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Final Regulatory Impact Analysis: Control of Emissions from Marine Diesel Engines

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

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CHAPTER 1: INTRODUCTION

EPA is adopting new standards for emissions of oxides of nitrogen (NOx), hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) from new diesel-cycle engines with a gross power output at or above 37 kilowatts used in marine vessels.[1] This Final Regulatory Impact Analysis (Final RIA) provides technical, economic, and environmental analyses of the new emission standards for the affected engines. The anticipated emission reductions will support EPA's effort to make significant, long-term improvements in air quality in many areas of the U.S. We project that the new standards for new marine diesel engines will reduce their emissions of HC by 8 percent, NOx by 15 percent, and PM by 11 percent in 2020. The NOx reduction is in addition to a 6 percent reduction in 2020 from international standards for U.S.-flagged vessels. Overall, the new requirements will 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 will be affected by this rulemaking. Chapter 3 provides a description of the range of technologies that may be available 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 below. Chapter 5 provides an overview of the health and welfare issues involved and presents the calculated reduction in emission levels resulting from the new 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 5 liters/cylinder or less. Category 2 includes engines with 5 to 30 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 NOx emissions standard developed by International Maritime Organization. This standard is considered to be the baseline case (or "Tier 1") for determining the benefits of the EPA standards. The MARPOL NOx standard is presented in Table 1-1.

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[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.

Table 1-1
MARPOL Marine Diesel Engine NOx Standard

Starting Date*	rated speed (n)	NOx g/kW-hr
2000	n >2000 rpm	9.8
	$130 \leq n \leq 2000$ rpm	$45 \times n^{-0.2}$
	n <130 rpm	17

*MARPOL limits are based on the date of vessel construction or engine modification.

EPA is adopting a second tier of standards for Category 1 and Category 2 marine diesel engines. Table 1-2 lists the new standards and the affected model years.

Table 1-2
Final Tier 2 Engine Emissions Standards and Dates

Category	Displacement (liters/cylinder)	Starting Date	NOx+HC (g/kW-hr)	PM (g/kW-hr)	CO (g/kW-hr)
1	power ≥ 37 kW disp. < 0.9	2005	7.5	0.40	5.0
	0.9 ≤ disp. < 1.2	2004	7.2	0.30	5.0
	1.2 ≤ disp. < 2.5	2004	7.2	0.20	5.0
	2.5 ≤ disp. < 5.0	2007	7.2	0.20	5.0
2	5.0 ≤ disp. < 15	2007	7.8	0.27	5.0
	15 ≤ disp. < 20, and power < 3300 kW	2007	8.7	0.50	5.0
	15 ≤ disp. < 20, and power ≥ 3300 kW	2007	9.8	0.50	5.0
	20 ≤ disp. < 25	2007	9.8	0.50	5.0
	25 ≤ disp. < 30	2007	11.0	0.50	5.0

This document presents an analysis of the projected regulatory impacts of the final 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 long-term costs apply for engines produced starting in the sixth year of production to show the effect of fully amortized fixed costs and learning in production. The listed engine costs (in 1997 dollars) reflect the full anticipated price increment resulting from the new 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 rulemaking 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 Tier 2 standards are incremental to the baseline represented by the MARPOL requirements. The aggregate cost-effectiveness of the final rule is $103 per ton for HC+NOx benefits ($23 per ton using long-term costs).

Table 1-3
Tier 2 Discounted Incremental Costs and Benefits by Power Rating

Power Rating	Cost Basis	Engine Cost	Operating Costs (NPV)	HC+NOx Benefits (annual tons)	Cost-Effectiveness
37-225 kW	Near-term	$1,806	$442	4.3	$470
	Long-term	$486			$164
225-560 kW	Near-term	$3,208	$704	26	$137
	Long-term	$846			$46
560-1000 kW	Near-term	$25,395	$206	80	$318
	Long-term	$856			$12
1000-2000 kW	Near-term	$22,818	$636	267	$87
	Long-term	$1,120			$5
2000+ kW	Near-term	$54,192	$12,430	750	$81
	Long-term	$13,019			$26

CHAPTER 2: INDUSTRY CHARACTERIZATION

I. Introduction

To help assess the potential impact of this 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

This emission control program covers all new 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 apply to all of them. Therefore, as discussed in the final rule preamble, EPA has divided 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 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 engines with a specific displacement at or above 5 liters to 30 liters per cylinder. Many of these engines have counterpart locomotive models. 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 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. The final emission standards take into account the fact that some Category 2 engines are larger and use different technology than locomotive engines. These technologies and their application to marine diesel engines are discussed in greater detail in Chapter 3.

Category 3 engines are very large engines, at or above 30 liters per cylinder. These are larger than any 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. The marine diesel engine categories are summarized in Table 2-1.

Table 2-1
Engine Category Definitions

Category	Displacement per Cylinder	Basic Engine Type
1	disp. < 5 liters (and power 37 kW)	Nonroad
2	5 disp. < 30 liters	Locomotive
3	disp. ≥ 30 liters	Unique, “Cathedral”

B. Category 1 Engine Subgroups

EPA has further divided Category 1 engines into several subgroups. These subgroups are similar to the land-based nonroad diesel engine subgroups, with one important change. EPA has based the marine subgroups on cylinder displacement rather than engine power. 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. Similarly, the common practice of bolting two marine engines together could in many cases move the combined engine artificially into a different 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. 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.

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.

Table 2-2 lists the displacement values we 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 for almost all engine models 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 for a family of engines that must meet a single set of requirements with a common implementation date.

The net effect of changing to a displacement-based grouping is hard to quantify. Somewhat greater emission reductions will likely result for the reasons described above, though it is difficult to identify the relative sales volumes of engines that fall above and below the threshold under both scenarios. The effect on costs is expected to be very small. As described above, no engines are 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 expenditures. Variable costs may be incurred for a greater number of engines, but the cost analysis in Chapter 4 makes clear that fixed costs dominate the overall cost impact of emission requirements.

Table 2-2
Nonroad Power Categories Corresponding
to Per-Cylinder Displacement Ranges

Displacement (liters/cylinder)	Approximate Corresponding Power Band from Land-based Nonroad Rulemaking	
power ≥37 kW displ.<0.9	37 kW<75	50 hp<100
0.9 displ.<1.2	75 kW<130	100 hp<175
1.2 displ.<2.5	130 kW<560	175 hp<750
2.5 displ.<5.0	kW≥560	hp≥750

C. Auxiliary and Propulsion Engines

All three categories of marine diesel engines can be further 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 4,000 to 6,000 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 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 may be performed either by engine manufacturers or post-manufacture marinizers. Some of these companies start with a completed engine and 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 "engine dressing" companies 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, we do not expect these changes to affect the emission characteristics of the engine.

IV. Description of Engine Manufacturers

The companies that are most immediately affected by the new emission standards are those that manufacture marine diesel 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 new emission standards. In other diesel engine rulemakings, both 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 new standards, 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 new emission standards, and those that will be exported. Consequently, relying on OE Link to paint a picture of the companies that may be affected by the new standards may result in an overestimate or underestimate of the magnitude of the potential impact of the final 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 that produce marine diesel engines in the United States. These manufacturers, listed in Table 2-3, are grouped into four categories. Domestic engine manufacturers (DEM) are companies who make complete marine engines. As described in the marinization discussion in the above section, these marine engines are likely to be derived from one of the manufacturer’s own land-based nonroad or 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 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 dressing engines and therefore not required to recertify their product to the new emission standards.

Table 2-3
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

Figure 2-1

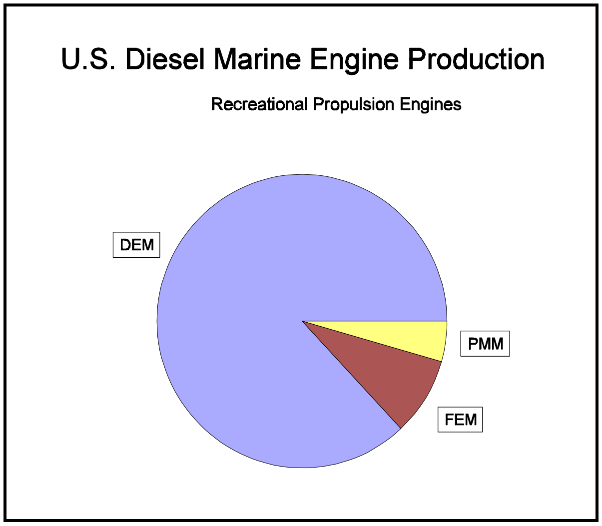
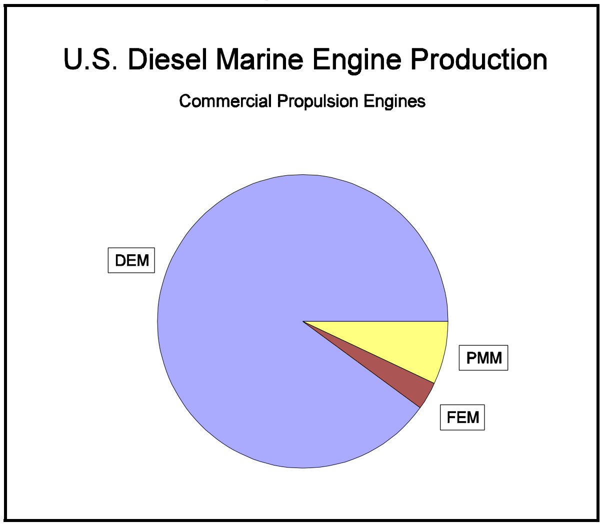


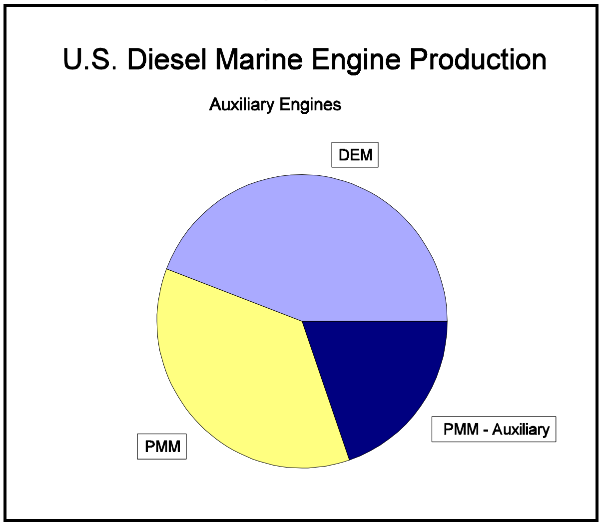
Figure 2-2



Note that companies involved only in dressing marine engines 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 these companies; there may therefore be tens if not hundreds of others. While an exact profile of the engine dressing industry would be interesting, it would be of limited value in this industry characterization since the final rule exempts them from certification requirements.

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. Remember 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.

Figure 2-3



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 dressing companies. 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 for auxiliary engines, preferring to leave this to smaller companies that can tailor their product to the special needs of marine customers. Alternatively, it could be the 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 this rulemaking; 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 2-4. Note that, with regard to domestic engine manufacturers, Table 2-4 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.

Table 2-4
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

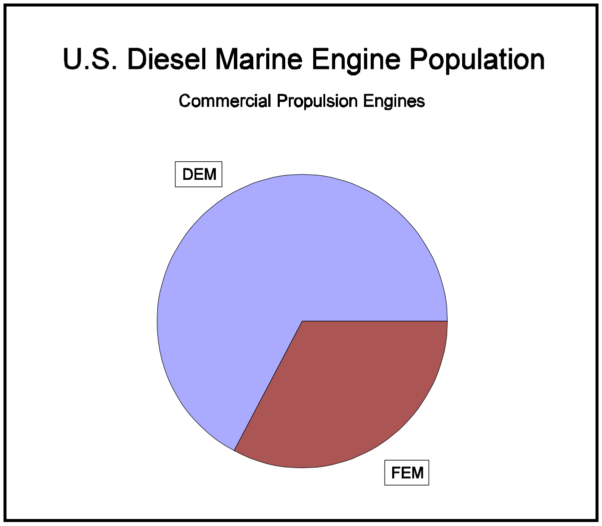


Figure 2-5

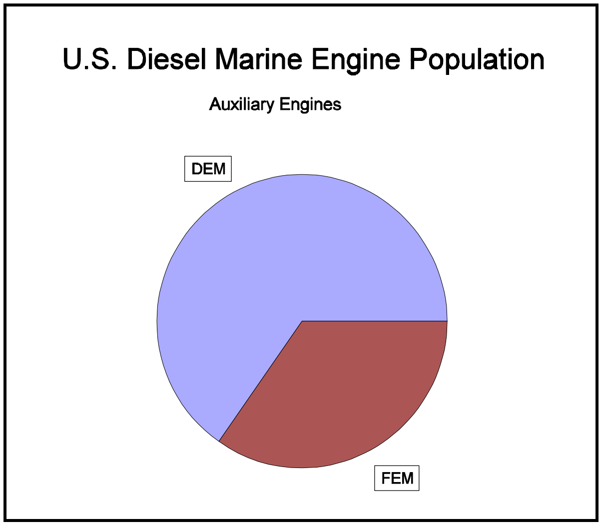


Figure 2-6

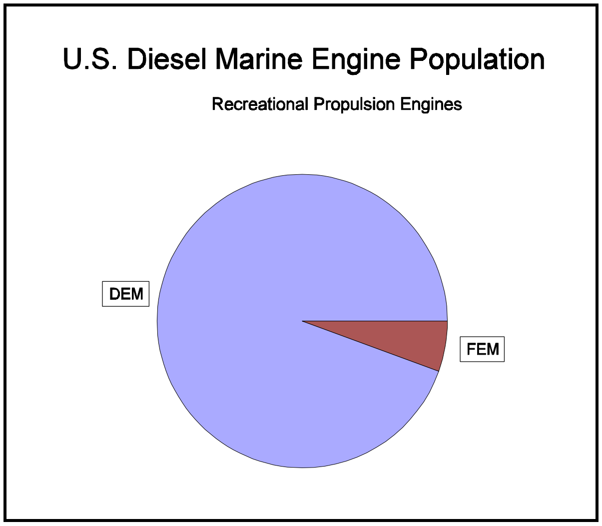
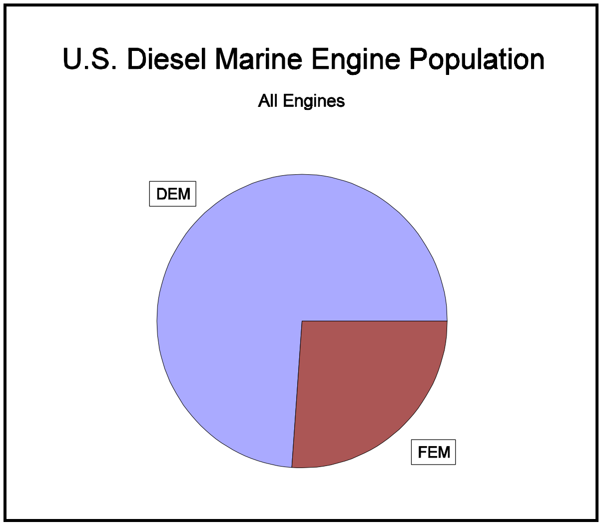


Figure 2-7



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 marine diesel market.

c) Other Marine Diesel Engine Manufacturers

Finally, there are at least four other marine diesel 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

