

NON-ROAD DIESEL EMISSION REDUCTION STUDY

Prepared for:

Puget Sound Clean Air Agency
Oregon Department of Environmental Quality
And U.S. Environmental Protection Agency

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SUMMARY REPORT

Rapid population growth in the Pacific Northwest challenges the maintenance of good air quality in this region. While stringent EPA regulations are helping to limit emissions from on-road highway vehicles, there are no equivalent regulations for off-road, heavy-duty diesel-engine (HDD) mobile sources, such as marine vessels, railroad locomotives and construction equipment. As a consequence, the emissions from these nonroad sources are becoming a significant component of the regional air pollution inventory, accounting for roughly 33% of the oxides of nitrogen (NOx), 28% of the oxides of sulfur (SOx), 14% of the $PM_{2.5}$ (respirable particulate matter with a diameter of less than 2.5 microns) and 13% of the volatile organic compounds (VOC).

The purpose of this study is to determine the most cost-effective methods for reducing the emission of air contaminants from off-road HDD mobile sources operating in the densely populated I-5 corridor and in the coastal waterways of Washington and Oregon. The air contaminants of concern are SOx, NOx, VOC's, diesel particulate, benzene, 1,3-butadiene and formaldehyde. The first four contaminants, either directly or indirectly through the atmospheric formation of smog and $PM_{2.5}$, impact human health and atmospheric visibility. In addition, the last four contaminants are implicated in the formation of human cancers and therefore are included in EPA's inventory of air toxics.

The Puget Sound Clean Air Agency will use the results of this study to help guide emission reduction initiatives that are both technically sound and cost effective.

The following sections will briefly summarize the technology and clean-fuel options that are available for five different classes of non-road, HDD mobile sources: construction equipment, railroad locomotives, workboats, ferries and cruise ships. These summaries will be followed by a comparison of the cost-effectiveness of the different emission reduction measures.

S1 Construction Equipment Options

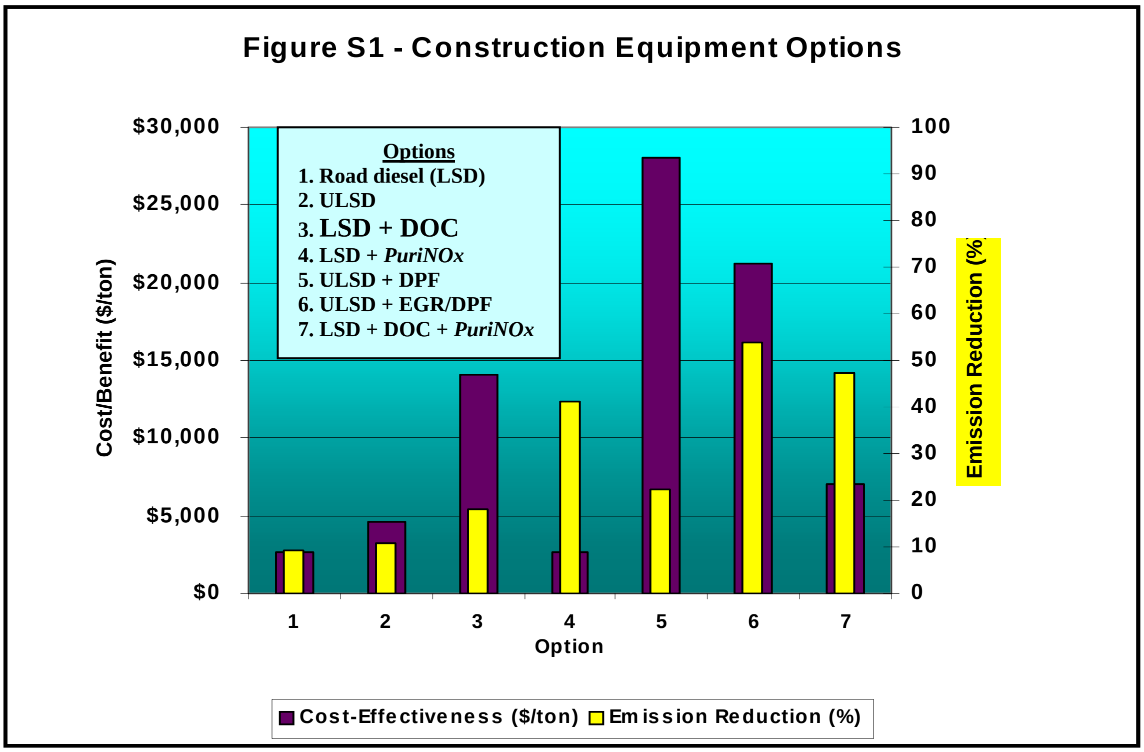
The construction equipment used as a representative "fleet" in this study consists of 12 pieces of equipment, selected out of a total of 375 pieces of off-road diesel-engined equipment, that are operated by the City of Seattle. Clean fuel options that are available for use in construction equipment are rebranded road diesel (LSD and ULSD), biodiesel, and fuel-water emulsions such as Lubrizol's PuriNOx. Biodiesel has higher NOx emissions, compared with off-road diesel, and is more expensive than ULSD. Its use may well be justified for reducing emissions of greenhouse gases but not for reducing emissions of the species of interest in this study. Therefore its use is not generally recommended for off-road diesel engines.

Technological, after-market emission-reduction options include diesel oxidation catalysts (DOC), diesel particulate filters (DPF) and exhaust gas recirculation (EGR). The existing engines may also be replaced with newer, low-emission engines. This option was not explored for construction equipment because it is expensive and, since construction equipment operates for a rather limited time each year, the cost per unit of operating time would be excessive.

The cost-effectiveness, expressed as a cost/benefit ratio, and the percent emission reduction provided by these different options are illustrated in Figure S1 below. The best options give the largest emission reduction (yellow bars) with the least cost (purple bars). It is apparent that options 1, 2, 4 & 7 are the most cost-effective (least cost/benefit ratios) options while options 4, 6 and 7 provide the greatest emission reduction.

Options 1 and 2, using low-sulfur diesel (LSD) and ultra-low sulfur diesel (ULSD), are two of the most cost-effective options but with little reduction in overall emissions.

Option 4, using a *PuriNOx* emulsion of water and low-sulfur diesel, provides both a low cost/benefit ratio and a large emission reduction. Similarly, Option 7 (LSD/*PuriNOx* + diesel oxidation catalyst) provides both a low cost/benefit ratio and a large emission reduction.



Option 6, the combination of exhaust gas recirculation (EGR) and diesel particulate filter (DPF) plus ULSD fuel, gives the greatest emission reduction but at a very high cost.

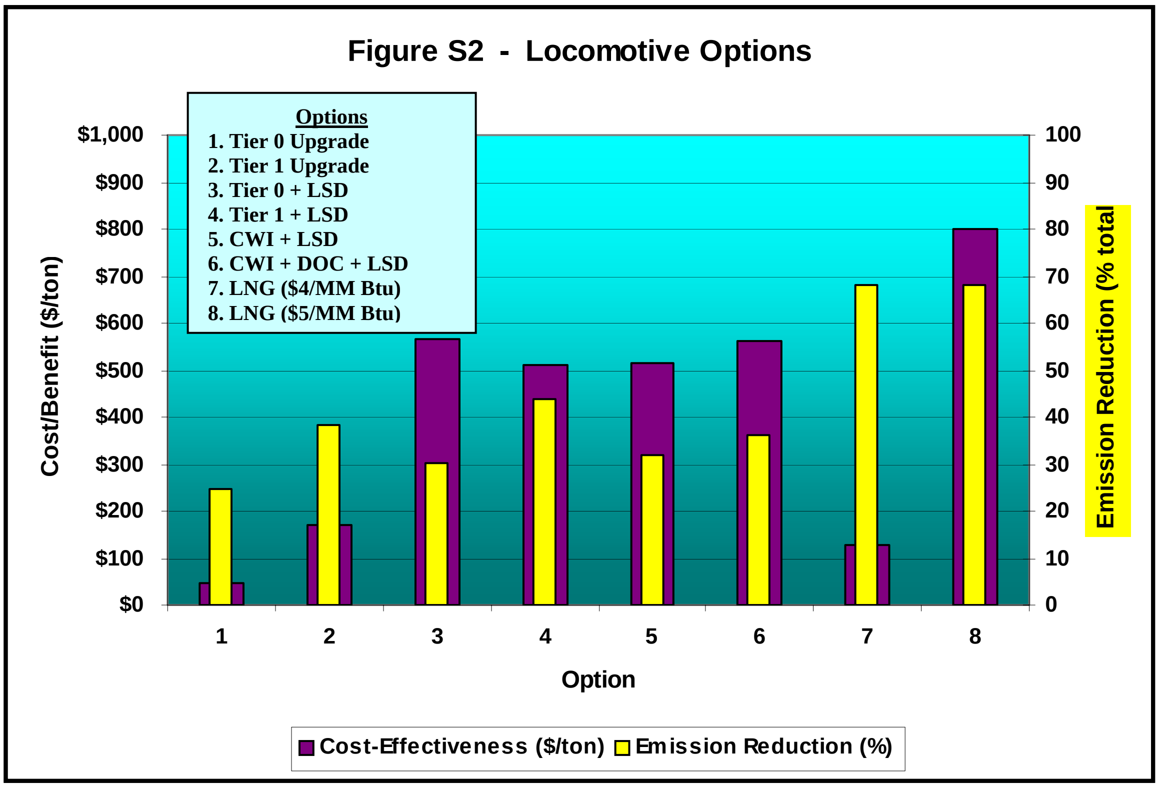
From this analysis it would appear that the most cost-effective choices for construction equipment consist of combinations of low-sulfur diesel (to reduce SOx emissions), *PuriNOx* (to reduce emissions of NOx and particulates) and diesel oxidation catalysts (to reduce VOC emissions, which include benzene, 1,3-butadiene and formaldehyde).

S2 Locomotive Options

The representative locomotive "fleet" investigated in this study consists of 53 line-haul and 14 yard engines operated by BNSF in the Pacific Northwest (Washington and Oregon). It does not include their transcontinental stock.

Figure S2 compares the cost-effectiveness ($/ton of emission reduction) and the percent emission reduction for the different options. These options were applied to both line-haul and yard engines except for the liquefied natural gas (LNG) options, which were applied only to those on line-haul.

The engine upgrades (EPA's Tier 0 and Tier 1) are cost-effective and produce significant reductions in NOx emissions. Similarly, Option 7 (using LNG duel-fuel in line-haul locomotives) is cost-effective if natural gas is available at a commodity price of $4/MM



Btu. But if natural gas is only available at a commodity price of $5/MM Btu or higher, which may be the case until less expensive, offshore LNG becomes available, than LNG is not cost-effective (e.g., Option 8). The LNG option, if exercised, could be implemented using dual-fuel technology that results in no derating of engine power.

Not shown in Figure S2 is the Hotstart/SmartStart idle-control system for locomotives, which actually has a negative cost-effectiveness for line-haul locomotives (-$456/ton of idling emission reduction) and an idling emission reduction of 82%. This package greatly reduces fuel consumption during idling and therefore actually saves enough money on reduced fuel consumption to pay for the installation! However, the Hotstart system is not cost effective for the smaller yard engines ($7,815/ton of idling emission reduction), which are often not running.

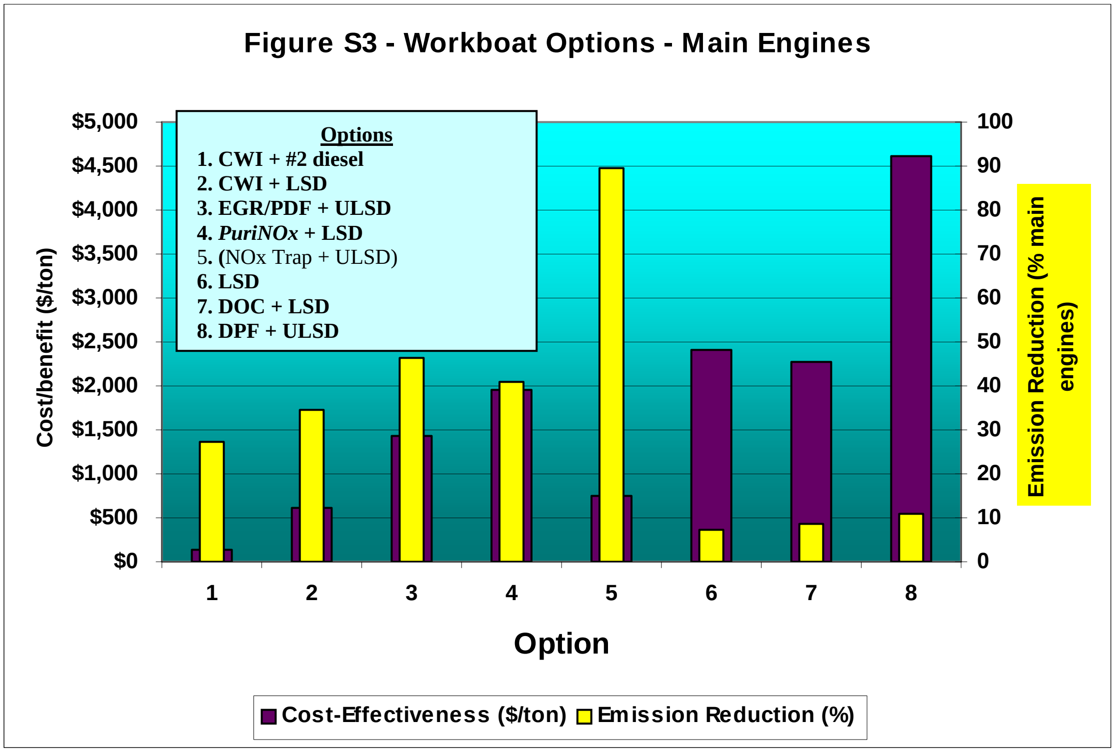
For yard engines a viable option is the conversion of the locomotive to hybrid, diesel-battery power. A hybrid system takes advantage of the fact that yard locomotives spend a large fraction of their time when they are operating in the idle mode of operation. A hybrid replacement has a cost-effectiveness of $1,022/ton of emission reduction and reduces yard emissions by over 95%. However, if the cost of converting a yard engine to hybrid power is compared to the cost of rebuilding the engine to Tier 1 standards, then the cost-effectiveness becomes -$1,605. In other words, converting to hybrid power incurs a much lower annual cost than does rebuilding to Tier 1. Also, an emission reduction of 86% is realized over that obtained from the Tier 1 rebuild.

S3 Workboat Options

A representative workboat fleet that formed the basis of this study consists of 19 vessels owned and operated by Tidewater Barge Lines on the Columbia River. These vessels typically have two larger, medium-speed diesel engines for propulsion and may also have one or more smaller, high-speed diesel gensets to provide power for their lighting and electronics.

The eight emission reduction options that were considered for the **main engines** are:

1. Use continuous water injection (CWI) with the off-road diesel (3000 ppm S) to reduce NOx emissions.
2. Use CWI with LSD (350 ppm S) to reduce NOx and SOx emissions.
3. Use exhaust gas recirculation (EGR) and diesel particulate filters (DPF) with ULSD to reduce NOx, particulate matter and SOx emissions.
4. Use a water-diesel emulsion (*PuriNOx*) with LSD to reduce emissions of NOx, particulates and SOx.



5. Use a "NOx Trap" to remove NOx from the exhaust (these are still in the prototype stage but are expected to become commercially available within a few years; their use requires ULSD to prevent poisoning of the catalyst).
6. Switch from off-road diesel to road diesel (LSD) to reduce SOx emissions.
7. Use diesel oxidation catalyst (DOC) in combination with LSD to reduce emissions of VOC compounds and the soluble portion of diesel particulates.
8. Use diesel particulate filters to reduce particulate emissions and VOC emissions.

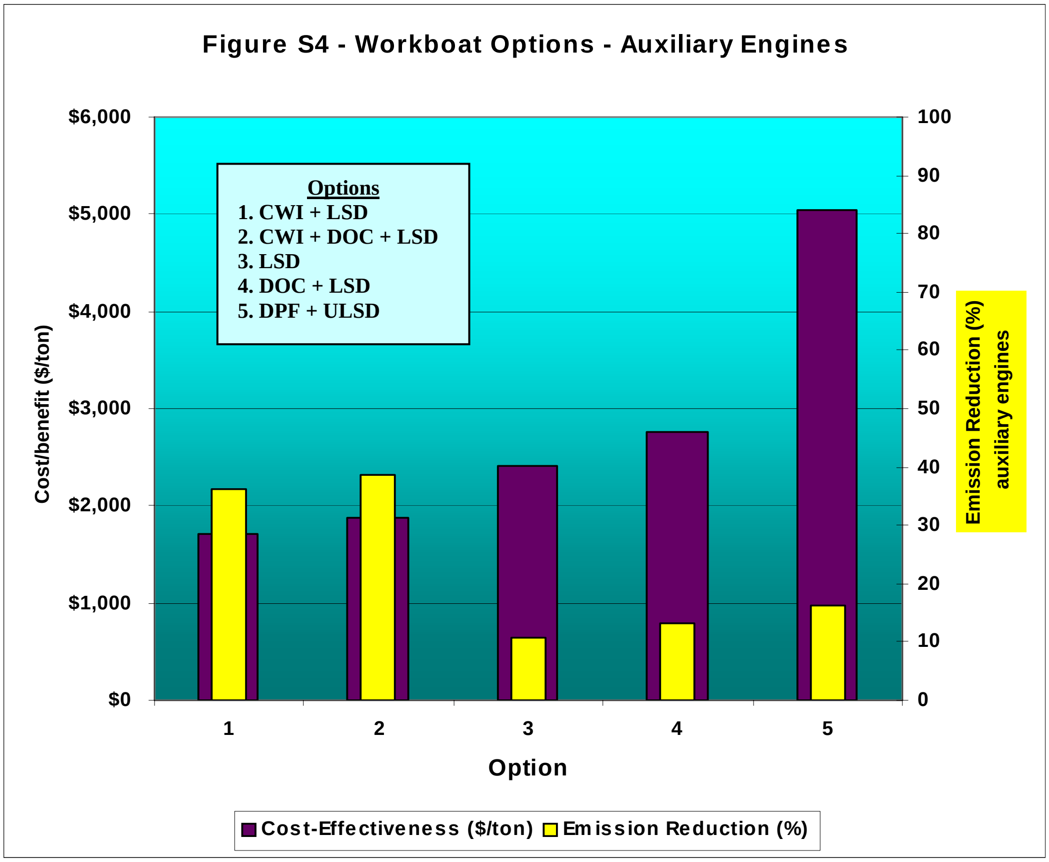
The cost-effectiveness ($/ton of total pollution reduction) and percent emission reduction for these different options is shown in Figure S3.

