be in the U.S. in a given year. “Power” refers to the population-weighted average rated power for a given power range. Two usage factors are included; “load” is the ratio between the average operational power output and the rated power, and “annual use” is the average hours of operation per year. Emission factors are applied on a brake-specific basis (g/kW-hr) and represent the weighted value between levels from baseline and controlled marine engines operating in a given calendar year. Emission inventories from Category 1 engines were calculated for HC, NO_x, CO, and PM. Although the proposed standards combine HC and NO_x, it is useful to consider the HC and NO_x emission impacts separately. The split between HC and NO_x for regulated engines is based on the data from Chapter 3 for technologies that are expected to be used to meet the proposed standards.

2. Inputs to the Inventory Calculations

Data on the various inputs were obtained from several sources. Engine populations were taken from the 1997 Power Systems Research (PSR) Parts Link database. This database contains marine engine populations and technical information by engine model for 1990 through 1997. From this data, EPA was able to focus on specific applications and power ranges. To determine turnover rates for the purpose of determining the introduction of controlled engines, scrappage rates are needed. Through the combination of historical population and scrappage rates, historical sales and retirement of engines can be estimated. EPA used the normalized scrappage rate developed by PSR and fit it to the data using assumed average useful lives for each of the three applications. Figure 5-1 presents the normalized scrappage curve. The average useful lives for each of the three applications were based on conversations with manufacturers and are estimated to be 15, 13, and 17 years respectively for recreational, commercial, and auxiliary marine diesel engines.

Figure 5-1: Normalized Scrappage Curve



To project future populations, EPA applied growth rates to each of the three application types. Based on the eight years of population data (1990-1997) supplied by the PSR Parts Link database, growth rates of 6.3 percent for recreational, 0.6 percent for commercial, and 7.5 percent for auxiliary were observed. EPA was concerned that eight years of data were not enough to determine a historical growth trend, especially since the growth rates for these years were so high for recreational and auxiliary marine engines. To estimate growth over a larger number of years, EPA relied on PSR’s OE Link database which provides detailed information on the U.S. production of marine diesel engines from 1980 to 1997. Based on the PSR production data, EPA calculated growth rates of 3.5 percent for recreational, 0.9 percent for commercial, and 1.5 percent for auxiliary marine diesel engines. In its final calculations, EPA used the growth rates based on U.S. production. Although the growth rate for recreational marine diesel engines is significantly larger than for commercial and auxiliary, EPA believes that it is reasonable due to recently expanded efforts of marine diesel engine manufacturers to break into this potentially high profit market.

Estimated engine populations are presented in Table 5-1. These figures show that recreational marine engines are the largest segment of the U.S. Category 1 marine diesel engine population. As will be shown below, however, their inventory contribution is much less than that of the smaller commercial population due to different usage rates.

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Table 5-1
Projected Category 1 Populations by Year [thousands]

	1995	2000	2005	2010	2020	2030
recreational	142	180	214	254	358	505
commercial	57	58	61	64	70	76
auxiliary	10	13	14	15	17	20

The remaining factors needed to estimate the category 1 emissions inventory are engine usage and emission rates. Recreational and commercial marine diesel engine usage characteristics are based on a compilation of data supplied to the EPA by the Engine Manufacturers Association (EMA). This data is based on five years of propulsion marine diesel engine sales from seven engine manufacturers who make up the strong majority of the U.S. market.^d Included in the data submission were average annual hours of use, load factors, and emission factors broken down by ranges of rated power and rated speed. Because the submission did not include auxiliary marine engines, conversations with individual manufacturers were used to develop usage inputs for these engines. Baseline emission factors were developed using the both the EMA submission and the data for uncontrolled marine diesel engines presented in Chapter 3. The usage inputs and baseline emission factors, used in the inventory calculations, are presented in Tables 5-2 and 5-3.

Table 5-2
Usage Inputs for Category 1 Inventory Calculations

Power Range [kW]	Load Factor [percent]			Annual Use [hours]		
	recreational	commercial	auxiliary	recreational	commercial	auxiliary
37-75	25	60	65	125	2320	2500
75-130	25	60	65	175	2350	2500
130-225	25	60	65	175	2270	2500
225-450	30	71	65	225	3240	2500
450-560	40	73	65	500	3770	2500
560+	40	79	65	500	4500	2500

^d Although difficult to compare directly, these sales figures seemed to agree with the PSR data fairly well.

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Table 5-3
Baseline Emission Factors for Category 1 Marine Engines

Power Range [kW]	HC [g/kW-hr]	NOx [g/kW-hr]	CO [g/kW-hr]	PM [g/kW-hr]
37-75	0.27	11	2.0	0.90
75-130	0.27	10	1.7	0.40
130-225	0.27	10	1.5	0.40
225-450	0.27	10	1.5	0.30
450-560	0.27	10	1.5	0.30
560-1000	0.27	10	1.5	0.30
1000+	0.27	13	2.5	0.30

The proposed emission standards, presented in Chapter 1, were used as the emission factors for the controlled engines. Not enough information is available at this time to account for deterioration or manufacturer compliance margins. EPA believes that these factors will not have a large effect on the final calculations. At worst, this methodology results in conservative benefit estimates since the standards represent levels at the useful lives of the engines. In the proposed program, HC and NOx are combined in a single numerical emission limit. To separate them for inventory analysis, EPA estimates that the proposed emissions limits will result in a 0.07 g/kW-hr reduction in HC. This estimate is based on the emission data from the low-emission engines presented in Chapter 3.

3. Inventory Results

Table 5-4 presents the estimated baseline emissions for recreational, commercial, and auxiliary marine engines. Although no standards have been proposed for recreational marine engines at this time, they are included in this analysis for completeness.

Table 5-4
Projected Category 1 Baseline Emissions by Year [thousand short tons]

		1995	2000	2005	2010	2020	2030
HC	recreational	0.6	0.8	0.9	1.1	1.6	2.2
	commercial	9.9	10.3	10.8	11.3	12.4	13.5
	auxiliary	0.7	1.0	1.1	1.2	1.4	1.6
	total	11.3	12.1	12.8	13.6	15.3	17.3
NOx	recreational	21.9	29.7	35.3	42.0	59.2	83.5
	commercial	382	398	416	435	476	520
	auxiliary	28.3	38.0	40.9	44.1	51.1	59.3
	total	432	465	492	521	586	663
PM	recreational	0.7	1.0	1.1	1.4	1.9	2.7
	commercial	12.0	12.5	13.1	13.7	14.9	16.3
	auxiliary	1.1	1.5	1.6	1.7	2.0	2.3
	total	13.9	14.9	15.8	16.8	18.9	21.4
CO	recreational	3.4	4.7	5.5	6.6	9.3	13.1
	commercial	60.2	62.8	65.6	68.6	75.1	82.1
	auxiliary	4.5	6.0	6.4	6.9	8.0	9.3
	total	68.0	73.4	77.6	82.1	92.4	105

This analysis suggests that commercial marine engines make up the majority of the Category 1 emissions (i.e. 85 percent of HC+NOx in 2000) even though they made up only 23 percent of the population of Category 1 engines in 2000. This is mostly due to the high annual use and load factors of these engines. By comparison, recreational engines represent 72 percent of the population in 2000, but account for only 6 percent of baseline Category 1 HC+NOx emissions. However, due to their higher projected growth rate, recreational engines become a growing source of marine diesel emissions in future years (10 percent of the baseline in 2020).

4. Emissions Benefits

Tables 5-5 and 5-6 show the expected impact of the proposed standards on HC, NOx, and PM emissions from commercial and auxiliary Category 1 marine diesel engines. For the applicable Category 1 engines, the proposed Tier 2 standards represent average reductions of 27 percent HC, 29 percent NOx, and 38 percent PM on a per engine basis. The proposed Tier 3 standards gain

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additional NOx benefits which represent a total reduction of 62 percent NOx from applicable new engines compared to baseline. These reductions vary for different power categories with the highest power categories showing the greatest reductions. This is reasonable since these engines are used more intensely than the others. It should be noted that for the cost-effectiveness calculations in Chapter 6, only the NOx reductions beyond the IMO standard are considered. For Category 1, the IMO standard represents a 3.5 percent reduction in NOx from new engines compared to baseline. The CO standard is intended to be a cap on the already low emissions from diesel engines; therefore, no emissions reductions are claimed here for CO.