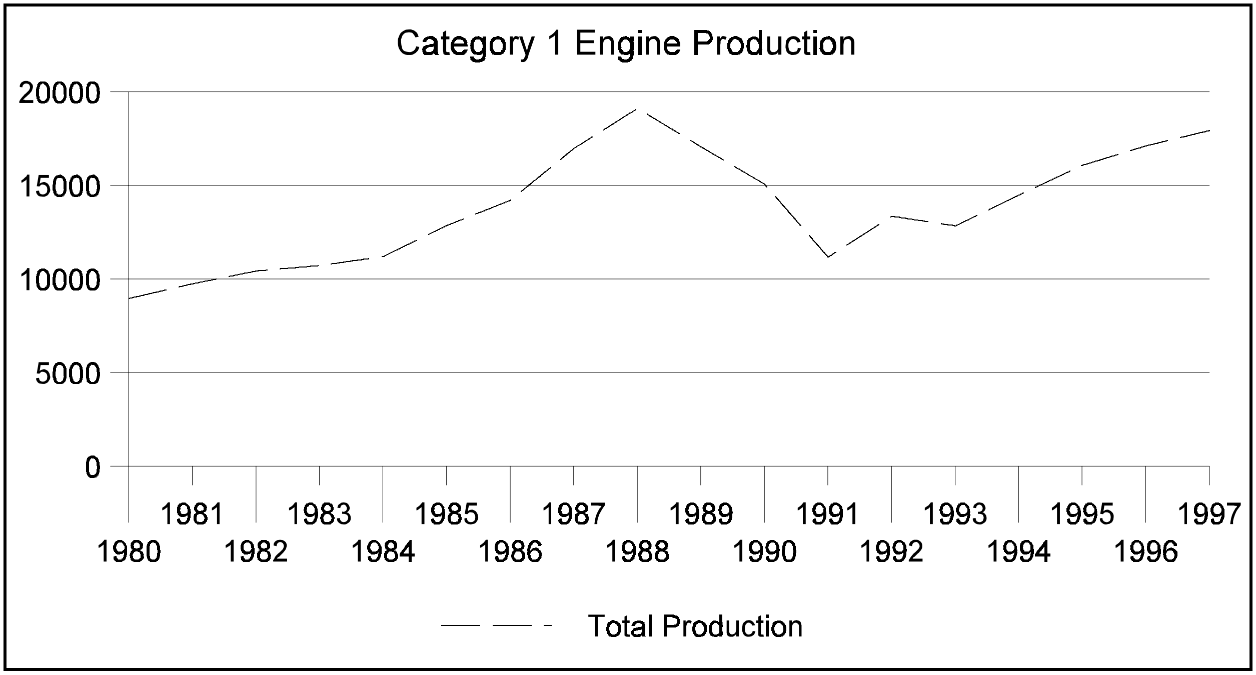
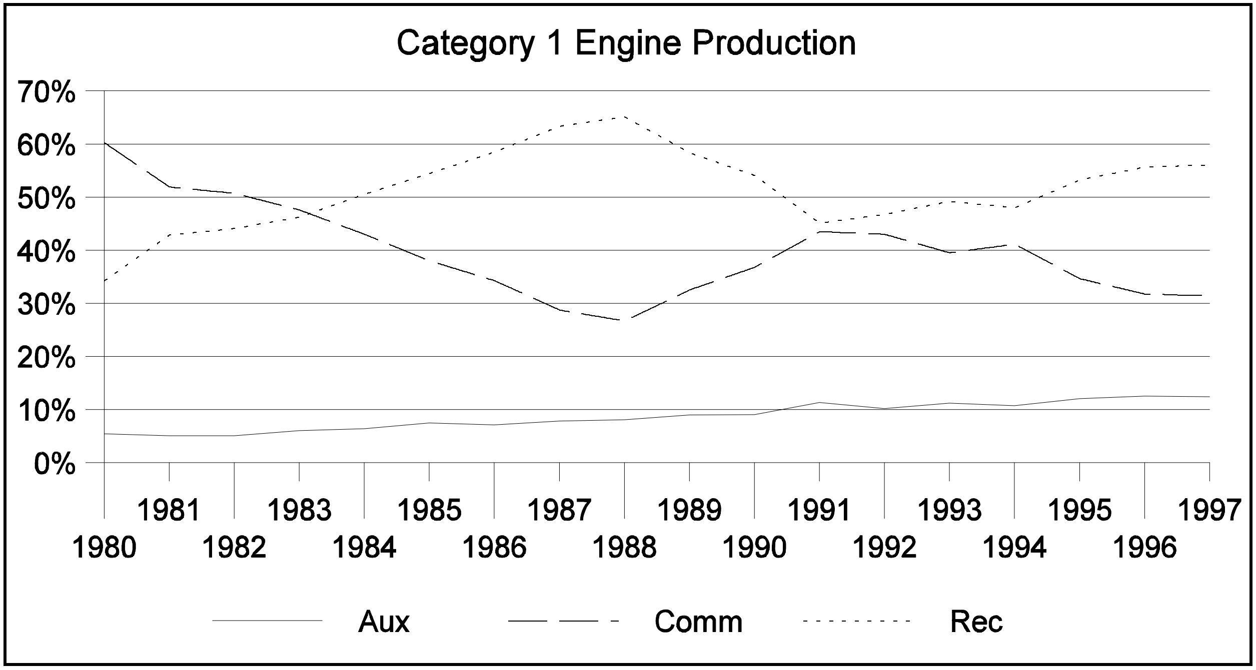


Figure 2-9 illustrates the portion of production for each segment of the industry, commercial propulsion engines, recreational propulsion engines, and auxiliary engines. According to this chart, auxiliary engines have had a fairly constant share of total production, increasing from about 7 percent at 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 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 produces the majority of these engines introduced into the U.S. Caterpillar is also actively pursuing sales of Category 2 engines. Several other companies have engines available, but do not focus on the marine market. General Electric sells the large majority of its engines for locomotives, though some of these engines find their way into marine vessels. Fairbanks Morse has produced Category 2 marine engines for a long time, but has shifted its focus to supplying engines into military applications, rather than the commercial applications that will be most affected by new emission standards. Several foreign companies produce engines that could be sold into the U.S. market, though companies buying new vessels for domestic use have most often 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.

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

With prices approaching or exceeding $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. Common 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 commonly 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 marine or locomotive engines into new marine vessels.

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 2-5 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 2-5
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
Fincantier Group/GMT	GMBH
Hanshin	Jadranbrod ULJANK
MAN-B&W	Kawasaki Heavy Ind.
MaK	Kirloskar Oil Engines Ltd.
Matsui Iron Works	Koloma Plant Joint Stock
Mitsubishi Heavy Ind. LTD	Maschinenbau Halberstadt
SEMT-Pielstick	Niigata
Wartsila-NSD	

V. 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 1 and 2 establish the location, number, size, and relevant factors associated with shipbuilding and boat building. Part 3 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.

- <u>Commercial Ships</u>—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 routs. 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 0.5 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.

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 made. domestically. 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 intense foreign competition.

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 feel 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.

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 mean 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

1. *Federal Register*, “Control of Emissions of Air Pollution from Nonroad Diesel Engines; Final Rule,” 63 FR 56968, October 23, 1998.

2. *Federal Register*, “Emission Standards for Locomotives and Locomotive Engines; Final Rule,” 63 FR 18978, April 16, 1998.

3. Boating Industry Magazine, “1997 Annual Industry Reviews: The Boating Business”, January 1998.

4. “Diesel & Gas Turbine Worldwide Catalog: Product Directory and Buyers Guide,” 1997 Edition, Volume 62.

5. Dunn & Bradstreet.

6. National Marine Manufacturers Association -http://209.94.233.3/iww/customers/nmma/.

7.. National Marine Manufacturers Association - “Monthly Statistical Report of the Recreational Marine Industry,” July 1997.

8. National Marine Manufacturers Association - “Monthly Statistical Report of the Recreational Marine Industry, ” July 1996.

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-base 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 new emission standards. Next, the emission test procedures for measuring and assessing the impacts of the new emission standards 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 a mix of technologies EPA believes will allow manufacturers to reach the Tier 2 emission standards.

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 operate a maximum of 200 to 1000 hours per year. They are intended for variable-load applications where the engine operates at full power no more than 15 minutes at a time and where the engine spends 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 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 are commercial fishing boats, ferries, and coastal freighters. In addition, most auxiliary marine engines 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 operates from 3000 to 5000 hours per year (60-100 hours per week), but spends 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 fall into this rating as well. This rating includes mostly Category 2 engines with some Category 1 engines.

Marine engines with a continuous rating are designed to operate under full load up to 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 tugboats to ocean-going vessels. Tugboat applications typically use Category 2 engines, but the majority of the ocean-going vessels use Category 3 engines. Great Lakes vessels may use either Category 2 or Category 3 propulsion 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.

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 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, a land-based engine that meets a particular set of emission limits may no longer meet these limits after it is marinized. 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-to-weight ratios much higher than land-based applications. The challenge presented by the new emission standards 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.

NOx 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 NOx. 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 NOx. 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 NOx 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 NOx and PM emissions requires different, sometimes opposing strategies. The key to controlling NOx emissions is reducing peak combustion temperatures since NOx 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 NOx 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 new emission standards for marine diesel engines can be met using technology that has been developed for and used on locomotive, land-based nonroad, and 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 NOx emissions, but increases PM. Manufacturers will need to integrate all of these variables into optimized systems to meet the new emission 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. NOx 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.

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 NOx 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 NOx. 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. NOx emissions might increase slightly at low loads as swirl increases. At high loads, swirl causes slight decreases in PM emissions and fuel consumption, but NOx 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 NOx, 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 NOx formation.[13] However, in conjunction with retarding the start of fuel injection, higher fuel injection pressures can lead to reduced NOx 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 NOx formation. Injecting most of the fuel into an established flame then allows for a steady burn that limits NOx emissions without increasing PM emissions. Rate shaping may be done either mechanically or electronically. Rate shaping has been shown to reduce NOx 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-pressure multiple injections to be used to reduce NOx 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 NOx 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 distributer 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 NOx 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 NOx 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 NOx 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.

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 NOx 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 NOx emissions may lead to more widespread use in the future.

3. Separate-circuit aftercooling

Separate-circuit aftercooling is a compromise approach to marine engine aftercooling that shows promise for addressing near-term emission standards. This system is much like current jacket-water cooling systems, except that one coolant loop is devoted to engine cooling and a second loop is devoted to removing heat from the aftercooler. The coolant loop devoted to the aftercooler provides more effective cooling than jacket-water aftercooling, without introducing the durability concerns of raw-water aftercooling.

In principle, separate-circuit aftercooling is very similar to systems on highway truck engines. The main difference between highway and marine applications is the fundamental cooling medium (or heat sink). Highway engines use air with high relative speeds through a heat exchanger to extract heat from the coolant running through the aftercooler. Marine engines have the same coolant loop, but extract heat from a heat exchanger (or keel cooler) with ambient water. Because water has a higher convection coefficient than air (especially without high air speeds), it should generally more efficient at removing heat from a system. Separate-circuit systems should therefore have a comparable level of cooling compared to highway engines, and superior cooling relative to land-based nonroad engines, which operate at slower speeds. Separate-circuit aftercooling could even overcool the engine intake air in some cases; a thermostat could be used to limit the cooling water flow when the system temperature gets too low.

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 a recent development in diesel engine control technology for obtaining significant NOx reductions. EGR reduces peak combustion chamber temperatures by slowing reaction rates and absorbing some of the heat generated from combustion. While NOx emissions are reduced, PM and fuel consumption can be increased, especially at high loads, because of the reduced oxygen available and longer burn times 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 NOx 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 NOx penalty due to increased ignition delay, but at high loads, some additional NOx 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 new emission 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 to investigate is the concern of catalyst poisoning in a salt-water environment.

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 NOx 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 NOx 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” may 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 NOx 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 duty cycles for testing as well as other issues specific to testing marine diesel engines.

A. Certification Duty Cycles

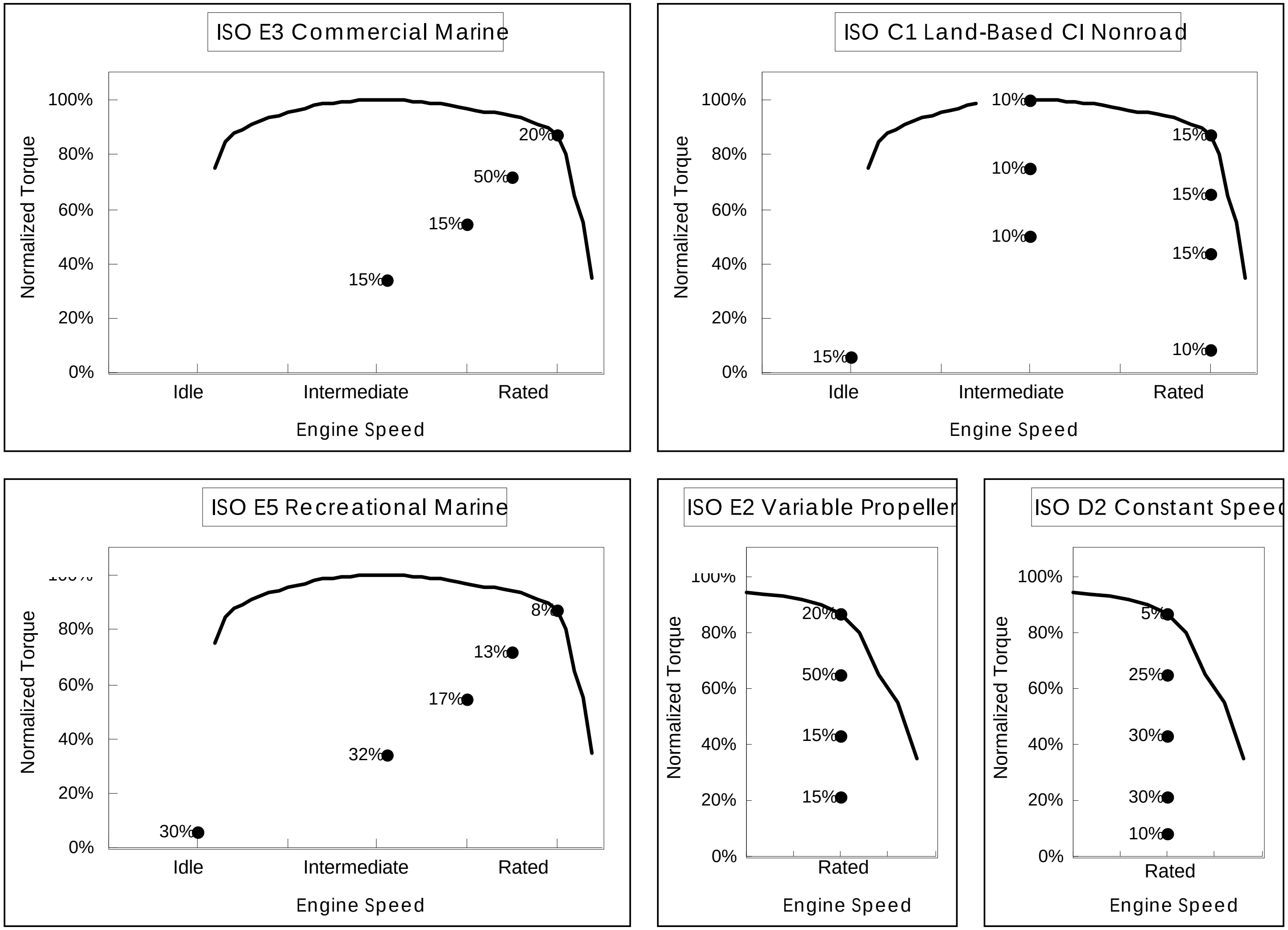
The E3 duty cycle is designated for propulsion marine diesel engines operating on a propeller curve. Both the E3 and the E5 are designed to represent marine diesel engines, and both cycles focus on operational modes which lie on a propeller curve. However, the E3 represents heavy-duty diesel marine engine operation, while the E5 represents 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. For this reason, EPA is using the E3 duty cycle for this program. Using a single cycle to represent all 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 specifies the C1 and D2 duty cycles. Auxiliary marine engines include any engines used on a marine vessel that 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 may run at a constant speed and use a variable-pitch propeller to control vessel speed. The E2 constant-speed propulsion marine duty cycle applies to 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 to maximize fuel efficiency. In general, these engines will operate at a constant speed near peak torque, except when maneuvering in port, where they operate along the lug curve. Because of the expense of the system, variable-speed engines are rarely used with variable-pitche propellers. ISO does not have a test duty cycle specifically designed for these engines. EPA believes that the most appropriate existing duty for these engines is the ISO C1 duty cycle. This is consistent with MARPOL Annex VI.