From Figure S3 it can be seen that the lowest cost/benefit options the first five, while the greatest emission reductions are afforded by options 2, 3, & 4. (Option 5 the catalytic "NOx trap" provides the greatest emission reduction at the most favorable cost/benefit ratio, but this technology is not commercially available at the time of this writing.)

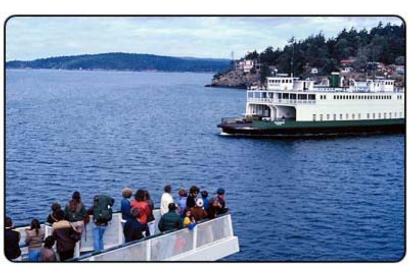
The first three options are the most cost-effective of those commercially available. Option 3 – the EGR/DPF system (commercially available from Johnson-Matthey) - appears to yield a good compromise between effectiveness and emission reduction.

Engine-replacements were not included in this study because of their extremely high cost. They would not be cost-effective unless supported by a state subsidy program similar to California's Carl Moyer program.

The five options that were considered for the **auxiliary engines** of the workboats are shown in Figure S4 below. The two most cost-effective options are seen to be using CWI with LSD to reduce NOx and SOx emissions, and CWI with DOC and LSD to reduce emissions of NOx, VOC, particulates and SOx. The other three options, by themselves, have a greater cost/benefit ratio and a lower emission reduction.



S4 Ferry Options

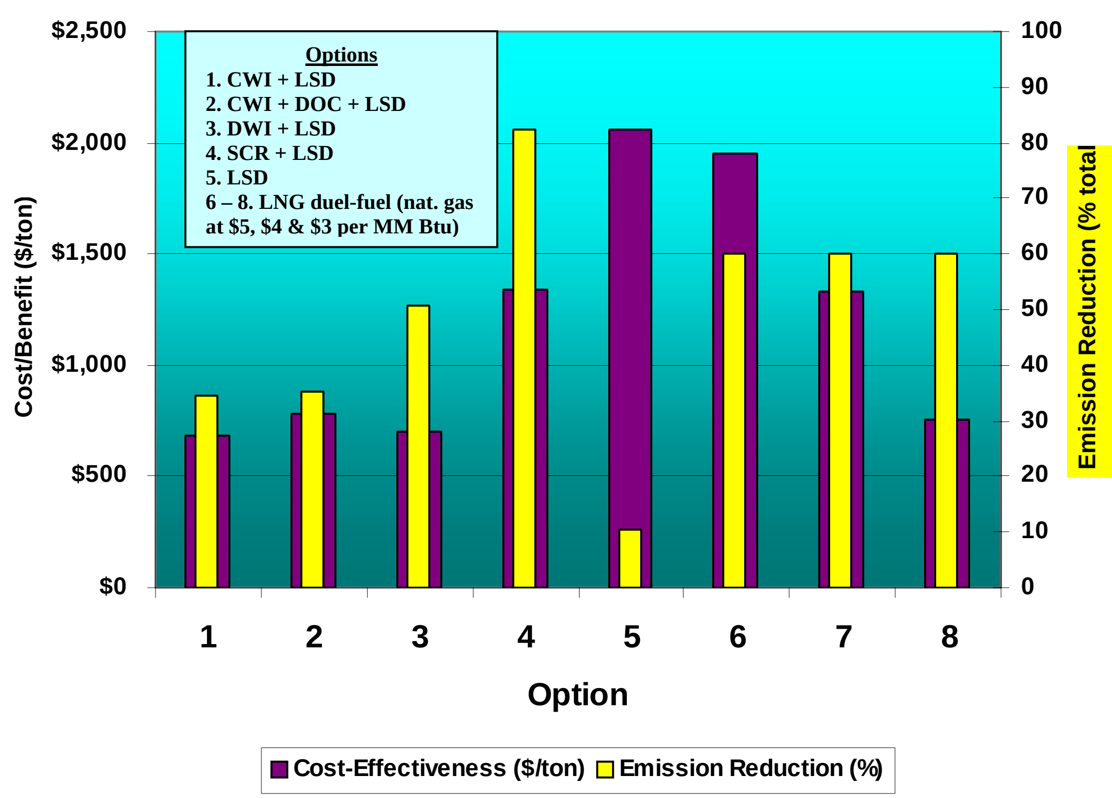


The ferry fleet used as a basis for this study consists of 29 vessels operated by Washington Sate Ferries in the Puget Sound area. The vessels vary in power from that of the smallest ferry, powered by two 67 hp John Deere engines, up to the largest ferry, which is equipped with four 4,000 hp EMD diesels.

The different emission reduction options that were studied for ferry engines are shown in Figure S5. The different technological options are applied to the main engines only, as this is the greatest cost-effectiveness can occur for ferries, while the use of low sulfur diesel (LSD) was applied to all engines.

The most cost-effective options are the first four, and LNG duel-fuel conversion of the main engines, if natural gas is available at $3/MM Btu (option 8). Selective catalytic reduction (SCR), option 4, provides the greatest emission reduction (over 80%), but at a higher cost/benefit ratio than does the use of direct water injection (DWI), option 3. However, DWI is presently available only from Wartsila and may not be retrofitable to all other marine engines. Therefore options 1, 2 & 4 will be most generally applicable to ferries.

Figure S5 - Ferry Options

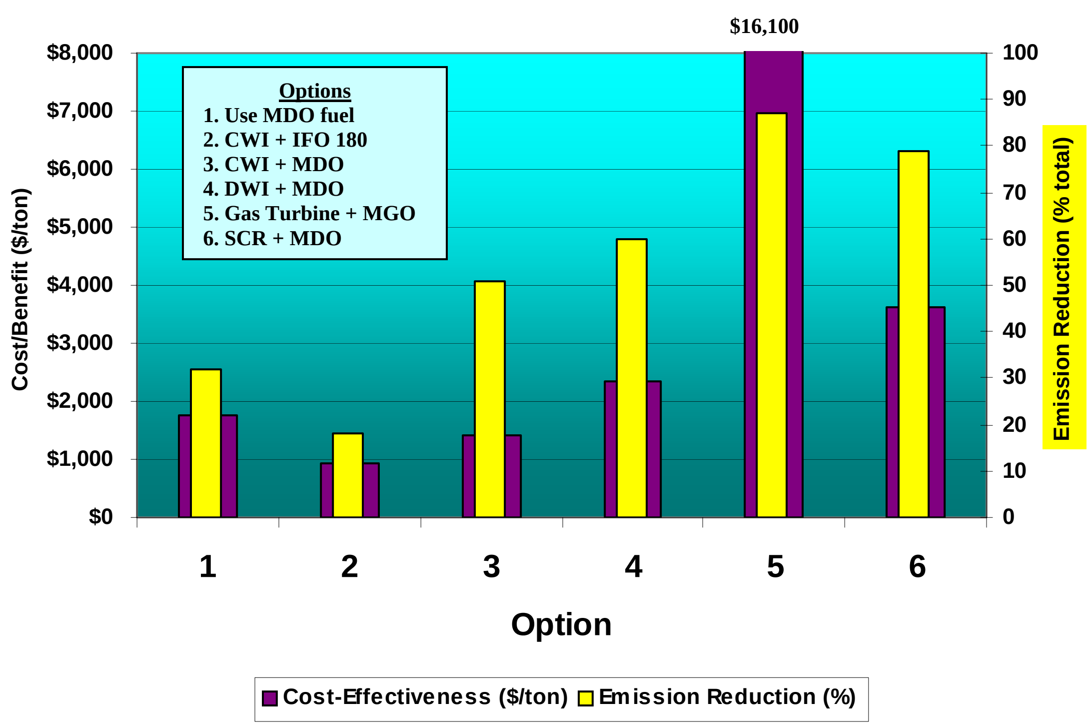


S5 Cruise Ship Options

The representative cruise ship "fleet" that is used in this study is based upon data from typical cruise ship which is extended to all 22 different vessels that call annually at the Port of Seattle. Cruise ships generally have several large medium-speed diesel gensets which produce the electrical power needed to drive electric propulsion motors, maneuvering thruster motors, navigation gear and hoteling requirements. The fuel used in these ships is usually an intermediate fuel oil (IFO 180) with a sulfur content of 2.4%.

The emission-reduction options that are applicable to all modes of cruise ship operation and which were included in this study are the use of marine diesel oil (MDO, assumed to be 0.13% S as measured in a previous Vancouver-area study), continuous water injection (CWI) alone or with MDO, direct water injection (DWI) with MDO, a new-engine alternative - a gas-turbine burning marine gas oil (MGO, assumed to be 0.13% S), and selective catalytic reduction of NOx (SCR) plus the use of MDO fuel.

Figure S6 - Cruise Ship Options - All Modes of Operation



These different options are shown in Figure S6. It can be seen that the first four options are the most cost-effective, while the last two provide the greatest emission reduction.

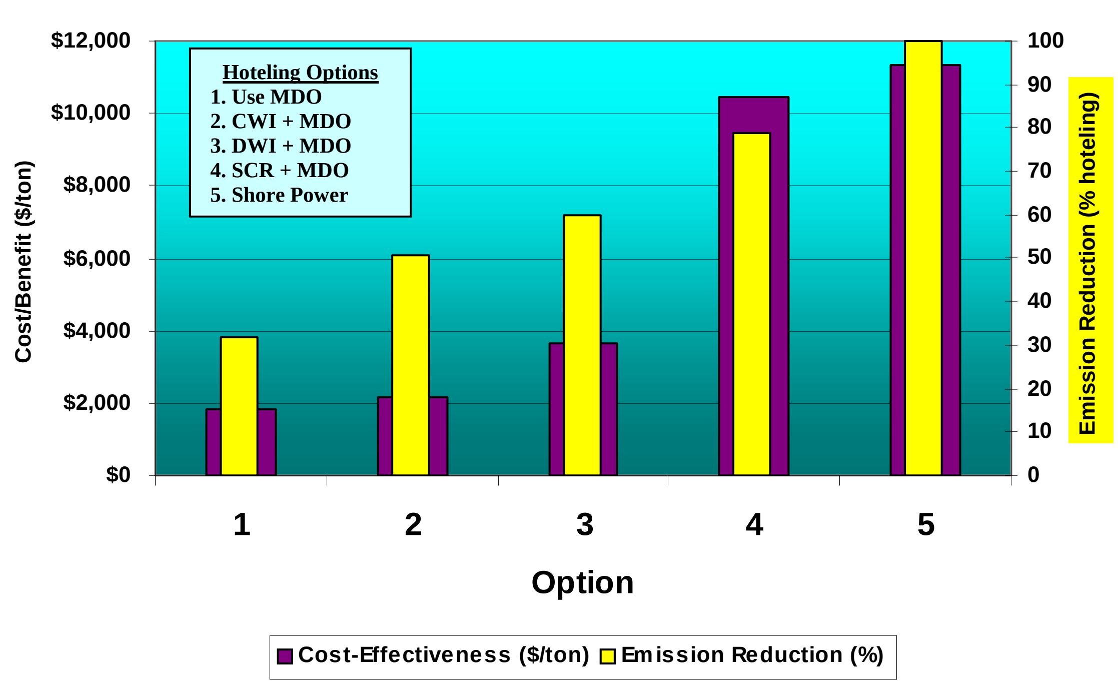
The use of a gas turbine solely for emission reduction in the Puget Sound region is very expensive ($16,100 per ton of emission reduction) but does reduce total emissions by 90%. The relatively low weight and small size of the gas turbine, as compared to diesel engines of the same power output, may increase the capacity of a cruise ship for paying passengers and thereby offset the increased operating costs.

The use of selective catalytic reduction (SCR) of NOx reduces emissions by at least 80% at a cost/benefit ratio of $3,600/ton of emission reduction. SCR is bulky, however, and may decrease the passenger capacity of cruise-ships, although it is widely used on ferries in Scandinavia where there are economic penalties associated with NOx emissions.

The use of continuous water injection (CWI) or direct water injection (DWI), in conjunction with MDO, are the most cost-effective options when used for all modes of vessel operation and can reduce emissions by 50% - 60%. As previously stated, DWI is at present retrofitable only on Wartsila's marine engines, although there is no reason why this injector technology cannot be adapted to other makes.

Figure S7 shows the five options that were studied for use in reducing emissions from hoteling only. Their cost/benefit ratio will be higher than if the same options are applied to all modes of operation, since capital expenditures will be almost the same while tons of emission reduction will be less because baseline emissions are less for hoteling than those for total vessel operation.

Figure S7 - Cruise Ship Options - Hoteling Only



The three most cost-effective options are again seen to be using MDO alone or with some form of water injection for NOx reduction. Shore power appears to reduce hoteling emissions by 100%, if no offset is made for somewhat increased emissions within the shore-based power grid. However, this is much less cost-effective than other options.

S6 Conclusions

Five different families of non-road, HDD mobile sources were studied in order to identify cost-effective ways to reduce their emissions within the Pacific Northwest.

- For construction equipment the use of a water-diesel emulsion such as *PuriNOx* can reduce total emissions by over 40% when used in conjunction with low sulfur diesel. The cost-effectiveness is estimated to be $2,600/ton of emission reduction for this option.

- For locomotives (mix of line-haul and yard engines) operating in the Pacific Northwest the most cost-effective emission reduction strategies is to rebuild the engines to Tier 0 or to Tier 1 NOx emission standards. These options have a low cost/benefit ratio of $46/ton and $170/ton, respectively. The most expensive option considered (using liquefied natural gas in converted duel-fuel engines on the line-haul locomotives) reduces total emissions by almost 70% at a cost of $802/ton, when the natural gas commodity price is at the present $5/MM Btu. However, if the natural gas commodity price drops down to $4/MM Btu, due say to imports of offshore LNG or availability of North Shore gas, then this option becomes more cost-effective at $128/ton.

- For workboats, such as barge tugs, the cost-effectiveness for effective emission reduction options for the main engines varied from $127/ton (using continuous water injection, CWI, with existing #2 diesel to give a 27% emission reduction) up to $1,430/ton (using exhaust gas recirculation, EGR, with diesel particulate filters, DPF, and low sulfur diesel to give a 46% emission reduction). Other technologies resulted in higher costs and with lower emission reductions.

- Emission reduction options applied to the auxiliary engines of workboats were less cost-effective, with costs in the order of $2,500/ton of emission reduction for two technologies (CWI + ULSD, and CWI + DOC + ULSD) that provide for 30% – 40% total emission reduction. Other technologies resulted in nearly double the cost ($5,000/ton) and with much lower emission reductions.

- Ferry emissions can be reduced by 82% at a cost of $1,300/ton of reduction through the use of selective catalytic reduction (SCR) of NOx. However, less costly technologies are available, albeit with lower emission reductions. The use of continuous water injection along with low sulfur diesel will, for instance, reduce emissions by 35% at a cost of $684/ton of emission reduction. Liquefied natural gas burned in duel-fuel converted diesel engines is cost-effective only if the commodity price of natural gas is less than $4 per million Btu's.

- For cruise ships operating within Puget Sound six different technologies were studied that would reduce emissions both while cruising and while hoteling (moored at dock). The options that provided significant emission reductions at low cost were the use of continuous water injection, along with MDO, which cost $1,400/ton of emission reduction and which gave a 51% total emission reduction, and the use of direct water injection along with MDO, which cost $2,300/ton of emission reduction and which gave a 60% total reduction in emissions. The use of MDO in place of fuel oil (IFO 180) is a positive initiative, with an emission reduction of 32% at a cost of $1,800/ton.

- If only the hoteling emissions from cruise ships are to be reduced this can be done using the same options as those applicable to all modes of operation, since similar engines are used for cruising and hoteling. In addition, the cruise ships can connect to shore power, as is done in Alaska. However, while this option results in the greatest emission reduction (nearly 100%) it does so at a cost of $11,000/ton of emission reduction. Other options, such as those described above, can reduce hoteling emissions by up to 60% at a cost of $3,700/ton or less. They are probably best implemented for reducing exhaust emissions both during hoteling and during cruising, since this provides the least cost per ton of emission reduction.

S7 Recommendations

This study compared the different emission reduction options, for five different families of non-road HDD mobile sources, based upon their cost-effectiveness (cost per ton of total emission reduction) and upon their percentage of emission reduction. Emissions of SOx, NOx, PM, VOC, formaldehyde, benzene and 1,3-butadiene were lumped together as "total emissions", even though the health effects of these different species vary widely. Therefore the current, commonly-used methodology is heavily weighted toward NOx and SOx reduction, because the rating criteria are based on total tons of emission reduction per dollar spent, instead of upon toxicity reduction, which may favor PM or VOC reductions.

An improved method of comparison recently developed by Genesis Engineering is to multiply the emission of each species by an index, whose magnitude is proportional to the toxicity of that species, and then to sum the resulting values to obtain a health-effect-weighted total. In this way technology that is effective in reducing toxic species, such as diesel particulate or some of the components of VOC, would be more favored over technologies that only are good at reducing the emissions of less toxic compounds. Monies spent upon pollution reduction would thereby provide a greater benefit to society.

It is therefore recommended that this study be extended to also estimate the toxicity-weighted cost-effectiveness for the different emission reduction strategies discussed above. These toxicity-weighted values of cost-effectiveness can then be compared with the values that were estimated in this study. Strategies to cost-effectively reduce air toxics may well differ from those that are cost-effective for reducing the smog-related pollutants. Air quality managers should have both sets of cost indices available in order to help them guide optimal emission-reduction initiatives.

ACKNOWLEDGEMENTS

Genesis Engineering Inc. (Gordon Esplin) prepared this report with major input from Levelton Engineering Ltd. (Roger Quan, Katherine Cheng and Trudi Trask), who prepared the baseline fleet emission estimates and who estimated annual fleet fuel consumptions where this data was otherwise unavailable.

Genesis Engineering Inc. is grateful to the participating fleet owners who cooperated in this study and gives special recognition to Holly Robinson of Tidewater Barge Lines, Tina Stoltz of Washington State Ferry, Rick Haggard of the City of Seattle and John Chavez of Burlington Northern Santa Fe Railroad.

Genesis Engineering Inc. is also grateful to the many other individuals and organizations who contributed to this study. They are listed in the References Section of this Report.

Finally, but not least, Genesis Engineering would like to give special thanks to the U. S. Environmental Protection Agency, Region X who provided the grant for this project and to Tom Hudson of the Puget Sound Clean Air Agency and Kevin Downing of the Oregon Department of Environmental Quality who initiated this project, brought together participating fleets of representative non-road HDD sources and who made it all happen.

