Commercial Marine Emissions and Life-Cycle Analysis of Retrofit Controls in a Changing Science and Policy Environment

■ James J. Corbett, P.E. and Paul S. Fischbeck

ABSTRACT

This paper considers the technical feasibility of achieving NO_x reductions through engine controls on existing ocean-going ships. International transport ships account for most of the NO_x emissions from shipping globally and regionally (Corbett and Fischbeck 1997; Corbett et al. 1999). Recently, regulatory efforts to control NO_x from ship propulsion have been adopted at the international level (IMO 1998)) along with related efforts at national levels (EPA 1998a; Lemieszewski 1999; National Swedish Maritime Administration 1996; Swedish Port and Stevedores Association 1999). The long working life of modern commercial ships, with world fleet averages greater than 20 years (UNCTAD 1995), implies that new-engine policies have limited value in meeting air-quality objectives in the near term. This has motivated efforts to control shipboard emissions with retrofit technologies. Nine technologies, demonstrated to control NO_x from existing engines, are described in terms of their ability to reduce emissions at the lowest life-cycle costs. The costs for these technologies are within the cost range of similar controls proposed for new marine engines and within the cost ranges for various land-based NO_x control efforts, suggesting that these are not only technically feasible but also are economically reasonable technologies for pollution control.

Controlling NO_x in Marine Diesel Engines

NO_x emissions can be reduced through primary and/or secondary control mechanisms. Primary methods affect the engine process directly and can reduce emissions by 10 to 50 percent; secondary methods reduce emissions without changing the engine performance from its full optimized setting and typically use equipment that is not integrally part of the engine itself (MAN B&W 1996). The types of methods that are commercially available include in-engine measures, mixtures of water in air or fuel, and selective catalytic reduction technology. Only selective catalytic reduction would be considered a secondary control method as defined above. Another way to consider these technologies is by whether control technologies require engine modifications (in-engine controls) or whether control strategies are implemented in the fuel or air system (pre-engine technologies) or in the exhaust system (post-engine technologies). These second definitions are used in the discussion below.

Nine specific NO_x control-technologies are considered, because of their application to existing marine engines or similar systems. In-engine NO_x control strategies include: 1) aftercooler upgrades, 2) engine derating, 3) injection timing delays, 4) fuel system modifications to increase supply pressure, 5) fuel injector upgrades, and 6) exhaust gas recirculation. Pre- and post-engine technologies that will be considered for NO_x control include: 1) water added to the combustion air, 2) water in fuel emulsions, and 3) selective catalytic reduction.

The literature discusses other engineering control strategies, some of which are proven to reduce NO_x in new marine engines or are being actively researched (Alexandersson et al. 1993; DOE 1997; EPA 1998b; NAVSEA 1992; NAVSEA 1994; NIAG 1996; Venkatesh 1996; Wartsila NSD 1998). These include direct in-cylinder water injection, in-cylinder ceramic coatings, non-thermal plasma systems, variable geometry turbocharging, etc. Since most of these technologies require substantial engine redesign that makes them infeasible for retrofitting on existing propulsion systems, they are not considered as options for achieving significant NOx reductions in the existing Fleet within the next couple of decades.

In-Engine NOx Controls

Aftercooler upgrades. Nearly all medium-speed and slow-speed marine engines have turbochargers with aftercooling to optimize fuel economy (Alexandersson et al. 1993). An aftercooler is used between the turbocharger and the engine to cool the charge air (Genovesi and Browning 1998). This cooling increases the intake air density and lowers the charge-air temperature. Both of these factors act to reduce the peak combustion temperature and NO_x emissions. NO_x reductions over naturally aspirated engines have been achieved through better cooling (Sierra Research 1991; Venkatesh 1996). However, additional NO_x reductions may be achieved through additional upgrades to the aftercooling system. Based on an average of the range of estimates reported in the literature (NAVSEA 1992; NAVSEA 1994; Sierra Research 1991; Venkatesh 1996), upgrading the aftercooler systems on ship engines might achieve a nominal NO_x reduction of 10%, with a lower bound of 0% and an upper bound of 22%. Space and weight requirements for this technology are assumed to include an additional cooler and corresponding piping, with an estimated volume of five cubic meters and an estimated weight of 4,500 kg. However, this may not be applicable to those engines already equipped with advanced cooling systems. For these plants, the degree of optimization is already high and improvements are not expected to reduce current emission levels by more than a few percent (Port of Los Angeles et al. 1994). This alternative is reported to result in an increase in fuel usage of approximately 2% (NAVSEA 1994). Moreover, over-optimized "supercooling" might actually increase NO_x emissions, because ignition delay will be larger at reduced temperatures. This could result in a larger premixed fuel charge, with corresponding increases in pressure and temperature at the beginning of combustion (Alexandersson et al. 1993).

Engine derating. NO_x emissions from diesel engines can sometimes be reduced by selecting a larger size engine (in terms of power capacity) than needed and using lower-rated fuel injectors (Sierra Research 1991). Space and weight requirements for this technology are negligible. This concept can be applied to existing engines, with an estimated NOx reduction between 5% and 23% (NAVSEA 1994). A nominal NO_x reduction for this evaluation is taken to be 14%, the midpoint of this range. However, operating a marine diesel engine at less than design-rated load tends to increase the brake-specific fuel consumption (bsfc); a nominal 4% increase in fuel consumption is reported (NAVSEA 1994; Sierra Research 1991). Smoke and particulate matter (PM) also increase because of less efficient operation (NAVSEA 1994).