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)



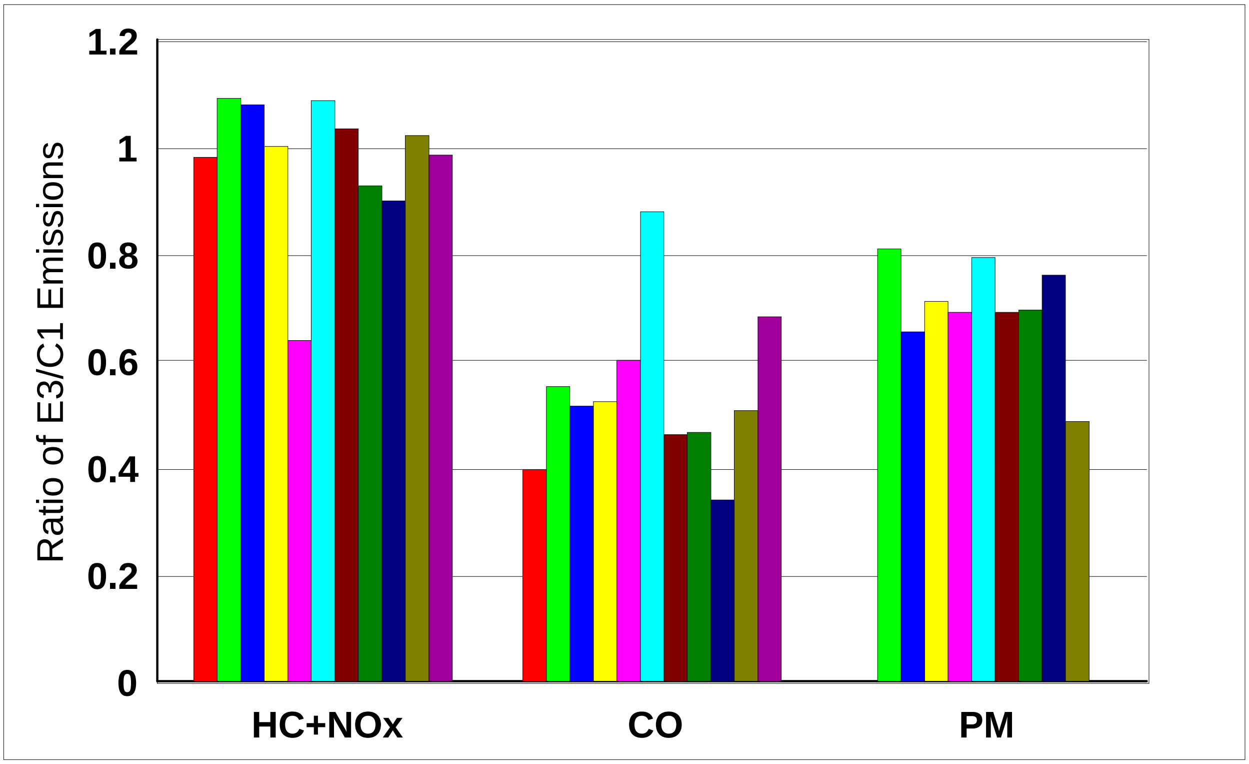
B. Relative Stringency of Duty Cycles

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 nine uncontrolled Category 1 marine diesel engines[37,38,39] and two nonroad diesel engines[40] show that HC+NOx emissions are approximately the same (2% lower on the E3) when measured on the E3 or C1 duty cycle. This suggests that emission levels determined using the E3 cycle are roughly equivalent to those determined using the C1 cycle. PM and CO emissions were measured to be, respectively, 30% and 46% lower on the E3 than C1. For controlled marine diesel engines, EPA anticipates that it will be somewhat easier to demonstrate compliance on the E3 cycle than the C1 cycle because of the lower measured PM and CO , the E3 only has half as many test modes, and the E3 does not include the peak torque mode that drives many nonroad diesel engine emission control designs. Figure 3-2 presents these results.

Figure 3-2: Ratio of Emissions on the E3 vs. C1 Duty Cycles



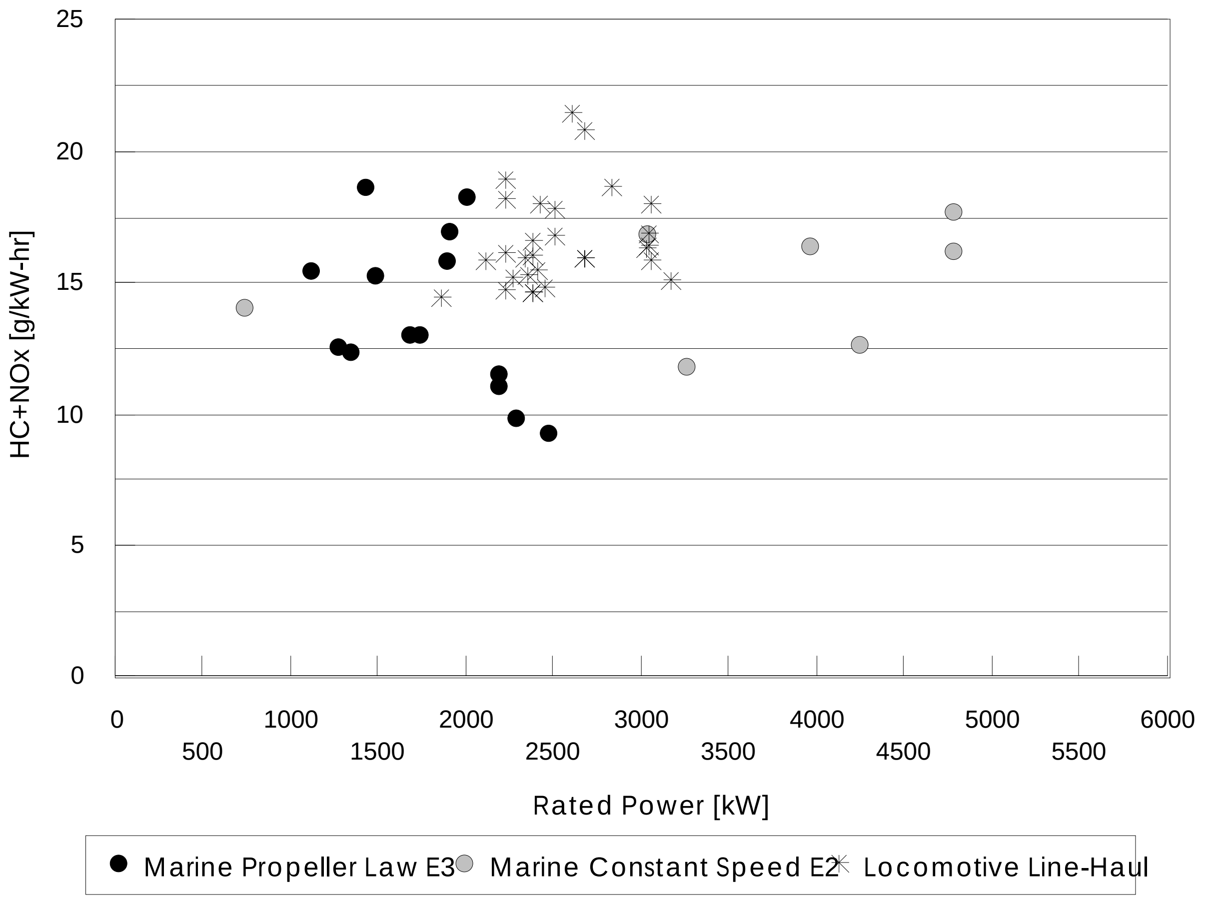
For constant-speed engines, both the nonroad and marine standards, the test procedure does not impact the stringency. Both rules use the D2 duty cycle for constant-speed engines.

2. Category 2 marine vs. locomotive line-haul

Category 2 emission standards 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 generally 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 engines[41] and twenty-three marine engines[42,43,44,45] 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 3-3: Comparison of HC+NOx Emissions for Marine and Locomotive Engines



C. Not-to-Exceed Provisions

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 operates with low emissions under all in-use speed and load combinations that can occur on a vessel, rather than just at the discrete test modes in the selected duty cycles. To ensure this, EPA is establishing requirements that extend to typical in-use operation. For propulsion marine engines certified to the E3 duty cycle, EPA is applying a "not-to-exceed" (NTE) zone based on the maximum power curve of the engine. Under this provision, the manufacturers must 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 are tied to the family emission limits. EPA reserves the right to test an engine in a lab or installed on a vessel to confirm compliance to this requirement.

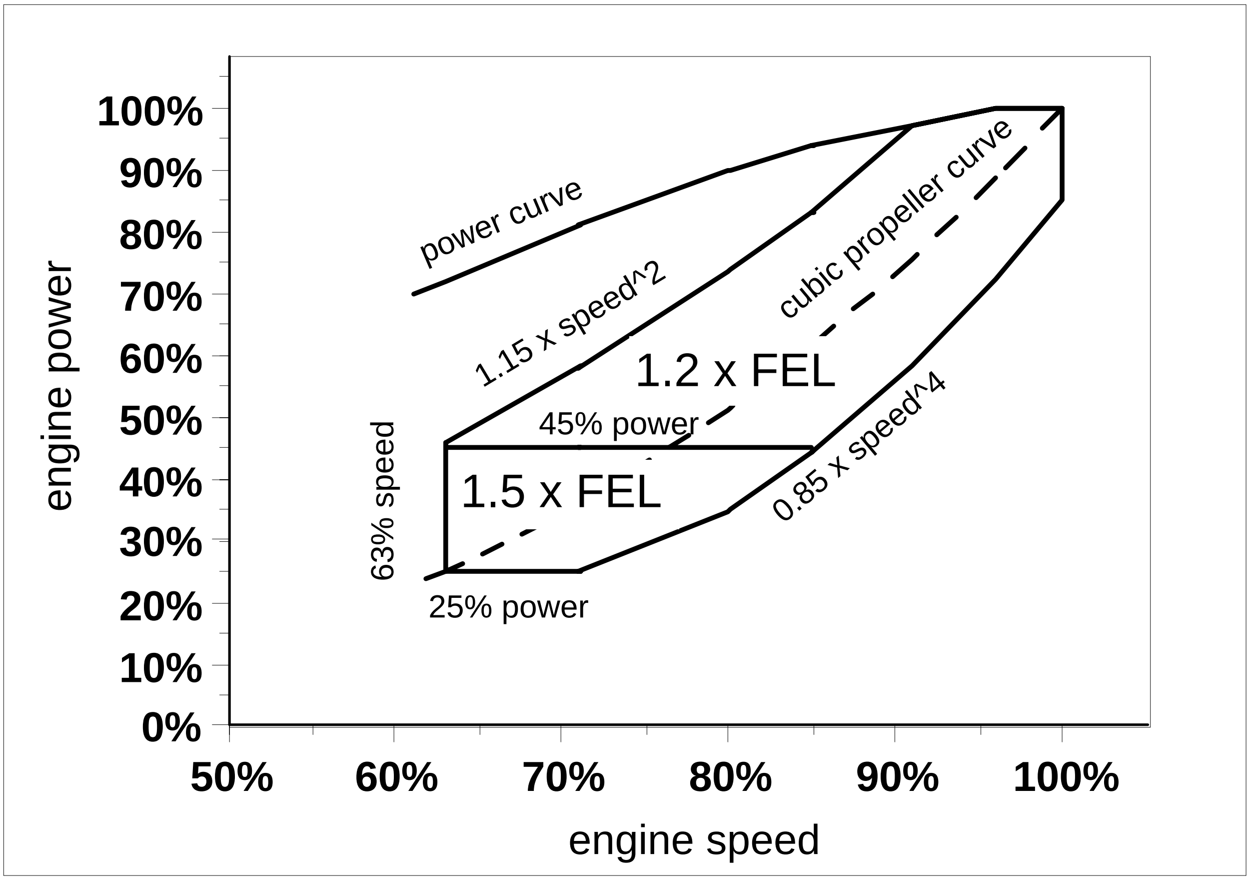
When testing the engine within the NTE zone, only steady-state operation will be considered. It is unlikely that transient operation is necessary under the NTE concept to ensure that emissions reductions are achieved. EPA designed the NTE zones to contain the operation near an assumed propeller curve that the steady-state cycles represent. EPA believes that the vast majority of marine operation in the NTE zone is steady-state. For planing vessels, EPA believes that the transient operation as a vessel comes to plane generally is along the torque curve and would not be within the NTE zone. However, EPA does not have enough data to reliably say where under the torque curve marine engines operate during transient operation. Also, EPA does not believe that the NTE zone should be extended to include areas an engine may see during transient operation but would never see during steady-state operation. For this reason, EPA does not believe that adding transient operation to the NTE requirements is necessary at this time. EPA would revise its opinion in the future if there were evidence that in-use emissions were increased due to insufficient emission control under transient operation.

This NTE zone concept is consistent with the recent guidance for highway engines.[46] However, highway engines have a much larger NTE zone which covers a full range of possible engine operation. In addition, 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 would not be subject to transient operation during NTE testing.

1. Shape of the NTE zones

For engines certified on the E3 cycle, the NTE zone is 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 maximum test power point of the engine. For the NTE zone, the upper boundary is based on a speed-squared propeller curve passing through the 115 percent load point at maximum test speed and the lower boundary is based on a speed to the fourth propeller curve passing through the 85 percent load point at maximum test speed. These propeller curves are believed to represent the full range of propeller curves seen in use (these curves are adjusted slightly for Category 2 engines, as described in the Summary and Analysis of Comments).[47] To prevent imposing an unrealistic cap on a brake-specific basis, EPA has limited this region to power at or above 25 percent of maximum test power and speeds at or above 63 percent of maximum test speed. These limits are consistent with Mode 4 in the E3 duty cycle. The NTE zone is illustrated in Figure 3-4. Also, the zone is split into two subzones with different emissions limits. These limits are discussed below. For engines operating in applications in which the in-use operation differs significantly from the NTE zone in Figure 3-3, manufacturers may petition for adjustments to the NTE zone for a given engine design.

Figure 3-4: Not-to-Exceed Zone for Category 1 E3 Engines



For variable-speed engines with variable pitch propellers, the NTE zone includes the entire NTE zone for engines certified on the E3 duty cycle. In addition, this zone includes the range of operation above 1.15 times the squared propeller curve for speeds greater than or equal to 63% of maximum test speed. This additional portion of the NTE zone represents operation near the lug curve that EPA understands is common for these applications. As with the NTE zone for engines certified to the E3 duty cycle, this zone is split into two subzones above and below 45% power with limits that are discussed below.

For constant-speed propulsion engines certified to the E2 duty cycle, EPA is using a similar approach to ensure 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 apply to the speed where the engine is designed to operate for all loads greater than or equal to 25 percent of maximum load at that speed. Because a constant speed can actually operate over a small range of engine speeds in-use, the NTE zone includes this small range of speeds. Below 25 percent load, EPA is not adopting a NTE cap because brake-specific emissions become large at low loads due to a small power level in the denominator. In addition, these engines generally do not spend much time operating at low loads. As with the NTE zone for propeller-curve engines, this zone is split into two subzones above and below 45% power with limits that are discussed below. Also, any variation in speed possible for the engine in use must be considered in the NTE zone.

EPA is not adopting any NTE provisions for auxiliary marine engines certified using the D2 and C1 duty cycles. EPA does not at this time 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 MARPOL requirements, EPA does not believe that it is appropriate to extend the NTE concept to Category 3 engines at the present time.

2. Emissions limits for the NTE zone

EPA is requiring emissions caps for the NTE zones which represent a multiplier times the weighted test result used for certification. Although ideally the engine should meet the certification level throughout the NTE zone, EPA understands that a cap of 1.0 times the standard is not 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 included in this rule.

For propulsion engines certified to the E3, C1, and E2 duty cycles, EPA believes that not-to-exceed limits of 1.2 times the emissions standard (or FEL) is appropriate for the subzone at or above 45% of maximum test power. Below 45% of maximum test power, the cap is 1.5. 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 3-5 presents the ratio of the modal emissions to the cycle weighted emissions from more than 30 Category 1 and 2 marine diesel engines.[b] This data shows that the 1.2 cap is easily achievable for HC+NOx at higher power, but may be more challenging at low powers (mode 4). This is why the cap is relaxed to 1.5 below 45% of maximum test power. Most of the engines are below these caps, and EPA believes that all marine diesel engines can be optimized to meet these caps, 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. The separate caps in the NTE zone also appear to be necessary for PM. About half of the engines already meet these limits and EPA believes that all engines could be designed for this requirement. It should be noted that the CO emissions data presented here were well below the new emission standards, so CO should not be a limiting factor.

EPA also collected modal data on a mechanically controlled and an electronically controlled commercial marine diesel engine.[48] This data is presented in Figures 3-6 and 3-7 which show operation under the whole NTE zone rather than just at four points. The mechanically controlled engine is very close to meeting the NTE requirement at all points, and at most points is well below the cap. For PM, this engine is above the NTE requirement along the minimum load boundary for the NTE zone. However this engine is not calibrated for emissions control. We believe that if the engine is designed to operate at these points, that it is important that manufacturers design the engine to achieve emissions levels at these points near the certified level.