Table of Acronyms

BHP	Brake Horse Power
BNSF	Burlington Northern Santa Fe Railroad
BTU	British thermal unit
CAC	Criteria air contaminants (CO, VOC, NOx, SOx, PM)
CARB	California Air Resources Board
CNG	Compressed Natural Gas (< 10 ppm S)
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CWI	Continuous Water Injection
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DWI	Direct Water Injection
EPA	US Environmental Protection Agency
G/HP-HR	Grams per horsepower-hour
G/KWH	Grams per kilowatt-hour
GB/PS	Georgia Basin/Puget Sound airshed
GEORGIA BASIN	Georgia Coast Cascade Air Basin (same as GB/PS)

GHG	Green House Gas (example – CO_2)
GJ	Gigajoule (277.8 kWh)
GVRD	Greater Vancouver Regional District
GCCAB	Georgia Coast Cascade Air Basin (same as GB/PS)
HA	Hectare (2.47 acres)
HC	Hydrocarbon gases (carbon-hydrogen molecules)
HFO	Heavy Fuel Oil (< 5% S)
IFO	Intermediate Fuel Oil (< 5% S)
IMO	International Maritime Organization
KW	Kilowatts power
LFV	Lower Fraser Valley
LNG	Liquefied Natural Gas (< 10 ppm S)
LSD	Low sulfur diesel (< 500 ppm S)
MDO	Marine Diesel Oil (300 – 5000 ppm S)
MM BTU	Millions of Btu's
NOx	Oxides of Nitrogen, reported as nitrogen dioxide
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter less than 2.5 microns in diameter
PPM	Parts per Million
S	Sulfur
SCFT	Standard Cubic Foot
SCR	Selective Catalytic Reduction (for NOx removal)
SHP	Shaft Horse Power
SOx	Oxides of Sulfur, reported as sulfur dioxide
TON	Short ton (2000 pounds)
TONNE	Metric ton (1000 kilograms)
TPY	Tons per Year
ULSD	Ultra-Low Sulfur Diesel (< 15 ppm S)
VOC	Volatile Organic Compounds (includes benzene, formaldehyde and 1,3 butadiene, as well as many other organic and hydrocarbon species which are volatile at ambient temperature)
WSF	Washington State Ferry

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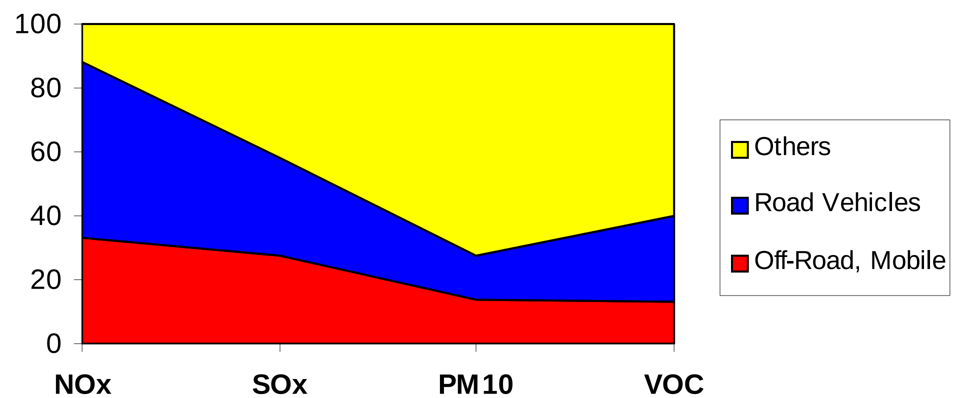
1.0 INTRODUCTION

1.1 Project Background

Rapid population growth in the Pacific Northwest challenges the maintenance of good air quality in this region. While stringent EPA regulations are helping to limit emissions from on-road highway vehicles, there are no equivalent regulations for off-road, heavy-duty diesel-engine (HDD) mobile sources, such as marine vessels, railroad locomotives and construction equipment. As a consequence, the emissions from nonroad sources are becoming a significant component of the regional air pollution inventory.

Total emissions of NOx, SOx, PM10 and VOC from HDD nonroad sources in Washington and Oregon during 1999 were 131,250 tons. Figure 1.1 shows the percent contribution of off-road, mobile sources to the total emissions in the State of Washington for the year 1999. The non-road sources contributed 33% of the oxides of nitrogen (NOx), 28% of the sulfur oxides (SOx), 14% of the inhalable particulate matter (particulate less than 10 microns in diameter, PM_{10}) and 13% of the volatile organic compounds (VOC). [150]

Figure 1.1 Emission Inventory
State of Washington Year 1999



A similar emission contribution from nonroad sources is expected in the State of Oregon, where nonroad diesel engines consume 25% of all diesel fuel used in the state but emit 65% of the particulate, 47% of the NOx and 91% of the SOx pollution from all diesel vehicles. [151]

Much of the concern over air pollution in the Pacific Northwest is focused on the heavily populated I5 corridor shown in Figure 1.2. For instance, according to EPA's 1996 National Air Toxics Assessment the three Oregon counties in the Portland metropolitan area, plus Clark County in Washington State, rank nationally in the 90th percentile or greater for concentration of diesel particulate. Multnomah County, the most heavily populated county in Oregon, ranks in the 95th percentile. In a preliminary assessment of health risk from air toxics the Oregon Department of Environmental Quality ranks diesel

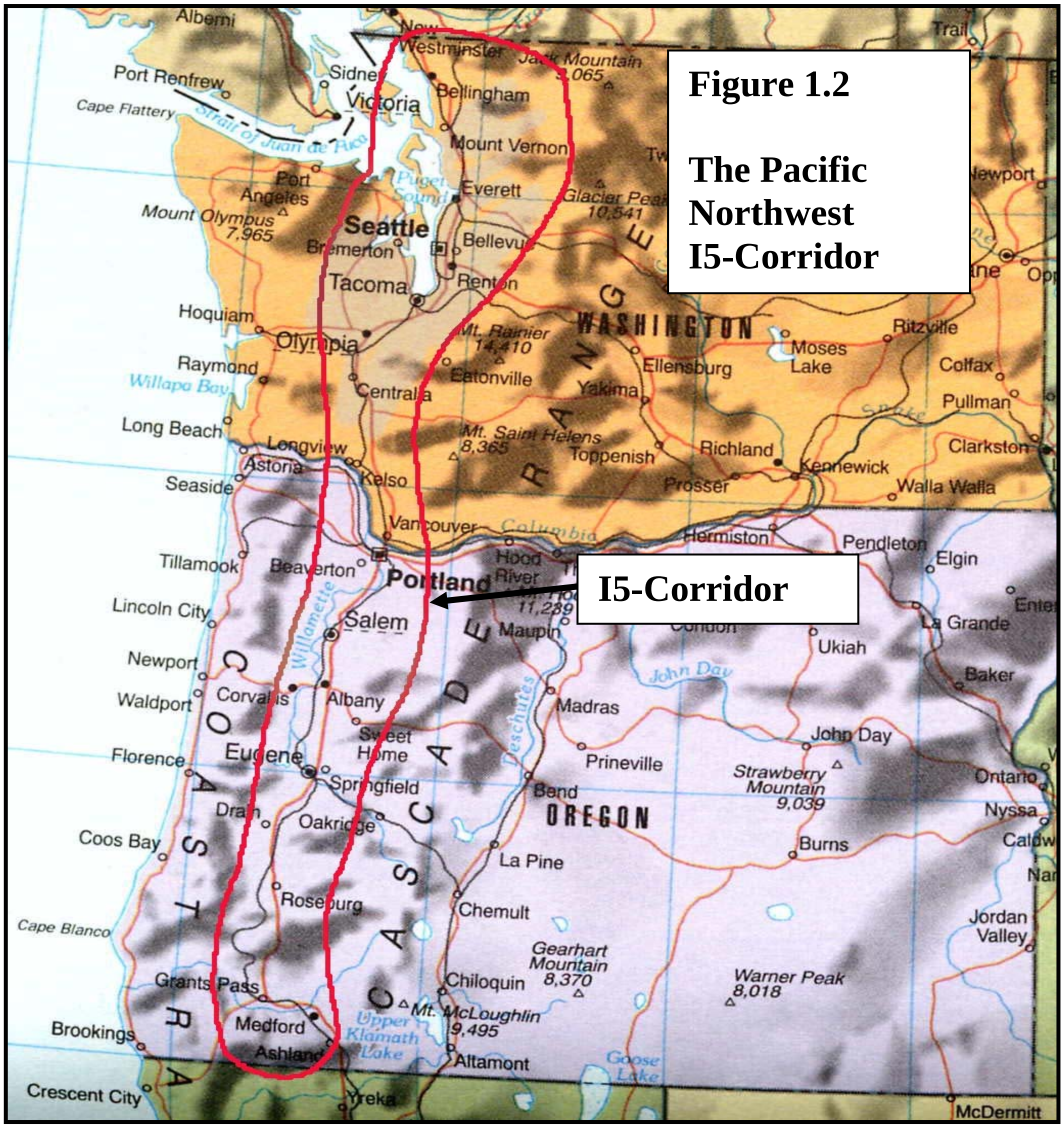


Figure 1.2

The Pacific Northwest I5-Corridor

particulate as the number one risk in the State, exceeding the combined risk from the next twelve air toxics by a factor of eight. [151]

In addition to the adverse health effects from breathing exhaust from nonroad diesel engines, there is a concern about the contribution to regional haze in Class 1 wilderness areas and other areas sensitive to visibility degradation, such as the Columbia Gorge Scenic Area. [151]

Clearly effective management of pollutant emissions is essential to the maintenance of good air quality in this region and to the protection of human health.

The purpose of this study will be to determine the most cost-effective methods for reducing the emission of air contaminants from off-road HDD mobile sources operating in the I-5 corridor and the coastal waterways of Washington and Oregon.

The air contaminants of major concern are SOx, NOx, VOC's, $PM_{2.5}$, benzene, 1,3-butadiene and formaldehyde. The first three of these pollutants contribute to the indirect, atmospheric formation of respirable particulate (particulate with a diameter of less than 2.5 microns, $PM_{2.5}$), which have negative health effects and which are also responsible for regional haze and visibility degradation. (NOx and VOC's also react to form photochemical smog, of which ozone is a major component.) Benzene, diesel $PM_{2.5}$, 1,3-butadiene and formaldehyde are air toxics implicated in the promotion of human cancers.

Carbon monoxide (CO), although a major pollutant, was not included in this study. CO is primarily of concern in areas of heavy urban traffic congestion as a result of car and truck emissions; its ambient concentration diminishes rapidly a short distance away from busy intersections. Even at some of the busiest, most congested intersections in Washington, monitoring sites have not registered CO concentrations exceeding air quality standards. In addition, records show that CO levels have dropped dramatically over the past two decades, probably as a result of better engine and catalytic converter technology and cleaner fuels.[152] Consequently, CO is not considered a significant air quality problem in the Pacific Northwest and will not be included in this study.

The strategy of this study will be to determine annual exhaust emissions (tons per year) and fuel costs for representative heavy-duty diesel (HDD) nonroad fleets (construction equipment, railroad locomotives, ferries, work-boats and cruise ships). We will then identify currently available emission reduction measures for the representative fleets, what the capital and operating costs of the various emission reduction initiatives are, and what pollution reduction results (tons per year of pollution reduction). The cost/benefit of different emission reduction options will then be calculated (the total annual cost of implementing the option divided by the resulting total tons per year of pollution reduction) and compared. The different emission reduction options for each fleet will then be prioritized and the best options recommended to the Puget Sound Clean Air Agency. The Puget Sound Clean Air Agency will use the study results to help guide emission reduction decision-making that is both technically sound and cost effective.

It should be noted here that benzene, 1,3-butadiene and formaldehyde are three components of the volatile organic compound (VOC) mixture, which may consist of hundreds or even thousands of different chemical species. The individual, base line emissions for benzene, 1,3-butadiene and formaldehyde are estimated for each of the five representative fleets in Section 4. However, for purposes of determining the overall cost-effectiveness of different emission-reduction options they are included with VOC. Hence it is assumed that a 30% reduction in VOC emissions also infers a 30% reduction in benzene, 1,3-butadiene and formaldehyde. Readers wishing to study the percent reduction of the individual pollutants may do so for each participating fleet by using the summary table available in the end of Sections 7 to 11.

The following two sections provide a brief overview of diesel engine emissions, the environmental effects of these emissions and government regulations to limit these emissions.

2.0 DIESEL ENGINE EMISSIONS

2.1 Introduction

The diesel engine has evolved into a fuel-efficient, reliable source of power for mobile sources. It has undergone a powerful development process resulting in a completely new generation of engines with considerably improved performance. For instance, the specific fuel consumption of a modern two-stroke diesel engine may be in the order of 160 g/kWh, as compared to 210 g/kWh or higher for older engines. Today the largest two-stroke diesel engines have an output of over 80 MW, which should be sufficient even for future proposed high-speed container ships. Owing to the high efficiency of diesel engines, the emissions of CO_2, CO and hydrocarbons are relatively low, however, high emissions of NOx are also characteristic of diesel engines. The same high combustion temperatures that give a high thermal efficiency in the diesel engine are also most conducive to NOx formation. By running on relatively low quality fuels with a low fuel consumption, large diesel engines offer enormous savings in fuel costs compared with those of alternative prime movers.

Figure 2.1 presents a mass balance for a modern ship's main diesel engine burning bunker oil, with 8 kg/kWh coming into the engine as fuel, air and lubricating oil; and with 8 kg/kWh leaving the engine as exhaust gas. About 0.40% of the exhaust is comprised of the air contaminants NOx, SOx, hydrocarbons and particulate, while 6.2% consists of the greenhouse gas CO_2.

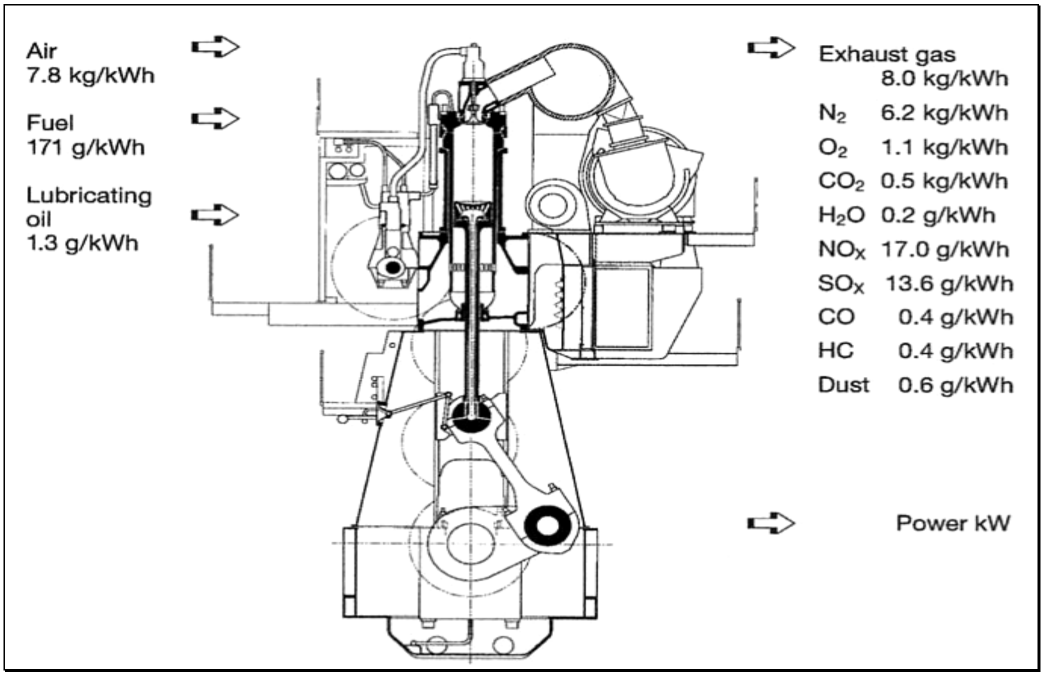


FIGURE 2.1 – TYPICAL MARINE DIESEL ENGINE EMISSIONS (Ref. 5)

Diesel engines are classified either as a 2-stroke or a 4-stroke, with the 2-stroke using one power stroke per revolution and the 4-stroke using two revolutions per power stroke. The large 2-stroke diesel requires an air mover (turbocharger or blower) to move the gases in and out of the engine, while the 4-stroke may be turbocharged or may be naturally aspirated.

Very large marine engines tend to be 2-stroke diesels whose low speed allows them to be directly coupled to an efficient, large-diameter propeller. The large 4-stroke marine engines must rotate faster and hence require a gearbox between the engine and the propeller. For instance, the Wartsila 12V64 4-stroke produces 23,280 kW (31,650 hp) at 400 rpm, as compared with the Sulzer RTA84T 2-stroke which produces 24,600 kW (33,480 hp) at 76 rpm. The higher speed of this 4-stroke allows it to be more compact and lighter (432 tonnes) compared to the 2-stroke (870 tonnes). But the slow-speed 2-stroke can get away with a very long stroke, resulting in a higher compression ratio and improved fuel efficiency, while still maintaining a low piston speed. The Sulzer RTA84T 2-stroke has a stroke of 3.15 meters and a piston speed of 8 m/s, as compared with the Wartsila 12V64 4-stroke which has a stroke of 0.77 meters and a piston speed of 11 m/s. The specific fuel oil consumption (SFOC) for the large marine 2-strokes is typically around 160 g/kWh, as compared with about 185 g/kWh for the larger 4-stroke diesels.

The intermediate-sized (thousands of horse-power) diesels may be either 2-stroke or 4-stroke. Almost all of the earlier diesel locomotive engines are of a 2-stroke design. For instance, the General Motors EMD 645E3 is a turbo-charged 2-stroke with a displacement of 645 c.i. per cylinder and an output of about 2300 hp at 900 rpm.

Modern small (hundreds of horse-power) diesel engines tend to be of the high-speed, 4-stroke design with high specific power and low exhaust emissions. Engine technology and special designs for reducing emissions will be discussed in a further section

2.2 Types of Emissions

As stated in the Introduction, uncontrolled emissions from heavy-duty diesel engines have a significant impact upon our air quality. This section will briefly review some of the adverse impacts that are caused by the various emission components. A more comprehensive review was recently carried out by the State and Territorial Air Pollution Administrators and the Association of Local Air Pollution Control Officers (two USA national associations), who discuss health and welfare impacts from heavy-duty diesel engines and quantify the financial benefits that may result from reducing these emissions.[22]

2.2.1 Nitrogen compounds

In most combustion processes oxides of nitrogen are normally formed and the most common of these are nitrogen oxide, NO, and nitrogen dioxide, NO_2. These compounds are usually labeled 'NOx", of which NO_2 forms approximately 5 per cent. Other oxides, such as N_2O and N_2O_5, are also present in trace amounts. In the atmosphere the NO is oxidized to NO_2 and nitric acid, HNO_3. Excessive emissions of NOx results in various environmental problems: a) nitrogen saturation of forest soil resulting in ground-water acidification, b) increased photochemical smog, e.g. ozone, O_3, in the lower atmosphere, c) direct gaseous damage to plants and organisms, d) the formation of inhalable (PM_{10}) nitrate particles which contribute to human morbidity and increase atmospheric haze, and e) increased global warming due to the potent "greenhouse" gas N_2O that has a global warming potential which is 320 times that of CO_2. Even though present in the atmosphere in only trace amounts, N_2O is expected to be responsible for approx. 5 - 6 per cent of the expected global temperature rise.