Injection timing delays. Reducing the pressure at auto-ignition by retarding the timing of fuel injection will lower the peak flame temperature and reduce NO_x; however, it also results in higher fuel consumption (Hellmann 1997; MAN B&W 1996). This is one of the simplest control strategies to implement, particularly on marine propulsion engines with electronic controls that allow the operator to "dial in" the injection timing without engine shut down (Broman 1998). Space and weight requirements for this technology are negligible. NO_x reductions ranging between 10% to 30% are reported, with an average reported reduction of 19% (Broman 1998; Hellmann 1997; MAN B&W 1996; NAVSEA 1994; Sierra Research 1991). Fuel penalties are estimated to result in about a 4% increase (MAN B&W 1996; NAVSEA 1994), and increases in PM, hydrocarbons, and carbon monoxide have been reported (Heywood 1988; MAN B&W 1996).

Fuel system modifications to increase supply pressure. As discussed above, diesel engines operate with excess air because the fuel and air are not homogeneously mixed when autoignition occurs. One way of obtaining a better fuel-air mixture is to improve fuel atomization. This can be done either by upgrading the fuel injectors (discussed next) or by increasing the injection pressure (Alexandersson et al. 1993). For many large marine engines, this means upgrading the common rail fuel system to accommodate a 25% to 50% increase in maximum injection pressures (Alexandersson et al. 1993). Avoiding excessive stresses and deformations on the fuel camshaft for existing engines may define the upper limit for existing engine retrofit and limit increases in fuel injection pressure. Space and weight requirements for this technology are negligible, although strengthening the camshaft may modify the engine dimensions. NO_x reduction ranges are similar to those from fuel injector upgrades discussed next, achieving reductions between 6% and 23% (MAN B&W 1996; Port of Los Angeles et al. 1994) with an average reported reduction of about 14% (slightly greater than for engine derating above). However, one report suggested that NO_x may increase under this alternative (NAVSEA 1994), and smoke may also increase (MAN B&W 1996). The average fuel penalty for this alternative is approximately 2% (MAN B&W 1996).

Fuel injector upgrades. Similar to increased fuel pressure, upgrading the fuel injectors has the objective of improving atomization. The number and distribution of injector holes is limited partly by the strength of the injector tip and partly by manufacturing limits on hole size; another limitation is the ability for the spray pattern to avoid oxygen deficient areas (Alexandersson et al. 1993). Space and weight requirements for this technology are negligible. According to one report, a NO_x reduction of 20% is possible at a fuel penalty of 3.5% (Alexandersson et al. 1993). In addition, one report suggested that smoke may increase (MAN B&W 1996). However, the range of data for different types of nozzles suggests that NO_x reductions could be expected to be in the same range as fuel pressure increases discussed above (MAN B&W 1996). A nominal value is taken for this analysis to be about 16% (slightly greater than fuel pressure increases above).

Exhaust gas recirculation. Exhaust gas recirculation (EGR) entails recirculating some of the exhaust gases into the cylinder with the intake air. This increases the specific thermal capacity and decreases the temperature in the combustion space, and displaces oxygen that might otherwise participate in the formation of NO_x (Alexandersson et al. 1993). Space and weight requirements for this technology are negligible. While this technology has been shown to reduce NO_x by 19% to 50% without affecting fuel consumption, engine manufactures do not recommend EGR for engines that use residual fuels (Alexandersson et al. 1993; MAN B&W 1996; Venkatesh 1996). This is because recirculating the levels of particulate matter and soot found in residual fuel exhaust increases engine wear. Moreover, EGR further increases emitted PM and soot by as much as 50% (Alexandersson et al. 1993). For this analysis, the nominal NO_x reduction is 34% (the average of the reported reductions).

Pre/Post-Engine NOx Controls

Water added to the combustion air. Conceptually similar to increased aftercooling discussed above, another way to cool the charge air is to inject water into the intake air. Water injection is a proven method to reduce NO_x in gas turbines (Sierra Research 1991; Urbach et al. 1997). Water injection into the air system (also referred to as fumigation) is easier to implement than water/fuel emulsions discussed next, but can cause corrosion of engine parts, and water quality is a greater concern (Sierra Research 1991; Venkatesh 1996). This technology is expected to require increased water distillation capacity and storage to supply up to 4,000 gallons per day. Water quality requirements are expected to require either a two-pass reverse osmosis (RO) or a waste heat distillation system. While the RO system is larger than the waste heat system, average values for the space and weight requirements of 38 m^3 and 19,000 kg, respectively, are used here to get an order-of-magnitude requirement (Choules 1999). This includes volume and mass for a separate day-tank for distilled water storage. A benefit of this technology is that the percent of water injected into the intake air can be varied to achieve various levels of NO_x reduction. However, smoke and PM emissions may increase, and a nominal fuel penalty of 3% can be expected (Port of Los Angeles et al. 1994). Reports indicate that NOx reductions can range from 5% to 60% (Hellen 1998; Port of Los Angeles et al. 1994; Sierra Research 1991; Venkatesh 1996; Woodyard 1998); an average value of 28% is used here.