Table 5-5
Projected Controlled Category 1
Commercial Marine Engine Emissions [thousand short tons per year]

Modeled Item		1995	2000	2005	2010	2020	2030
HC	controlled level	9.9	10.3	10.5	10.0	9.4	10.0
	benefit	0.0	0.0	0.3	1.3	3.0	3.5
	reduction	0%	0%	3%	12%	24%	26%
NOx	controlled level	382	396	396	341	217	203
	benefit	0.0	1.2	20.4	93.7	258	316
	reduction	0%	0%	5%	22%	54%	61%
PM	controlled level	12.0	12.5	12.5	11.3	9.8	10.3
	benefit	0.0	0.0	0.6	2.3	5.2	6.0
	reduction	0%	0%	4%	17%	35%	37%

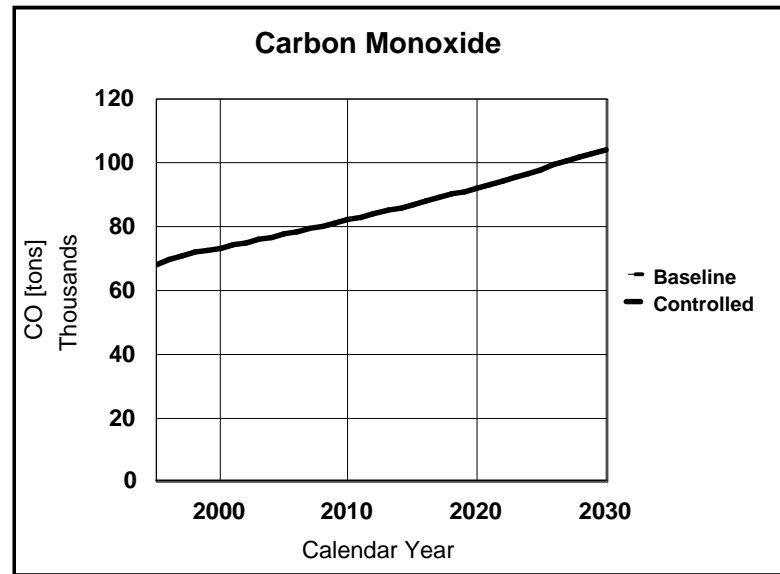
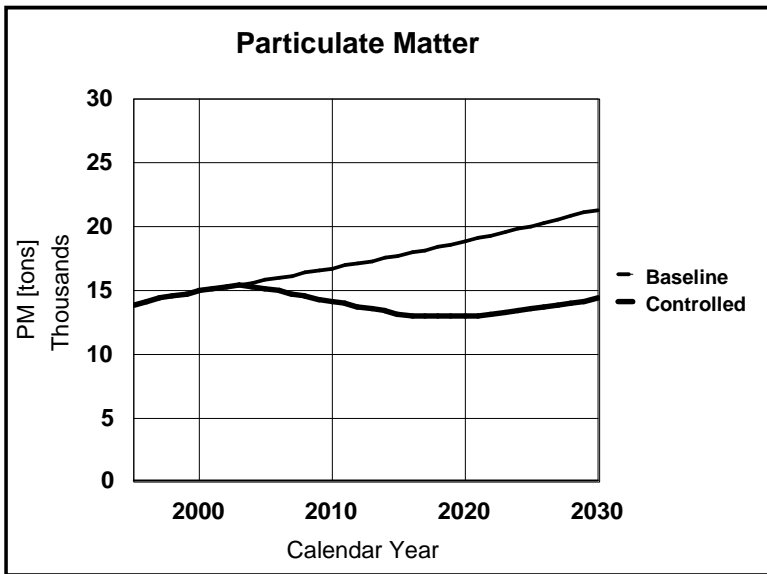
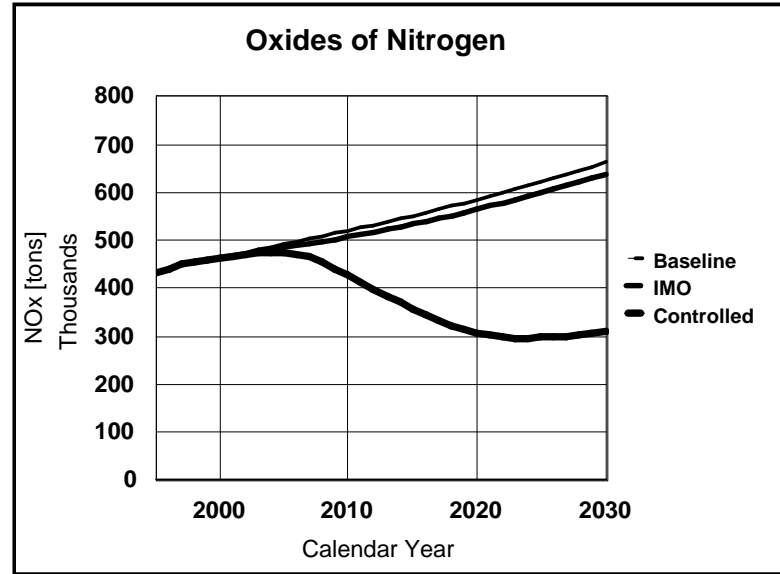
Table 5-6
 Projected Controlled Category 1
 Auxiliary Marine Engine Emissions [thousand short tons per year]

Modeled Item		1995	2000	2005	2010	2020	2030
HC	controlled level	0.7	1.0	1.1	1.1	1.1	1.2
	benefit	0.0	0.0	0.0	0.1	0.3	0.4
	reduction	0%	0%	3%	10%	22%	25%
NOx	controlled level	28.3	37.9	39.3	36.4	26.7	23.5
	benefit	0.0	0.1	1.6	7.6	24.4	35.8
	reduction	0%	0%	4%	17%	48%	60%
PM	controlled level	1.1	1.5	1.5	1.5	1.3	1.4
	benefit	0.0	0.0	0.1	0.3	0.7	1.0
	reduction	0%	0%	5%	16%	36%	41%

As described in the notice of proposed rulemaking, EPA intends to require that manufacturers comply with emission limits at any speed and load that can occur on a vessel. These “not-to-exceed” provisions are needed to keep pace with the increasing sophistication of diesel engine technology. These provisions are intended to ensure that engines are in fact operating within allowable emission levels, rather than requiring emission reductions beyond that called for by the emission limits. This analysis of emission benefits thus does not take into account any additional benefit associated with not-to-exceed provisions.

Figure 5-2 presents EPA projections for Category 1 HC, NOx, PM, and CO emissions as a whole. The graphs included in this figure show baseline emissions as well as the expected control under the proposed standards. The NOx projection distinguishes the slight benefits associated with the IMO NOx standard from the benefits associated with this proposal. In 2010, the proposed standards are expected to result in reductions of 11 percent HC, 20 percent NOx, and 16 percent PM from Category 1 marine diesel engines. Once the effects of the proposed standards are fully phased in (i.e. in 2035 the proposed emission levels would result in reductions of 23 percent HC, 58 percent NOx, and 33 percent PM from Category 1 marine diesel engines. These figures are lower than the per engine reductions because they do not include any potential future emissions reductions from recreational marine diesel engines.

Figure 5-2: Projected Baseline and Controlled Emissions Levels from Category 1 Marine Diesel Engines



B. Category 2

1. Baseline Emission Inventories

Baseline emissions inventories for Category 2 marine diesel engines are based on an analysis developed by Corbett and Fischbeck.¹ In that analysis, two separate methods were used to develop inventories for U.S. flagged vessels and foreign vessels used in U.S. domestic waters. In addition, the study investigated marine engine types and replacement rates. Below is an overview of the analysis; more detail may be found in the report.

Emissions inventories for U.S. flagged vessels were estimated using ship registry data on commercial vessels greater than 100 gross registered tons. The general methodology is based on estimates of daily fuel consumption. Specifically, engine rated power, operation, fuel consumption and fuel specific emissions factors, developed by Lloyd’s Register, were used to generate annual mass of emissions from a given vessel. These emission numbers were multiplied by the number of U.S. flagged vessels for discrete applications to generate a baseline emission inventory for domestic ships.

Estimated emissions inventories for foreign ships operating in U.S. navigable waters were based on cargo movements and waterways data. Using cargo movements and geographical data, the ton-miles of cargo moved in each region were calculated for the Great Lakes, inland waterways, and coastal waters up to 200 miles offshore. Emissions per ton mile were based on the usage and emission factors used for U.S. vessels described above, average dead weight tonnage per ship, assumed cargo capacity factors, and average vessel speed for the duty cycle. The results from this analysis are presented in Table 5-7.