Acidification of the soil means an increase in the acidity of the soil, resulting in a dramatic change in the health of the soil. When an ecosystem receives an addition of "fixed" nitrogen in the form of ammonia or nitrates there is initially an increased growth in most plants. However, when the ecosystem receives more nitrogen than these organisms are able to process the excess nitrogen, in the form of nitrates, enters the groundwater, carrying with them important nutrients such as magnesium, calcium and potassium. There is also a release of metals, e.g. aluminum and cadmium, which are poisonous to the roots of trees, to fish and to other organisms.

Hydrocarbons and nitrogen oxides act together under the influence of sunlight, forming photochemical oxidants. Most important of these oxidants is ozone, which is directly injurious to human health, causes significant economic damage to organic materials such as paints, plastics, rubber and textiles, and which is responsible for damage to forests, crops and other vegetation.

Apart from damage from acidification and photochemical oxidants, several types of direct gaseous damage also affect the environment. Nitrogen oxides damage trees and crops directly through leaves and pine needles and may affect the health of sensitive groups of the population causing respiratory and other problems.

2.2.2 Sulfur compounds

The sulfur compounds occurring in the exhausts from heavy-duty diesel engines are sulfur oxides (SOx), predominantly SO_2, and to a lesser extent SO_3 (2-3 per cent). Sulfate, SO_4, may also be emitted in small amounts combined with metals (Na, Ca) in particulate matter. The emission of sulfur oxides is a major cause of the acidification of soil and water. Furthermore, the emissions of sulfur oxides lead to directly adverse effects on human health (i.e. an increase in respiratory problems) and to corrosion of buildings and other materials. Sulfur dioxide is converted to sulfate particles in the atmosphere. These are a major contributor to ambient $PM_{2.5}$ (respirable particulate matter less than 2.5 microns in diameter), which has a strong impact on human morbidity as well as contributing to atmospheric haze.

2.2.3 Volatile organic compounds

Organic compounds are molecules containing carbon, oxygen, hydrogen, and often other types of atoms. It is common practice to separate the organic compounds into volatile organic compounds (VOC) and non-volatile organic compounds, depending upon their volatility at ambient temperature. (A subset of the organic compounds are the hydrocarbons, which are molecules consisting only of carbon and hydrogen atoms. The literature often confuses the terms hydrocarbons and VOC.) The non-volatile organic compounds form the soluble organic fraction of particulates (SOFP) and are approximately 25% - 30% of the total mass of diesel particulates.

The organic compounds are formed partly as a consequence of incomplete fuel combustion and partly from free-radical reactions within the combustion process. They may exist in several different forms and more than 300 different compounds have been identified in emissions from diesel-powered vehicles[6]. Polycyclic aromatic hydrocarbons, PAH, occur both in a gaseous phase as well as in a particle bound form in the exhausts. This group of organic compounds include several which have proved to cause cancer and are mutagenic substances; such as benzo (a) pyrene, cyclopenta (cd) pyrene and fluoranthene. PAH derivatives, such as nitro-PAH and methyl-PAH, may be responsible for a significant part of the carcinogenic effect. Another environmental hazard from the emission of organic compounds, which now frequently attracts attention, are the organochlorine derivatives, which may form in trace amounts during combustion. These include chlorophenols, chlorobenzenes, polychlorinated biphenyls (PCB), dioxins and furans. These substances, and particularly PCB and dioxins, are soluble in fats, extremely difficult to break down and are among the most toxic compounds we know. Their possible origin from heavy-duty diesel engines may be: a) lubricating oil, which contains additives such as chloroparaffins and chlorinated solvents, b) addition of waste oil in the fuel and c) chloride compounds in the combustion air.

Aldehydes and other light organic compounds, e.g. alkenes and alkyl benzenes, occur in the diesel exhausts. These compounds, in conjunction with NOx, may contribute to the formation of photochemical oxidants, which may damage crops and forests and also directly affect human health (carcinogenicity, mutagenicity, irritation of eyes and mucous membranes).

Benzene, 1, 3–butadiene, and formaldehyde are three VOC compounds that have been identified as air toxics, have direct effects upon human health and which derive from the exhaust of diesel engines.

2.2.4 Particulate Matter

For purposes of discussing the effects of particulate matter upon human health, particulate matter is classified as total particulate matter (PM), inhalable particulate matter (PM_{10}), or as respirable particulate matter ($PM_{2.5}$). Total particulate matter is the total material that can be collected upon a filter under specified temperature conditions. PM_{10} is all filterable particulate mater with a diameter of less than 10 microns, which is the approximate cut-off diameter for nasal inhalation. $PM_{2.5}$ is all filterable particulate matter with a diameter of less than 2.5 microns in diameter, which is the approximate cut-off diameter for particles that can penetrate deep into the lungs. Total particulate matter includes both PM_{10} and $PM_{2.5}$. It is the $PM_{2.5}$ particles that are of major human health concern.

Particulate matter in the exhaust gases consists mainly of unburned carbon and ashes but will also contain trace metals and SOFP, including bound polynuclear aromatic hydrocarbons (PAH). In general the particles are small (90 per cent < 1 micron) and are therefore able to penetrate into the finest cavities of the lungs (alveoli) and cause health problems. Certain PAH compounds have a direct mutagenic effect and may cause cancer.

In 1998, following an exhaustive 10-year scientific assessment process, the California Air Resources Board (CARB) identified particulate matter from diesel-fueled engines as a toxic air contaminant. In the California South Coast Air Basin, the potential risk associated with diesel particulate emissions is estimated to be 1,000 per million people. Compared to other air toxics the Board has identified and controlled, diesel particulate emissions are estimated to be responsible for about 70% of the total ambient air toxics risk. As a result of this study, CARB has initiated a comprehensive plan (Diesel Risk Reduction Plan) to significantly reduce these emissions[23].

2.2.4 CO and CO_2

Carbon monoxide, CO, forms as a consequence of incomplete combustion. The gas is photochemically active and directly toxic in very high proportions, and persons suffering from heart and vascular diseases are sensitive to it.

Carbon dioxide, CO_2, is formed in comparatively large amounts in all types of combustion processes. In spite of the fact that CO_2 has no direct harmful effect on nature it is the most important of the so-called greenhouse gases. Elevated concentrations of these gases disturb the global heat balance by returning the long-wave radiation that is normally emitted away from the earth. At present, CO_2 from the burning of fossil fuel amounts to almost three times the quantity that vegetation is able to consume.

2.3 Emission Formation

2.3.1 NOx

Nitrogen oxides, NOx, are formed during combustion through several chemical reactions[7]; a) through a reaction between the oxygen and the nitrogen in the combustion air ("thermal NOx"), b) through oxidation of the nitrogen bound in the fuel ("fuel NOx"), and c) through a two-step mechanism where the nitrogen of the air reacts with hydrocarbon radicals during the forming of cyano- and amino-radicals then oxidizing to NOx ("prompt NOx"). In marine diesel engines most NOx is formed via the thermal mechanism described below.

The transformation of air nitrogen to thermal NOx may be described in a simplified way by the following gas phase reactions (known as the 'Zeidovich mechanism') [8]:

$$O + N_2 \Rightarrow NO + N \quad (1)$$

$$N + O_2 \Rightarrow NO + 0 \quad (2)$$

$$N + OH \Rightarrow NO + H \quad (3)$$

Eqn 1 controls the speed of the overall reaction, and the concentration of O radicals is crucial. In order for NO to form, the combustion temperature and the concentration of oxygen must be sufficiently high for there to be sufficient atomic oxygen O; an increase in temperature and added air will lead to increased NO formation. In practice, the rate of formation of NO will be insignificant if the combustion temperature drops below approx. 1200°C. And as a rule of thumb, it can be said that NOx formation at temperatures above 1200°C increases by a factor of ten for every 100°C rise. At each temperature there is an equilibrium concentration of NO, which, however, takes a certain time to establish itself. This means that the shorter the duration at a high temperature the less thermal NO is formed. Taking these factors into account (combustion temperature, availability of oxygen and duration) the process can be controlled so that it reduces the formation of NO.

The nitrogen compounds in the fuel constitute approximately 0.2 - 0.5 percent by weight of heavy fuel oil and are present in the fuel as different types of organic substances (pyrides, amines, amides, etc.). During combustion volatilization occurs and then pyrolysis, giving lighter volatile nitrogen compounds which will further react. These substances (mainly volatile amines and cyanides) can react through either a) an oxidation where 'fuel NO' is formed or b) a formation of nitrogen, N_2, from a simple breakdown or from a reduction reaction with NO. Both reactions may occur mainly in the gaseous phase and to a certain extent as surface-catalyzed reactions, e.g. on solid soot particles. The exact mechanisms are complex and many different radicals are involved. In order to simplify the process it is possible to describe reaction chains with three global reactions (eqn 4 - 6), where NH_3 represents the volatile nitrogen compounds.

$$NH_3 + O_2 \Rightarrow NO \quad (4)$$

$$NH_3 + NO \Rightarrow N_2 \quad (5)$$

$$NH_3 \Rightarrow N_2 \quad (6)$$

Among the different combustion variables, it is the fuel/air ratio that has the most important effect on the formation of fuel NO. The formation increases, however, rather slowly when the surplus of air rises above stochiometric amounts, but decreases rapidly when going towards more fuel-rich mixing conditions. A temperature decrease does not reduce fuel NO very much over 800 - 1700°C, while thermal NO decreases dramatically with a lower temperature. The formation of fuel NO is not significantly affected by the way that nitrogen is bound in the fuel.

During combustion the above mentioned mechanism may be used to control the emission of NO, as a surplus of fuel promotes the formation of N3, while a surplus of air causes mainly NO to be formed. Certain NOx control technologies use similar reactions to Eqn. 5 through an addition of nitrogen compounds in the exhaust gases, e.g. NH_3, $(NH_2)_2CO$ (urea), etc., with or without a catalyst (respectively known as Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR)[9].

Formation of prompt NO occurs through what is known as the 'Fenimore Mechanism' [10] (eqn 7-12) and contributes only to a small extent to the total NO emission. Reaction mechanisms where the nitrogen originates from the air occur in the gas phase in flames over a comparatively wide temperature range.

$$CH + N_2 \Rightarrow HCN + N \quad (7)$$

$$N + O_2 \Rightarrow NO + O \quad (8)$$

$$N + OH \Rightarrow NO + H \quad (9)$$

$C2 + N_2 \Rightarrow 2CN$ (10)

$CN + O \Rightarrow C + NO$ (11)

$CN + O_2 \Rightarrow CO + NO$ (12)

The NO_2 share of the total NOx emission is comparatively low (5-10 per cent) and is formed through an oxidation of NO partly at high temperatures with HO_2 radicals (eqn 13), and partly at lower temperatures and longer durations with O_2 (eqn 14).

$NO + HO_2 \Rightarrow NO2 + OH$ (13)

$2NO + 02 \Rightarrow 2NO_2$ (14)

2.3.2 SOx and $SO_4^{=}$

Unlike the nitrogen oxides, sulfur oxides are formed solely from the oxidation of the fuel-bound sulfur compounds[7]. When fuel is burned almost all the sulfur (95 per cent is a general opinion) is emitted to the air, while a smaller part is bound as sulfate in ashes and particles. Both organic and inorganic sulfur compounds contained in the fuel are rapidly oxidized at combustion temperatures primarily to sulfur dioxide, SO_2 (eqn 15), which may then be oxidized by means of O radicals or O_2 to sulfur trioxide, SO_3 (eqn 16 -17) [11].

$\text{Fuel } S + O_2 \Rightarrow SO_2$ (15)

$SO_2 + O \Rightarrow SO_3$ (16)

$2SO_2 + O2 \Rightarrow 2SO_3$ (17)

If there were to be sufficient time for the thermodynamic balance to stabilize in the exhaust flue, the SO_2 would be more or less completely oxidized to SO_3. In practice, however, only a very small share (1-5 per cent) of the SO2 has sufficient time to oxidize to SO_3. The fraction of formed SO_3 increases with combustion temperature and surplus air. SO_3 cannot exist in a free condition if traces of water vapor are present. Instead, it leads to the forming of a mist of sulfuric acid, H_2SO_4, through a rapid reaction (eqn 18) most frequently at low temperatures after the gas has been emitted to the air.

$SO_3 + H_2O \Rightarrow H2SO4$ (18)

Furthermore, a part of the sulfuric acid reacts with basic compounds in the fuel, which gives neutral sulfates. Alternatively, condensation may occur on particles and other surfaces, depending on the temperature and moisture of the flue gas (eqn 19). For a given SO_3 content and moisture in the flue gas there is a temperature (the so called acid dew point, approx. 110-160°C), below which the flue gas temperature should not be cooled if condensation of sulfuric acid is to be avoided.

$$H_2SO_4 + H_2O \Rightarrow H3O^+ + HSO_4^- \quad (19)$$

The drops of condensation and acidic soot are very corrosive, thereby resulting in damage to properties that are impacted by these pollutants as well as adversely affecting human health.

The emitted SO_2 gas is converted to acidic sulfate $PM_{2.5}$ in the atmosphere which is injurious to human health and which is frequently a major component of regional haze and visibility degradation.

2.3.2 Organic Compounds

Most organic compounds that can be measured in the exhaust gases are not originally present in the fuel, but have been formed from the fuel during incomplete combustion. Alternatively, some of the heavy organic compounds may come from residual products originating from the fuel. Polycyclic aromatic hydrocarbons, PAH, may be formed through radical reactions between hydrocarbon fragments, with subsequent ring closure and dehydration (i.e. hydrocarbon radicals form stable fragments of the benzene type). Optimum formation temperature for benzo (a) pyrene and many other similar PAH compounds is 700°C. A prerequisite for low organic compound emissions is a sufficiently high combustion temperature and an excess of combustion air (conditions normally occurring within modern diesel engines). Under such circumstances a complete combustion of any organic compounds that have been formed to CO_2 and water will occur.

2.3.3 Particles

Occurrences of particles in exhaust gases from diesel engines may be considered as originating from four different sources:

1. Gas phase polymerization reactions originating from acetylene, C_2H_2 (a pyrolysis product) may happen very fast and also, within 1 msec, small spherical carbon (soot) particles are formed. These particles grow to approx 50 nanometers (nm) in diameter and then undergo aggregation, finally forming large chains of molecules (emitted particles). The polymerization of the acetylene begins with an abstraction step with hydrogen radicals, which is then followed by further reactions with acetylene molecules (the so called 'Frenklach Mechanism' [7]). Furthermore there are ring closure and dehydration reactions resulting in the formation of large polycyclic aromatic compounds.

The rate-determining step is considered to be the formation of the first aromatic ring and the pyrolysis speed is of vital importance for the formation of soot. Fuels with high contents of aromatics and conjugated hydrocarbons often lead to high emissions of soot[7]. Depending on the type of flame in the combustion chamber the temperature may affect the soot emission in both positive and negative ways. In the diffusion flames, higher combustion temperatures result in higher soot emissions, but in the premixed flames more typical of diesel engines it is the other way around[7].

2. During combustion residual noncombustible ash products, e.g. cenospheres from the burned-out oil drops contribute to the soot emission. This source increases with increasing ash content and sulfur content of the fuel and forms an important component of PM_{10} emissions from diesel engines.
3. A certain amount of soot may condense on the walls of the combustion chamber. As a result soot flakes may build up and then detach from the walls, providing a source for the largest soot particles.
4. The lubricating oil may also contribute to the soot production in ways that are similar to the ones already mentioned, e.g. dispersion and condensation aerosols.

Combustion measures to decrease particle emissions usually resemble those used to decrease emissions of hydrocarbons, i.e. higher combustion temperatures and more excess air. As a consequence there is a compromise between emissions of NOx and those of hydrocarbons and particles. In order to solve this problem with regards to heavy diesel-powered trucks, engine manufacturers have in some cases chosen to adjust their engines in order to reduce NOx, and then reduced the other emissions by means of an exhaust oxidation catalyst (oxidation of hydrocarbons) and a diesel-soot particle trap (filter) [12].

2.4 The Effect of Fuel Oil Characteristics on Levels of Emissions

The heavy, residual oil from the bottom of the vacuum distillation column in an oil refinery is enriched in sulfur and metals. In the past this residual oil was usually sold as a heavy “bunker oil” for power generation or for burning in large marine vessels. Typically the market price for this residual oil stream is equal to, or less than, the price of the parent crude oil. Hence it is a “waste” stream. Refineries may be able to upgrade the residual oil to more valuable products through difficult and expensive processing. In this case no heavy oil is available for sale as marine fuel. Low-sulfur heavy fuel oils are significantly more expensive than the normal residual oils and are produced by starting with an expensive, ”sweet” crude oil and by allowing more of the potential distillate product to join the bottom stream, i.e., by changing the set up of the distillation column. Distillates are used to make the revenue-generating products such as diesel oil, light fuel oils, jet fuel and gasoline. The distillates are first desulfurized by catalytically reacting them with hydrogen (hydro-treating) so that the products meet federal limits on sulfur concentration.

Marine fuels that are used in large ocean-going vessels are of two types: heavy fuel oils or bunker, and marine diesel oil (MDO). The fuel oils in turn are classified as Intermediate Fuel Oils (IFO-380 and IFO-180) and are inexpensive mixtures of residual oil and distillates. IFO-380 has a viscosity of 380 centistokes and is a mixture of approximately 98% residual oil and 2% distillate. (The distillate is added as a "flux" to reduce the viscosity of the fuel.) IFO-180 is a mixture of roughly 88% residual oil and 12% distillate and has a viscosity of 180 centistokes. Since IFO-180 contains more valuable distillate than does IFO-380, it fetches a higher market price, typically USA$9/tonne more. (One tonne equals one thousand kilograms). The heavy bunkers have to be heated and cleaned (centrifuged and filtered) before burning in specially designed diesel engines.

Heavy fuel oil has much higher organic nitrogen content, sulfur content and metals content than does the lighter distillate fuels. This results in higher emissions of NOx, SOx and particulate.