Water in fuel emulsions. Water emulsification in the fuel is a proven technique to reduce NO_x, and it lends itself to application with residual fuels that often already contain some emulsified water and other blended fuels (MAN B&W 1996). A standard engine design permits the addition of about 20% water (as a percent of fuel mass) at full load, although more that 50% water has been tested (MAN B&W 1996). Additional distillation capacity may not be needed at 20% or less water injection. However, if it is needed, the quality of water is not as important to this technology as it is for water added to the intake air, discussed above. If additional distillation is required, average values for the space and weight requirements of 25 m^3 and 13,000 kg, respectively, are used here to get an order-of-magnitude requirement (Choules 1999). These values are somewhat smaller than above, because emulsification is not expected to require a separate tank for distilled water storage. Emulsification may require some special equipment and emulsifying agents to ensure fuel stability and reliable engine starts. Fuel consumption using this technology has been shown to vary from a fuel savings of 6% to fuel penalties of similar size (Alexandersson et al. 1993), although most reports show an increase in fuel consumption (MAN B&W 1996; NAVSEA 1994; Venkatesh 1996). This analysis used 2%, an average of reported fuel penalties. NO_x reductions ranged widely for this technology (from 20% to 73%), mostly as a result of the ability to select the water content in the emulsification and therefore the NO_x control (Alexandersson et al. 1993; MAN B&W 1996; Port of Los Angeles et al. 1994; Venkatesh 1996). An average value of 42% NO_x reduction was chosen for this assessment. In addition to these reductions, this technology is reported to reduce PM and carbon monoxide through better fuel atomization as the water vaporizes explosively creating secondary atomization (Alexandersson et al. 1993).

Selective catalytic reduction (SCR). SCR provides the greatest reductions in NO_x emissions of any of the technologies discussed above, and marine application of this technology has been the focus of considerable interest (Alexandersson et al. 1993; Cooper and Peterson 1995; Gibson and Groene 1991; MAN and B&W 1997; MAN B&W 1996; Venkatesh 1996; Wartsila NSD 1994; Woodyard 1998). Catalytic reactions with ammonia or urea reduce the oxidized nitrogen to nitrogen gas according to the following reactions (Alexandersson et al. 1993):

For ammonia catalyst:

$$4\ NO + 4\ NH_3 + O_2 \longrightarrow 4\ N_2 + 6\ H_2O \qquad (1)$$

$$6\ NO_2 + 8\ NH_3 \longrightarrow 7\ N_2 + 12\ H_2O \qquad (2)$$

And for urea catalyst:

$$6NO + 2(NH_2)_2CO \longrightarrow 5N_2 + 4H_2O + 2CO_2 \qquad (3)$$

$$6NO_2 + 4(NH_2)_2CO \longrightarrow 7N_2 + 8H_2O + 4CO_2 \qquad (4)$$

Although both types of catalyst systems have been installed on marine vessels, urea may be favored because it is non-toxic and biologically harmless and can be transported without problems (Woodyard 1998). Installation of SCR systems imposes additional space and weight requirements, with an average of 33 m^3 and 3,100 kg reported taken from various reports in the literature cited above. However, Wartsila NSD has been developing a “compact SCR” system that equals the size of and replaces current silencer systems installed aboard ships (Mullen 1998). Reported NO_x reductions can be as high as 98%, although the reduction at lower engine loads can be as low as 57% (MAN B&W 1996). An average of 81% from

Table 1

Summary of NO_x Control Technology Performance Attributes

CONTROL TECHNOLOGY	NOMINAL NO_x REDUCTION (%)	NOMINAL REDUCTION IN PM AND OTHER POLLUTANTS (%)*	NOMINAL INCREASED FUEL USE (%)
Aftercooler upgrade	10	-1	2
Engine derating	14	-10	4
Fuel pressure increase	14	-21	2
Injector upgrade	16	-21	2
Injection Timing Retard	19	-11	4
Water in combustion air	28	1	3
Exhaust gas recirculation	34	-51	0
Water/fuel emulsion	42	15	2
Selective catalytic reduction	81	0	0

** Negative values in this column represent an increase in emissions of other pollutants.*

reported values is used here as the nominal NO_x reduction for SCR. While SCR does not increase fuel consumption and can be installed on engine systems using high-sulfur residual fuel (MAN B&W 1996), the technology involves the consumption of ammonia or urea. Catalyst consumption rates equal about 2% of the fuel consumption (about 16 kg/h of operation) (Alexandersson et al. 1993).

Summary of NOx Control Technologies

Table 1 presents a summary of the technology discussion above, focused on the attributes most important in considering the NO_x -control potential. The determination of nominal values for NO_x reduction was described above. Nominal values quantifying the effects of each technology on other pollutants were developed similarly from the literature, but with much less information available. These quantitative values are taken from the available literature; however, it should be acknowledged that the emissions trade-off between NO_x reduction and increased emissions for other pollutants, especially PM, is not always reported.

For example, increases in PM and smoke are consistently reported for injection timing retard; these increases are reported to be nearly linear with reductions in NO_x according to one source (Heywood 1988), but less than linear as reported by another (MAN B&W 1996). Therefore, the intent here is that data included in this study, while quantitative in form, serve to inform the reader qualitatively that a given NO_x control technology may have greater trade-offs compared to other control technologies, in that they increase either other pollutants or fuel consumption — or both.

Cost and Pollution Reduction Assessment

This section describes the approach to estimating life-cycle costs per ship of including existing engines in NO_x control policies. Because these technologies are currently available for marine application, costs were directly taken or derived from publicly available sources. The results, presented as net present values, define a set of preferred technologies according to their NO_x reduction potential.