Table 5-7
Baseline Emissions from Category 2 CI Marine
Engines Operated in U.S. Waters [thousand short tons per year]

Year	HC	NOx	PM	CO
2000	11.1	267	6.1	34.1
2010	12.3	295	6.8	37.7
2020	13.6	325	7.5	41.7
2030	15.0	360	8.3	46.0
2040	16.5	397	9.1	50.8

2. Emission Benefits

To calculate the emissions benefits of the proposed standards, the replacement rates of old engines with new engines must be known. For this analysis, the average useful life of 23 years

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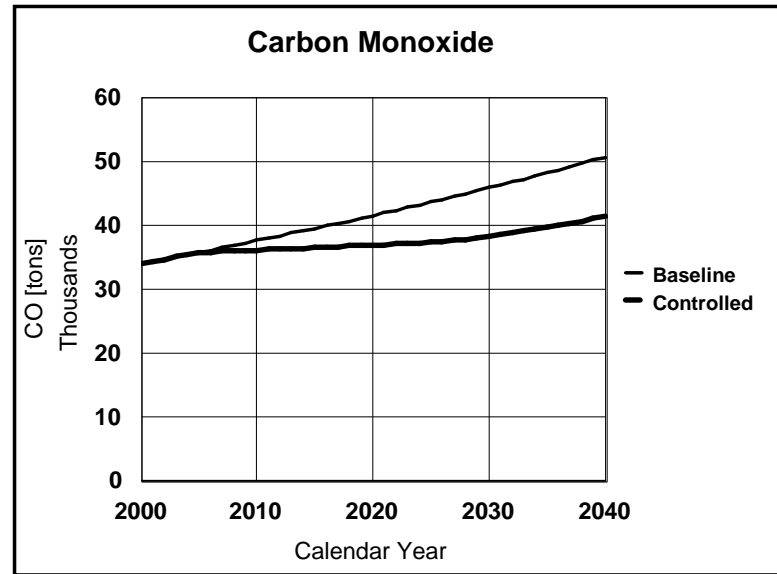
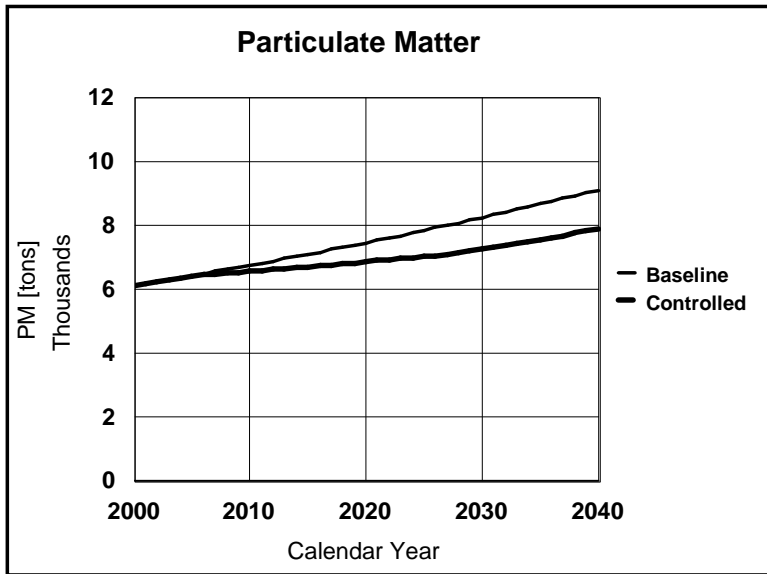
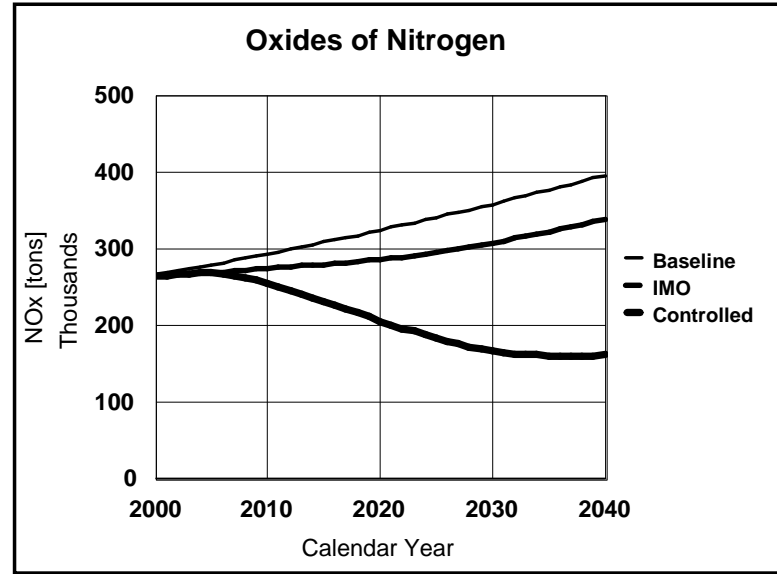
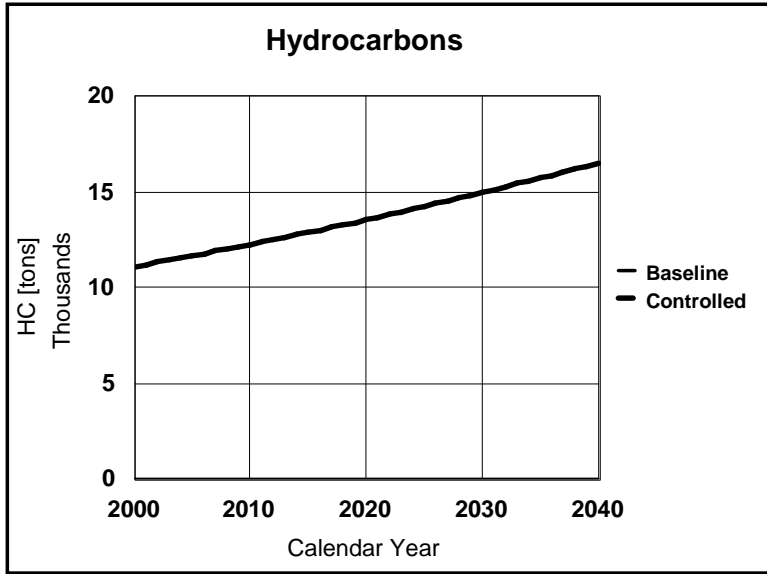
reported in the report by Corbett and Fischbeck was used. This report also discusses a growth rate of 2 percent based on production and turnover in recent years. However, EPA was concerned that a few years of data was not enough to establish a growth trend for this industry. Therefore, EPA conservatively is using a growth rate of 1 percent which is more consistent with the Category 1 growth rates used in this analysis. By combining the 23 year average useful life with the normalized scrappage curve presented in Figure 5-1 and the estimated growth rate, EPA developed the replacement schedule used for the inventory analysis. Because of the high average age of the U.S. fleet, EPA believes that it is likely that their will be higher turnover than usual in the near future. This would result in greater benefits sooner. However, EPA has not made any attempts to include this dynamic in its inventory analysis.

Emissions reductions were based on the baseline brake-specific emission levels presented in Chapter 3 and the proposed standards presented in Chapter 1. Since EPA is only claiming NO_x reductions from the proposed standards beyond those resulting from the IMO standards, the IMO reduction was calculated. The IMO standard will result in an average reduction of 15 percent from new engines compared to baseline engines. On a per engine basis, the proposed Tier 2 standards represent reductions of 47 percent NO_x, 16 percent PM, and 19 percent CO compared to baseline Category 2 emissions levels. The proposed Tier 3 standards result in a total reduction in NO_x of 64 percent compared to baseline. In the benefits modeling described here, these reductions are only applied to engines in U.S. flagged vessels operated in U.S. waters. No HC benefits are claimed for Category 2 engines due to their already low HC emissions. Because of the slow turnover rates, the full effects of these reductions would not be seen until after 2045. Projected benefits of the IMO requirements and the proposed standards for Category 2 engines are shown in Table 5-8. No NO_x reductions are assumed for foreign flagged ships since it is unknown at this time which countries will adopt the IMO requirements. Foreign flagged ships make up about 4 percent of the Category 2 NO_x inventory in U.S. waters.

Table 5-8
Projected Emission Reductions from Category 2
CI Marine Engines Operated in U.S. Waters [thousand short tons]

Year	IMO NO _x	EPA NO _x	PM	CO
2000	1.6	0.0	0.0	0.0
2010	19.2	20.2	0.2	1.4
2020	38.3	81.3	0.6	4.6
2030	50.5	142	1.0	9.3
2040	58.1	177	1.2	10.5

Figure 5-3: Projected Baseline and Controlled Levels for Category 2 Marine Diesel Engines



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As described for Category 1 engines above, this calculation of emission benefits for Category 2 engines does not take into account any additional benefits for not-to-exceed provisions.