Diesel engines on smaller vessels, such as ferries and workboats, burn a lighter, less viscous diesel oil (MDO). This diesel is made from valuable distillates and therefore fetches a much higher price than does the heavy bunker oils. The MDO designation is generic, as are the IFO's, and simply requires that the fuels meet a minimum specification designated, for example, by ISO 8217 –1996E. (ISO is the International Standards Organization). Low sulfur MDO may be a rebranded road diesel. However, in order to meet an ISO 8217 –1996E fuel specification it must have a minimum flash point of 60°C.

Where diesel-fueled vessels are concerned, NOx emissions usually originate from the reaction between the oxygen and nitrogen of the air at high temperatures, and thus the nitrogen content of the fuel (rather low) does not overly effect the total emission. However, fuel-derived NOx becomes important when using heavy fuel oil because such fuels contain more organic nitrogen than marine diesel oil and other distillate fuels. Heavy fuel oil can contain up to 0.5% nitrogen which increases the total NOx emissions by as much as 10% [5]. The fuel-air ratio that is required by a certain fuel oil therefore has a significant effect on the NOx emission. Also, the high temperature and the larger surplus of air in a direct-injected diesel engine (marine application) favor the formation of NOx as compared to a pre-chamber diesel engine (passenger cars) [13].

The sulfur content of the oil, on the other hand, is of vital importance to the SOx and particulate emissions. Oils with alkaline elements, e.g. Ca, Na, Mg, often present in additives to the lubricating oil, may counteract the formation of particles of a corrosive character. The emission of particles has proved to increase with fuels containing more sulfur, while emissions of NOx, CO and hydrocarbons have remained more or less the same[14].

The SOx emissions are directly proportional to the sulfur content in the fuel. Bunker oils in the PNW are typically around 24,000 ppm S, MDO and off-road diesel vary from 1000 ppm S to 4000 ppm S, low-sulfur road diesel is less than 500 ppm sulfur (typically 350 ppm S) and ultra-low sulfur road diesel is less than 15 ppm sulfur (typically 5 – 10 ppm

S). Hence exchanging a 24,000-ppm S bunker fuel for MDO fuel may reduce SOx emissions by 90%. Similarly, exchanging off-road diesel for low-sulfur road diesel may reduce SOx emissions by 90%. Particulate emissions are related to fuel sulfur, fuel ash and to the combustion efficiency of the engine. As a rough guideline, particulate emissions will be reduced by at least 10% when going from bunker to MDO, and by at least 5% when going from off-road diesel to low-sulfur road diesel. (EPA estimates a 5 to 9 % reduction in PM emissions when you switch from on-road to ULSD and non-road to ULSD respectively. [118])

A high content of aromatics and olefins lowers the cetane rating (ignitability) resulting in the fuel giving higher emissions of hydrocarbons, NOx, CO and particles. In general lighter fuels (low density and lower content of aromatics) lead to lower particle and NOx emissions[14].

Conversion of crude oil to diesel fuel may in some cases lead to deterioration in operative quality and hence there are many additives used to improve the characteristics of both fuel oil and lubricating oil[15]. Examples of additives that may be used in fuel oils and lubricating oils are combustion improvers, anticorrosives, detergents, 'pour point depressants', sediment inhibitors, etc. These substances often represent sources of chlorine and metals that are later emitted to air, leading to potential environmental impacts. Concerning the analysis of oils, there are no regular analyses of undesirable ingredients in the fuel, e.g., the chlorine compounds.

3.0 DIESEL ENGINE EMISSION STANDARDS

3.1 Marine Diesel Engines

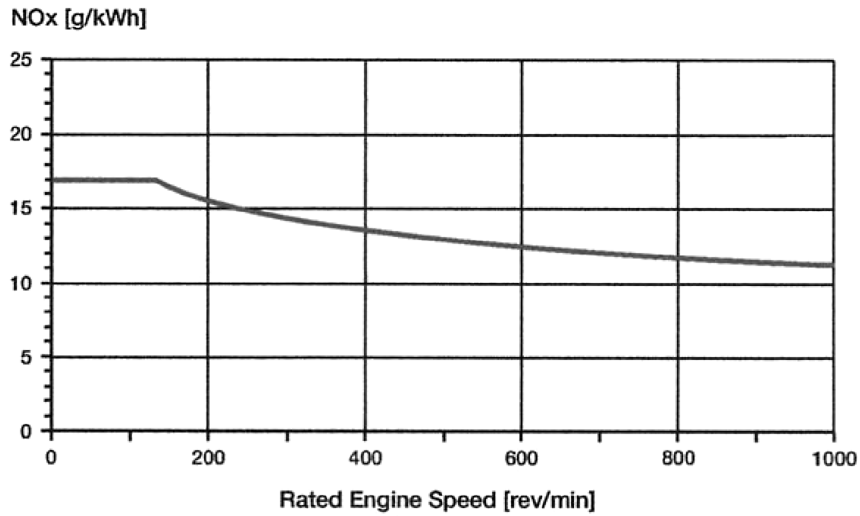
3.1.1 USA Marine Diesel Engines (Adapted from ref.24)

Background

On September 27, 1997, the International Maritime Organization (IMO) adopted International Convention on the Prevention of Pollution from Ships, also referred to as MARPOL 73/78. Annex VI to that Convention contains requirements to limit NOx emissions from marine diesel engines (but sets no limits for HC, CO, or PM). The Annex VI NOx limits, listed in Figure 3.1, apply to new engines greater than 130 kW installed on vessels constructed on or after January 1, 2000, or which undergo a major conversion after that date.

i) 17 g/kWh when n is less than 130
II) $45 \cdot n^{-0.2}$ g/kWh when n is 130 rpm or more, but less than 2000 rpm
iii) 9.84 g/kWh when n is 2000 rpm or more

where n = rated engine speed



The three test cycles D2, E2 and E3 apply to three different engine categories namely:
D2: Generating sets with intermittent load, including shipboard generating sets
E2: Constant-speed heavy-duty engines for ship propulsion, including engines with a controllable-pitch propeller
E3: Variable-speed heavy-duty engines for ship propulsion equipped with a fixed-pitch propeller

Table: Weighting factors (f) for the test cycles D2, E2 and E3 in the Technical Code of the IMO regulation for NO_X emissions

% rated speed		100	100	100	100	100	100	91	80	63
% rated load		100	75	50	25	10	100	75	50	25
Weighting factor [f]	cycle D2	0.05	0.25	0.30	0.30	0.10	–	–	–	–
	cycle E2	0.20	0.50	0.15	0.15	–	–	–	–	–
	cycle E3	–	–	–	–	–	0.20	0.50	0.15	0.15

$$NO_x weighted = \frac{\sum_i f_i \times NO_{x_i}\left(\frac{g}{h}\right)}{\sum_i f_i \times P_i\,(kW)}$$

Figure 3.1 – NOx Emission Limit - IMO Reg. 13, Annex VI, MARPOL73/78 (Ref.5).

On November 23, 1999, the EPA signed the final rule "Control of Emissions of Air Pollution from New CI Marine Engines at or above 37 kW" *[40 CFR Parts 89, 92 | FR 64, No. 249, 73300-73373, 29 Dec 1999]*. The adopted standards for small- and medium-size engines are based on the land-based standard for nonroad engines, while the largest engines (so called "Category 3") are expected, but not required by the 1999 rule, to comply with MARPOL Annex VI limits.

The decision to leave the largest Category 3 engines unregulated triggered a lawsuit against the EPA by environmental organizations. A court settlement was reached that required the EPA to propose NOx emission limits for Category 3 engines. The proposal published by the EPA on May 29, 2002 *[40 CFR Part 94 | FR 67, No. 103, 37548-37608]*, calls for establishing Category 3 emission standards virtually equivalent to the MARPOL Annex VI limits.

Diesel engines used in recreational vessels, exempted from the 1999 marine rule, are covered in the "Emission Standards for New Nonroad Engines—Large Industrial Spark-ignition Engines, Recreational Marine Diesel Engines, and Recreational Vehicles" regulation, signed on September 13, 2002.

Applicability

The scope of application of the marine engine rule covers all new marine diesel engines at or above 37 kW, including both propulsion and auxiliary marine diesel engines. A propulsion engine is one that moves a vessel through the water or assists in guiding the direction of the vessel (for example, bow thrusters). Auxiliary engines are all other marine engines.

Classification of drilling rigs depends on their propulsion capability. Drilling ships are considered marine vessels, so their engines are subject to the marine rule. Semi-submersible drilling rigs that are moored to the ocean bottom, but have some propulsion capability, are also considered marine vessels. In contrast, permanently anchored drilling platforms are not considered marine vessels, so none of the engines associated with one of these facilities are marine engine.

Consistently with the land-based nonroad regulation, a portable auxiliary engine that is used onboard a marine vessel is not considered to be a marine engine. Instead, a portable auxiliary engine is considered to be a land-based auxiliary engine and is subject to the land-based nonroad requirements. To distinguish a marine auxiliary engine installed on a marine vessel from a land-based portable auxiliary engine used on a marine vessel, EPA specified in that rulemaking that an auxiliary engine is installed on a marine vessel if its fuel, cooling, or exhaust system are an integral part of the vessel or require special mounting hardware. All other auxiliary engines are considered to be portable and therefore land-based.

The following engine categories are exempted from the 1999 marine regulation:

Engines used in recreational vessels (recreational diesel engines are subject to separate standards, outboard and personal watercraft spark ignited engines are regulated by another rule)

- Emission certified new land-based engines modified for marine applications (provided certain conditions are met)
- Competition (racing) engines

- Engines used in military vessels (National Security Exemption)
- Engines Category 1 and 2 used on ocean vessels with Category 3 propulsion, so called Foreign-Trade Exemption (proposed to be eliminated)
- Other exemptions (testing, display, export...) may also apply to marine engines.

Not all of the above exemptions are automatic. Engine or vessel manufacturers, or vessel owners, may need to apply for a specific exemption to the EPA.

The same emission standards apply to engines fueled by diesel fuel and by other fuels.

Engine Categories

For the purpose of emission regulations, marine engines are divided into three categories, as listed in Table 3.1. Each of the categories represents a different engine technology. Categories 1 and 2 are further divided into subcategories based on the engine displacement per cylinder.

Table 3.1 – Marine Engine Categories

Category	Displacement per Cylinder (D)	Basic Engine Technology
1	D < 5 dm^3 (and power >= 37 kW)	Land-based nonroad diesel
2	5 dm^3 <= D < 30 dm^3	Locomotive engine
3	D >= 30 dm^3	Unique marine design

As an example, the container ship COSCO *YUN HE* has a MAN B&W main engine with a bore/stroke of 900mm x 2916mm with a cylinder displacement of 1,855 dm^3 (liters). Therefore this is a Category 3 engine. The *YUN HE*'s auxiliary engine, on the other hand, has a bore/stroke of 320mm x 350mm and a cylinder displacement of 28.1 liters. It is a Category 2 engine.

The B.C. Ferry fleet's main engines are Category 2 and 3 in the larger ferries and Category 1 in the smaller vessels, such as the *MV Quinsam* and the *Skeena Queen*. The auxiliary engines in the larger vessels are mainly Category 1. Workboats also use typically Category 1 engines.

Emission Standards

Engines Category 3

Category 3 engines are very large marine diesel engines, which can achieve power ratings in excess of 75,000 kW, typically used for the propulsion of ocean-going vessels. Emission control technologies that can be used on these engines are limited. The most important of the limitations is the fuel on which they are operated, called residual fuel. This fuel is the by-product of distilling crude oil to produce lighter petroleum products. It possesses high viscosity and density, which affects ignition quality, and it typically has high ash, sulfur and nitrogen content in comparison to marine distillate fuels. Furthermore, residual fuel parameters are highly variable because its content is not regulated. The EPA estimated that residual fuel can increase engine NOx emissions from 20-50% and PM from 750% to 1250% when compared to distillate fuel.

In the 1999 rule, EPA has not adopted any emission standards for the Category 3 engines. The proposal of May 29, 2002 considers three sets of standards: (1) first tier standards, (2) second tier standards, and (3) voluntary low-emission engine standards. The first tier standards would be equivalent to the internationally negotiated IMO MARPOL NOx limits, as shown in Figure 2.2. They would be enforceable under U.S. law for new engines built in 2004 and later. These limits would be achieved by engine-based controls, without the need for exhaust gas after treatment. A subsequent second tier of standards, also achieved through engine-based controls, would apply to new engines built after 2006 or later. The voluntary low-emission engine standards would require advanced control technologies such as selective catalyst reduction, water-based emission reduction techniques, or fuel cells.

The proposed standards would apply to engines installed on vessels flagged in the U.S. It is currently not clear if the U.S. government has the authority to impose such standards for foreign ships, which present the vast majority of vessels entering U.S. ports.

The Annex VI is not yet in force, pending ratification by a number of member states, including the U.S. Once adopted, the Annex VI limits will apply retroactively, effective January 1, 2000. Therefore, many ocean vessel operators worldwide started installing complying engines beginning in the year 2000.

Engines Category 1 and 2

Emission standards for engines category 1 and 2 are based on the land-based standard for nonroad and locomotive engines. The emission standards, referred to as Tier 2 Standards by the EPA, and their implementation dates are listed in Table 3.2 below. The regulated emissions include NOx + THC, PM, and CO. There are no smoke requirements for marine diesel engines. The regulators believed that the new PM standards would have a sufficient effect on limiting smoke emissions.

In the earlier proposal, the EPA also listed a more stringent Tier 3 standard to be introduced between 2008 and 2010. The Tier 3 standard was not adopted in the final 1999 rule. The EPA intends to address this next tier of emission standards in a separate ruling.

Table 3.2 – Tier 2 Marine Emission Standards*					
Engine Category	**Cylinder Displacement (D)** (dm^3)	**NOx+THC** (g/kWh)	**PM** (g/kWh)	**CO** (g/kWh)	**Date**
1	Power >= 37 kW D < 0.9	7.5	0.40	5.0	2005
	0.9 <= D < 1.2	7.2	0.30	5.0	2004
	1.2 <= D < 2.5	7.2	0.20	5.0	2004
	2.5 <= D < 5.0	7.2	0.20	5.0	2007[a]
2	5.0 <= D < 15	7.8	0.27	5.0	2007[a]
	15 <= D < 20 Power < 3300 kW	8.7	0.50	5.0	2007[a]
	15 <= D < 20 Power >= 3300 kW	9.8	0.50	5.0	2007[a]
	20 <= D < 25	9.8	0.50	5.0	2007[a]
	15 <= D < 30	11.0	0.50	5.0	2007[a]
* - Tier 1 standards equivalent to IMO NOx limits. a – Proposed Tier 1 certification requirement starting in 2004.					

Blue Sky Series Program

The regulation sets a voluntary "Blue Sky Series" program that permits manufacturers to certify their engines to more stringent emission standards. The qualifying emission limits are listed in Table 3.3.

Table 3.3 – "Blue Sky Series" Voluntary Emission Standards		
Cylinder Displacement (D), (dm^3)	**NOx+THC** (g/kWh)	**PM** (g/kWh)
Power >= 37 kW & D < 0.9	4.0	0.24
0.9 <= D < 1.2	4.0	0.18
1.2 <= D < 2.5	4.0	0.12
2.5 <= D < 5.0	5.0	0.12
5.0 <= D < 15	5.0	0.16
15 <= D < 20 & Power < 3300 kW	5.2	0.30
15 <= D < 20 & Power >= 3300 kW	5.9	0.30
20 <= D < 25	5.9	0.30
15 <= D < 30	6.6	0.30

The Blue Sky program begins upon the publication of the rule and extends through the year 2010. At that time the program will be evaluated to determine if it should be continued for 2011 and later engines.

Test Cycles

The engine Category 1 emissions are tested on various ISO 8178 cycles (E2, E3, E5 cycles for various types of propulsion engines, D2 cycle for auxiliary engines). Engines belonging to Category 2 are tested on locomotive test cycles.

In addition to the ISO test cycle measurement, which are averages from several test modes, the regulation sets "not-to-exceed" (NTE) emission limits, which provide assurance that emissions at any engine operating conditions within an NTE zone are reasonably close to the average level of control. NTE zones are defined as areas on the engine speed-power map. The emission caps within the NTE zones represent a multiplier (between 1.2 and 1.5) times the weighted test result used for certification for all of the regulated pollutants (NOx + THC, CO, and PM).

The test fuel for marine diesel engine testing 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.

Useful Life and Warranty Periods

For Category 1 engines, EPA established a useful life of 10 years or 10,000 hours of operation. For Category 2 engines, EPA established a useful life of 10 years or 20,000 hours of operation. The warranty periods are 5 years or 5,000/10,000 hours for engines Category 1/2, respectively.

Other Provisions

The regulation contains several other provisions, such as emission Averaging, Banking, and Trading (ABT) program, deterioration factor requirements, production line testing, in-use testing, and requirements for rebuilding of emission certified engines.

3.1.2 European Union Diesel Engines (From ref.24)

The European legislation for nonroad diesel engines was promulgated on February 27, 1998. The regulations for nonroad diesels were introduced in two stages: Stage I implemented in 1999 and Stage II from 2001 to 2004, depending upon engine size. Engines used in ships were not covered by the Stage I/II standards. On December 27, 2002 the European Commission finalized a proposal for Stage III regulations, whose limits and timing is harmonized with the USA Tier 2 standards shown in Table 2.2 above. The Stage III standards apply to marine engines used for inland waterway vessels. Presumably emission-reduction technology developed to meet these standards would also carry over to engines used in salt-water vessels.

3.1.3 International Maritime Organization (IMO)

The International Maritime Organization (IMO) is a Specialized Agency of the United Nations dealing with the technical aspects of shipping**.** IMO has 150 Member States and two Associate Members. Proposals from Member States are passed to a Committee for discussion prior to sending to the IMO Assembly for endorsement in the form of a Resolution. The Marine Environmental Protection Committee (MEPC) handles environmental matters. Regulations and amendments to regulations that are passed by the IMO Assembly take the form of Annexes and Protocols to the original International Convention for the Prevention of Pollution From Ships (MARPOL 73/78).

In 1997 MEPC completed Annex VI and the Assembly endorsed the Annex. However, in order for the Annex to be fully implemented it must be ratified by at least 15 nations controlling at least 50% of the world shipping, followed by a one-year implementation period. As of December 2001 only five Member States (Bahamas, Norway, Sweden, Malawi and Singapore) controlling only 7% of the tonnage, had ratified Annex VI. Recent discussions with senior MEPC representatives have indicated that it is expected that the required number of nations and tonnage will ratify the Annex within approximately two years.

Within Annex VI, Regulation 14 limits marine fuel sulfur to 4.5% (w/w), except in SOx Emission Control Areas, where the limit is either 1.5% or, where gas-cleaning equipment is used to reduce exhaust emissions, to less than 6.0 g SOx/kWh. A SOx Emission Control Area is a type of Special Area, which is defined as a sea area in which, for technical reasons relating to oceanographical and ecological conditions and sea traffic, the adoption of special mandatory methods for the prevention of sea pollution is required. The Baltic Sea and North Sea area are at present the only designated SOx Emission Control Areas.