Cost Estimating Methodology

Two basic types of cost data are considered: fixed and annual. Fixed costs of NO_x control include retrofit design, hardware and equipment, installation. Annual costs result from fuel penalties associated with retrofit NO_x controls, other materials such as ammonia or urea in SCR systems, and other operating expenses (mostly labor) resulting directly from the retrofit technology.

Data for these cost estimates is taken as

Table 2

Retrofit Design Costs for Existing Engine NO_x Control Technologies

CONTROL TECHNOLOGY	RETROFIT DESIGN (R&D-LIKE) COSTS ($) PER ENGINE MANUFACTURER	RETROFIT DESIGN (R&D-LIKE) COSTS ($) PER SHIP
Aftercooler upgrade*	$336,000	$700
Engine derating**	$0	$0
Fuel pressure increase*	$1,000,000	$2,100
Injector upgrade*	$1,500,000	$3,300
Injection Timing Retard**	$0	$0
Water in combustion air†	$834,000	$1,800
Exhaust gas recirculation*	$500,000	$1,100
Water/fuel emulsion†	$834,000	$1,800
Selective catalytic reduction†	$834,000	$1,800
Total Retrofit Design Costs	$5,838,000	$12,700

** Used U.S. EPA R&D costs for these technologies.*
*** Engine derating and injection timing retard are not considered to incur retrofit design costs.*
† Used average of U.S. EPA R&D costs for all technologies they reported.

reported where possible and derived below otherwise. This analysis uses new engine technology costs developed by U.S. EPA for the largest marine engines addressed by the proposed rule (EPA 1998a), except where other technology cost data was considered to be more detailed. U.S. EPA costs were used for the following technologies: 1) aftercooler upgrades, 2) fuel system modifications to increase supply pressure, 3) fuel injector upgrades, and 4) exhaust gas recirculation. The primary exception to this is that where U.S. EPA calculated only the incremental costs on top of a new engine without NO_x controls, this analysis used the full price of equipment. Another modification is that labor rates are assumed to be $500 per person-day, typical of labor rates (plus benefits) in public shipyards (Rivenbark 1996). Costs developed here are idealized to some degree, as they apply to the "typical" engine propelling large ships operating internationally. However, these costs were discussed and were generally validated through discussions with representatives of Wartsila NSD Corporation (Broman and Koivisto 1999).

A retrofit-design cost-estimating method that is similar to the approach used by the U.S. EPA to estimate new engine R&D costs (EPA 1998b). was applied. Retrofit design costs were considered to be similar to new engine research and development costs, including both manufacturer costs to design a general solution to the problem, and specific implementation costs for various types of ships in the fleet. This analysis estimated the retrofit costs on a per ship basis for each technology, in order to determine how design costs would be distributed across the fleet. For this calculation it was assumed that all transport ships in the existing world fleet are engaged in international maritime transportation (LMIS 1996). The number of ships to be retrofit was distributed across the primary engine manufactures for large marine propulsion engines. According to Lloyd's Registry, the top nine engine manufacturers provide the main engines to more than 66% of the world's ships (LMIS 1996). (The next two manufacturers, Deutz and S.K.L., account for about 4% each; the last two manufacturers, Akaska and Niigata, account for about 3% each.) The top five manufactures, MAN-B&W, Wartsila-NSD, Hanshin, Mitsubishi, and MaK, account for more than 50% of the main propulsion engine systems on transport ships. These manufactures account for an even larger percent of recently built ship engines—engines with significant remaining working life and therefore most likely to be retrofit with NO_x controls. A ten-year retrofit implementation schedule was used to estimate the number of retrofits that would occur in the first year. Similar to the U.S. EPA method, this approach places retrofit design costs up front and makes the estimate larger (more conservative). These costs are shown in **Table 2**.

Hardware costs for engine derating assumed that new injectors were needed that would limit the maximum engine power to the lower rating. Injection timing retard has no hardware costs, only labor costs to retime the engine. Additional water distillation capacity was assumed in the costs for humidification of combustion air, with distillation costs provided through an industry quote (Choules 1999) and other costs taken from a report for U.S. EPA (Venkatesh 1996). The same increased distillation capacity was assumed for water/fuel emulsification, with equipment costs for emulsification provided by a Swedish Transport Research Board report (Alexandersson et al. 1993). Costs for SCR technology onboard ship were also taken from the Swedish Transportation Research Board report (Alexandersson et al. 1993).

To estimate annual fuel costs, estimated average daily fuel usage was converted to an annual basis and multiplied by the percent increase in fuel usage presented above for each technology. This annual increase in fuel usage was then multiplied by a representative price for fuel based on a review of prices published during the last several years in a weekly industry publication (MGN 1999). A price of $66 per ton fuel was used for residual fuels, and a price of $130 per ton was used for marine distillate oil. Other annual costs were taken from the various sources that provided technology costs.

Fixed, Annual and NPV Costs

Table 3 presents the fixed and annual costs estimated for each NO_x reduction technology considered. Several observations can be made at this point. First, hardware and installation costs vary considerably, but generally increase with increased NO_x reduction (compare Table 1 and Table 2). The exceptions are the costs estimated for injection timing retard and exhaust gas recirculation. Second, retrofit design costs are generally similar across technologies. Third, annual maintenance and operating costs appear generally small compared to increased annual fuel costs, with the exception of SCR. This is expected since SCR does not increase fuel consumption but does involve significant consumption of either urea or ammonia, as discussed above.