For HC+NOx, the electronically controlled marine engine is well below the NTE caps for the whole zone. For PM, this engine really only has difficulty with the NTE caps at full power. However, this engine is not calibrated for emissions control. In addition, data on other commercial marine engines shown in Figure 3-5 suggest that most commercial marine engines do not have this problem at full power.

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[b] This data is cited and presented in more detail elsewhere in this chapter.

Figure 3-5: Ratio of Modal Emissions to Cycle Weighted Emissions

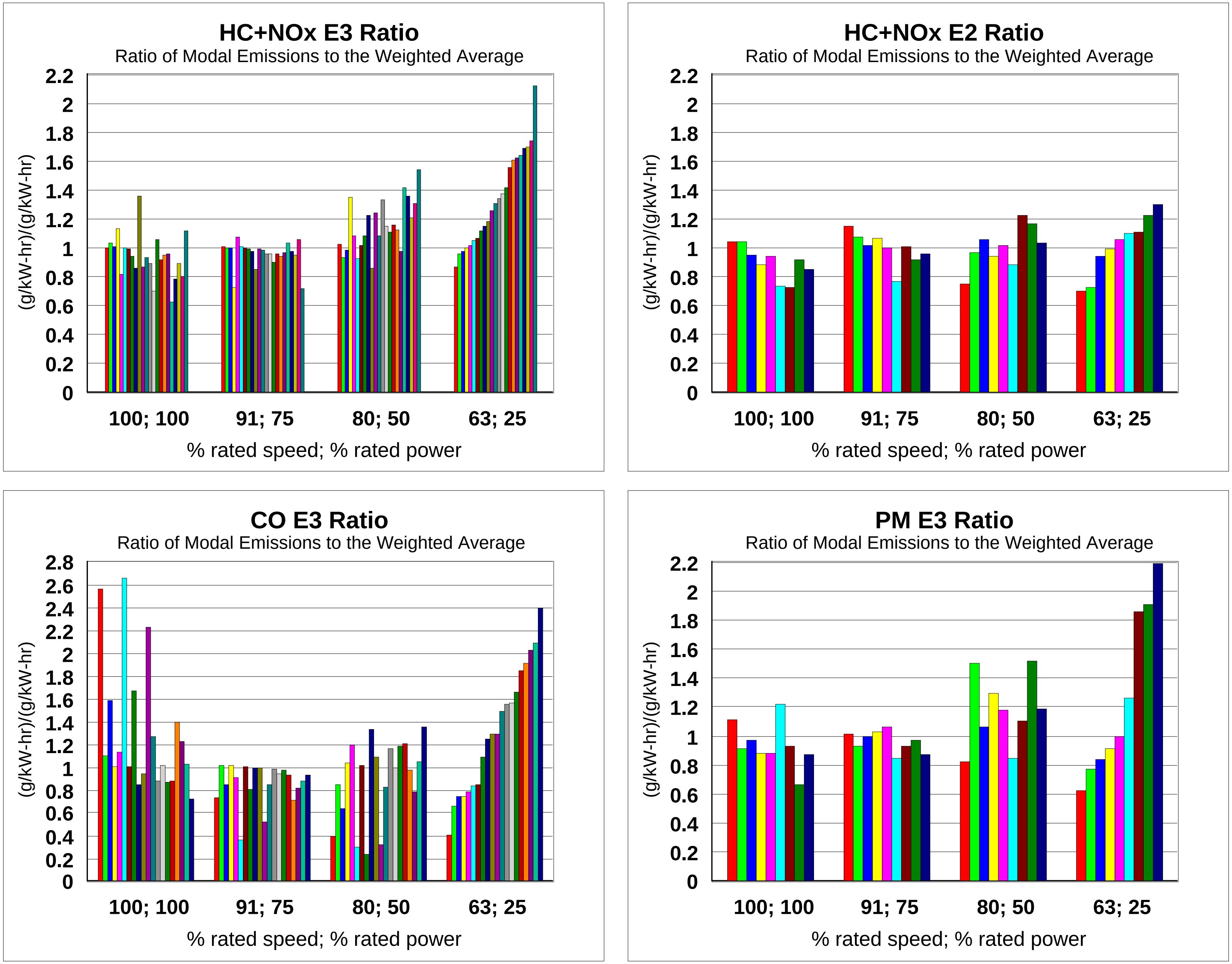
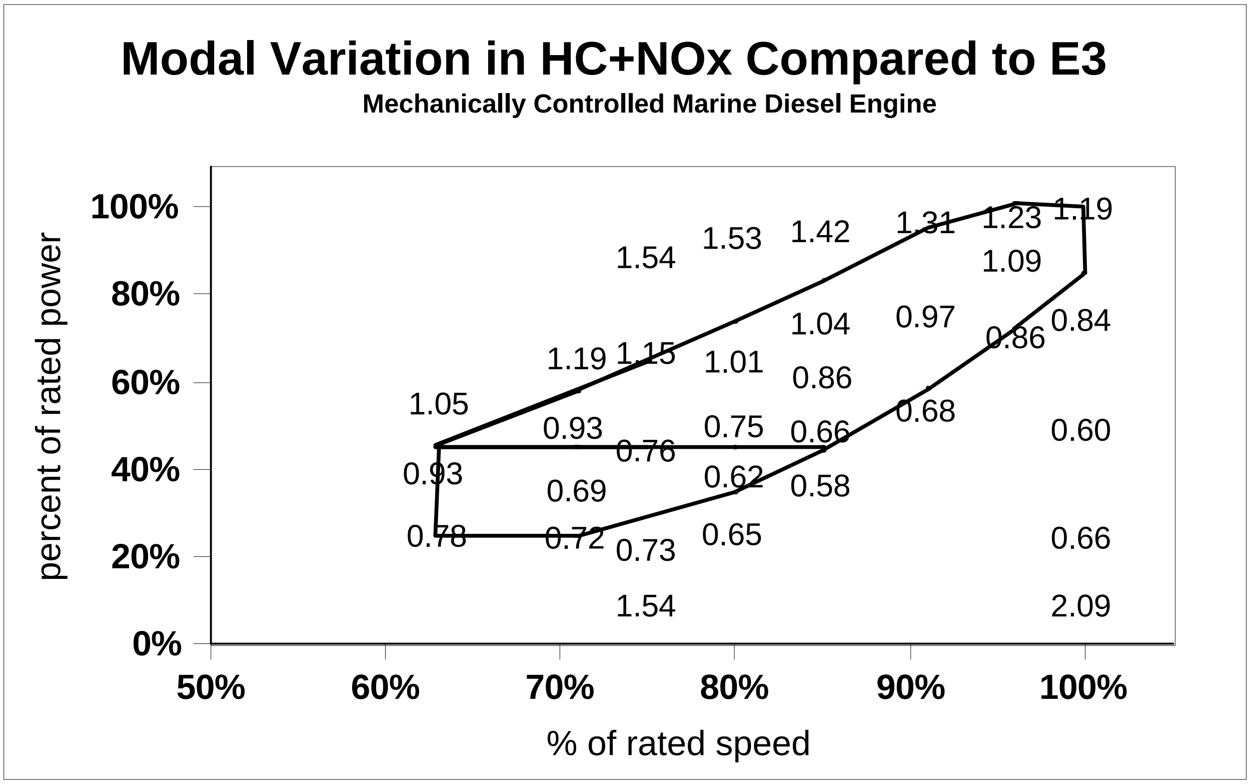


Figure 3-6: Ratio of Modal to E3 Emissions Compared to the NTE Zone for an Electronically Controlled Marine Diesel Engine



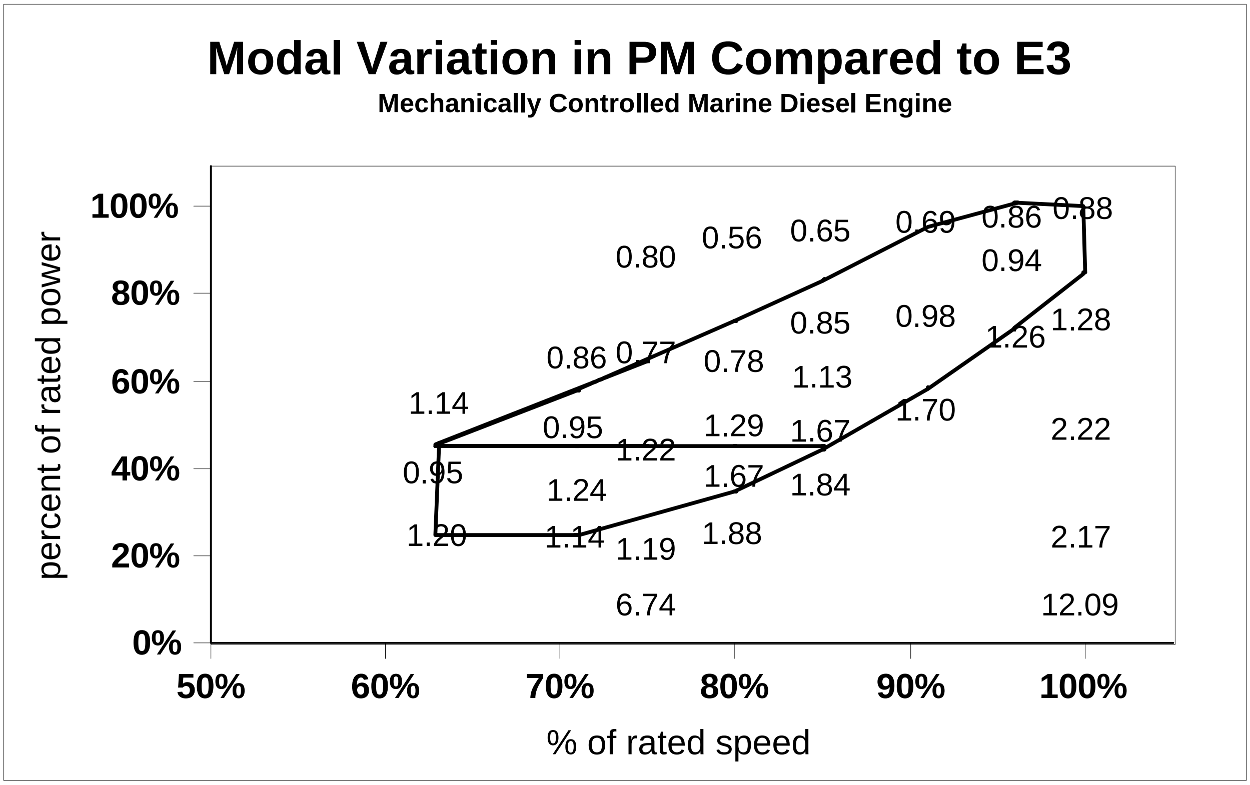
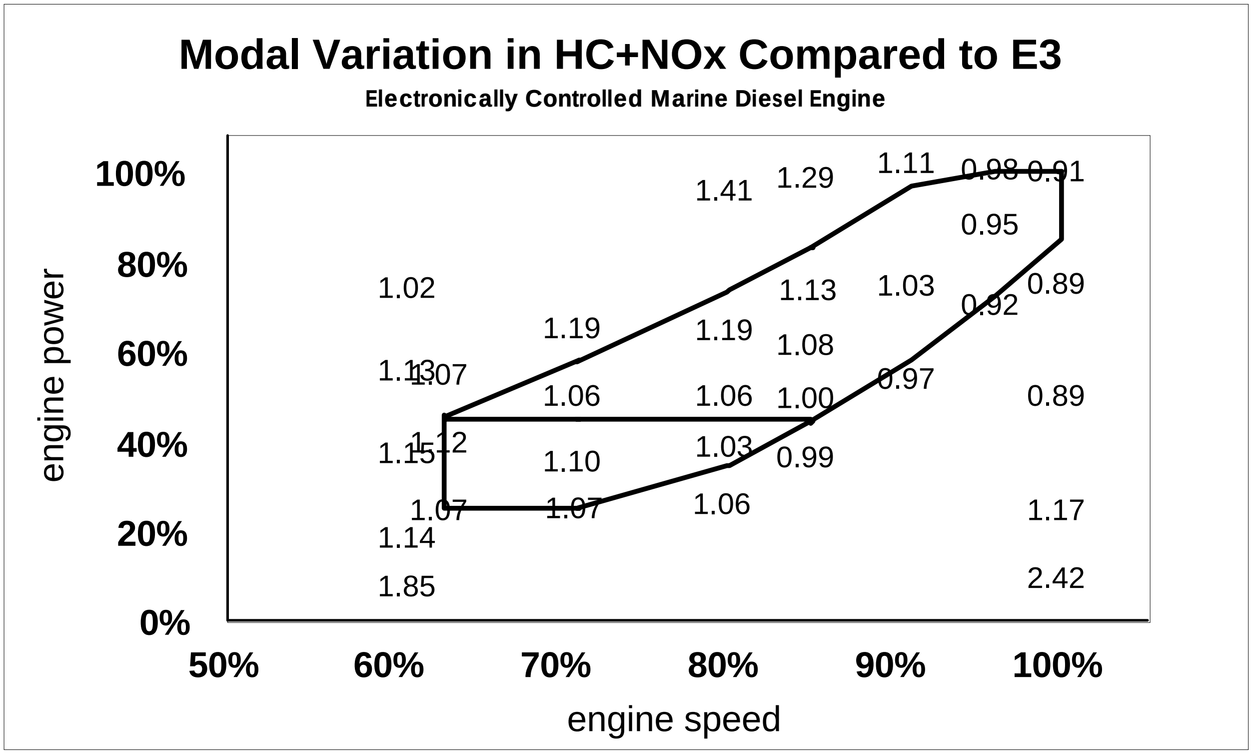
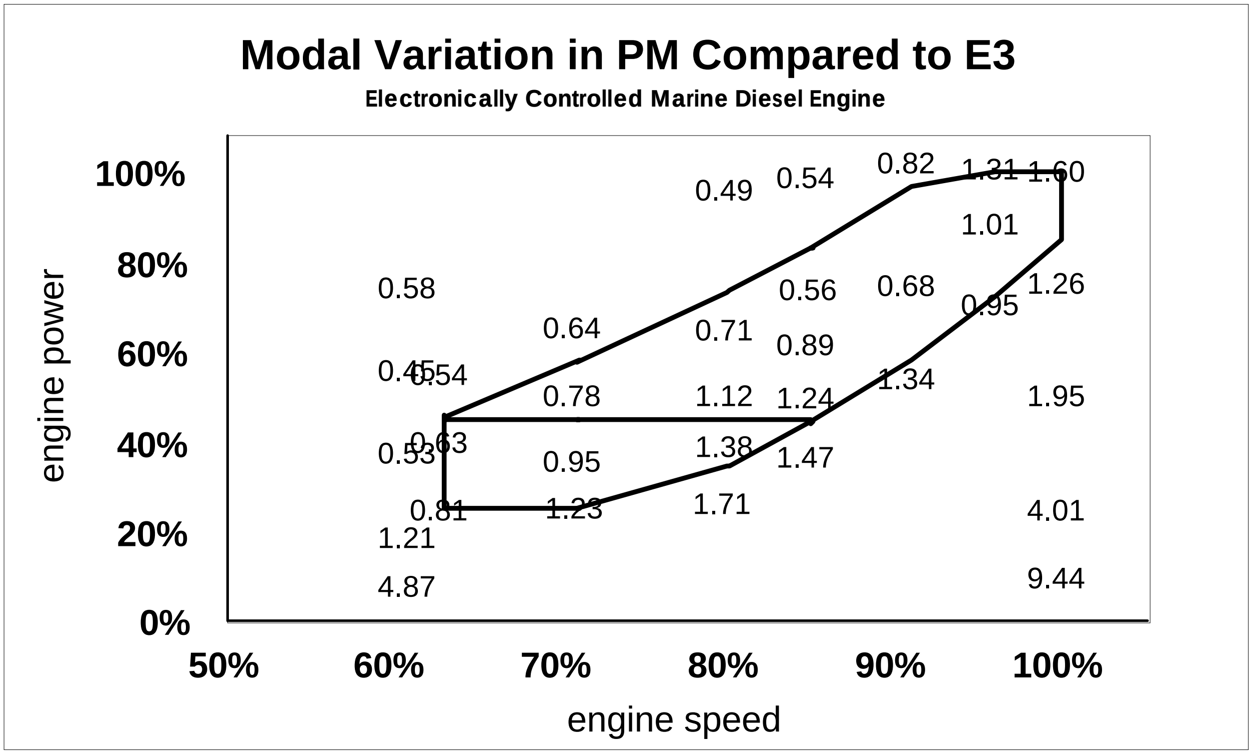


Figure 3-7: Ratio of Modal to E3 Emissions Compared to the NTE Zone For an Electronically Controlled Marine Diesel Engine





The use of electronic controls should give marine engine manufactures more flexibility in how they meet the cap under all operation compared 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 facilitate in-use testing.