Proposals to the IMO for designation of a SOx Emission Control Area have to include:

1. A clear delineation of the proposed area of application of SOx controls.
2. A description of land and sea areas at risk from ship SOx emissions.
3. A complete environmental assessment of the land and sea impacts of the ship SOx emissions, along with meteorological and other conditions which may exacerbate the impacts.
4. The nature of the ship traffic in the proposed SOx Emission Control Area, including the traffic patterns and density of such traffic.
5. A description of control measures taken by the proposing State to address land-based sources of SOx emissions that affect the sea area at risk.

During 2000 the sulfur concentration in 54,000 samples of residual oil, representing 49 million metric tonnes, or 40% - 50% of the heavy fuel bunkers sold annually worldwide, was measured by MEPC Committee members.[59] The average sulfur concentration was

2.7%, with over 80% of the samples between 2 and 4%, and 50% between 2.5% and 3.5%.

In addition to their clean fuels regulations, the IMO also have adopted NOx standards in 1997 (see Fig 3.1). The standards apply to all vessels over 130 kW (174 h.p.) installed on new vessels. However, the standards are not enforceable until 15 countries representing at least 50% of the gross tonnage of the world's merchant shipping ratify them. To date, this has not occurred, and the United States is among the countries that have not yet ratified it. Nevertheless, most marine engine manufacturers are currently producing IMO compliant engines because the standards when implemented are retroactive to January 1, 2000.[60]

The MEPC committee is currently focused on greenhouse gas emissions from ships and has a working group developing an IMO strategy for greenhouse gas reduction.[61]

Although the process to have the West Coast designated a *Special SOx Emission Control Area* under the IMO mechanism is expected to be complex and protracted, there are a number of advantages to working within the IMO framework, most notably in the areas of compliance and enforcement. Under the IMO regulations of Annex VI all ships will be required to keep logs of fuel quantity and sulfur levels, and must make these logs available for inspection to all port authorities. Also, engine logs must be made available and these logs will indicate the time and location where the engines were switched to low sulfur fuel. While there are other possible courses of action that could be considered, including a mix of voluntary non-regulatory early actions and regulatory or economic instruments over the long term, these actions will be difficult to apply off shore due to the international protocol of "right of free passage".

Presentations and discussions at recent marine workshops have indicated a desire by a number of U.S. federal, state and regional authorities for a total west coast of North America solution to the problem of marine emissions. This could be an IMO Special SOx Control Area covering all of the coast from California to Alaska, or a coordinated and compatible U.S. and Canada federal, state, provincial and municipal regulatory action plan.

Further information on IMO activities can be obtained from their web site www.imo.org

3.1.4 Swedish Environmentally Differentiated Fairway Fees (Ref. 26)

In 1996 a tripartite agreement was reached between the Swedish Maritime Administration (SMA), the Swedish Ship Owners Association and the Swedish Ports' and Stevedores' Association to reduce sulfur and nitrogen oxides emissions from ships calling at Swedish ports by 75% in the early years of the 21st century.

In 1998 a Swedish Maritime Administration ordinance on environmentally differentiated fairway dues entered into force. The system is based on two charging components. The first one, which is environmentally differentiated, is based on the size, the gross tonnage

(GT), of the ship. This portion of the due is charged a maximum of 18 times a year for a passenger ship and a maximum of 12 times a year for each individual cargo ship. The second component is based on the amount of goods loaded and/or unloaded in Swedish ports and is not affected by the differentiation. The differentiation aims at establishing economic incentives for ships, irrespective of flag, to reduce emissions of sulfur and nitrogen oxides, while not per se altering the total sum of SMA charges for ships calling at Swedish ports. Thus the scheme is supposed to be income neutral for the fee-financed Swedish Maritime Administration.

The charging levels for the size-related part of the fairway dues are differentiated with respect to the sulfur content of the bunker fuel and the certified emission levels of NOx per kWh for the ships' machinery. The differentiation with respect to sulfur in the ships' bunker fuel is straightforward. A ship that certifies that it only uses low sulfur bunker fuel (0.5% sulfur or less for ferries and 1% sulfur or less for other ships) will be granted a discount of 0.9 SEK (Sweden krona) per GT. For NOx-emissions the differentiation scheme is slightly more complicated. The charges per GT vary according to the NOx emission rate per kWh for the ship's machinery. For ferries and other ships (not tankers) the charge is 3.40 SEK/GT if emissions are 2 g/kWh or less. The charge is increasing linearly up to the level of 5 SEK/GT if emissions are 12 g/kWh or more. (US$0.1188/SEK; Feb.27, 2003).

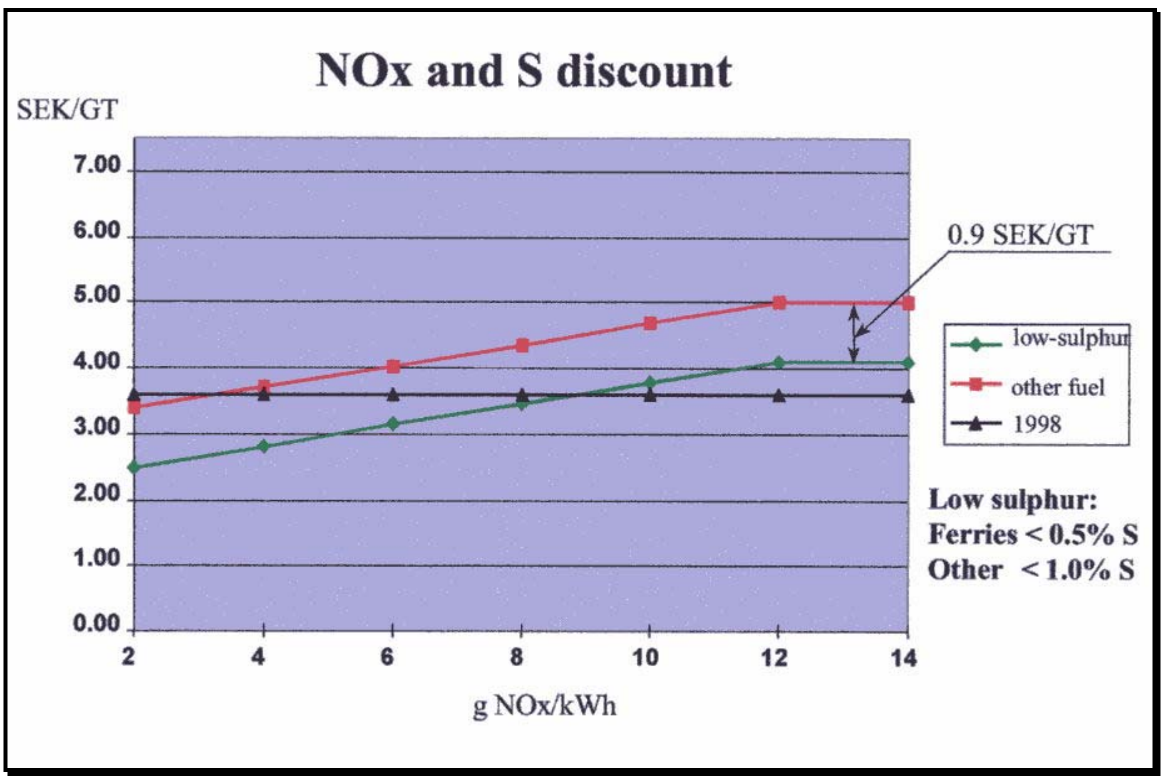


Figure 3.2. SWEDISH FAIRWAY FEES (Swedish Kroners /Ship Gross Tonne, ref. 26)

In order to encourage the installation of NOx abatement technique, especially catalytic converters (SCR), the Swedish Maritime Administration granted reimbursement as high as 40% of the investment cost if the technique was installed before the year 2000, and up to 30% for installations thereafter. The possibility to receive such reimbursement ceased in January 2002.

To receive reimbursement for low-sulfur bunker fuel the ship owner has to provide a document declaring that the ship permanently and under all conditions is operated with a bunker fuel containing less than 0.5% sulfur for ferries and less than 1% sulfur for other ships. Ships apply for a document of compliance for reduced fairway dues via *Sulfur Oxide (SOx) Reduction Attestation*, a form that is sent to the Swedish Maritime Administration. The Swedish Maritime Administration then issues a *Document of Compliance for reduced Fairway Dues from Sulfur Oxide Reduction (SOx)*. The Swedish Maritime Administration also issues a *National Air Pollution Prevention Certificate (NOx)* to ships with certified levels of NOx/kWh. The certificate is mainly based on MARPOL Annex VI NOx Technical Code.

According to a recent estimate (SMA Annual Report 2001) the charging system for Swedish fairways and ports has helped to induce substantial decreases of maritime emissions of NOx and SOx. The overall emission reduction in the areas of the Baltic Sea and the North Sea has been estimated to 50,000 tons for SOx and 27,000 tons for NOx (calculated as NO_2).

The existing system is presently under review, not for the fact that it is not a success, but because of the overall principle of how to more accurately relate the dues to environmental marginal costs that would encourage a more environmentally friendly shipping.[153]

3.2 Locomotive Regulations

3.2.1 **USA EPA** (Ref. 62)

Three separate sets of emission standards have been adopted, with applicability of the standards dependent on the date a locomotive is first manufactured. The first set of standards (Tier 0) applies to locomotives and locomotive engines originally manufactured from 1973 through 2001, any time they are manufactured or remanufactured. The second set of standards (Tier 1) apply to locomotives and locomotive engines originally manufactured from 2002 through 2004. These locomotives and locomotive engines will be required to meet the Tier 1 standards at the time of original manufacture and at each subsequent remanufacture. The final set of standards (Tier 2) apply to locomotives and locomotive engines originally manufactured in 2005 and later. Tier 2 locomotives and locomotive engines will be required to meet the applicable standards at the time of original manufacture and at each subsequent remanufacture. Electric locomotives, historic steam-powered locomotives, and locomotives originally manufactured before

1973 do not contribute significantly to the emissions problem, and thus, are not included in this rulemaking.

Table 3.4a - Exhaust Emission Standards for Locomotives [iii]

Tier and duty-cycle	**Gaseous and Particulate Emissions (g/bhp-hr)**			
	THC [i]	CO	NOx	PM
Tier 0 line-haul duty-cycle	1.00	5.0	9.5	0.60
Tier 0 switch duty-cycle	2.10	8.0	14.0	0.72
Tier 1 line-haul duty-cycle	0.55	2.2	7.4	0.45
Tier 1 switch duty-cycle	1.20	2.5	11.0	0.54
Tier 2 line-haul duty-cycle	0.30	1.5	5.5	0.20
Tier 2 switch duty-cycle	0.60	2.4	8.1	0.24
Base – line haul [ii]	0.48	1.28	13.0	0.32
Base – switch [ii]	1.01	1.83	17.4	0.44

i. HC standards are in the form of THC for diesel, bio-diesel, or any combination of fuels with diesel as the primary fuel; NMHC for natural gas, or any combination of fuels where natural gas is the primary fuel; and THCE for alcohol, or any combination of fuels where alcohol is the primary fuel.

ii. Base-line (existing) locomotive fleet emission factors (refs. 63, 64).

iii. Excludes Canadian and Mexican locomotives used in border traffic and incidental excursions in the USA.

In addition to the exhaust emission standards, this final rule establishes smoke opacity standards for all locomotives and locomotive engines.

Table 3.4b - Smoke Standards for Locomotives (Percent Opacity - Normalized)

	Steady-state	30-sec peak	3-sec peak
Tier 0	30	40	50
Tier 1	25	40	50
Tier 2	20	40	50

The bottom of Table 3.4a shows that, except for NOx emissions, existing locomotives are generally meeting Tier 0 and Tier 1 requirements.

3.2.2 Europe (Ref. 65)

While not applicable to the USA, the current European locomotive standards are included here for those readers who may wish to compare them with the EPA standards. In Europe the International Union of Railways/Union Internationale des Chemins de fer (UIC) enforces mandatory compliance among its members. The European limits will be introduced in three phases (UIC I, UIC II, UIC III), depending on when engines are freshly manufactured. They are published in UIC Leaflet 624. Compliance by member railways is designated obligatory. The leaflet includes the limiting values for traction diesel engines for all power ranges and is not limited only to engines greater than 560 kW. The UIC has recommended that engine manufacturers use the ISO-F test cycle for railway traction engines. This test cycle is taken from the International Organization for Standardization (ISO) Standard 8178 on reciprocating internal combustion engines — Exhaust emission measurement, which contains a special Cycle F for traction units. This cycle reflects the way the engine functions in railway vehicles. It is the basis for UIC Leaflet 623-2. The values are shown in Table 3.5.

Table 3.5 — European Emissions Limits for Diesel Locomotives
Units: grams per brake horsepower per hour (g/bhp-hr

Applicability (as to when engine built)	**NOx**	**HC**	**CO**	**PM**
UIC I (Prior to 12.31.2002)	8.9	0.60	2.20	N/A
UIC II (01.01.2003 - 12.31.2007)	7.1	0.60	2.20	0.19
UIC III (after 01.01.2008)	4.5	0.37	1.50	0.15

The above values are applicable to medium-speed (under 1,000 rpm) diesel engines producing over 750 HP (560 kW). The UIC recommends that emissions standards for the smaller engines fitted in DMU (diesel multiple units) passenger railcars should reference EURO II standards, the European test for road and utility vehicle engines. Note that the UIC and EPA limits correspond fairly closely. UIC limits for particulate matter (PM) do not come into effect until UIC II, but they are somewhat lower than the corresponding EPA Tier 1 and Tier 2 levels.

3.2.3 Locomotive Duty Cycles (Ref. 65)

The duty cycle of locomotives is of interest relative to the estimation of emissions produced in railway operations. A review has shown that the duty cycles can vary considerably between authorities. This variation is shown in Table 3.6. The EPA values for engine idling are used in this study to determine the effectiveness of idle-reduction technology.

Table 3.6 - Duty Cycles Used by Different Authorities (% of time)

Throttle Notch	EPA Freight	EPA Switch	AAR Freight	AAR Switch	ISO (Europe)	RAC Freight	RAC Switch	GE Freight	EMD Freight
8	16.2	0,8	28.0	0.0	25.0	12.0	5.0	14.0	17.0
7	3.0	0.2	3.0	0.0	0.0	4.0	2.0	3.0	4.0
6	3.9	1.5	3.0	1.0	0.0	4.0	2.0	3.0	4.0
5	3.8	3.6	3.0	1.0	0.0	4.0	2.0	4.0	4.0
4	4.4	3.6	3.0	2.0	15.0	4.0	2.0	4.0	4.0
3	5.2	5.8	3.0	4.0	0.0	4.0	2.0	3.0	4.0
2	6.5	12.3	3.0	5.0	0.0	4.0	2.0	5.0	4.0
1	6.5	12.4	3.0	10.0	0.0	4.0	2.0	5.0	5.0
Dyn.Brk	12.5	0.0	8.0	0.0	0.0	0.0	0.0	4.0	9.0
Idle	0.0	0.0	0.0	0.0	0.0	60.0	81.0	50.0	46.0
Low Idle	38.0	59.8	43.0	77.0	60.0	0.0	0.0	0.0	0.0

Note that the ISO (Europe) duty cycle (referencing the ISO-F test cycle) is similar to the AAR 3-mode cycle, i.e., 25 Rated, 15 Intermediate and 60 Idle.

3.3 Off-Road Heavy-Duty Diesels

3.3.1 EPA Engine Regulations (Adapted from DieselNet[66])

Background

The first federal standards (Tier 1) for new nonroad (or off-road) diesel engines were adopted in 1994 for engines over 37 kW (50 hp), to be phased-in from 1996 to 2000. In 1996, a Statement of Principles (SOP) pertaining to nonroad diesel engines was signed between EPA, California ARB and engine makers (including Caterpillar, Cummins, Deere, Detroit Diesel, Deutz, Isuzu, Komatsu, Kubota, Mitsubishi, Navistar, New Holland, Wis-Con, and Yanmar. On August 27, 1998, the EPA signed the final rule reflecting the provisions of the SOP. The 1998 regulation introduced Tier 1 standards for equipment under 37 kW (50 hp) and increasingly more stringent Tier 2 and Tier 3 standards for all equipment with phase-in schedules from 2000 to 2008. The Tier 1-3 standards are met through advanced engine design, with no or only limited use of exhaust gas after treatment (oxidation catalysts). Tier 3 standards for NOx + HC are similar in stringency to the 2004 standards for highway engines, however Tier 3 standards for PM were never adopted.

On April 15, 2003, the EPA signed proposed Tier 4 emission standards to be phased-in over the period of 2008-2014. The proposed Tier 4 standards require that emissions of PM and NOx be further reduced by over 90%. Such emission reductions can be achieved through the use of control technologies—including advanced exhaust gas after-treatment—similar to those required by the 2007-2010 standards for highway engines. To enable sulfur-sensitive control technologies—such as catalytic particulate filters and NOx adsorbers—the EPA proposed reductions in the sulfur content in nonroad diesel fuels, as follows:

- 500 ppm effective 2007 for fuels used in nonroad, locomotive and marine engines
- 15 ppm effective 2010 for nonroad fuel (but not for locomotive or marine fuels)

In most cases, federal nonroad regulations also apply in California, whose authority to set emission standards for new nonroad engines is limited. The federal Clean Air Act Amendments of 1990 (CAA) preempt California's authority to control emissions from new farm and construction equipment under 175 hp *[CAA Section 209(e)(1)(A)]* and require California to receive authorization from the federal EPA for controls over other off-road sources *[CAA Section 209 (e)(2)(A)]*. To a certain degree, the U.S. nonroad emission standards are also harmonized with European nonroad emission standards.

EPA emission standards for nonroad diesel engines are published in the U.S. Code of Federal Regulations, Title 40, Part 89 *[40 CFR Part 89]*.

Applicability

The standards cover mobile nonroad diesel engines of all sizes used in a wide range of construction, agricultural, and industrial equipment and in some marine applications. Examples of regulated applications include farm tractors, excavators, diesel lawn tractors, bulldozers, logging equipment, portable generators, road graders, forklifts, and sailboat auxiliary propulsion units. Effective May 14, 2003, the definition of "nonroad engines" was changed to also include all diesel powered engines—including stationary ones—used in agricultural operations in California. This change applies only to engines sold in the state of California; non-mobile engines sold in other states are not subject to EPA nonroad emission standards.

Excepted from the nonroad regulation are engines used in locomotives and underground mining equipment, and also engines over 37 kW (50 hp) used in marine vessels.