The net present value (NPV) of these estimates was calculated using a 15% interest rate. Adopting a very conservative approach, we assume that all existing ships, when retrofitted, would have a remaining life span of 23 years, equal to the average life of a new ship. This is considered to be conservative since a longer period increases the NPV and the current average age of the oceangoing fleet is greater than 18 years (LMIS 1996). (Ages reported from 1996 registry data. The average age of container ships in 1996 was about 11 years (LMIS 1996).) In other words, this would represent the NPV

Table 3

Summary of Fixed and Annual Costs for NOx Control Technologies

	FIXED COSTS		ANNUAL COSTS	
CONTROL TECHNOLOGY	**Retrofit Design (R&D-like) Costs**	**Hardware and Installation Costs**	**Increased Maintenance and Operating Costs**	**Increased Fuel Costs**
Aftercooler upgrade	$700	$11,000	$0	$27,000
Engine derating	$0	$34,000	$1,500	$54,000
Fuel pressure increase	$2,100	$34,000	$0	$29,000
Injector upgrade	$3,300	$38,000	$0	$24,000
Injection Timing Retard	$0	$250	$3,000	$54,000
Water in combustion air	$1,800	$130,000	$2,600	$34,000
Exhaust gas recirculation	$1,100	$2,500	$0	$2,600,000
Water/fuel emulsion	$1,800	$117,000	$1,000	$31,000
Selective catalytic reduction	$1,800	$283,000	$30,000	$0

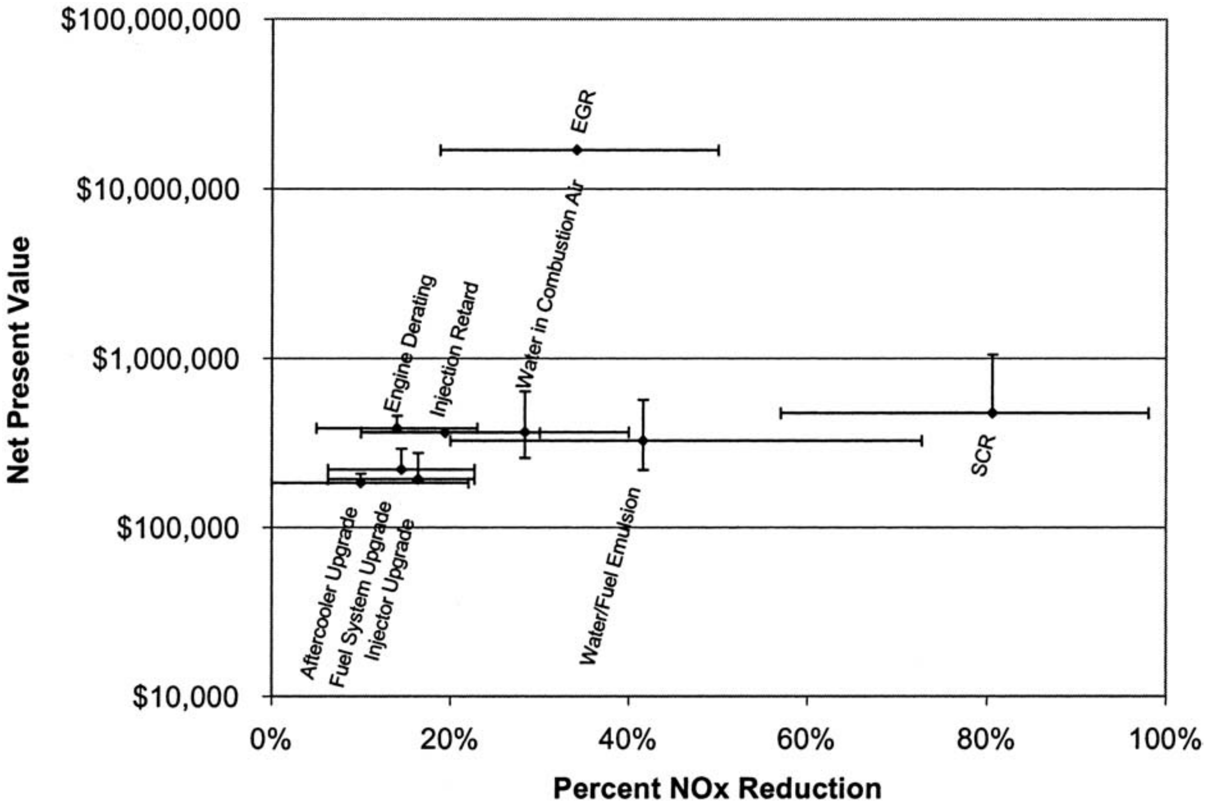

FIGURE 1:
NPV (i=15%) of Control Costs (Fixed + Annual) of NOX Control for Existing Engines (emission control assumed during 100% of operations)

costs of a ship that was one year old when retrofit. With a 15% discount rate this assumption has less effect on the NPV costs than a lower discount rate would. **Table 4** presents the NPV costs for each technology.

Discussion and Summary

The results in Table 4 include the nominal NOx reductions drawn from the literature. However, these NOx reduction values may vary across the ranges discussed above, either as a result of uncertainty in technology effectiveness or as a result of intentional variations in engineering design. For example, the percent of water in water/fuel emulsions may be adjusted to achieve different levels of NO_x control. Additionally, while annual costs should be relatively robust, since they depend on the increased annual fuel usage more than any other factor, the NPV cost estimates in Table 4 may be sensitive to errors in estimated fixed costs. Specifically, U.S. EPA reports that after-market engine equipment may cost three times the cost for that equipment when provided in a new engine package (EPA 1998b).