Figure 5-3 presents EPA projections for Category 2 HC, NO_x, PM, and CO emissions. The graphs included in this figure show baseline emissions as well as the expected control under the proposed standards. The NO_x projection shows the fraction of the total benefits which can be attributed to the IMO NO_x standard. Because engines on foreign flag vessels are not included in the proposed regulations, the percent reductions from engines on vessels operating in U.S. waters is not as high as the percent reductions for new engines. The HC standard is intended to be a cap on the already low emissions from Category 2 diesel engines; therefore, no emissions reductions are claimed here for HC.

C. Category 3

1. Baseline Emissions

Baseline emissions were calculated for Category 3 using the same methodology that was used for Category 2. The difference between Category 2 and 3 is that foreign vessels only make a small fraction of the national NO_x for Category 2, while they make up about half of the national NO_x for Category 3. This difference is easily explained by the fact that most Category 3 engines are used on ocean-going vessels, and while U.S. is a large foreign trade country, most of the ocean-going vessels that visit U.S. ports are foreign flag. Baseline emission results from the Category 3 inventory calculations are presented in Table 5-9.

Table 5-9
Baseline Emissions from Category 3 CI Marine
Engines Operated in U.S. Waters [thousand short tons per year]

Year	HC	NO _x	PM	CO
2000	8.1	273	21.2	25.0
2010	9.0	301	23.4	27.6
2020	9.9	333	25.8	30.5
2030	10.9	368	28.6	33.7
2040	12.1	406	31.5	37.2

2. Emission Benefits

This section calculates the emissions benefits for Category 3 engines associated with adopting the IMO requirements for Category 3 engines on U.S. flagged ships. Emissions benefits were calculated using the same useful life and growth rate used for in the Category 2 analysis based on

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the limited data available to EPA. NO_x reductions were determined by comparing the data in Chapter 3 to the proposed emission limits presented in Chapter 1. As discussed in Chapter 3, it was assumed that engines that certify on diesel oil but operate on residual fuel would have 10 percent higher NO_x emissions in use.

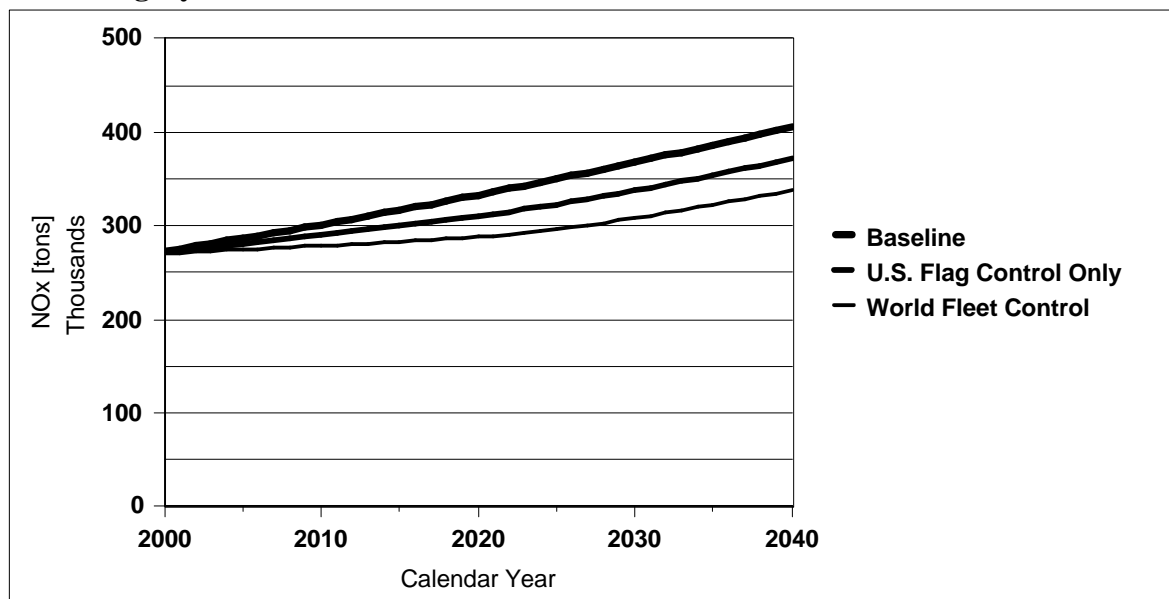
EPA estimates that adopting the IMO requirements will result in a 17 percent reduction in NO_x from applicable new Category 3 engines. If this standard were only met on U.S. flagged ships, only about a 9 percent reduction in NO_x is anticipated once all U.S. flag ships meet the IMO NO_x standard. However, foreign flag ships may reduce NO_x as other nations adopt the IMO provisions. The U.S. flag reductions and the potential effects (in U.S. waters) of world wide application of the IMO NO_x standard are both presented in Table 5-10 and Figure 5-4.

Table 5-10
Projected NO_x Reductions from Category 3
CI Marine Engines Operated in U.S. Waters [thousand short tons]

	U.S. Flag	Foreign Flag*	Total*
2000	1.0	0.9	1.9
2010	11.4	11.2	22.5
2020	22.7	22.3	45.0
2030	29.8	29.4	59.2
2040	34.3	33.8	68.1

* The U.S. could only ensure that the reductions from U.S. flagged ships are achieved.

Figure 5-4: Projected Baseline and Controlled National NO_x Emissions from Category 3



D. Nationwide Totals

For the purposes of this analysis, the CI marine inventory has been divided into five sections: Category 1 recreational, commercial, and auxiliary; Category 2; and Category 3. Of these five categories, Category 1 commercial, Category 2, and Category 3 engines dominate the baseline inventory from CI marine engines. Figure 5-5 makes this point by showing the baseline relative NO_x contributions of each of these classes for 2020. Distributions for HC, PM, and CO are similar.

The reductions that can be associated with EPA's proposed standards come from Category 1 and Category 2. However, the benefits of adopting IMO standards for engines used on U.S. vessels are included in Figure 5-6 which presents the projected 2020 NO_x inventory with the implementation of the proposed standards. Because of the relatively less stringent standards for Category 3 engines, they become a bigger fraction (from 27 percent to 38 percent) of the emissions inventory in 2020.