Locomotive and marine engines are subject to separate EPA regulations; mining engine emissions are regulated by the Mine Safety and Health Administration (MSHA).

A new definition of a compression-ignition (diesel) engine is used in the regulatory language since the 1998 rule that is consistent with definitions established for highway engines. The definition focuses on the engine cycle, rather than the ignition mechanism, with the presence of a throttle as an indicator to distinguish between diesel-cycle and otto-cycle operation. Regulating power by controlling the fuel supply in lieu of a throttle corresponds with lean combustion and diesel-cycle operation. This language allows the possibility that a natural gas-fueled engine equipped with sparkplugs is considered a compression-ignition engine.

Emission Standards

Tier 1-3 Standards

The 1998 nonroad engine regulations are structured as a 3-tiered progression. Each tier involves a phase in (by horsepower rating) over several years. Tier 1 standards were phased-in from 1996 to 2000.

Table 3.7
EPA Tier 1-3 Nonroad Diesel Engine Emission Standards, g/kWh (g/bhp·hr)

Engine Power	Tier	Year	CO	HC	NMHC+NOx	NOx	PM
kW < 8 (hp < 11)	Tier 1	2000	8.0 (6.0)	-	10.5 (7.8)	-	1.0 (0.75)
	Tier 2	2005	8.0 (6.0)	-	7.5 (5.6)	-	0.80 (0.60)
8 ≤ kW < 19 (11 ≤ hp < 25)	Tier 1	2000	6.6 (4.9)	-	9.5 (7.1)	-	0.80 (0.60)
	Tier 2	2005	6.6 (4.9)	-	7.5 (5.6)	-	0.80 (0.60)
19≤ kW < 37 (25 ≤ hp < 50)	Tier 1	1999	5.5 (4.1)	-	9.5 (7.1)	-	0.80 (0.60)
	Tier 2	2004	5.5 (4.1)	-	7.5 (5.6)	-	0.60 (0.45)
37 ≤ kW < 75 (50 ≤ hp < 100)	Tier 1	1998	-	-	-	9.2 (6.9)	-
	Tier 2	2004	5.0 (3.7)	-	7.5 (5.6)	-	0.40 (0.30)
	Tier 3	2008	5.0 (3.7)	-	4.7 (3.5)	-	-†
75 ≤ kW < 130 (100 ≤ hp < 175)	Tier 1	1997	-	-	-	9.2 (6.9)	-
	Tier 2	2003	5.0 (3.7)	-	6.6 (4.9)	-	0.30 (0.22)
	Tier 3	2007	5.0 (3.7)	-	4.0 (3.0)	-	-†
130 ≤ kW < 225 (175 ≤ hp < 300)	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.40)
	Tier 2	2003	3.5 (2.6)	-	6.6 (4.9)	-	0.20 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
225 ≤ kW < 450 (300 ≤ hp < 600)	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.40)
	Tier 2	2001	3.5 (2.6)	-	6.4 (4.8)	-	0.20 (0.15)

Table 3.7 **EPA Tier 1-3 Nonroad Diesel Engine Emission Standards, g/kWh (g/bhp·hr)**							
Engine Power	**Tier**	**Year**	**CO**	**HC**	**NMHC+NOx**	**NOx**	**PM**
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
450 ≤ kW < 560 (600 ≤ hp < 750)	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.40)
	Tier 2	2002	3.5 (2.6)	-	6.4 (4.8)	-	0.20 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
kW ≥ 560 (hp ≥ 750)	Tier 1	2000	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.40)
	Tier 2	2006	3.5 (2.6)	-	6.4 (4.8)	-	0.20 (0.15)
† Not adopted, engines must meet Tier 2 PM standard.							

The more stringent Tier 2 standards take effect from 2001 to 2006, and yet more stringent Tier 3 standards phase-in from 2006 to 2008 (Tier 3 standards apply only for engines from 37-560 kW).

Tier 1-3 emissions standards are listed in Table 3.7 above. Nonroad regulations are in the metric system of units, with all standards expressed in grams of pollutant per kWh.

Voluntary, more stringent emission standards that manufacturers could use to earn a designation of "Blue Sky Series" engines (applicable to Tier 1-3 certifications) are listed in Table 3.8.

Table 3.8 **EPA Voluntary Emission Standards for Nonroad Diesel Engines, g/kWh (g/bhp·hr)**		
Rated Power (kW)	**NMHC + NOx**	**PM**
kW < 8	4.6 (3.4)	0.48 (0.36)
8 ≤ kW <19	4.5 (3.4)	0.48 (0.36)
19 ≤ kW <37	4.5 (3.4)	0.36 (0.27)
37 ≤ kW < 75	4.7 (3.5)	0.24 (0.18)
75 ≤ kW <130	4.0 (3.0)	0.18 (0.13)
130 ≤ kW < 560	4.0 (3.0)	0.12 (0.09)
kW > 560	3.8 (2.8)	0.12 (0.09)

Engines of all sizes must also meet smoke standards of 20/15/50% opacity at acceleration/lug/peak modes, respectively.

Proposed Tier 4 Standards

The proposed Tier 4 standards would be phased-in from 2008-2014. Tier 4 emissions standards are listed in Table 3.9.

Tier 4 engines must have less than 22% smoke opacity.

The Tier 4 standards also require closed crankcase ventilation. In turbocharged engines, crankcase emissions may be discharged into the ambient atmosphere. In such case, crankcase emissions must be measured during emissions testing and added to tailpipe emissions.

Similarly to earlier standards, the Tier 4 regulation includes such provisions as averaging, banking and trading of emission credits and a FEL limits for emission averaging.

Table 3.9 – Proposed Tier 4 Emission Standards, g/kWh (g/bhp-h) Refs.67, 68

Engine Power	Year	NOx	PM
kW < 19 (hp < 25)	2008	-	0.40 (0.30)
19≤ kW < 56 (25 ≤ hp < 75)	2013	(3.5)*	0.03 (0.022)
56 ≤ kW < 130 (75 ≤ hp < 175)	2012-2014	0.40 (0.30)	0.02 (0.015)
130 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)	2011-2014	0.40 (0.30)	0.02 (0.015)
kW > 560 (hp > 750)	2011-2014	0.40 (0.30)	0.02 (0.015)

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Test Cycles and Fuels

Nonroad engine emissions are measured on a steady-state test cycle that is nominally the same as the ISO 8178 C1, 8-mode steady-state test cycle. Other ISO 8178 test cycles are allowed for selected applications, such as constant-speed engines (D2 cycle), variable-speed engines rated under 19 kW (G2 cycle), and marine engines (E3 cycle).

Tier 4 standards have to be met over both the steady-state test and the nonroad transient cycle, NRTC (with the exception of engines < 19 kW, which are transient tested beginning 2013). Two NRTC tests are defined: a general version and a constant-speed engine version. Tier 4 engines also have to meet not-to-exceed standards (NTE), which are measured without reference to any specific test schedule. In most cases, the NTE limits are set at 1.25 times the regular standard (Table 3) for each pollutant. The purpose of the added testing requirements is to prevent the possibility of "defeating" the test cycle by electronic engine controls and producing off-cycle emissions.

A change from measuring total hydrocarbons to nonmethane hydrocarbons (NMHC) has been introduced in the 1998 rule. Since there is no standardized EPA method for measuring methane in diesel engine exhaust, manufacturers can either use their own procedures to analyze nonmethane hydrocarbons or measure total hydrocarbons and subtract 2% from the measured hydrocarbon mass to correct for methane.

Fuels with sulfur levels no greater than 0.2 wt% are used for certification testing of Tier 1-3 engines. Model year 2008-2010 of Tier 4 engines are certified using fuel of 300-500 ppm sulfur. Model year 2011 and later engines are certified using fuel of 7-15 ppm sulfur.

Engine Useful Life

Emission standards listed in the above tables must be met over the entire useful life of the engine. EPA requires the application of deterioration factors (DFs) to all engines covered by the rule. The DF is a factor applied to the certification emission test data to represent emissions at the end of the useful life of the engine.

The engine useful life and the in-use testing liability period, as defined by the EPA for emission testing purposes, are listed in Table 3.10 for different engine categories. The Tier 4 proposal maintains the same engine useful life periods.

Table 3.10
Useful Life and Recall Testing Periods

Power Rating	**Rated Engine Speed**	**Useful Life**		**Recall Testing Period**	
		Hours	Years	Hours	Years
< 19 kW	all	3000	5	2250	4
19-37 kW	constant speed engines ≥3000 rpm	3000	5	2250	4
	all others	5000	7	3750	5
>37 kW	all	8000	10	6000	7

Environmental Benefit and Cost

1998 regulation

At the time of signing the 1998 rule, the EPA estimated that by 2010 NOx reductions on the order of a million tons per year, from full implementation of the rule, would be the equivalent of taking 35 million passenger cars off the road.

The costs of meeting the emission standards were expected to add under 1% to the purchase price of typical new nonroad diesel equipment, although for some equipment the standards may cause price increases on the order of 2-3%. The program was expected to cost about $600 per ton of NO_x reduced.

Tier 4 Proposal

When fully phased in, annual emission reductions are estimated at 825,000 tons of NOx and 125,000 tons of PM. By 2030, 9,600 premature deaths would be prevented annually due to the implementation of the proposed standards.

The estimated costs for added emission controls for the vast majority of equipment was estimated at 1-2% relative to the typical retail price. For example, for a 175 hp bulldozer that costs approximately $230,000 it would cost an additional $2,600 to add the advanced emission controls and to design the bulldozer to accommodate the modified Tier 4 engine.

EPA estimated the cost of producing 500-ppm fuel to be on average 2.5 cents per gallon. Average costs for 15-ppm fuel are estimated to be an additional 2.3 cents per gallon, for a combined cost of 4.8 cents per gallon.

3.3.2 Other Nonroad Diesel Engine Regulations

Other nonroad diesel engine regulations (e.g. Europe and Japan) are presented in the DieselNet website www.dieselnet.com.

4.0 Non-Road Baseline Emissions

The five heavy-duty diesel HDD fleets that participated in this study include commercial marine vessels and land-based nonroad vehicles. The fleets are shown below.

- Tidewater Barge Lines - Workboats
- Washington State Ferries (WSF) - Ferries
- Princess Cruise Line – Cruise ships
- City of Seattle – Construction equipment
- Burlington Northern and Santa Fe Railway Company (BNSF) – Locomotives

For the baseline emission estimates, each fleet has provided its own available data on engine population, equipment characteristics, fleet activity and operating modes. Detailed description of each fleet is provided in the sections that follow.

Princess Cruise Lines had agreed to participate in the study from the outset, but provided data only for the Diamond Princess, which is a new vessel that Princess Cruise Lines had not yet taken possession of at the time of writing of this report. The Diamond Princess was not considered to be representative of typical cruise ships operating in the Puget Sound area, nor was it subject to the same types of control technology as the existing fleet. For this reason, alternative sources of data on cruise ship emissions and operating modes was used, as described in Section 4.1.3.

It should be noted here that the five participating fleets contribute only a minor portion of the total HDD nonroad emissions of NOx, SOx, PM and VOC in the Pacific Northwest. The combined five study fleets contribute approximately 24% of these emissions; if the locomotive study fleet is excluded then the remaining four study fleets contribute about 5% to the total HDD nonroad emissions in the PNW.

4.1 Fleet Description

4.1.1 Workboats

The Tidewater Barge Lines operates barges and tugs along the Columbia River system. This workboat fleet consists of 19 vessels and the majority of these vessels are equipped with two diesel engines. A listing of the vessels and their main engines is shown in Table 4.1.

In addition to the main engines, there are generators on the vessels to meet power requirements.

For baseline emission estimates, Tidewater Barge Lines has also provided fuel consumption data and operating hours for each vessel in 2001.

Table 4.1 - Tidewater Barge Lines Fleet Summary

Vessel	Engine Manufacturer	Engine Type	Engine Horsepower
Tidewater	Fairbanks Morse	103808 1/8	1,800
Legend	Fairbanks Morse	338D 8 1/8 OP	2,200
Chief	EMD	12 645 E5	2,150
Sundial	Wartsila	VASA 8R-22/26	1,700
Liberty	Caterpillar	3516 DITA	1,500
Outlaw	EMD	12-645-E6	1,500
Hurricane	EMD	12-645-E2	1,500
Captain Bob	EMD	12-645-E2	1,500
Challenger	EMD	12-645-E2	1,500
Comet	EMD	12-645-E2	1,500
Defiance	Fairbanks Morse	38D81/8OP	1,500
Maverick	Caterpillar	3512 DITA	1,175
Betty Lou	Caterpillar	3512 DITA	1,060
Rebel	EMD	R8-645-E2	1,000
Invader	Caterpillar	D398TA	900
Mary Gail II	Caterpillar	D379	575
John Ackerman	Caterpillar	--	400
Husky	Detroit Diesel	8V92T	380
James Russell	Detroit Diesel	6-711N	240

4.1.2 Ferries

The Washington State Ferries operates a fleet of 29 ferries serving the Puget Sound Area. Table 4.2 shows the vessels in this fleet and the routes where each vessel has served in 2001.

In addition to the main engines, each ferry vessel may also be equipped with diesel vital generators, in-service generators, emergency generators and boilers. For the baseline emissions inventory, WSF has provided engine data and 2001 annual estimates of fuel use and operating hours for the main engines and generators on each ferry vessel.

Table 4.2 - Washington State Ferry Fleet Summary

Vessels	Vessel Class	Main Engines		Routes Served in 2001	Percent Days Served on Given Route
		Number	Engine HP		
Cathlamet	Issaquah	2	2,500	Seattle/Bremerton Mukilteo/Clinton	<1 100
Chelan	Issaquah	2	2,500	Seattle/Bremerton Mukilteo/Clinton Anacortes/San Juans Faunt/SW/Vashon	17 24 37 22
Chinook	Passenger Only Fast Ferry	4	1,800	Seattle/Bremerton	100
Elwha	Super	4	3,400	Anacortes/San Juans Anacortes/Sidney BC	4 96
Evergreen State	Evergreen State	2	1,600	Anacortes/Sidney BC Faunt/SW/Vashon	71 29
Hiyu		2	430	Decommissioned	--
Hyak	Super	4	2,240	Seattle/Bremerton Anacortes/San Juans Anacortes/Sidney BC	96 2 2
Illahee	Steel Electric	2	1,200	Anacortes/San Juans	100
Issaquah	Issaquah	2	2,500	Seattle/Bremerton Faunt/SW/Vashon	23 77
Kalama	Passenger Only	4	960	Seattle/Vashon	100
Kaleetan	Super	4	2,240	Seattle/Bremerton Anacortes/San Juans	25 75
Kitsap	Issaquah	2	2,500	Seattle/Bremerton Anacortes/San Juans Faunt/SW/Vashon	66 2 32
Kittitas	Issaquah	2	2,500	Mukilteo/Clinton	100
Klahowya	Evergreen State	2	2,550	Faunt/SW/Vashon	100
Klickitat	Steel Electric	2	1,200	Pt. Townsend/Keystone	100
Nisqually	Steel Electric	2	1,200	Pt. Defiance/Tahlequah Pt. Townsend/Keystone	49 51
Puyallup	Jumbo Mk II	4	4,000	Seattle/Bainbridge Isl. Edmonds/Kingston	16 84
Quinault	Steel Electric	2	1,200	Anacortes/San Juans Pt. Townsend/Keystone	8 92
Rhododendron	Rhododendron	2	800	Pt. Defiance/Tahlequah	100
Sealth	Issaquah	2	2,500	Anacortes/San Juans Faunt/SW/Vashon	86 14
Skagit	Passenger Only	4	960	Seattle/Vashon	100
Snohomish	Passenger Only Fast Ferry	4	1,800	Seattle/Bremerton	100
Spokane	Jumbo Mk I	4	2,875	Edmonds/Kingston	100
Tacoma	Jumbo Mk II	4	4,000	Seattle/Bainbridge Isl.	100
Tillikum	Evergreen State	2	2,550	Faunt/SW/Vashon	100
Tyee	Passenger Only	2	1,450	Seattle/Bremerton Seattle/Vashon	10 90
Walla Walla	Jumbo Mk I	4	2,875	Seattle/Bremerton Seattle/Bainbridge Isl. Edmonds/Kingston	45 9 46
Wenatchee	Jumbo Mk II	4	4,000	Seattle/Bainbridge Isl.	100
Yakima	Super	4	2,240	Anacortes/San Juans	100

4.1.3 Cruise Ships

Several Cruise Lines operate ships that call to or begin in Seattle en route to Alaska or California. Collectively, approximately 22 different vessels make about 120 visits to the Port of Seattle each year. The gross weight of these vessels ranges from 15,000 to 80,000 tonnes with a fleet average of about 55,000 tonnes. The major cruise carriers in this area are Holland America, Norwegian Cruise Line, and Princess Cruises. Princess Cruise Lines participated in this study but only provided limited data on the new Diamond Princess, which is not expected to be operational until 2004. In order to develop an emissions baseline more representative of the existing cruise ship fleet in the Puget Sound area, data was used for Holland America's Statendam, a vessel which operates out of the Port of Vancouver and has a size and speed within the range of cruise ships calling on the Port of Seattle. Vessel specifications and fuel usage for the Statendam were obtained as part of an Environment Canada emission-testing program [137]. The Statendam has a gross tonnage of 55,451 tonnes, and a length of 219 meters. It operates two V-12 Sulzer AV-40 4-stroke diesel engines (8640 kW each) and two 8-cylinder Sulzer 8ZAL40S 4-stroke diesel engines (5760 kW each) while hoteling. Indications from the PSCAA and the Port of Seattle were that cruise ship movements and time in mode within the Port of Seattle are comparable to that of the Port of Vancouver. Accordingly, Pacific Pilotage Authority records of cruise movements to and in Vancouver, British Columbia were used to calculate average cruising and hoteling times.

The sulfur content of the fuel used by the cruise vessels is assumed to be 2.4%, which is representative of area average sulfur for marine fuel.

4.1.4 Construction Equipment

The entire City of Seattle heavy-duty diesel fleet consists of some 400 pieces of equipment. Of this fleet, engine data was provided for 12 selected pieces of construction equipment, which are listed in Table 4.3. Since the power rating of the majority of the equipment was not readily available, engine manufacturers' websites were searched for ratings on specified models. In cases where an exact model match was not obtained, ratings from engines in the same model series or equipment class were used to fill the data gaps.

Although this fleet uses ultra low sulfur fuel (with a sulfur content as low as 50ppm), this fuel is not typically used by construction fleet in the study area. Hence, baseline emission estimates were based on the use of a more representative diesel fuel containing 3000-ppm sulfur, as per guidance from the Puget Sound Clean Air Agency.