EPA recognizes the difficulties of complying to the caps over an NTE zone with a mechanical engine due to the restriction of a fixed injection timing. However, the split zone with different caps should address this difficulty. 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 new requirements through optimization of the engine calibration.

3. Ambient Conditions

air temperature and humidity

Ambient air conditions, including temperature and humidity, have a significant effect on emissions from marine engines in use. 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 13-30°C (55-86°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 ranges were based on temperatures seen during ozone exceedences, except that the upper end of the air temperature range has been adjusted to account for the cooling effect of a body of water on the air above it.[49] We are also aware, however, that marine engines sometimes draw their intake air from an engine compartment or engine room with such that intake air temperatures are substantially higher than fresh air temperatures. We are therefore retaining 35°C as the upper end of the specified range for engines that don't draw their intake air from the outdoor ambient. The air temperature and humidity ranges are otherwise consistent with those developed for NTE testing of highway heavy-duty diesel engines.

For NTE testing in which the air temperature or humidity is outside of the range, the emissions must be corrected back to the specified air temperature or humidity range. These corrections must be consistent with the equations in 40 CFR Part 89, Subpart E except that these equations correct to 25°C and 10.7 grams per kilogram of dry air while corrections associated with the NTE testing shall be to the nearest outside edge of the specified ranges. For instance, if the outdoor ambient temperature were higher than 30°C for an engine with a that drew fresh outdoor air into the intake, a temperature correction factor may be applied to the emissions results to determine what the emissions would be at 30°C.

EPA believes that these ranges of ambient air conditions will have a small effect on emissions within the NTE requirements. For commercial marine engines using aftercooling, the charge air temperature is insensitive to ambient air temperature compared to the cooling effect of the aftercooler. SwRI tested this theory and found that when the ambient air temperature was increased from 21.9 to 32.2°C, the cooling water to the aftercooler of a commercial marine engine only had to be reduced by 0.5°C to maintain a constant charge air temperature.[50] At the same time, the effect of varying temperatures on turbocharger performance and the corresponding effect on PM emissions is not well understood. According to the CFR correction factor, there is only a ±3% variation in NOx in the NTE humidity range.

water temperature

Ambient water temperature also may affect emissions due to its impact on engine and charge air cooling. For this reason, NTE testing includes a range of ambient water temperatures from 5 to 27°C (41 to 80°F). The water temperature range is based on temperatures that marine engines experience in the U.S. in use. 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 does not believe that the range of ambient water temperatures discussed above will have a significant effect on the stringency of the NTE requirements. Following the normal engine test practice recommended by SAE[51] for aftercooled engines, the cooling water temperature would be set to 25±5°C. This upper portion of the NTE temperature range is within the range suggested by SAE for engine testing. For lower temperatures, manufacturers would be able to use a thermostat or other temperature regulating device to ensure that the charge air is not overcooled. In addition, the SAE practice presents data from four aftercooled diesel engines on the effects of cooling medium temperature on emissions. For every 5°C increase in temperature, HC decreases 1.8%, NOx increases 0.6%, and PM increases 0.1%.

EPA is aware that many marine engine installations are designed for operation in a given climate. For example, to stay within the engine manufacturer's specified operating temperatures, a fishing vessel operating in Alaska does not need to be designed for 27°C water temperatures. In this case, the boat builder could take advantage of the cooler water to build a smaller heat-exchanger system. This vessel operating in a warmer climate would likely not stay within the specified ranges for the engine. This would likely increase engine emissions, but could also drastically shorten the engine's operating life. EPA will perform in-use testing on engines where they operate. If we find a vessel that operates in a way that does not meet the engine manufacturer's specifications, we may pursue an enforcement action against the boat builder or the vessel operator.

In addition, EPA understands that there are times when someone may need to compromise emission control for startability or safety reasons. Manufacturers aren't responsible for the NTE requirements under start-up conditions. In addition, manufacturers may petition to be exempt from emission-control requirements under specified extreme conditions such as engine overheating where emissions may increase under the engine protection strategy.

D. Emissions Sampling

Aside from the duty cycle, the test procedures for CI marine engines are 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 has based 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 is 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 emissions is through the use of full dilution sampling. However, for larger engines the exhaust flows become so large that conventional dilute testing requires 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, the MARPOL NOx Technical Code specifies analytical instruments, test procedures, and data reduction techniques for performing test-bed and in-use emission measurements.[52] 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 this final rule become enforceable.

Because marine engines often become an integral part of a vessel and cannot easily be removed, EPA reserves 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 a portable 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.

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 highway to nonroad to marine occurs. Table 3-1 provides more detail on the baseline technology mix.

Table 3-1
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 are presented in Table 3-2 and compared to the new emission standards.[53,54,55,56,57,58] For the eleven of the propulsion marine engines, the results are based on the E3 test cycle; for the other two, results were only available on the C1 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 the levels of today's Category 1 marine diesel engines to meet the new emission standards. On average, EPA is requiring significant reductions in HC+NOx and PM; however, the CO standards will act as a cap to prevent increased emissions..

Table 3-2
Emissions Data from Baseline Category 1 Marine Diesel Engines

Rated Power (kW)	Technology Mix	Emissions Data g/kW-hr				New Standards		
		HC	NOx	CO	PM	HC+NOx	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	7.5	5.0	0.4
134	turbocharged	0.28	8.4	0.44	0.16	7.2	5.0	0.2
157	naturally aspirated	—	10.8	—	—			
199	turbocharged, aftercooled, electronic injection	0.16	10.3	1.2	0.21			
216	turbocharged	—	7.5	—	—			
235	turbocharged jacket-water aftercooled	—	8.9	—	—			
237	turbocharged	0.03	9.1	1.4	—			
262	turbocharged raw-water aftercooled	0.37	7.8	0.7	—			
265	turbocharged jacket-water aftercooled	0.35	9.4	0.6	—			
280	turbocharged jacket-water aftercooled	—	7.8	—	—			
336	turbocharged	0.09	7.0	1.6	0.17			
447	turbocharged jacket-water aftercooled	0.52	9.7	1.7	0.17			
746	turbocharged, unit injection, jacket-water aftercooled	0.39	16.2	2.6	—			
895	turbocharged jacket-water aftercooled	0.27	9.7	1.3	—			

* 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 marinized 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 and two engines tested by Caterpillar.[59,60] Also, we have NOx data on nine locomotive engines tested over the E3 duty cycle. According to the source[61] of this locomotive data, this data should approximate marine engine data. The E3 weighted emission results from these engines are presented in Table 3-3. Of the five marine 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 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.[62,63] The Lloyd's data is included in Figure 3-3. The Lloyd's data is particularly interesting because it measures emissions from commercial vessels in-use.

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

Rated Power (kW)	Technology Mix	Emissions g/kW-hr				New Standards		
		HC	NOx	CO	PM	HC+NOx	CO	PM
902	locomotive	—	17.7	—	—	7.8	5.0	0.27
1120	turbocharged, unit injection, jacket-water aftercooled	0.50	14.9	2.0	—			
1183	locomotive	—	20.9	—	—			
1357	locomotive	—	21.0	—	—			
1460*	turbocharged	0.50	16.5	1.1	0.52			
1584	locomotive	—	21.1	—	—			
1710*	turbocharged	0.03	13.1	1.4	0.17			
1801	locomotive	—	17.9	—	—			
1828	locomotive	—	15.2	—	—			
1900*	turbocharged, aftercooled	0.03	16.4	4.1	0.27			
2001	turbocharged, unit injection, jacket-water aftercooled	0.55	17.8	2.6	—			
2190*	turbocharged	0.00	11.3	4.9	0.32			
2289	locomotive	—	17.8	—	—			
2356	locomotive	—	16.2	—	—			
2380*	turbocharged, two-stroke opposed piston	0.11	9.5	0.9	—			
2745	locomotive	—	18.6	—	—			

* 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).[64,65] 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.[66] Power density (rated engine power/engine weight) is sacrificed to operate at maximum efficiency rather than maximum output. In comparison, commercial Category 2 and Category 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 (NOx) and particulate matter (PM) emissions. For diesel engines there is an exponential relationship between NOx 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 NOx formation conditions. However, these conditions do provide for a high 95%-burn combustion temperature, which minimizes non-volatile carbon PM emissions.[67] In addition, the use of bunker fuel can result in higher NOx 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.[68] 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 marine diesel duty cycles. This data is presented in Table 3-4. To generate the E2 weighted results, the raw Lloyd's data was converted to mass rates by converting all NOx reported volume concentrations to NO_2 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 MARPOL. 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.

Table 3-4
Emission Data from Baseline Category 3 Marine Diesel Engines

Rated Power [kW]	Rated Speed [rpm]	Measured NOx [g/kW-hr]	MARPOL 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.[c] Table 3-5 presents emissions data from several low-emission marine engines based on the E3 marine test cycle.[69,70,71,72,73]

Figure 3-8 compares the emission results from the baseline and low-emission high-speed marine engines presented in this chapter to the new emission standards. The emission levels of these demonstration engines compare favorably to the new standards.

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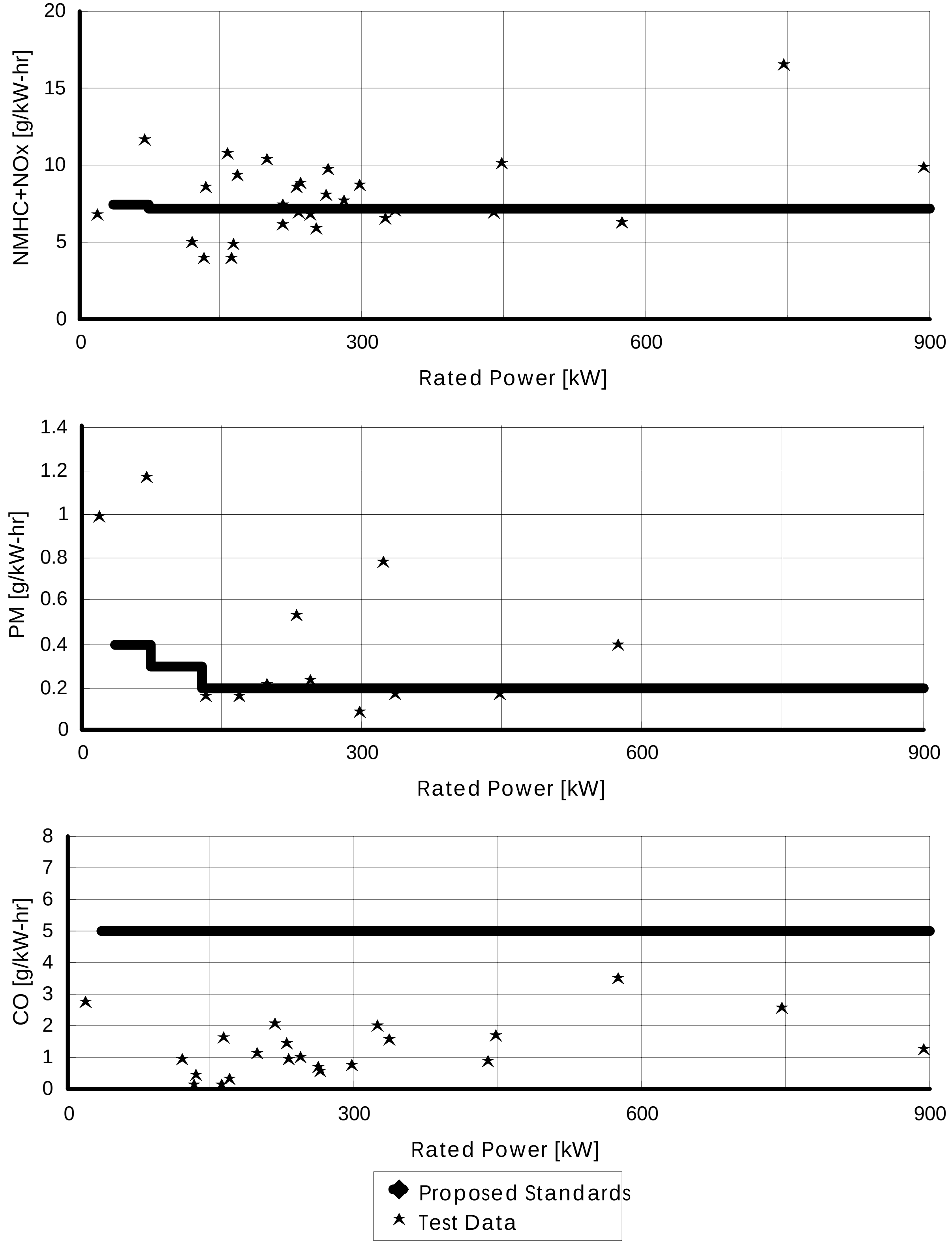
[c] The only problem that was reported was due to the calibration of the electronic controls on one engine type. This problem has been resolved.

Table 3-5
Emissions Data from Low-Emission Category 1 Marine Diesel Engines

Rated Power (kW)	Technology Mix	Emissions g/kW-hr				New Standards		
		HC	NOx	CO	PM	HC+NOx	CO	PM
120	turbocharged, raw-water aftercooled, electronic control	0.09	5.0	0.96	—	7.2	5.0	0.3
132	turbocharged, raw-water aftercooled, IDI	0.05	4.0	0.13	**	7.2	5.0	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	7.2	2.0	0.27

* This data is based on C1 test cycle.
** No PM data was collected, but the manufacturer reported that there was no visible smoke.

Figure 3-8: Diesel Marine Engine Emissions Compared to the 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 technologies listed below will be sufficient for meeting both the new emission standards and the NTE requirements.

A. Category 1 Marine Diesel Engines

EPA anticipates that timing retard may be used in many Category 1 marine diesel applications, especially in certain modes of engine operation to ensure adequate control of NOx emissions across the whole NTE zone. 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 will be making greater 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, NOx, 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. Electronically controlled common rail engines should prove to be capable of meeting even lower emission levels in the future, especially for smaller engines.

EPA projects that all Category 1 marine diesel engines will be turbocharged and most will be aftercooled to meet Tier 2 emission standards. Aftercooling strategies will likely be a mix of jacket-water and separate-circuit aftercooling. EPA does not expect a significant increase in the use of raw-water charge air cooling for marine engines as a result of this rule. Chapter 4 presents a possible scenario of how these technologies could be used on Category 1 marine diesel engines to meet the Tier 2 standards.

By setting 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 new emission standards, EPA projects that the majority of these engines will continue to be turbocharged and aftercooled. EPA believes that separate-circuit aftercooling will most likely be considered more attractive than jacket-water 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.

C. Category 3 Marine Diesel Engines

EPA anticipates that Category 3 engines will be able to achieve the MARPOL NOx 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 NOx emissions. Reducing NOx 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 reduces NOx 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 MARPOL 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.[74] 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 applying the recently finalized test fuel specifications for nonroad diesel engines to Category 1 and Category 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 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 new emission standards is 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 test fuel specifications are presented in Table 3-6. Because testing conducted by EPA is limited to the test fuel specifications, it is important that the test fuel be representative of in-use fuels.

Table 3-6
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.[75] Table 3-7 summarizes current ASTM standards for a marine distillate oil, residual fuel, and the two most common IF blends.

Table 3-7
Comparison of ASTM Fuel Specifications[76]

	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

The use of residual fuel has two important consequences. First, it is more difficult to handle. Because of it’s 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.

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.[77] 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.[78] 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.[79]

Residual fuel also has a detrimental effect on particulate matter (PM) emissions. One Category 3-engine study[80] 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 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 NOx formation. Fuel injection changes and other NOx control strategies therefore typically reduce engine noise, sometimes dramatically.

The impact of the new emission 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 new 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 new emission 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 new emission standards. The costs of individual technologies are developed in considerable detail and then combined according to the projections of technology changes. EPA developed the costs for individual technologies in cooperation with ICF, Incorporated and Geraghty & Miller in a combination of reports related to diesel engine emission controls.[1,2]

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 generally correspond with the displacement values used to differentiate among the standards.