Figure 5-5: 2020 Baseline CI Marine NOx Inventory Distribution

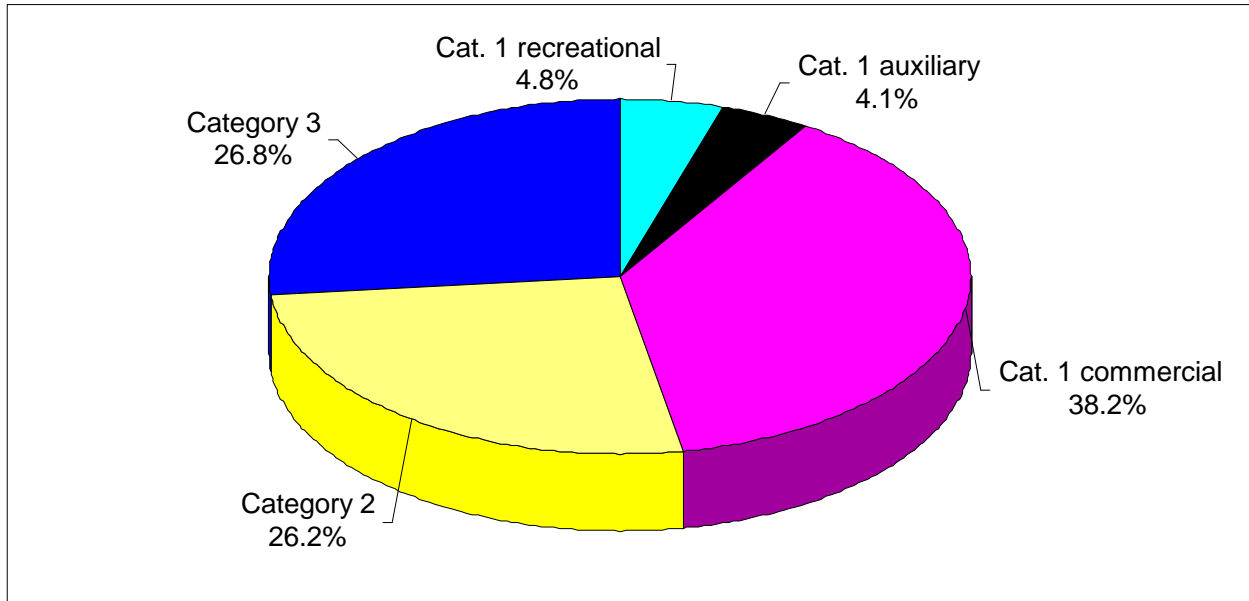
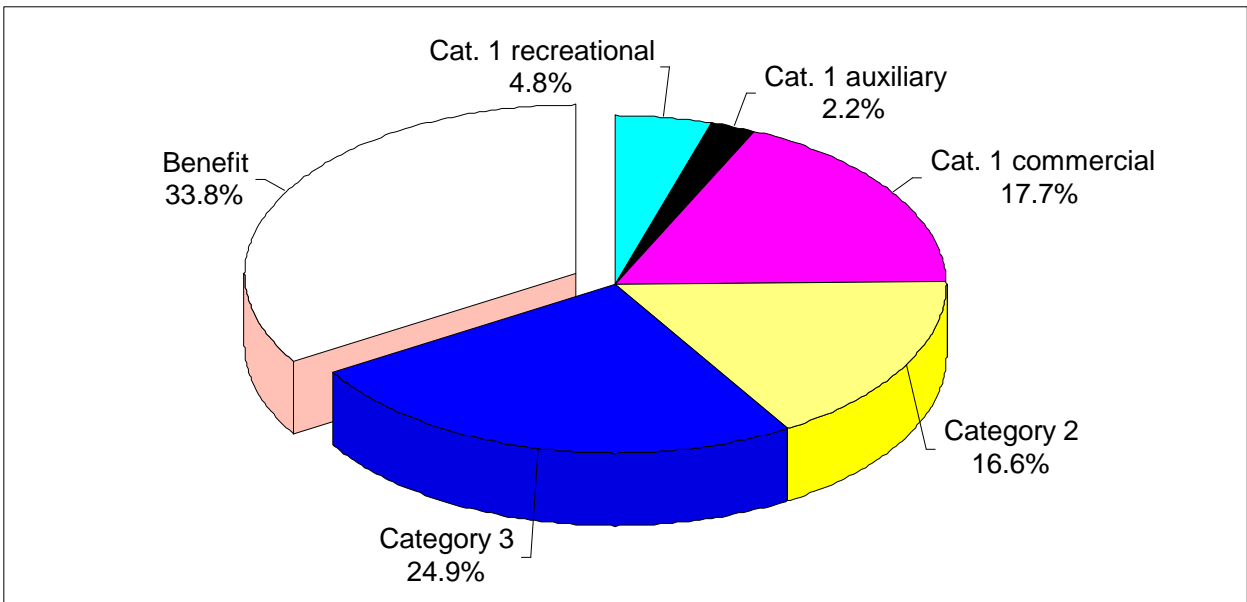


Figure 5-6: 2020 Controlled CI Marine NOx Inventory Distribution



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EPA used nationwide emission estimates from the 1997 Trends Report² to compare the relative emissions contribution from CI marine engines to other emission sources. Because Trends does not report estimates for 1998, figures for 2000 are used here as the baseline. The national HC, NO_x, PM, and CO emissions inventories are summarized in Table 5-11 along with the EPA estimates for CI marine engines. These data, presented in Table 5-10, indicate that emissions from baseline CI marine engines account for 8.1 percent of NO_x and 4.8 percent of PM from mobile sources and 4.4 percent of NO_x and 1.0 percent of PM nationwide. CI marine engines account for less than one percent of volatile organic sources (VOC) or CO for mobile sources.

Table 5-11
2000 National Emissions [thousand short tons]

Emission Source	VOC	NO _x	PM	CO
CI Marine	31	1,005	42	133
Other Nonroad	2,044	4,930	593	16,286
On-Highway	4,482	6,397	238	44,244
Total Mobile Sources	6,526	12,332	873	60,663
Other Sources	9,567	10,550	3,270*	19,199
Total Nationwide Emissions	16,093	22,882	4,143	79,862

*does not include erosion or fugitive dust.

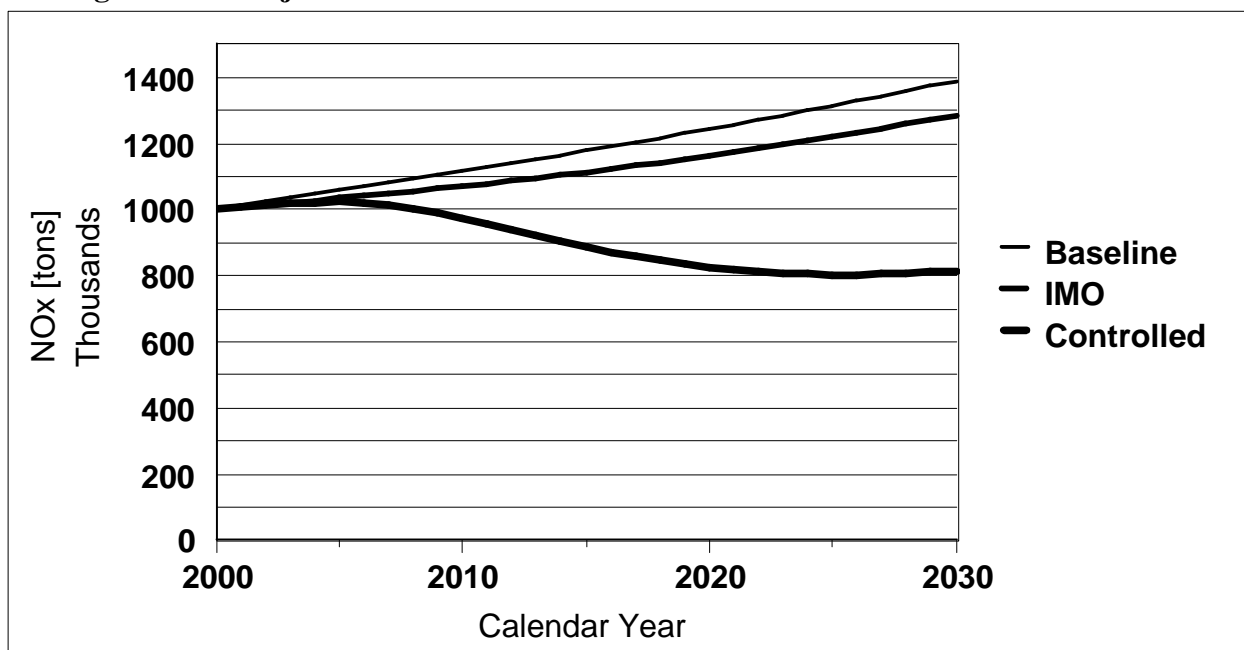
Table 5-12 contains the baseline annual emissions from marine diesel engines as a whole as well as projections of the annual emissions with the IMO requirements and proposed standards in place. Figure 5-7 presents the NO_x reductions graphically. According to this analysis, the proposed standards would result in reductions, beyond the IMO ratification, of 9 percent HC, 28 percent NO_x, 12 percent PM, and 3 percent CO from marine diesel engines in 2020.

Nationally, the proposed standards would result in reductions of 1.3 percent NO_x and 0.1 percent PM. The percent reduction would be much higher for port areas. This is especially true for Los Angeles-South Coast, Baton Rouge, Beaumont-Port Arthur, and similar ports where marine diesel engines account for a large fraction of the NO_x emissions.

Table 5-12
Total Emissions Reductions from the Proposed Rule

		2000	2010	2020	2030
HC 10 ³ short tons	baseline	31.3	34.8	38.7	43.2
	controlled	31.3	33.3	35.4	39.3
	reduction	0%	4%	9%	9%
NOx 10 ³ short tons	baseline	1,005	1,117	1,244	1,390
	IMO	1,001	1,072	1,162	1,287
	controlled	1,001	965	819	815
	reduction	0%	10%	28%	34%
PM 10 ³ short tons	baseline	423.	46.9	52.2	58.2
	controlled	42.3	44.1	45.7	50.2
	reduction	0%	6%	12%	14%
CO 10 ³ short tons	baseline	133	147	165	184
	controlled	133	146	160	177
	reduction	0%	1%	3%	4%

Figure 5-7: Projected National CI Marine Baseline and Controlled NOx Emissions



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E. Other Impacts of NOx Emission Reductions

The NOx reductions described above are expected to provide reductions in the concentrations of secondary nitrate particulates. NOx can react with ammonia in the atmosphere to form ammonium nitrate particulates, especially when ambient sulfur levels are relatively low. EPA believes that the best estimate of atmospheric NOx to PM conversion rates available at this time is provided by SAI.³ SAI used a combination of ambient concentration data and computer modeling that simulates atmospheric conditions to estimate the conversion of NOx to PM nitrate. Ambient data was collected from 72 ozone, 64 NOx, and 14 NOMC monitoring sites for use in oxidation calculations. Data was also collected from 45 nitrate/NOx monitoring sites for use in the equilibrium calculations. For the purpose of modeling, the 48 continental states were divided into nine regions, and rural areas were distinguished from urban areas. The model was designed to perform the equilibrium calculation to estimate particulate nitrate formation for different regions, seasons, and times of day and then was calibrated using ambient data.