Figure 1 graphically presents the NO_x control technologies according to their relative costs and pollution control and illustrates the sensitivity of these concerns on the NPV costs. Horizontal bars describe the range of reported NO_x reductions and vertical bars describe the range of NPV costs if retrofit design costs were ignored and if fixed costs were three times greater (consistent with after-market cost factors reported by U.S. EPA). In addition, the lower cost bound for water in combustion air and water/fuel emulsions has removed costs associated with adding distillation capacity, assuming that existing capacity may be sufficient.

It should be emphasized that all costs shown in Figure 1 assume that control technologies are operated at all times. This study does not explore the potential impact of scenarios where operation of NO_x control equipment is more limited.

Table 4

*Summary of Expected NOx Reductions and Fixed, Annual and NPV Costs for NO_x Control Technologies Applicable to Existing Engines**

		FIXED COSTS	ANNUAL COSTS	
CONTROL TECHNOLOGY	NOMINAL NO_x REDUCTION (%)	HARDWARE, INSTALLATION, AND RETROFIT DESIGN	MAINTENANCE, OPERATING, AND FUEL	NPV COSTS (15% interest annually over 23 years)
Aftercooler upgrade	10	$12,000	$27,000	$184,000
Engine derating	14	$34,000	$55,000	$386,000
Fuel pressure increase	14	$36,000	$29,000	$220,000
Injector upgrade	16	$41,000	$24,000	$192,000
Injection Timing Retard	19	$250	$57,000	$363,000
Water in combustion air	28	$134,000	$36,000	$365,000
Exhaust gas recirculation	34	$3,500	$2,640,000	$16,900,000
Water/fuel emulsion	42	$119,000	$32,000	$325,000
Selective catalytic reduction	81	$285,000	$30,000	$475,000

• Some differences from previous numbers may appear due to rounding of calculations.

Relative Feasibility of NOx Control Technologies

As seen in Figure 1, the point estimates developed in this paper suggest a clear progression of preferred technologies that provide increasing NO_x reductions at the least cost. The least-cost control curve would include 1) aftercooler upgrade, 2) fuel injector upgrade, 3) water/fuel emulsion, and 4) selective catalytic reduction. The technologies that simply appear too expensive include 1) engine derating, and 2) exhaust gas recirculation. EGR appears to be beyond serious consideration for existing engines unless it can become feasible during engine operation with residual fuel.

The order of these results does not appear to change if the fixed costs shift together, either higher or lower, within the ranges shown. Even if fixed costs increase by a factor of three, representing typical differences between OEM price and retail mark-up for parts (EPA 1998b), the relative cost ranking of these technologies does not substantially change. An anomaly of the method presented here is that these per-ship costs assume one main engine per ship. For ships with multiple main engines, the relative cost differences could change—but not for all technologies. For example, the five technologies with lower NO_x reductions (aftercooler upgrade, derating, fuel system upgrade, injector upgrade, and injection timing retard) would typically require that each engine be retrofit individually. Depending on the method, this could also apply to the water in combustion air technique. However, water/fuel emulsions and selective catalytic reduction can be retrofit in the common fuel system before both engines or in a common exhaust system, respectively. This implies that costs for higher NO_x control using pre- or post-engine technologies could be more economical for multiple-engine configurations.

Perhaps more important are the horizontal ranges for each technology. Particularly for the technologies with lower nominal NO_x reductions, the overlap is significant. This may imply that where costs are similar, an operator may select the technology with greater nominal NO_x control, even if it exceeds the minimum required control. This could ensure greater confidence in the amount of NO_x reduction and some insurance against future regulatory changes. The most interesting technologies in this regard may be humidification of intake air or water/fuel emulsions. With such a wide range of NO_x reduction, the ability to control the technology performance during operation may be desirable for an operator.

Technology Cost Impact on the Ship Operator

These technology costs of control will not be negligible, especially to the ship operator. **Table 5** identifies the general operating costs