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.[3] 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. Costs are presented in 1997 dollars.

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 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 +	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. In most cases, 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 overstates the actual impact of the emission standards.

As discussed in Chapter 3, manufacturers of Category 1 engines are expected to comply with the new emission standards by conducting basic engine modifications, upgrading fuel systems, and improving aftercooling systems. Manufacturers of Category 2 engines are expected to redesign combustion chambers, improve high-pressure fuel injection systems, and upgrade or add turbocharging and aftercooling. While the final emission standards vary for different sizes of Category 2 engines, this analysis presents only a single set of cost estimates for all these engines. The Category 2 emission standards are based on the technological capabilities of engines, taking into account the generally observed increase in emission levels with greater engine size. The graduated standards therefore call for a common set of technologies for all the different sizes of Category 2 engines. The Category 2 cost estimates therefore represent the whole range of Category 2 engines. As described above, this is not meant to imply that manufacturers will, in practice, adopt a uniform set of technologies to comply with emission standards.

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, adjusting fuel injection parameters, 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.

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.[d] 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. As an attempt to take this into account, we present the full cost of the control technologies in this chapter, then apply a credit to some of these costs for calculating the cost-effectiveness of the rulemaking, as described in Chapter 6.

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.[4]

Cost estimates for fuel injection upgrades are derived from estimates for nonroad engines. Variable costs are carried directly 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 are also considered. The anticipated R&D effort should be focused primarily on transferring established engine technologies to marine engines. Projected fixed costs are therefore reduced from

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

the levels anticipated for redesigning nonroad engines. EPA's general expectation is that one-third of the previously anticipated level of R&D will 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 the new emission standards. 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

Engine Size	R&D
100 kW	$490,000
400 kW	$498,000
750 kW	$1,400,000
1500 kW	$1,400,000
3000 kW	$1,870,000

As described in the preamble to the final rule, the manufacturers are responsible to comply with emission limits at any speed and load that can occur on a vessel. EPA believes it is not appropriate to consider additional costs for manufacturers to comply with these "off-cycle" requirements. This is because we expect that manufacturers can manage engine operation to avoid unacceptable variation in emission levels by more effectively using the technologies that will be used to meet the emission limits more broadly, rather than by use of additional hardware. For example, manufacturers can adust fuel injection parameters to avoid excessive emissions. The split-zone approach described in Chapter 3 is designed to accommodate normal variation in emission levels at different operating points. This approach involves no additional variable cost. The estimated R&D expenditures 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. Fuel Injection Improvements

All engines are expected to see significant improvements in their fuel injection systems. We also expect some engines to see incremental improvements in existing unit injector designs (see

Table 4-4). Better control of injection timing and increased injection pressure contribute to reduced emissions.

An additional alternative is a common rail injection system. The principal benefit of common rail technology is that injection pressure is not 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.[5] 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 4-5.

Table 4-4
Unit Injection Improvements

	100 kW	400 kW	750 kW	1500 kW	3000kW
Component costs per engine	$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 (1995 $)	$182	$375	—	—	$5,882
Composite Unit Cost (1997 $)	$190	$392	—	—	$6,150

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

Table 4-5
Common Rail Fuel Injection

	100 kW	400 kW	750 kW	1500kW	3000kW
Component costs per engine	$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 (1995 $)	$296	$381	$5,417	$5,315	$19,868
Composite Unit Cost (1997 $)	$310	$398	$5,665	$5,558	$20,776

B. 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 nonroad Tier 2 emission levels. Remaining engine modifications reflect the need to adapt these 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 cost savings for non-emission benefits are applied in the cost-effectiveness calculation. 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 new emission standards. 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 4-6 shows the estimated per-engine costs for these modifications.

Table 4-6
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

C. Turbocharging

EPA expects that turbocharging will be needed by all marine diesel engines rated over 37 kW. 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 will be needed for adding turbocharging alone. This accounts for the fact that much of the capital costs for turbocharger development is borne by the turbocharger manufacturer, which is then reflected in the hardware cost to the engine manufacturer. Total turbocharger cost impacts are presented in Table 4-7.

Turbocharging can be used to increase power, which leads to 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 is not needed to comply with emission standards. As described at the end of Section II, these non-emission benefits support the analytical approach of assigning only half the cost of turbocharging as an impact of the new emission standards.

Table 4-7
Turbocharging

	100 kW	400 kW	750 kW	1500 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

D. 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 4-8 and 4-9, 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 4-10). The ample supply of cooling water and its greater convection coefficient relative to air support our 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 involves 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.

Table 4-8
Incremental Cost of Adding Jacket-Water Aftercooling

	100 kW	400kW	750 kW	1500 kW	3000kW
Component costs per engine	$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 4-9
Incremental Cost of Adding Separate-circuit Aftercooling

	100 kW	400kW	750 kW	1500 kW	3000 kW
Component costs per engine	$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	$2,378	$7,276	—	—	$59,236

Table 4-10
Incremental Cost of Converting from Jacket-Water to Separate-circuit Aftercooling

	100 kW	400 kW	750 kW	1500 kW	3000kW
Component costs per engine	$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

E. 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 a fuel injection 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 4-11.

Table 4-11
Incremental Rebuild Costs

	100 kW	400 kW	750 kW	1500 kW	3000kW
Incremental hardware costs per engine:					
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
Incremental labor hours per engine:					
Turbocharger	1	—	—	—	6
Jacket-water aftercooling	5	5	—	—	—
Separate-circuit aftercooling	11	20	40	60	90
Aftercooling upgrade	6	15	30	45	68

F. 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 4-12 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 $10,000 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 4-13. 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 final rule exclude the smallest companies from requirements to conduct production line testing.

Table 4-12
Certification

	100 kW	400 kW	750 kW	1500 kW	3000kW
Total fixed costs	$30,000	$30,000	$40,000	$40,000	$50,000
Fixed cost per engine	$58	$70	$687	$600	$897
Composite Unit Cost	$58	$70	$687	$600	$897

Table 4-13
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

G. Total Engine Costs

These individual cost elements can be combined into a calculated total for the new emission standards 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 response to the new emission standards.

To comply with emission standards, manufacturers are expected to rely on turbocharged engines with extensive modification to injection systems 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. One exception to that is our expectation that manufacturers will not need to add electronic controls to comply with the marine diesel emission standards. 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.

We also expect manufacturers to take a variety of approaches to improve fuel systems. 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.

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 4-14, estimated costs for complying with emission standards increase with increasing power ratings. Estimated cost impacts range from $1,800 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 costs (Table 4-15). 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.

Long-term costs decrease due to two principal factors. First, the analysis anticipates that manufacturers recover their initial fixed costs for tooling, and R&D certification over a five-year period. Fixed costs are therefore applied only to the first five model years of production.

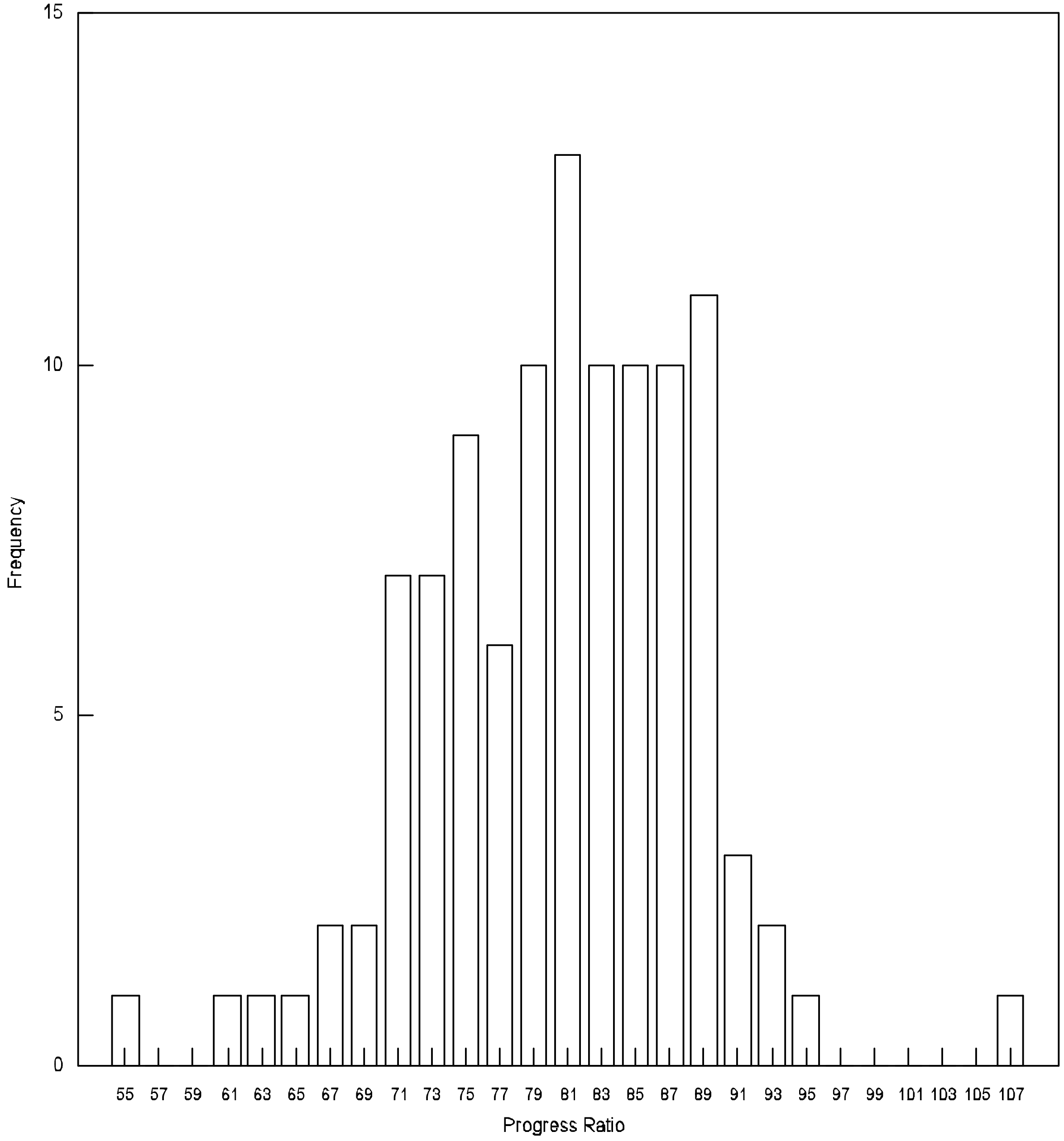
The second modification is related to the effects of the manufacturing learning curve. The learning curve literature asserts that as cumulative production increases, the input requirements may decrease as well. The magnitude of the reduction in production requirements may be expressed as a progress ratio, p, where each doubling of cumulative past production leads to a "p" percent reduction in input requirements, hence unit cost. Areas involving direct labor and material are usually the source of the greatest savings. These include, but are not limited to, a reduction in the number or complexity of component parts, improved component production, improved assembly speed and processes, reduced error rates, and improved manufacturing process. These all result in higher overall production, less scrappage of materials and products, and better overall quality. As each successive p cycle takes longer to complete, production proficiency generally reaches a relatively stable level, beyond which increased production does not necessarily lead to markedly decreased costs.

Companies and industries learn differently. On average, it appears that doubling a firm’s cumulative output may be associated with the decrease in the unit cost by 20% (Alchian 1963, Argote and Epple 1990, Benkard 1999, Dutton and Thomas 1984). Dutton and Thomas (1984) report rates varying from a 45 percent savings to a 7 percent increase in unit costs (see Figure 4-1). The effect of learning curve seems to be less in the chemical industry and the nuclear power industry where a doubling of cumulative output is associated with 11% decrease in cost (Lieberman 1984, Zimmerman 1982). The effect of learning is more difficult to decipher in the computer chip industry (Gruber 1992).

However, there are two qualifiers to the general findings. First, many of the empirical estimations of the effect of learning curve implicitly assume that there is no depreciation of the learning. In contrast, Benkard (1999) finds that a firm’s knowledge may depreciate 39% in one year. Argote, et al (1990) increases this estimate to 96% in one year. This suggests that under some circumstances the effects of learning may not result in enduring cost savings.

Second, estimating cost from learning curves is very approximate. Dutton and Thomas (1984) state that without understanding the dynamics of learning, a simplistic use of learning curve to predict future costs has proved to be unreliable. Alchian (1963) finds that the difference between the estimated labor use using learning curves and the actual labor used is 25% on average (using industry learning curve, the difference ranges from +73% to -45%).

Figure 4-1
Distribution of Progress Ratios



From 22 field studies (n = 108).

Figure 18
Dutton and Thomas 1984

EPA applied a p value of 20 percent in this analysis. That is, the variable costs were reduced by 20 percent for each doubling of cumulative production. Using one year as the base unit of production, the first doubling occurs at the start of the third model year and the second doubling at the start of the fifth model year. To align with the five-year amortization of fixed-costs, EPA incorporated the second doubling at the start of the sixth model year. Variable costs are reduced by a total of 36 percent using two "p" cycles with "p" valued at 20 percent. For a sensitivity analysis of this assumption, see Table 4-16.

EPA believes the use of the learning curve is appropriate to consider in assessing the cost impact of diesel engine emission controls. The learning curve applies to new technology, new manufacturing operations, new parts, and new assembly operations. While all the technologies projected in this analysis specify either upgraded existing designs or transferred nonroad engine developments, the changes envisioned nevertheless require manufacture of new components and assemblies, involving new manufacturing operations. 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 manufacturers gain experience with these new systems, comparable learning is expected to occur with respect to unit labor and material costs.

Table 4-14 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 up to 90 percent demonstrate the predominance of research and other fixed costs in the total estimated impact of the emission standards.

Focusing on the learning curve's effect on the cost estimates shows the sensitivity of these assumptions. Applying one stage of learning results in a 7 percent reduction in total costs for 100, 400, and 3000 kW engines. The 750 and1500 kW engines rely predominantly on fixed costs, so the learning curve has a negligible effect on those engines. Applying the second stage of learning would further decrease the cost by 6 percent to 13 percent of the total cost. Table 4-16 contrasts these two learning curve scenarios.

Table 4-14
Engine Costs

	100 kW		400 kW		750 kW		1500 kW		3000kW	
	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost
Common rail	0%	—	0%	—	100%	$5,665	100%	$5,558	0%	—
Unit injection upgrade	100%	$190	100%	$392	0%	—	0%	—	100%	$6,150
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%	$238	0%	—	0%	—	0%	—	10%	$5,924
Upgrade to separate-circuit aftercooling	15%	$140	30%	$762	0%	—	0%	—	80%	$12,570
Certification + PLT	100%	$158	100%	$170	100%	$837	100%	$750	100%	$1,097
Total Cost per Engine (yr. 1-5)	—	$1,806	—	$3,208	—	$25,395	—	$22,818	—	$54,192
Total Cost per Engine (yr. 6 and later)**	—	$486	—	$846	—	$856	—	$1,120	—	$13,019

*"Fraction" denotes the percentage of engines estimated to require each of the new or improved technologies.
**Variable costs are reduced by a total of 36 percent using two "p" cycles with "p" valued at 20 percent. For a sensitivity analysis of this assumption, see Table 4-16.

Table 4-15
Rebuild Costs

	100 kW		400 kW		750 kW		1500 kW		3000kW	
	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost	Fraction*	Cost
Incremental hardware costs per engine:										
Common rail	0%	—	0%	—	100%	$169	100%	$520.00	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	—	$245	—	$408	—	$169	—	$520.00	—	$7,062
Incremental labor costs per engine:	—	$116	—	$168	—	$0	—	$0.00	—	$1,778
Total cost per rebuild	—	$361	—	$576	—	$169	—	$520	—	$8,840
Total rebuild cost per engine (npv)	—	$441	—	$703	—	$207	—	$635	—	$12,430

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

Table 4-16
Long-Term Costs—Sensitivity of Learning Curve Assumptions

Number of p cycles	100 kW	400 kW	750 kW	1500 kW	3000kW
1	$606	$1,065	$904	$1,267	$16,109
2	$486	$846	$856	$1,120	$13,019

H. 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 NOx 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. EPA therefore conducted a sensitivity analysis to show the costs associated with a fuel penalty resulting from relying on retarded timing.