The results from the SAI report state that the fraction of NOx converted to nitrates (g/g) ranges from 0.01 in the northeast to 0.07 in southern California. Using a simple average, the average fraction of NOx converted to nitrates is approximately 0.04. The effects of the conversion fraction of future PM reductions are shown in Table 5-13.

Table 5-13
Equivalent PM Emissions for
CI Marine Engines [thousand short tons per year]

Year	Total NOx Reductions	Equivalent PM Reductions
2005	38	1.5
2010	152	6.1
2015	298	11.9
2020	425	17.0

The expected reductions in NOx emissions should also positively affect visibility, acid deposition, and estuary eutrophication. Both NO₂ and nitrate particulates are optically active, and in some urban areas, NO₂ and nitrate particulates can be responsible for 20 to 40 percent of the visible light extinction. The effect of this proposed action on visibility should be small but potentially significant, given that it is expected to reduce national NOx emissions by about 1.5 percent in 2020. This would result in a 0.3 to 0.6 percent reduction in haze. For areas with active ports, this reduction would be significantly higher.

The NOx control described above is also expected to provide benefits with respect to acid deposition. The annual NOx reduction expected in 2020 from the proposed standards for marine diesel engines is comparable to the 400,000 ton per year reduction expected from Phase I of the

Agency’s acid rain NOx control rule (59 FR 13538, March 22, 1994), which was considered to be a significant step toward controlling the ecological damage caused by acid deposition. It is not clear how reductions from marine engines will compare to reductions from stationary sources with elevated stacks; however, some reduction in the adverse effects of acid depositions should occur as a result of this proposed rule.

This proposed action should also lead to a reduction in the nitrogen loading of estuaries. This is significant since high nitrogen loadings can lead to eutrophication of the estuary, which causes disruption in the ecological balance. The effect should be most significant in areas heavily affected by atmospheric NOx emissions. One such estuary is Chesapeake Bay, where as much as 40 percent of the nitrogen loading may be caused by atmospheric deposition. Also, marine engine emissions by definition occur in the marine environment; therefore, reductions in exhaust emissions from marine engines are expected to benefit the marine environment.

F. Air Toxics

The term “hydrocarbons” includes many different molecules. Speciation of the hydrocarbons would show that many of the molecules are those which are considered to be air toxics including benzene, formaldehyde, acetaldehyde, and 1,3-butadiene. Because EPA does not have speciated data on diesel marine engine hydrocarbon emissions, the reductions in air toxics can only be estimated here. This analysis was done using data on on-highway heavy-duty diesel engines.^{4,5,6,7} According to this data, hydrocarbons from an on-highway HDDE include approximately 1.1 percent benzene, 7.8 percent formaldehyde, 2.9 percent acetaldehyde, and 0.6 percent 1,3-butadiene. Table 5-14 shows the estimated air toxics reductions associated with the hydrocarbon reductions in this rule when the on-highway HDDE results are extended to this source.

Table 5-14
Estimated Annual Air Toxics Reductions [short tons]

Year	Benzene	Formaldehyde	Acetaldehyde	1,3-Butadiene
2005	4	26	10	2
2010	15	114	42	9
2015	35	258	95	20
2020	41	305	112	24

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1. Corbett, J., Fischbeck, P., “Commercial Marine Emissions Inventory and Analysis for United States Continental and Inland Waterways,” Order No. 8A-0516-NATX, August 21, 1998.
2. “National Air Pollutant Emission Trends, 1900-1996,” U.S. EPA, EPA-454/R-97-011, December 1997.
3. “Benefits of Mobile Source NO_x Related Particulate Matter Reductions,” Systems Applications International, EPA Contract No. 68-C5-0010, WAN 1-8, October 1996.
4. Springer, K., “Investigation of Diesel-Powered Vehicle Emissions VII,” U.S. EPA, EPA-460/3-76-034, 1977.
5. Springer, K., “Characterization of Sulfates, Odor, Smoke, POM and Particulates from Light and Heavy-Duty Engines – Part IX,” U.S. EPA, EPA-460/3-79-007, 1979.
6. Bass, E., and Newkirk, M., “Reactivity Comparison of Exhaust Emissions from Heavy-Duty Engines Operating on Gasoline, Diesel, and Alternative Fuels,” Southwest Research Institute, SwRI 9856, 1995.
7. College of Engineering - Center for Environmental Research and Technology, “Evaluation of Factors that Affect Diesel Exhaust Toxicity,” submitted to California Air Resources Board, Contract No. 94-312, 1998.

CHAPTER 6: COST-EFFECTIVENESS

This chapter assesses the cost-effectiveness of the proposed hydrocarbon and oxides of nitrogen emission standards for marine diesel engines. This analysis relies in part on cost information from Chapter 4 and emissions information from Chapter 5 to estimate the cost-effectiveness of the proposed standards in terms of dollars per short ton of total HC+NO_x emission reductions. This chapter also examines the cost-effectiveness of the proposed PM standards. Finally, the chapter compares the cost-effectiveness of the proposed provisions with the cost-effectiveness of other NO_x and PM control strategies from previous EPA rules.

The analysis presented in this chapter is performed for marine diesel engines and vessels using the same nominal power ratings as presented in Chapter 4. An estimate of the industry-wide cost-effectiveness of the proposed standards, combining all of the nominal engine sizes, is also presented.

Benefits associated with the IMO provisions are not included in this analysis. Marine diesel engines greater than or equal to 130 kW will be subject to an international NO_x standard prior to the implementation of the standards proposed under this rule. Therefore, the baseline emissions case assumes emission control to the IMO standard for engines installed on vessels in 2000 and later. Because the proposed EPA standards only apply to Category 1 and 2, no cost-effectiveness analysis is provided for Category 3.

Two types of cost-benefit analyses are performed in this chapter. The first analysis focuses on individual engines and examines total costs and total emission reductions over the typical lifetime of an average marine diesel engine discounted to the beginning of the engine's life. This analysis is provided for the proposed Tier 2 and for the incremental costs and benefits associated with the proposed Tier 3 standards. The second method looks at the net present value (NPV) of a stream of costs and benefits over a standardized period of time (30 years). Over this period, the calculation includes the proposed program as a whole.

As described in Chapter 4, several of the anticipated engine technologies will result in improvements in engine performance that go beyond emission control. While the cost estimates described in Chapter 4 do not take into account the observed value of performance improvements, these non-emission benefits should be taken into account in the calculation of cost-effectiveness. EPA believes that an equal weighting of emission and non-emission benefits is justified for those technologies which clearly have substantial non-emission benefits, namely electronic controls, fuel injection changes, turbocharging, and engine modifications. For some or all of these technologies, a greater value for the non-emission benefits could likely be justified. This has the effect of halving the cost for those technologies in the cost-effectiveness calculation. The cost-effectiveness values in this chapter are based on this calculation methodology. Table 6-2 provides a side-by-side comparison of cost-effectiveness values with and without accounting for the non-emission benefits. Cost-effectiveness figures in other tables in this chapter are presented taking the non-emission

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benefits into account and would therefore need to be adjusted similarly to exclude non-emission benefits from the calculation.

I. Engine Lifetime Cost-Effectiveness of the Proposed Standards

A. HC+NO_x

The cost-effectiveness of the proposed HC+NO_x standards was calculated for the various nominal marine engine power ratings described in Chapter 4. For this analysis, the entire cost of the proposed program is attributed to the control of HC and NO_x emissions. As discussed in Chapter 4, the estimated cost of complying with the proposed standards varies depending on the model year under consideration (i.e. year 1 versus year 6 for Tier 3). Therefore, this analysis includes the per-engine cost-effectiveness results for the different model years during which the costs are expected to change. This analysis focuses on costs and benefits for individual engine types; therefore, the costs presented in this section represent the actual cost-effectiveness as it affects a given engine. All of the costs and benefits are discounted at seven percent to the model year of the marine engine.