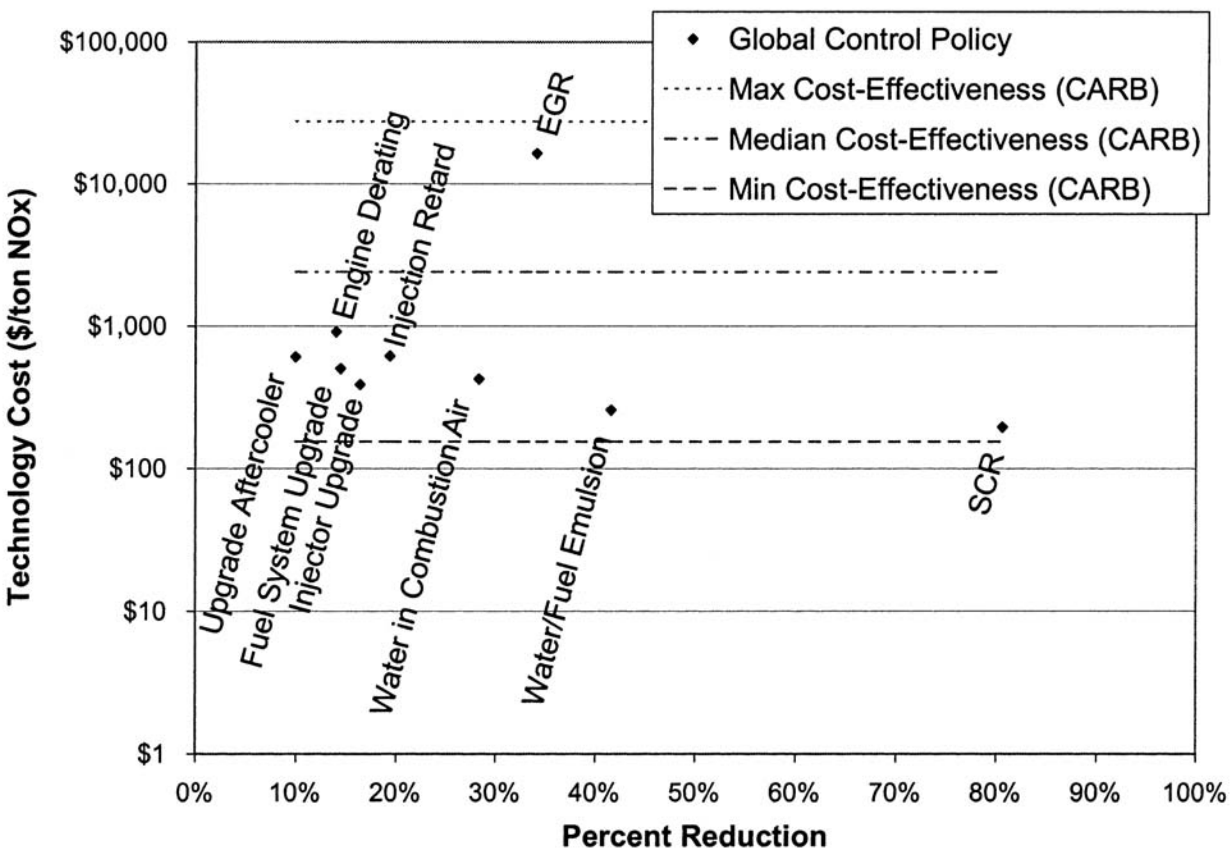

FIGURE 2:
Cost-effectiveness of NO_X Control Technologies ($ per ton NO_X)

for an international bulk carrier, noting that fuel is the largest factor affecting total operating cost (*Wartsila* NSD, 1997). As a first-order analysis of the annual cost impact of NO_x control technologies on vessel operations, the annualized cost for SCR operated during 100% of main engine operations (the technology with the maximum annual cost of all preferred technologies) was used to get an potential upper bound estimate. Using an annualized cost of about $86,000 and an estimated annual fuel cost of $1.34 million, NO_x controls equal approximately 6% of annual fuel costs. If fuel costs equal nearly 60% of the operating cost of a ship, then NO_x control costs equal less than 4% of total operating costs. This could be more or less significant to a shipping company depending upon the rate of policy implementation requiring NO_x technology retrofit, because the ship operator will need to factor this cost into shipping rates. Operators at the margin could be most affected by aggressive policies in this regard.

The impact on the price of goods is expected to be lower. Freight rates equal between 4% and 13% of the import price of low-value bulk commodities, with a worldwide average of about 9% of import value (UNCTAD 1995). The commodity prices of higher-value goods such as manufactured items or containerized cargoes are less affected by transaction costs such as freight rates. Although freight rates include other costs (such as bunker surcharges and currency adjustment factors, port delay and additional port surcharges) that are not explicitly defined in Table 5, it is assumed here that these are contained in the other operational costs (UNCTAD 1995). With shipping contributing about 9% to the cost of goods and the assumption that in the long run 100% of operator costs will be passed on to the consumer, the 4% change in operating costs could eventually increase by about 0.3% the costs of goods.

Moreover, if fuel prices were to increase so would the annual costs associated with fuel penalties for NO_x control technology. However, the direct effect of increasing fuel prices on total operating costs would increase both the baseline fuel cost and the annual technology cost by the same percentage (or less for capital intensive technologies like SCR). However, while the fuel penalties of most of the NO_x control technologies considered in this work could be motivation enough, any significant increase in fuel prices would promote research into minimizing these fuel-related costs of NO_x control.

Cost-effectiveness Comparison With Other NOx Control Efforts

A cost-effectiveness comparison of retrofit NO_x controls can be made with NO_x control strategies for new ships and with NO_x control strategies for other combustion sources (both mobile and stationary). Cost-effectiveness is defined by regulators as the annualized cost of control divided by the annual mass of emissions reduced (Koeberlein et al. 1997). Policymakers use cost-effectiveness primarily to compare control technologies and regulations in terms of relative costs to benefits. For purposes of this analysis, cost-effectiveness represents the annual technology cost divided by the annual amount of NO_x emissions avoided.

Two numbers are needed to estimate cost-effectiveness. First, the annual cost of each technology is computed by annualizing its net present value. This analysis uses NPV costs that were annualized over 23 years (the same period used to estimate the NPV costs in Figure 1). A sensitivity analysis annualizing the 23-year NPV over a ten-year period increased the annualized costs for capital intensive technologies (e.g., 10-year annualized costs increase by 26% for SCR, by 25% for water/fuel emulsion and water in combustion air, and by 14% for after-cooler upgrade). (Absolute annual cost differences were less than $700 in all cases. For simplicity, this analysis ignores the transient costs that may occur during implementation of NO_x control and the effects of fleet growth or emissions increase over time.) However, this difference using a 10-year period does not change significantly any of the insights resulting from the longer annualization period.