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. This cost results from increased fuel consumption. Considering the established effectiveness of timing retard as a strategy to control NOx 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. 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 $10 million in the first year the new standards apply, increasing to a peak of about $29 million in 2007 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 $5 million after 2011.

Chapter 4 References

1.“Estimated Economic Impact of New Emission Standards for Heavy-Duty Highway Engines,” Acurex Environmental Corporation Final Report (FR 97-103), March 1997 (Docket A-97-50; document IV-A-3). The Acurex Environmental Corporation has since changed its name to Arcadis Geraghty & Miller.

2.“Incremental Cost Estimates for Marine Diesel Engine Technology Improvements,” Memorandum from Louis Browning and Kassandra Genovesi, Arcadis Geraghty & Miller, to Alan Stout, EPA, September 30, 1998 (Docket A-97-50; document II-A-2).

3."Update of EPA's Motor Vehicle Emission Control Equipment Retail Price Equivalent (RPE) Calculation Formula," Jack Faucett Associates, Report No. JACKFAU-85-322-3, September 1985 (Docket A-97-50; document IV-A-5).

4.Tables showing the full development of cost estimates for each technology are included in a memorandum to the docket entitled, “Final Cost Estimates for Marine Diesel Engine Emission Control Technology,” November 17, 1999 (Docket A-97-50; document IV-B-3).

5. “The Year in Review: The Beat Goes On,” Diesel Progress, June 1998, pp. 42, 44, 68 (Docket A-97-50; document II-G-13).

6.“Cat Gears Up Next Generation Fuel Systems,” Diesel Progress, August 1998, p. 82 (Docket A-97-50; document II-G-12).

7. See reference 2—Arcadis Geraghty & Miller, 1998.

8. See reference 2—Arcadis Geraghty & Miller, 1998.

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CHAPTER 5: ENVIRONMENTAL IMPACTS

This chapter describes the expected environmental impacts of the new emission standards, which focus on reducing HC, NOx, CO, and PM emissions. Specifically, the first part of the chapter will discuss the health and welfare impacts of these pollutants. The second part of the chapter estimates the total nationwide emissions inventory for marine diesel engines and projects future emissions and emission reductions.

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 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 (NOx), 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 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 adopting new standards for CO. Carbon monoxide 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 rulemaking, 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 and some Great Lakes vessels. Because of the distinctly different characteristics between the design and operation of the marine diesel engines in these three categories, the final rule has provisions that are unique to each category. 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 engines were divided into recreational, commercial, and auxiliary applications. The applications were further divided into power ranges consistent with the way the standards apply to different sets of engines. 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:

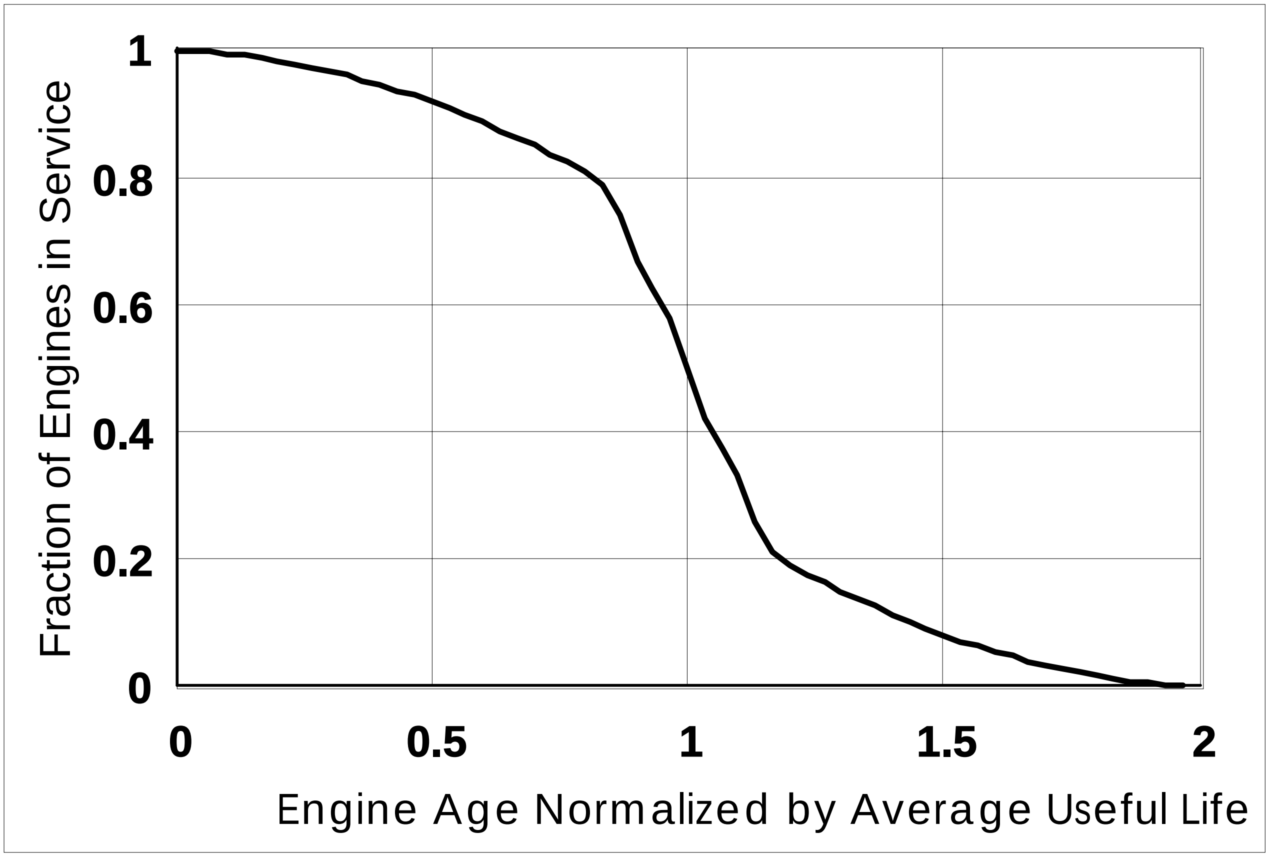
$$Emissions = \sum_{rec,com,aux}\left[\sum_{ranges}\left(population \times power \times load \times annual\,use \times emission\,factor\right)\right]$$

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, NOx, CO, and PM. Although the emission standards combine HC and NOx, it is useful to consider the HC and NOx emission impacts separately. The split between HC and NOx for regulated engines is based on the data from Chapter 3 for technologies that are expected to be used to meet the new emission 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.

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.[e] 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

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[e] Although difficult to compare directly, these sales figures seemed to agree with the PSR data fairly well.

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 new 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. HC and NOx are combined in a single numerical emission limit. To separate them for inventory analysis, EPA estimates that the HC emissions will be reduced by 0.07 g/kW-hr reduction. 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 the final rule does not include standards for recreational marine diesel engines, 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 new emission standards on HC, NOx, and PM emissions from commercial and auxiliary Category 1 engines. The Tier 2 standards should reduce emissions from each of these engines by 26 percent for HC, 29 percent for NOx, and 38 percent for PM. 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 MARPOL standard are considered. For Category 1, the MARPOL standard represents a 3.5 percent reduction in NOx from new engines compared to baseline. The CO standard serves as a cap on the already low emissions from diesel engines; therefore, no emissions reductions are claimed here for CO. EPA is not including standards for Category 1 recreational engines in this rule. Thus, while Category 1 recreational engine emissions will be reduced somewhat as a result of the MARPOL standards, EPA is not claiming any benefits for Category 1 recreational engines here. Also, no Category 1 recreational engine emission reductions are included in the cost-effectiveness calculations in Chapter 6.

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	367	330	351
	benefit	0.0	1.2	20.2	68.0	145	170
	reduction	0%	0%	5%	16%	31%	33%
PM	controlled level	12.0	12.5	12.5	11.4	9.8	10.3
	benefit	0.0	0.0	0.5	2.3	5.1	6.0
	reduction	0%	0%	4%	16%	34%	37%

* The NOx reductions shown here include reductions from the MARPOL standards as well as those from the Tier 2 standards beyond the MARPOL standards. In 2030 the MARPOL standards account for 12 percent of the total Category 1 NOx reductions.

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	39.4	38.8	37.7	41.3
	benefit	0.0	0.1	1.5	5.2	13.4	18.0
	reduction	0%	0%	4%	12%	26%	30%
PM	controlled level	1.1	1.5	1.6	1.5	1.3	1.4
	benefit	0.0	0.0	0.1	0.3	0.7	1.0
	reduction	0%	0%	4%	15%	35%	41%

* The NOx reductions shown here include reductions from the MARPOL standards as well as those from the Tier 2 standards beyond the MARPOL standards. In 2030 the MARPOL standards account for 12 percent of the total Category 1 NOx reductions.

In 2010, the new standards are expected to result in reductions of 12 percent HC, 16 percent NOx, and 16 percent PM from Category 1 marine diesel engines. Once the effects of the new standards are fully phased in (i.e. in 2035 the new emission standards will lead to estimated reductions of 24 percent HC, 27 percent NOx, and 36 percent PM from Category 1 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. Table 5-7 shows the actual numbers of category 1 commercial and recreational engines subject the MARPOL and Tier 2 standards.

Table 5-7
Projected Category 1 Commercial and Auxiliary Engines Subject to Standards

	Uncontrolled	MARPOL	Tier 2
2000	67,000	3,900	0
2005	50,100	17,500	6,900
2010	32,600	17,500	28,300
2020	6,000	8,300	72,400
2030	600	1,500	93,900

As described in the preamble to the final rule, the manufacturers are responsible to 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 help 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.

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 5-8.

Table 5-8
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

2. Emission Benefits

To calculate the emissions benefits of the new emission standards, the replacement rates of old engines with new engines must be known. For this analysis, the average useful life of 23 years 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 emission standards presented in Chapter 1. Since EPA is only claiming NOx reductions from the new emission standards beyond those resulting from the MARPOL standards, the MARPOL reduction was calculated. The MARPOL standard will result in an average reduction of 14 percent from new engines compared to baseline engines. On a per engine basis, the Tier 2 standards represent reductions of 38 percent NOx. 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. Also, the PM and CO standards for Category 2 engines serve as caps, and no reductions in those pollutants are claimed. Because of the slow turnover rates, the full effects of these reductions will not be seen until after 2045. Projected benefits of the MARPOL requirements and the new standards for Category 2 engines are shown in Table 5-9. No NOx reductions are assumed for foreign flagged ships since it is unknown at this time which countries will adopt the MARPOL requirements. Foreign flagged ships make up about 4 percent of the Category 2 NOx inventory in U.S. waters. Table 5-10 shows the projected number of Category 2 engine subject to the MARPOL and Tier 2 standards.

Table 5-9

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

Year	MARPOL NOx	EPA NOx
2000	1.4	0.0
2010	17.0	11.1
2020	33.8	41.7
2030	44.5	72.1

Table 5-10
Projected Category 2 Engines Subject to Standards

	Uncontrolled	MARPOL	Tier 2
2000	1,550	66	0
2005	1,283	416	0
2010	995	498	293
2020	396	480	1,097
2030	103	179	1,897

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.

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 NOx for Category 2, while they make up about half of the national NOx 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 5-11.

Table 5-11
Baseline Emissions from Category 3 CI Marine
Engines Operated in U.S. Waters [thousand short tons per year]

Year	HC	NOx	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

2. Emission Benefits

This section calculates the emissions benefits for Category 3 engines associated with adopting the MARPOL 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 the limited data available to EPA. NOx reductions were determined by comparing the data in Chapter 3 to the emission limits presented in Chapter 1. As discussed in Chapter 3, the analysis assumes that engines certifying on diesel oil but operating on residual fuel have 10 percent higher NOx emissions in use. Because the MARPOL standards are not part of this rule, and EPA is setting no additional requirements for Category 3 engines, no benefits are claimed for Category 3 engines in the cost-effectiveness calculations contained in Chapter 6.

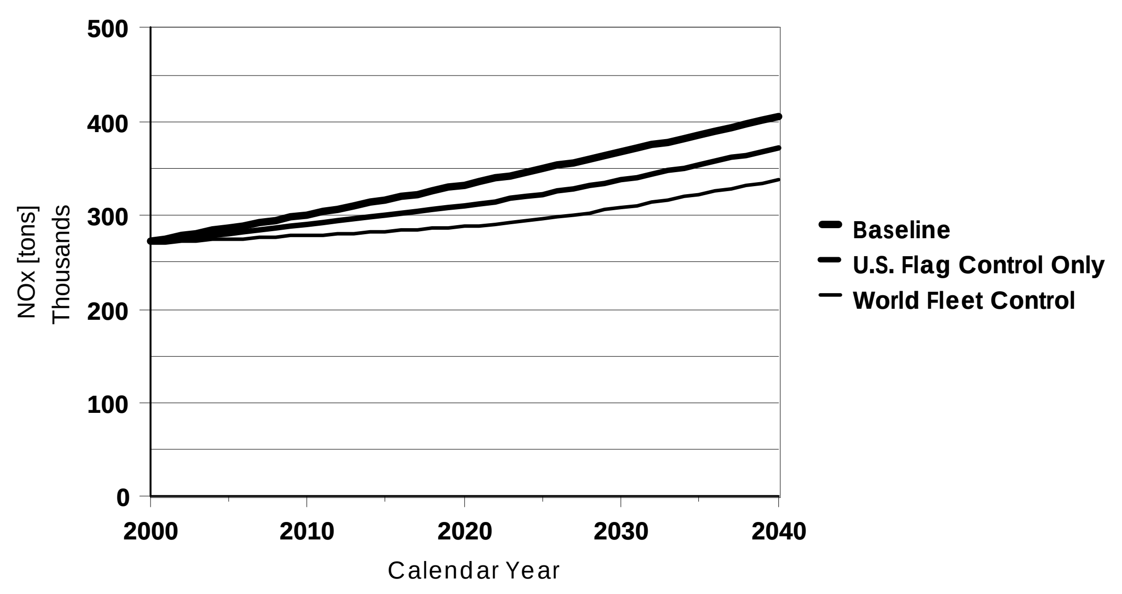
EPA estimates that adopting the MARPOL requirements will result in a 17 percent reduction in NOx from applicable new Category 3 engines. If this standard were only met on U.S. flagged ships, only about a 9 percent reduction in NOx is anticipated once all U.S. flag ships meet the MARPOL NOx standard. However, foreign flag ships may reduce NOx as other nations adopt the MARPOL provisions. The U.S. flag reductions and the potential effects (in U.S. waters) of world wide application of the MARPOL NOx standard are both presented in Table 5-12 and Figure 5-1.

Table 5-12
Projected NOx 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

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

Figure 5-1: Projected Baseline and Controlled National NOx 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.

The reductions associated with the new emission standards come from Category 1 commercial and auxiliary, and Category 2. 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.

EPA used nationwide emission estimates from the 1997 Trends Report[2] 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, NOx, PM, and CO emissions inventories are summarized in Table 5-13 along with the EPA estimates for CI marine engines. These data indicate that emissions from baseline CI marine engines account for 8.1 percent of NOx and 4.8 percent of PM from mobile sources and 4.4 percent of NOx 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 5-13
2000 National Emissions [thousand short tons]

Emission Source	VOC	NOx	PM	CO
CI Marine	31	1,005	42	133
Other Nonroad	2,044	4,930	593	16,286
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 5-14 contains the baseline annual emissions from marine diesel engines as a whole as well as projections of the annual emissions with the MARPOL requirements and EPA's new emission standards in place. According to this analysis, the new emission standards will yield reductions from the baseline of 8 percent HC, 21 percent NOx, and 11 percent PM from marine diesel engines in 2020. Only NOx reductions beyond those resulting from the MARPOL standards are claimed to result from the Tier 2 standards. Thus, only those reductions beyond those resulting from the MARPOL standards are included in the cost-effectiveness values shown in Chapter 6. In 2020 the Tier 2 standards will result in a 15 percent NOx reduction below the levels expected from the MARPOL standards.

Table 5-15 contains a similar analysis as that shown in Table 5-14 but is limited only to those engines covered by the Tier 2 standards (Category 1 commercial and auxiliary, and Category 2). This analysis shows that, within the group of engines subject to the Tier 2 standards, the new emission standards will yield reductions from the baseline of 12 percent HC, 27 percent NOx, and 24 percent PM from Category 1 commercial and auxiliary, and Category 2 marine diesel engines in 2020. In 2020 the Tier 2 standards will result in a 23 percent NOx reduction below the levels expected from the MARPOL standards for this group of engines.