1. Tier 2

EPA calculated the costs and benefits for Tier 2 and Tier 3 separately. Tier 2 benefits are those achieved from the proposed Tier 2 standards beyond the IMO requirements. Tier 2 costs are compared to baseline technology. EPA conservatively did not make an attempt to estimate costs for any development work or new technology that could be attributed to the IMO requirements and, therefore, removed from this analysis. Table 6-1 presents the Tier 2 discounted cost-effectiveness for marine diesel engines at the five nominal marine power ratings.

Table 6-1
Discounted Cost-Effectiveness (\$/short ton) of the Proposed
Tier 2 HC+NO_x Standards for Marine Diesel Engines with Nominal Power Ratings

Nominal Power (kW)	Engine & Vessel Costs	Operating & Compliance NPV Costs	NPV Benefits (short tons)	Discounted Cost-Effectiveness
100	\$1,570	\$368	4.3	\$449
400	\$2,452	\$564	26	\$116
750	\$22,610	\$103	80	\$283
1500	\$20,068	\$318	267	\$76
3000	\$41,539	\$6,215	829	\$58

Table 6-2
Comparison of Cost-Effectiveness Methodologies for Tier 2

Nominal Power	Not Accounting for Non-emission Benefits		Accounting for Non-emission Benefits	
	Incremental Purchase Price	Discounted Cost-Effectiveness	Incremental Purchase Price	Discounted Cost-Effectiveness
100	\$2,577	\$738	\$1,570	\$449
400	\$4,249	\$201	\$2,452	\$116
750	\$25,319	\$317	\$22,610	\$283
1500	\$22,725	\$5	\$20,068	\$4
3000	\$54,103	\$76	\$41,539	\$58

Category 1, Category 2, and aggregate marine diesel engine cost-effectiveness figures for the proposed Tier 2 HC+NOx standards were also calculated. To accomplish this, each nominal power rating was assumed to represent a range of engine power ratings. Each of the ratings was then weighted using 1997 marine engine populations. Table 6-3 shows how the nominal power ratings were applied to the population as a whole.

Table 6-3
1997 Marine Diesel Engine Populations by Power Category

Category	Nominal Power (kW)	Power Range (kW)	Population
Category 1	100	37 - 225	42,700
	400	225 - 560	23,700
	750	560 - 1000	2,400
	1500	1000 +	2,600
Category 2	3000	all	1,600

Table 6-4 presents the Tier 2 aggregate cost-effectiveness for Category 1 and 2 both individually and combined. Population weighted costs and were divided by the population weighted discounted benefits to determine the aggregate cost-effectiveness figures. These figures suggest that the proposed Tier 2 standards for HC+NOx from marine diesel engines are very cost-effective. This result is largely due to the high hours of operation performed annually by these engines and their long useful lives.

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Table 6-4
Discounted Cost-Effectiveness (\$/short ton) of the
Proposed Tier 2 HC+NO_x Standards for Category 1 and 2 Marine Diesel Engines

	Engine & Vessel Costs	Operating & Compliance NPV Costs	NPV Benefits (short tons)	Discounted Cost-Effectiveness
Category 1	\$3,247	\$422	24	\$156
Category 2	\$41,539	\$6,215	829	\$58
Combined	\$4,070	\$547	41	\$113

2. Tier 3

Tier 3 cost-effectiveness was separated from the Tier 2 cost-effectiveness so that both of the proposed standards could be investigated separately. This is important because of the long lead time associated with the proposed Tier 3 standards and the anticipated feasibility review. Although the cost and benefits associated with Tier 3 will probably change as part of the feasibility review, this analysis gives EPA's best estimate of cost-effectiveness of the proposed Tier 3 HC+NO_x standards based on incremental costs and benefits beyond the proposed Tier 2 HC+NO_x standards. Table 6-5 presents the Tier 3 discounted incremental cost-effectiveness for marine diesel engines at the five nominal marine power ratings.

Table 6-5
Discounted Cost-Effectiveness (\$/short ton) of the Proposed Tier 3
HC+NOx Standards for Marine Diesel Engines with Nominal Power Ratings

Nominal Power (kW)	Model Year Grouping	Engine & Vessel Costs	Operating & Compliance NPV Costs	NPV Benefits (short tons)	Discounted Cost-Effectiveness
100	1 to 5	\$4,353	\$478	4.2	\$1,155
	6 +	\$688			\$279
400	1 to 5	\$5,149	\$655	30	\$196
	6 +	\$1,071			\$58
750	1 to 5	\$22,365	\$1,469	77	\$308
	6 +	\$3,362			\$62
1500	1 to 5	\$21,761	\$2,518	136	\$178
	6 +	\$5,884			\$62
3000	1 to 5	\$34,649	\$2,003	290	\$127
	6 +	\$2,550			\$16

Table 6-6 presents the Tier 3 aggregate incremental cost-effectiveness for Category 1 and Category 2, both individually and combined. These aggregate figures are determined using the population estimates in Table 6-3. As with Tier 2, the additional costs and benefits associated with the proposed Tier 3 standards for HC+NOx from marine diesel engines are very cost-effective.

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Table 6-6
Discounted Cost-Effectiveness (\$/short ton) of the Proposed
Tier 3 HC+NO_x Standards for Category 1 and 2 Marine Diesel Engines

	Model Year Grouping	Engine & Vessel Costs	Operating & Compliance NPV Costs	NPV Benefits (short tons)	Discounted Cost-Effectiveness
Category 1	1 to 5	\$5,859	\$644	20	\$327
	6 +	\$1,095			\$87
Category 2	1 to 5	\$34,649	\$2,003	290	\$127
	6 +	\$2,550			\$16
Combined	1 to 5	\$6,478	\$673	26	\$278
	6 +	\$1,126			\$70

B. PM

EPA has also estimated the cost-effectiveness of the proposed PM emission standards for marine diesel engines for each of the nominal power ratings. Because no additional reductions in PM are proposed for Tier 3 at this time, the PM cost-effectiveness is calculated for Tier 2 only. The per-engine PM emission reduction estimates were developed in Chapter 5. For costs, EPA assumed that half of the increased engine and vessel costs projected in Chapter 4 were allocated for PM control. Because the entire cost of the proposed program was included in the HC+NO_x analysis, this analysis for PM cost-effectiveness is only a supplement to the cost-effectiveness calculations. EPA believes that this analysis is conservative given the stringency of the HC+NO_x standards and results in an upper end estimate of the cost-effectiveness of the proposed PM control. In addition it should be noted that the HC+NO_x cost-effectiveness calculations discussed above include the entire cost of the engine modifications that EPA believes would result due to this proposed rule. Table 6-7 contains the resulting cost-effectiveness for each of the nominal power ratings.

Table 6-7
Discounted Cost-Effectiveness (\$/short ton) of the Proposed
PM Standards for Marine Diesel Engines with Nominal Power Ratings

Nominal Power (kW)	Model Year Grouping	Engine & Vessel Costs	Operating & Compliance NPV Costs	NPV Benefits (short tons)	Discounted Cost-Effectiveness
100	1 to 5	\$785	\$184	0.13	\$7,416
	6 +	\$194			\$2,892
400	1 to 5	\$1,226	\$282	0.93	\$1,629
	6 +	\$318			\$648
750	1 to 5	\$11,305	\$52	2.87	\$3,961
	6 +	\$42			\$33
1500	1 to 5	\$10,034	\$159	6.20	\$1,644
	6 +	\$130			\$47
3000	1 to 5	\$20,770	\$3,108	6.58	\$3,628
	6 +	\$3,159			\$952

Table 6-8 presents the aggregate of these numbers for Category 1 and 2 both separately and together. This aggregation of the cost-effectiveness figures was performed in the same way as for the HC+NO_x cost-effectiveness analysis. The results of this analysis show low cost-effectiveness numbers for PM control. These costs would probably also be considered low even if all of the engine and vessel costs associated with this proposed rulemaking were applied to the PM cost-effectiveness analysis.

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Table 6-8
Discounted Cost-Effectiveness (\$/short ton) of the
Proposed PM Standards for Category 1 and 2 Marine Diesel Engines

	Model Year Grouping	Engine & Vessel Costs	Operating & Compliance NPV Costs	NPV Benefits (short tons)	Discounted Cost-Effectiveness
Category 1	1 to 5	\$1,623	\$211	0.77	\$2,396
	6 +	\$228			\$573
Category 2	1 to 5	\$20,770	\$3,108	6.20	\$3,852
	6 +	\$3,159			\$1,011
Combined	1 to 5	\$2,035	\$274	0.89	\$2,592
	6 +	\$291			\$633

C. Comparison with Cost-Effectiveness of Other Control Programs

In an effort to evaluate the cost-effectiveness of the proposed standards, EPA has summarized the cost-effectiveness results for four other recent EPA mobile source rulemakings that required reductions in NO_x emissions. Where HC+NO_x cost-effectiveness was not reported, NO_x cost-effectiveness-figures are reported. NO_x cost-effectiveness figures should be close to HC+NO_x cost-effectiveness figures since NO_x is the primary focus of the proposed standards and because NO_x emissions are generally much higher than HC emissions for diesel engines. Table 6-9 summarizes the cost-effectiveness results from the heavy-duty vehicle portion of the Clean Fuel Fleet Vehicle Program, the most recent HC+NO_x engine standards for highway heavy-duty diesel engines, and the nonroad Tier 2 standards.