Table 5

Operational Costs for a Bulk Carrier [Wartsila NSD, 1997]

Total Operational Costs	100%
Fuel Costs	59%
Crew Expenses	24%
Repair and Maintenance Costs	7%
Other Operational Costs	9%

The second number that is needed is the estimated annual NO_x emissions reduced from the inventory through control. This can be estimated on a per-ship basis, or by using the estimated NO_x reduced in the actual region of control. A comparison of the two methods using our previous inventory work (Corbett and Fischbeck 1997; Corbett et al. 1999) showed that the differences between these approaches are relatively small, although cost-effectiveness on a per-ship basis provides the highest costs. We present the per-ship cost-effectiveness results in **Figure 2**. It is worth noting that the most cost-effective technology is SCR. Although it is the most costly retrofit technology considered here, the significant NO_x reduction potential (denominator) offsets its higher technology cost (numerator). The minimum, median, and maximum cost-effectiveness values accepted by the California Air Resources Board for stationary engines (Koeberlein et al. 1997) are presented in Figure 2 as well, and discussed below.

Cost-effectiveness estimates for existing marine diesel engines compare well with other NO_x control efforts for both mobile and stationary sources. As shown in **Table 6**, NO_x regulations for stationary internal combustion engines (which are most similar to marine diesel engines) have ranged in cost-effectiveness between $140 per ton NO_x removed and $25,000 per ton NO_x removed (Koeberlein et al. 1997). CARB has also reported cost-effectiveness for mobile sources, including those with diesel engines (Koeberlein et al. 1997). The U.S. EPA estimated the cost-effectiveness of Tier

Table 6

Summary of Cost-Effectiveness for NO_x Control from Existing Ships (This Work) and Other Recent NO_x Control Programs

NO_x RULE	POLLUTANTS CONSIDERED	COST-EFFECTIVENESS ($/ton NO_x removed)
This study, all nine control technologies (low = SCR, high = EGR)	NO_x	$200 - $16,000
U.S. EPA proposed Tier 2 for new marine engines (including IMO)	HC + NO_x	$76 - $738
U.S. EPA proposed Tier 2 and Tier 3 for new marine engines (excluding IMO)	HC + NO_x	$30 - $280
Clean fuel fleet program (heavy-duty)	NO_x	$1,300 - $1,500
2.5 g/hp-hr NMHC* + NOx standards for highway heavy-duty engines	NMHC* + NO_x	$100 - $600
Locomotive engine standards	NO_x	$160 - $250
Non-road Tier 2 standards	NMHC* + NO_x	$480 - $540
Various CARB mobile source emissions control measures	Both THC + NO_x and NO_x only	$180 - $38,000
Various CARB stationary IC engine measures	NO_x	$140 - $25,000

2 and Tier 3 standards for new marine diesel engines, and provided four other recent U.S. EPA mobile source regulations that required NO_x reductions (EPA 1998b). These cost-effectiveness estimates are summarized in **Table 6**.

Conclusion

This paper discussed the mechanisms of NO_x formation and presented nine NO_x control technologies that are applicable to existing marine engines. These technologies can be ranked in terms of their emission-control potential and their cost to define a technology "feasibility frontier" that includes four control technologies (in order of increasing control and cost): aftercooler upgrade, injector upgrade, water/fuel emulsion, and selective catalytic reduction. Estimated annual costs of these technologies are shown to be less than 4% of annual operation costs. Under appropriate policy implementation, freight rates could include these NO_x control costs with only a marginal impact on bulk commodity prices and a negligible effect on the prices of higher-value commodities. Moreover, the NO_x control costs for preferred technologies according to this study are clearly within cost-effectiveness ranges for other NO_x control strategies, such as controls proposed for new marine engines and controls for other mobile or stationary sources on land. These results, based on technologies currently installed in shipboard applications, suggest that retrofit NO_x control technologies can be feasible, both technically and economically.

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DR. JAMES J. CORBETT, P.E. *is an assistant professor of Marine Policy in the Graduate College of Marine Studies at the University of Delaware, in Newark, Delaware. His research evaluates air emissions from international and domestic shipping and develops feasible technology-policy measures to reduce their impacts on climate change and air quality. He has authored more than 10 peer-reviewed articles related to the environmental impacts and technology-policy mitigation alternatives of air pollution from ships. Dr. Corbett is a graduate of the California Maritime Academy, with a masters degree in mechanical engineering and masters and doctoral degrees in engineering and public policy from Carnegie Mellon University. He formerly held a commission in the Naval Reserve as an Engineering Duty officer and is a member of ASNE, SNAME, ASME, among other professional organizations.*

DR. PAUL FISCHBECK *is an Associate Professor in the Departments of Engineering and Public Policy and Social and Decision Sciences at Carnegie Mellon University, in Pittsburgh, Pennsylvania. He holds a Ph.D. from Stanford University. His research focuses on the quantification and communication of uncertainty, including both theoretical improvements to decision analysis and numerous applied real world problems. Using a systems approach, he and Corbett have quantified the pollution caused by international shipping and proposed several engineering and economic solutions. He is currently studying performance-based regulations and how they can be used to improve fire-safety systems and oil-tanker design. He is a retired Navy captain.*