Nationally, the new emission standards will yield estimated reductions of 0.9 percent NOx and 0.1 percent PM, with greater percentage reductions expected in 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 NOx emissions. It is also important to note that the emission reductions in densely populated port areas may be of greater value.

Table 5-14
Total Emission Reductions from all Commercial CI Marine Engines

		2000	2010	2020	2030
HC 10^3 short tons	baseline	31.3	34.8	38.7	43.2
	controlled	31.3	33.4	35.4	39.3
	reduction	0%	4%	8%	9%
NOx 10^3 short tons	baseline	1,005	1,117	1,244	1,390
	MARPOL	1,001	1,074	1,167	1,292
	controlled	1,001	1,004	987	1,056
	reduction*	0%	10%	21%	24%
PM 10^3 short tons	baseline	42.3	46.9	52.2	58.2
	controlled	42.3	44.4	46.4	51.2
	reduction	0%	4%	11%	12%

* This reduction is from the baseline. The Tier 2 standards are expected to achieve a 15 percent reduction in 2020 from the levels expected from the MARPOL standards.

Table 5-15
Emission Reductions from Engines Subject to Tier 2 Standards

		2000	2010	2020	2030
HC 10^3 short tons	baseline	22.4	24.7	27.3	30.1
	controlled	22.4	23.3	24.0	26.2
	reduction	0%	6%	12%	13%
NOx 10^3 short tons	baseline	702.2	773.5	852.2	939.0
	MARPOL	699.6	742.3	797.5	871.1
	controlled	699.6	672.1	618.0	634.7
	reduction*	0%	13%	27%	32%
PM 10^3 short tons	baseline	20.1	22.2	24.4	27.0
	controlled	20.1	19.7	18.6	20.0
	reduction	0%	11%	24%	26%

* This reduction is from the baseline. The Tier 2 standards are expected to achieve a 23 percent reduction in 2020 from the levels expected from the MARPOL standards.

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 5-16.

Table 5-16
Equivalent PM Emissions for
CI Marine Engines [thousand short tons per year]

Year	Total NOx Reductions	Equivalent PM Reductions
2005	37	1.5
2010	113	4.5
2015	193	7.7
2020	257	10.3

The expected reductions in NOx emissions should also positively affect visibility, acid deposition, and estuary eutrophication. Both NO_2 and nitrate particulates are optically active, and in some urban areas, NO_2 and nitrate particulates can be responsible for 20 to 40 percent of the visible light extinction. The effect of this rulemaking on visibility should be small but potentially significant, given that it is expected to reduce national NOx emissions by about 0.9 percent in 2020. This results in an estimated 0.2 to 0.4 percent reduction in haze. For areas with active ports, this reduction would be significantly greater.

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 new emission standards is about 65 percent of 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 rulemaking.

The new emission standards 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. Many of these molecules are considered toxic air emissions, 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 toxins can only be estimated here. This analysis was done using data on highway heavy-duty diesel engines.[4,5,6,7] According to this data, hydrocarbons from an highway HDDE include approximately1.1 percent benzene, 7.8 percent formaldehyde, 2.9 percent acetaldehyde, and 0.6 percent 1,3-butadiene. Table 5-17 shows the estimated air toxics reductions associated with the hydrocarbon reductions in this rule when the highway HDDE results are extended to this source.

Table 5-17
Estimated Annual Air Toxics Reductions [short tons]

Year	Benzene	Formaldehyde	Acetaldehyde	1,3-Butadiene
2005	4	26	10	2
2010	15	109	41	8
2015	28	196	73	15
2020	36	255	95	20

Chapter 5 References

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

3. “Benefits of Mobile Source NOx 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 new hydrocarbon and oxides of nitrogen emission standards. This analysis relies in part on cost information from Chapter 4 and emissions information from Chapter 5 to estimate the cost-effectiveness of the new standards in terms of dollars per short ton of total HC+NOx emission reductions. This chapter also examines the cost-effectiveness of the PM standards. Finally, the chapter compares the cost-effectiveness of this final rule with the cost-effectiveness of other NOx and PM control strategies from previous EPA rulemakings.

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 new emission standards, combining all of the nominal engine sizes, is also presented.

Benefits associated with the MARPOL provisions are not included in this analysis. Marine diesel engines greater than or equal to 130 kW will be subject to an international NOx standard prior to the implementation of EPA's new emission standards. Therefore, the baseline emissions case assumes emission control to the MARPOL standard for engines installed on vessels in 2000 and later. Because the new EPA standards apply only to Category 1 and Category 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. 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 whole set of new requirements.

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.

As shown in Table 4-2, some engines are using turbocharging and aftercooling technologies currently. Turbocharging and aftercooling provide important advantages in improving fuel consumption and power density. This shows that the turbocharging and aftercooling improvements for these engines provide benefits independent of emission control that justify their additional cost. Smaller engines have generally not adopted these technologies in the absence of emission standards. We expect the same non-emission benefits would apply to these engines when they adopt the anticipated technologies, since turbocharging and aftercooling have similar effects on engines of varying sizes. EPA understands, however, that market forces alone are not sufficient to drive these changes. As a result, manufacturers that adopt these technologies to comply with emission standards incur a cost that should be attributed to the standards. As the larger engines demonstrate, it would likely be appropriate to assign very close to 100 percent of the cost of these changes to non-emission benefits.

A similar assessment applies to fuel injection improvements. Manufacturers upgrading to higher-pressure injection with better control of injection parameters have the ability to improve both emissions and engine performance generally. The experience with highway engines shows, for example, that manufacturers have improved fuel consumption and extended total engine lifetimes during a period of tightening emission standards. While it is more difficult to quantify the non-emission benefits associated with fuel injection improvements, it is clear that these benefits are real. To avoid underestimating the cost impacts of the rulemaking, EPA believes it is most appropriate to assign equal weighting to emission and non-emission benefits for these technologies. The analysis therefore assesses 50 percent of the total costs of these technologies as an impact of the emission standards.

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. However, all costs shown in this chapter (with the exception of the "Accounting for Non-emission Benefits" columns in Table 6-2) are the entire costs of the technology, not just the portions attributed to emission reduction.

I. Engine Lifetime Cost-Effectiveness of the New Standards

A. HC+NOx

The cost-effectiveness of the new HC+NOx standards was calculated for the various nominal marine engine power ratings described in Chapter 4. For this analysis, the entire cost of the program is attributed to the control of HC and NOx emissions. As discussed in Chapter 4, the estimated cost of complying with the new emission standards varies depending on the model year under consideration (i.e. year 1 versus year 6). 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 achieved from the Tier 2 standards beyond the MARPOL 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 MARPOL 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 engine power ratings. Table 6-1 also 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 similarly.

Table 6-1
Discounted Cost-Effectiveness ($/short ton) of the Tier 2 HC+NOx Standards

Nominal Power (kW)	Model Year Grouping	NPV Benefits (short tons)	Emission Benefits Only			Accounting for Non-Emission Benefits		
			Operating & Compliance NPV Costs	Engine & Vessel Costs	Discounted Cost-Effectiveness	Operating & Compliance NPV Costs	Engine & Vessel Costs	Discounted Cost-Effectiveness
100	1 to 5	4.3	$442	$1,806	$521	$221	$1,175	$470
	6 +			$486	$215		$272	$164
400	1 to 5	26	$704	$3,208	$151	$352	$1,920	$137
	6 +			$846	$60		$458	$46
750	1 to 5	80	$206	$25,395	$319	$103	$22,562	$318
	6 +			$856	$13		$772	$12
1500	1 to 5	267	$636	$22,818	$88	$318	$20,039	$87
	6 +			$1,120	$7		$860	$5
3000	1 to 5	750	$12,430	$54,192	$89	$6,215	$41,494	$81
	6 +			$13,019	$34		$7,214	$26

Category 1, Category 2, and aggregate marine diesel engine cost-effectiveness figures for the 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 6-2 shows how the nominal power ratings were applied to the population as a whole.

Table 6-2
1997 Marine Diesel Engine Populations by Power Category

Category	Nominal Power (kW)	Power Range (kW)	Population
Category 1	100	37 - 225	42,690
	400	225 - 560	23,691
	750	560 - 1000	2,414
	1500	1000 +	2,596
Category 2	3000	all	1,569

Table 6-3 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 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.

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

Engine Class	Model Year Grouping	NPV Benefits (short tons)	Emission Benefits Only			Accounting for Non-Emission Benefits		
			Operating & Compliance NPV Costs	Engine & Vessel Costs	Discounted Cost-Effectiveness	Operating & Compliance NPV Costs	Engine & Vessel Costs	Discounted Cost-Effectiveness
Category 1	1 to 5	24	$528	$3,833	$185	$264	$2,831	$131
	6 +			$641	$50		$372	$27
Category 2	1 to 5	750	$12,430	$54,192	$89	$6,215	$41,494	$64
	6 +			$13,019	$34		$7,214	$18
Aggregate	1 to 5	39	$784	$5,979	$172	$392	$3,663	$103
	6 +			$1,163	$50		$519	$23

B. PM

EPA has also estimated the cost-effectiveness of the Tier 2 PM emission standards for each of the nominal power ratings. 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 program was included in the HC+NOx 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+NOx standards and results in an upper end estimate of the cost-effectiveness of the new PM standards. In addition, it should be noted that the HC+NOx cost-effectiveness calculations discussed above include the entire cost of the engine modifications that EPA believes will result from this final rule. Table 6-4 contains the resulting cost-effectiveness for each of the nominal power ratings.

Table 6-4
Discounted Cost-Effectiveness ($/short ton) of the New PM Standards

Nominal Power (kW)	Model Year Grouping	NPV Benefits (short tons)	Emission Benefits Only			Accounting for Non-Emission Benefits		
			Operating & Compliance NPV Costs	Engine & Vessel Costs	Discounted Cost-Effectiveness	Operating & Compliance NPV Costs	Engine & Vessel Costs	Discounted Cost-Effectiveness
100	1 to 5	0.13	$221	$903	$8,600	$111	$588	$5,341
	6 +			$243	$3,550		$136	$1,886
400	1 to 5	0.93	$352	$1,604	$2,112	$176	$960	$1,227
	6 +			$423	$837		$229	$437
750	1 to 5	2.87	$103	$12,698	$4,465	$52	$11,281	$3,953
	6 +			$428	$185		$386	$153
1500	1 to 5	6.20	$318	$11,409	$1,892	$159	$10,020	$1,642
	6 +			$560	$142		$430	$95
3000	1 to 5	6.58	$6,215	$27,096	$5,062	$3,108	$20,747	$3,625
	6 +			$6,510	$1,934		$3,607	$1,020

Table 6-5 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+NOx 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 rulemaking were applied to the PM cost-effectiveness analysis.

Table 6-5
Discounted Cost-Effectiveness ($/short ton)
of the PM Standards for Category 1 and 2 Engines

Engine Class	Model Year Grouping	NPV Benefits (short tons)	Emission Benefits Only			Accounting for Non-Emission Benefits		
			Operating & Compliance NPV Costs	Engine & Vessel Costs	Discounted Cost-Effectiveness	Operating & Compliance NPV Costs	Engine & Vessel Costs	Discounted Cost-Effectiveness
Category 1	1 to 5	0.77	$264	$1,916	$2,848	$132	$1,416	$2,021
	6 +			$321	$763		$186	$415
Category 2	1 to 5	6.20	$6,215	$27,096	$5,374	$3,108	$20,747	$3,849
	6 +			$6,510	$2,053		$3,607	$1,083
Aggregate	1 to 5	0.89	$392	$2,989	$3,797	$196	$1,831	$2,276
	6 +			$581	$1,093		$260	$511

C. Comparison with Cost-Effectiveness of Other Control Programs

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

A comparison of the cost-effectiveness numbers in Table 6-6 with the cost-effectiveness results presented throughout this chapter for marine diesel engines shows that the cost-effectiveness of the Tier 2 HC+NOx 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 6-6 and 6-7 reflect the aggregate cost-effectiveness for the program rather than the high and low for individual engines.

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

EPA Rule	Pollutants Considered in Calculations	Cost-Effectiveness ($/ton)
Clean Fuel Fleet Vehicle Program (Heavy-duty)	NOx	$1,300 - $1,500
2.5 g/hp-hr NMHC*+NOx Standard for Highway Heavy-Duty Engines	NMHC*+NOx	$100 - $600
Locomotive Engine Standards	NOx	$160 - $250
Nonroad Tier 2 Standards	NMHC*+NOx	$480 - $540

* 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 6-7 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 6-5 are more favorable than either of the urban bus programs and comparable to the nonroad Tier 2 standards.

Table 6-7
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

II. 30-Year Cost-Effectiveness of the New 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. 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+NOx

Table 6-8 presents the stream of costs and benefits associated with the new HC+NOx standards. The discounted cost-effectiveness of the HC+NOx standards over a 30-year period is $106/ton for Category 1, $46/ton for Category 2, and $92/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 diesel engines.

B. PM

Table 6-9 presents the stream of costs and benefits associated with the new PM standards. As with the per-engine analysis, EPA conservatively applied half of the incurred costs to PM control. The discounted cost-effectiveness of the new PM standards over a 30-year period is $1,272/ton for Category 1. No PM benefits are claimed for Category 2. The same relationship exists for these PM cost-effectiveness figures compared to the per-engine PM cost-effectiveness figures as does for the HC+NOx analysis.

Table 6-8
30-Year Stream of Costs and Benefits for the HC+NOx Standards

Calendar Year	Category 1		Category 2	
	Costs (10^6 $)	Benefits (10^3 tons)	Costs (10^6 $)	Benefits (10^3 tons)
2004	$10.1	7.0	$0	0
2005	$10.2	14.3	$0	0
2006	$23.2	21.7	$0	0
2007	$26.2	31.3	$2.9	2.7
2008	$17.7	41.0	$2.9	5.5
2009	$9.1	50.7	$3.0	8.3
2010	$9.2	60.5	$3.0	11.1
2011	$6.6	70.2	$3.0	14.0
2012	$4.0	79.9	$0.5	17.0
2013	$4.0	89.6	$0.5	20.0
2014	$4.1	99.1	$0.5	23.0
2015	$4.1	108.5	$0.6	26.0
2016	$4.1	116.7	$0.6	29.1
2017	$4.2	124.2	$0.6	32.2
2018	$4.2	131.0	$0.6	35.4
2019	$4.3	136.3	$0.6	38.5
2020	$4.3	141.0	$0.6	41.7
2021	$4.4	145.1	$0.6	44.9
2022	$4.4	148.7	$0.6	48.1
2023	$4.4	151.8	$0.6	51.4
2024	$4.5	154.7	$0.6	54.6
2025	$4.5	157.3	$0.6	57.8
2026	$4.6	159.7	$0.6	61.1
2027	$4.6	162.0	$0.6	64.3
2028	$4.7	164.1	$0.6	67.1
2029	$4.7	166.2	$0.6	69.7
2030	$2.4	168.1	$0.7	72.1
2031	$2.4	169.8	$0.7	74.4
2032	$2.4	171.5	$0.7	76.6
2033	$2.5	173.2	$0.7	78.3
2034	$2.5	175.0	$0.7	80.0
NPV	**$112.2**	**1063.1**	**$13.8**	**301.8**

Table 6-9

30-Year Stream of Costs and Benefits for the PM Standards

Calendar Year	Category 1	
	Costs (10^6 \$)	Benefits (10^3 tons)
2004	$5.0	0.3
2005	$5.1	0.6
2006	$11.6	0.9
2007	$13.1	1.3
2008	$8.9	1.7
2009	$4.5	2.1
2010	$4.6	2.5
2011	$3.3	2.9
2012	$2.0	3.3
2013	$2.0	3.7
2014	$2.0	4.1
2015	$2.1	4.5
2016	$2.1	4.8
2017	$2.1	5.1
2018	$2.1	5.4
2019	$2.1	5.6
2020	$2.2	5.8
2021	$2.2	6.0
2022	$2.2	6.2
2023	$2.2	6.3
2024	$2.2	6.4
2025	$2.3	6.5
2026	$2.3	6.6
2027	$2.3	6.7
2028	$2.3	6.8
2029	$2.4	6.9
2030	$1.2	7.0
2031	$1.2	7.1
2032	$1.2	7.1
2033	$1.2	7.2
2034	$1.2	7.3
NPV	**$56.1**	**44.1**