A comparison of the cost-effectiveness numbers in Table 6-9 with the cost-effectiveness results presented throughout this chapter for marine diesel engines shows that the cost-effectiveness of the proposed HC+NO_x standards are more favorable than the cost-effectiveness results of any of these recent rules. To be consistent with the cost-effectiveness values for other programs, the marine diesel numbers shown in Tables 6-9 and 6-10 reflect the aggregate cost-effectiveness for the program rather than the high and low for individual engines.

Table 6-9
Summary of Cost-Effectiveness for Recent EPA NO_x Control Programs

EPA Rule	Pollutants Considered in Calculations	Cost-Effectiveness (\$/ton)
Clean Fuel Fleet Vehicle Program (Heavy-duty)	NO _x	\$1,300 - \$1,500
2.5 g/hp-hr NMHC*+NO _x Standard for Highway Heavy-Duty Engines	NMHC*+NO _x	\$100 - \$600
Locomotive Engine Standards	NO _x	\$160 - \$250
Nonroad Tier 2 Standards	NMHC*+NO _x	\$480 - \$540
Proposed Marine Diesel ≥ 37kW Standards	HC+NO _x	\$30 - \$280

* nonmethane hydrocarbons (roughly equivalent to total HC for diesel engines)

For comparison purposes, EPA has also summarized the cost-effectiveness results for three other recent EPA mobile source rulemakings that required reductions in PM emissions. Table 6-10 summarizes the cost-effectiveness results for the most recent urban bus engine PM standard and the urban bus retrofit/rebuild program. The PM cost-effectiveness results presented earlier in Table 6-8 are more favorable than either of the urban bus programs and comparable to the nonroad Tier 2 standards.

Table 6-10
Summary of Cost-Effectiveness for Recent EPA PM Control Programs

EPA Rule	Cost-Effectiveness (\$/ton)
0.05 g/hp-hr Urban Bus PM Standard	\$10,000 - \$16,000
Urban Bus Retrofit/Rebuild Program	\$25,500
Nonroad Tier 2 Standards	\$700 - \$2,320
Proposed Marine Diesel ≥ 37kW Standards	\$600 - \$2,600

II. 30-Year Cost-Effectiveness of the Proposed Standards

Another tool that can be used to evaluate the cost-effectiveness of a regulatory program is to look at the costs incurred and the emissions benefits achieved over a fixed period of time. The standard period of time associated with this type of rulemaking is 30 years. In this analysis, the net present value (NPV) of the costs incurred from 2000 to 2030 is divided by the NPV of the benefits achieved over this same time period. NPV is calculated using a seven percent time value of money and a seven percent time value of emission reductions. Because this analysis relies on the stream of effects of the proposed rule over time, Tier 2 and Tier 3 are combined for a single cost-effectiveness result. The streams of costs presented here are based on the cost figures developed in Chapter 4. Non emission benefits are not accounted for here.

A. HC+NO_x

Figure 6-11 presents the stream of costs and benefits associated with the proposed standards for HC+NO_x. The discounted cost-effectiveness of the proposed HC+NO_x standards over a 30-year period is \$156/ton for Category 1, \$51/ton for Category 2, and \$131/ton for the aggregate. It should be noted that these figures are a little higher than those presented above for year 6 on a per-engine basis. This difference is because the per-engine analysis relates costs to their resulting benefits while the stream of costs analysis compares costs incurred to benefits achieved in a fixed time frame. In other words, many of the costs incurred prior to 2030 will not achieve benefits until after 2030. This is, in part, due to the long lives and slow turnover of marine engines.

B. PM

Table 6-12 presents the stream of costs and benefits associated with the proposed standards for PM. As with the per-engine analysis, EPA conservatively applied half of the incurred costs to PM control. The discounted cost-effectiveness of the proposed HC+NO_x standards over a 30-year period is \$3,243/ton for Category 1, \$3,384/ton for Category 2, and \$3,256/ton for the aggregate. The same relationship exists for these PM cost-effectiveness figures compared to the per-engine PM cost-effectiveness figures as does for the HC+NO_x analysis.

Table 6-11
30-Year Stream of Costs and Benefits for the Proposed HC+NO_x Standards

Calendar Year	Category 1		Category 2	
	Costs (10 ⁶ \$)	Benefits (10 ³ tons)	Costs (10 ⁶ \$)	Benefits (10 ³ tons)
2004	\$18.8	7.2	\$0	0
2005	\$19.0	14.5	\$0	0
2006	\$22.2	24.1	\$3.8	3.5
2007	\$22.4	33.7	\$3.8	7.1
2008	\$53.4	51.3	\$3.8	10.8
2009	\$38.8	69.2	\$3.9	14.5
2010	\$42.3	88.6	\$7.0	20.2
2011	\$39.3	108	\$3.9	26.0
2012	\$39.3	128	\$3.9	31.9
2013	\$15.9	148	\$4.0	37.8
2014	\$15.9	167	\$4.0	43.8
2015	\$13.9	186	\$1.2	49.9
2016	\$14.0	204	\$1.2	56.1
2017	\$14.0	222	\$1.2	62.3
2018	\$14.1	238	\$1.2	68.6
2019	\$14.1	253	\$1.2	74.9
2020	\$14.2	265	\$1.2	81.3
2021	\$14.2	277	\$1.2	87.7
2022	\$14.3	286	\$1.2	94.1
2023	\$14.4	295	\$1.3	101
2024	\$14.4	302	\$1.3	107
2025	\$14.5	308	\$1.3	114
2026	\$14.5	314	\$1.3	120
2027	\$14.6	319	\$1.3	126
2028	\$14.6	324	\$1.3	132
2029	\$14.7	329	\$1.3	137
2030	\$14.8	333	\$1.3	142
2031	\$14.9	337	\$1.3	147
2032	\$15.1	340	\$1.4	151
2033	\$15.2	343	\$1.4	155
2034	\$15.4	347	\$1.4	159
NPV	\$292	1,864	\$30.2	590

Regulatory Impact Analysis

Table 6-12
30-Year Stream of Costs and Benefits for the Proposed PM Standards

Calendar Year	Category 1		Category 2	
	Costs (10 ⁶ \$)	Benefits (10 ³ tons)	Costs (10 ⁶ \$)	Benefits (10 ³ tons)
2004	\$9.4	0.3	\$0	0
2005	\$9.5	0.6	\$0	0
2006	\$11.1	1.0	\$1.9	0.4
2007	\$11.2	1.4	\$1.9	0.7
2008	\$26.7	1.8	\$1.9	0.11
2009	\$19.4	2.2	\$1.9	0.15
2010	\$21.1	2.6	\$3.5	0.19
2011	\$19.6	3.0	\$2.0	0.23
2012	\$19.7	3.4	\$2.0	0.27
2013	\$7.9	3.8	\$2.0	0.31
2014	\$8.0	4.2	\$2.0	0.35
2015	\$7.0	4.6	\$0.6	0.39
2016	\$7.0	4.9	\$0.6	0.43
2017	\$7.0	5.2	\$0.6	0.47
2018	\$7.0	5.5	\$0.6	0.52
2019	\$7.1	5.7	\$0.6	0.56
2020	\$7.1	5.9	\$0.6	0.60
2021	\$7.1	6.0	\$0.6	0.64
2022	\$7.1	6.2	\$0.6	0.69
2023	\$7.2	6.3	\$0.6	0.73
2024	\$7.2	6.4	\$0.6	0.77
2025	\$7.2	6.5	\$0.6	0.82
2026	\$7.3	6.6	\$0.6	0.86
2027	\$7.3	6.7	\$0.6	0.90
2028	\$7.3	6.8	\$0.7	0.93
2029	\$7.3	6.9	\$0.7	0.97
2030	\$7.4	7.0	\$0.7	1.00
2031	\$7.5	7.1	\$0.7	1.03
2032	\$7.5	7.1	\$0.7	1.05
2033	\$7.6	7.2	\$0.7	1.07
2034	\$7.7	7.3	\$0.7	1.09
NPV	\$146	45.0	\$15.1	4.46