Table 4.3 - Selected Equipment in the City of Seattle Construction Fleet

Equipment	Make	Model	Horsepower
Backhoe Loader	CASE	590SL	99
Backhoe Loader	Caterpillar	446B	102
Loader	CASE	921C	248
Excavator	Caterpillar	312BL	83*
Tolt Track Excavator	CASE	9010B	186
Grader	Champion/Volvo	720A	190
Tolt Grader	John Deere	772BH	170
Watershed Grader	Caterpillar	--	162
Wheel Loader	John Deere	624H	160
Wheel Loader	Caterpillar	IT 28F	120*
Asphalt Pavement Grinder	Wirtgen America	W 1000	213
Dozer	CASE	850G	99*

* Data supplied by the City of Seattle

4.1.5 Locomotives

Burlington Northern and Santa Fe Railway Company operates close to 70 line-haul and switch/yard locomotives within the States of Washington and Oregon. As shown in Table 4.4, these locomotive engines range in size from 1,000 to 2,500 horsepower. In addition, transcontinental rail traffic also brings locomotives into these States.

For this baseline study, BNSF has prepared its own estimates of major criteria pollutants including NO_X, SO_2, CO, PM and HC. Section 4.2.7 provides further details on the compilation of the complete baseline inventory for all pollutants of interest for the locomotive fleet.

Table 4.4 - Burlington Northern and Santa Fe Railway Locomotive Fleet Summary

States	Manufacturer/Model	Number of Engines	Horsepower
Washington	GM/GP-38-2	13	2,000
	GM/GP38	3	2,000
	GM/GP38X	2	2,000
	GM/GP35	1	2,500
	GM/GP39-2	7	2,300
	GM/G[39E	3	2,300
	GM/GP39M	8	2,300
	GM/SW1000	5	1,000
	GM/SW1200	4	1,200
	GM/SW1500	2	1,500
	GM/SD9	3	1,750
	GM/SD38P	1	2,000
Oregon	GM/GP-38-2	5	2,000
	GM/GP38	1	2,000
	GM/GP39-2	1	2,300
	GM/GP39M	3	2,300
	GM/SW1000	1	1,000
	GM/SW10	1	1,000
	GM/SW1500	1	1,500
	GM/SD9	1	1,750
	GM/RNWE4541	1	2,300

4.2 Emissions Estimation Methodologies

4.2.1 General Methodology

The general methodology for estimating pollutant emissions from nonroad sources is not complex, using calculations of the following type:

$$E = P \times LF \times T \times EF$$

where:

E = emissions of a given pollutant from a given engine for given mode
P = engine rated power
LF = load factor (fraction of rated power) for given engine mode
T = operating time for given engine mode
EF = emission factor for given pollutant for given engine mode

For the baseline inventory, the power rating of the diesel engines were provided by fleet operators. Engine load factors at each operating mode were obtained directly from operators if available or from published data for the same engine class. Fleet specific activity level, or engine operating time, was also obtained directly from fleet operators when available.

In the absence of engine rated power and load factor information, emissions were based on the following equation:

$$E = EF \times F$$

Where:

E = emissions of a given pollutant from a given engine for a given mode

EF = emission factor for given pollutant for a given engine mode

F = fuel consumed by a given engine in a given mode

Fuel-based or power output-based pollutant emission factors used in this study are derived from a number of sources, including emission testing programs, published nonroad inventories and regulatory guidance documents.

4.2.2 Pollutant Speciation

Published emission factors for nonroad sources typically include NO_X, SO_2, PM and HC. For the other pollutants of interest in this study, including $PM_{2.5}$, VOC, Benzene, Formaldehyde and 1,3 Butadiene, speciation profiles were used to determine emissions of these compounds.

$PM_{2.5}$ fraction has been estimated to be 92% of PM_{10} and the PM_{10} fraction was assumed to be equivalent to total PM. This applies to all nonroad diesel engines and is consistent with the assumptions adopted by EPA in its development of regulatory emission requirements for nonroad diesel engines [143].

Hydrocarbons are usually reported as total hydrocarbons (THC) in emission measurement studies for mobile sources. The EPA has developed conversion factors for hydrocarbon emission results [144]. This EPA guidance gives a VOC to THC ratio of 1.053, which is used in the baseline emission estimates in converting hydrocarbon to VOC emissions. The conversion multiplier is greater than one to reflect the addition of oxygenated species, such as aldehydes and alcohols, to the THC.

In the development of regulatory requirements to reduce emissions from nonroad diesel engines, EPA has also focused on several major air toxics including Benzene, Formaldehyde and 1,3 Butadiene. These air toxics are constituents of VOC in diesel engine emissions. The air toxics fractions of VOC for land-based engines, published by EPA, are shown in Table 4.5 [143]. For marine diesel engines, the same fractions were used. This is consistent with the methodology for the compilation of marine vessel inventories [135].

Table 4.5 - Air Toxics Fractions of VOC

Air Toxics	Fractions of VOC
Benzene	0.020
Formaldehyde	0.118
1,3 Butadiene	0.002

The following sections describe fleet specific inventory input data and estimation methodologies.

4.2.3 Workboat Emission Estimation Methodology

Base Quantities for Workboats

2001 annual fuel consumption for each vessel was provided by Tidewater. This annual fuel represents the total amount used by the main engines and generators on-board. However, the split between fuel used by the main engines and the generators was not available. As a first approximation, the fuel used by the generators was estimated by the engine power ratings provided by Tidewater and the brake specific fuel consumption (bsfc) factor. In the absence of fleet specific bsfc factor, a published value of 243 g fuel per kWh was assumed for this study. This factor was applied to tugboat auxiliary engines in a recent marine inventory study for the Galveston-Houston area [149]. Based on an averaged generator operating hours available for 2002, the annual fuel consumed by generators was estimated. The fuel used by the main engines was then obtained by difference.

Emission Factors for Workboats

Since fleet specific data on engine operating mode, load level and time are not readily available, the baseline emissions for this workboat fleet were estimated based on fuel consumption estimates, as discussed in the previous Section, and fuel-based emission factors described below.

Main engine pollutant emission factors are based on published values for Category 2 diesel engines [136]. These factors are shown in Table 4.6. The emission factors for the on-board generators, shown in Table 4.7, are from the EPA baseline inventory compiled in the development of marine diesel engine emission standards [139]. The power output based emission factors are converted to fuel-based values using the brake specific fuel consumption factors of 210 g fuel/kWh for the main engines and 243 g/kWh for the generators.

Table 4.6 - Emission Factors for Category 2 Marine Diesel Engines

Engines	Emission Factors (g/kWh)*		
	NOx	HC	PM
Marine Diesel	13.4	0.134	0.32

*Environ [136] (per EPA)

Table 4.7 - Emission Factors for Category 1 Diesel Engines

Power Range (kW)	Emission Factors (g/kW-h)*		
	NOx	HC	PM
37-75	11	0.27	0.9
75-130	10	0.27	0.4
130-225	10	0.27	0.4
225-450	10	0.27	0.3
450-560	10	0.27	0.3
560-1000	10	0.27	0.3
1000+	13	0.27	0.3

*EPA [139]

SO_2 emissions are dependent on fuel sulfur level and the amount that is converted to sulfate particulate. The following mass balance approach was adopted from the EPA baseline inventory developed in support of its emission standard development to reduce emissions from nonroad diesel engines [143].

$$E_{SO_2} = FQ * S * (1-SO_4) * 64/32$$

where:

E_{SO_2} = SO_2 emissions (tonnes)
FQ = Fuel quantity (tonnes)
S = Sulfur in fuel (weight fraction)
SO_4 = Sulfur fraction converted to sulfate particulate = 0.02247
64/32 = SO_2 to sulfur molecular weight ratio

The speciation profiles, described in Section 4.2.2, are used to compile estimates for $PM_{2.5}$, VOC, Benzene, Formaldehyde and 1,3 Butadiene.

Vessel Activities for Workboats

For vessels operating within inland river ports, there are primarily two modes of operation, namely cruising and maneuvering [140]. Maneuvering occurs when a tug maneuvers a barge through a lock, into a fleeting area or a dock. For a normal trip, hoteling time is expected to be negligible [140].

Tidewater has provided total main engine operating time for each vessel. However, data on the split between maneuvering and cruising time is not available. To be able to reasonably estimate such a split, information including vessel routes, number of trips by a vessel on a given route and the time spent at each of the two modes on a given trip are needed. However, this detailed level of information is not readily available.

According to Tidewater, its operation is concentrated in the Portland harbor. It has two harbor vessels that operate short, intra-harbor trips and two dedicated vessels assigned to particular runs between Portland and Astoria. Its Snake River boat typically crosses the 4 Snake River locks once a week to travel to and from the Tri-Cities area. The remaining vessels are line haul boats operating on long trips from Portland to Tri-Cities. These long trips require the navigation or maneuvering through the 4 Columbia River locks and stops along the way to deliver or pick up barges. Given that the majority of Tidewater's vessels operate on long trips, the total cruising time for each trip should be much higher than maneuvering time. Hence for a first approximation, it has been assumed that maneuvering time, as a fraction of the total trip time, is negligible.

For auxiliary generator engines, the annual operating time is not available for 2001. However, the total generator operating time for most of the vessels was available for 2002. Although generator-operating time varies from year to year, an averaged operating time of 2,858 hours for each generator was estimated based on the 2002 data as a first approximation for the baseline estimates. This is consistent with the annual operating time of 2,500 hours for Category 1 engines that was estimated by EPA in its 1999 regulatory impact analysis report for marine diesel engines [139].

4.2.4 Ferry Emission Estimation Methodology

Base Quantities for Ferries

For each ferry in its fleet, WSF has provided data on the annual fuel consumed and operating hours for the main engines and generators for 2001. Given that the operation of each ferry consists of four distinctive modes, namely loading/unloading, maneuvering, underway and tie-up, the corresponding fuel requirement at each mode is different and is dependent on the engine load and operating time at that mode. Descriptions of the four ferry operating modes, as defined by WSF, are given in Table 4.8.

Since the mode of operation also influences the quantity of pollutants emitted as a result of the difference in fuel requirements, a better resolution of annual fuel consumption data is needed to improve the accuracy of the baseline emission estimates for the ferry fleet. Consequently, WSF conducted an internal survey of ferry Chief Engineers to determine the engine load levels and the time a vessel spends at each operating mode for a given route

Table 4.8 - Descriptions of Ferry Operation Modes

Modes	Descriptions
Loading/Unloading	In this mode, vessels are pushing against the dock to keep them in place while ferry customers drive off and onto the vessels. The main engines, vital generators (where they are present), and the ship service generators are operating in this mode.
Maneuvering	In this mode, vessel may be quickly changing % of maximum operating loads as it pull away from a dock, avoid other traffic or obstacles, or slow down to enter a slip. This operational mode is typically very short in duration relative to the others. The main engines, vital generators (where they are present), and the ship service generators are operating in this mode.
Underway	In this mode, vessel may be running at close to its maximum % operating load in order to make its schedule commitments. On a long route, this mode of operation constitutes a large part of the service hours. Obviously, on a short route, this mode of operation may constitute less of the service hours than loading and unloading. The main engines, vital generators (where they are present) and the ship service generators are operating in this mode.
Tie-up	Although vessels run long hours, they do not operate 24 hours a day 7 days per week. Vessels may tie up between 2 and 10 hours out of a 24 -hour a day schedule. Most vessels, with the exception of the Jumbo Mark II's, are not running any engines during this mode. Periodically during tie-up, vessels may run the emergency generators for a couple of hours per month as required the U.S. Coast Guard to ensure that these systems are operational.

For vessels that served a single route in 2001, total fuel consumption for each engine type was split into the various operating modes by proration factors that are derived from engine load level and operating time at a given mode. Sample calculations for the main engine fuel split by mode for the Vessel Spokane is provided in Appendix 1.

For vessels that served multiple routes in 2001, total fuel consumption for each engine type was first split by route and then by operation mode. Sample fuel split calculations for the Vessel Sealth are also provided in Appendix 1.

Emission Factors for Ferries

Main engine pollutant emission factors are based on published values for Category 2 diesel engines [136]. These factors are shown in Table 4.6 in Section 4.2.3.2. while the emission factors for the on-board generators are shown in Table 4.7 of the same Section. Emission factors for boilers are given in Table 4.9.

The emission factors for maneuvering operation are derived based on published ratios of measured maneuvering to underway emissions and these ratios are shown in Table 4.10. Although the sampling methodology was different, the ratios reported by Lloyd [148] for medium speed engines were consistent with those from measurements made by Environment Canada [137] on a B.C. ferry. For this study, the Environment Canada ratios were used since the dataset also included the ratio for particulate.

Table 4.9 - Emission Factors for Boilers

Source	Emission Factors (kg/tonne fuel)*		
	NOx	HC	PM
Boilers	12.3	0.38	1.9

* Environ, 2000 [136]

Table 4.10 - Ratio of Transient/Maneuvering to Steady State/Underway Emissions

Engine Type	NOx	HC	PM	Data Source
Medium/Slow Speed	0.9	1.5	--	Lloyd [148]
Medium Speed Ferry	0.97	1.43	1.41	EC [137]

As discussed in Section 4.2.3.2, SO_2 emissions are dependent on fuel sulfur level and the amount that is converted to sulfate particulate. The SO_2 estimation methodology given in this previous Section is adopted for the ferry fleet. The speciation profiles, described in Section 4.2.2, are used to compile estimates for $PM_{2.5}$, VOC, Benzene, Formaldehyde and 1,3 Butadiene.

Vessel Activities for Ferries

Information on the routes served by each vessel in 2001 are shown in table 4.2 and this was obtained from WSF for a separate project [147]. Vessel operating time for loading/unloading, maneuvering, underway and tie-up modes for a given route were provided by WSF from rough estimates furnished by ferry Chief Engineers.

4.2.5 Cruise Ship Emission Estimation Methodology

Base Quantities for Cruise Ships

As data was not available for all of the cruise ships operating in Puget Sound, engine and fuel use information from a typical cruise vessel, Holland America's Statendam was used. The Statendam has a gross tonnage of 55,451 tonnes, and a length of 219 meters, equivalent to the average cruise ship operating on the West Coast.

The Statendam operates two V-12 Sulzer AV-40 4-stroke diesel engines (8640 kW each) at 80% load while underway. While hoteling, two 8-cylinder Sulzer 8ZAL40S 4-stroke diesel engines (5760 kW each) are operated at 65% load.

Cruise ship movement and hoteling times in Seattle were not available from US sources. However, records of cruise ship movements by time were available in a database form from the Pacific Pilotage, a Canadian agency. Cruise ship hoteling times in Vancouver, BC, were calculated by matching consecutive movements times and were assumed to be comparable to those in Seattle. The Pacific Pilotage data did contain some travel times for cruise vessels moving between Vancouver and Seattle. As the majority of cruise traffic to or from Seattle is en-route to Alaska, the time to Vancouver was taken as the time in Washington State.

Emission Factors for Cruise Ships

In support of the development of emission standards for Category 3 C.I. engines, the EPA has compiled a baseline inventory for in-port and non-port vessel emissions [145]. Emissions were calculated for underway and hoteling modes for this inventory. Table 4.11 shows the EPA emission factors for NO_X, HC and PM. The emission factors were applied to the engine power rating and load as listed in Table 4.12.

Table 4.11 - Emission Factors for Category 3 Medium Speed Marine Diesel Engines

	Emission Factors (g/HP-h)		
	NOx	**HC**	**PM**
Underway or Reduced Speed Zone	12.38	0.40	1.31

Table 4.12 - Power Rating and Load Factors for typical Cruise Engine

	Main Engine	Auxiliary Engine
Engine	V-12 Sulzer AV-40 4-stroke diesel	8-cylinder Sulzer 8ZAL40S 4-stroke diesel
Number of Engines	2	2
Power Rating (kW), each Engine	8640	5760
Load Factor	80%	65%

As discussed in Section 4.2.3.2, SO_2 emissions are dependent on fuel sulfur level and the amount that is converted to sulfate particulate. Assuming fuel sulfur content of 2.4%, the SO_2 emission factor is 10.0g/kWh. The speciation profiles, described in Section 4.2.2, are used to compile estimates for $PM_{2.5}$, VOC, Benzene, Formaldehyde and 1,3 Butadiene.

Vessel Activities for Cruise Ships

The number of planned sailings to, from, or calling the Port of Seattle was obtained from the Cruise Mates website. The website lists the departure dates and cruise length by vessel and cruise carrier for 2003 through to 2005. The average number of cruises and vessels traveling on the west coast annually was calculated from this information.

4.2.6 Construction Equipment Emission Estimation Methodology

An updated draft version of the EPA *NONROAD* model (EPA [141]) was released for review in June 2003. The model allows for estimation of exhaust and crankcase releases of criteria pollutants and air toxics from nonroad diesel engines, including construction equipment. This latest version has been extensively revised resulting in emission estimates that are significantly different from those generated in the previous version of the model.

Although the *NONROAD* model allows the user to define a sub-county region, such as the City of Seattle, this option requires the user to edit input files to adapt to local conditions and also provide additional input data. The required changes to the input files may result in the possibility of changing the model in ways that lead to invalid results [141]. Given that this current model is currently under review, it was not used to generate baseline emission estimates for the City of Seattle construction equipment included in this study. Instead, applicable *NONROAD* default data, such as emission factors and deterioration rates, are adopted for this study.

Base Quantities for Construction Equipment

The majority of the power rating of the construction equipment included in this study is not readily available. As mentioned in Section 4.1.4, this data gap was filled by information published in engine manufacturers' website for the same model or for engines of the same series. A listing of the actual and assumed power ratings for the equipment has been shown in Table 4.3.

Information on the operating modes and load factors were also not readily available as operating condition for these equipment are quite varied. Consequently, default values used in the EPA *NONROAD* model were adopted and are shown in Table 4.13.

Table 4.13 - Selected Equipment in the City of Seattle Construction Fleet

Equipment	Make	Model	Load Factors*
Backhoe Loader	CASE	590SL	0.21
Backhoe Loader	Caterpillar	446B	0.21
Loader	CASE	921C	0.21
Excavator	Caterpillar	312BL	0.59
Tolt Track Excavator	CASE	9010B	0.59
Grader	Champion/Volvo	720A	0.59
Tolt Grader	John Deere	772BH	0.59
Watershed Grader	Caterpillar	--	0.59
Wheel Loader	John Deere	624H	0.21
Wheel Loader	Caterpillar	IT 28F	0.21
Asphalt Pavement Grinder	Wirtgen America	W 1000	0.43
Dozer	CASE	850G	0.59

* EPA [142]

Emission Factors for Construction Equipment

Based the methodology used by the EPA *NONROAD* model, the baseline pollutant emission factors were derived by applying transient adjustment factors (TAF) and engine deterioration factors (DF) to the steady state emission factors. The TAF adjustment accounts for operations at variable speed and load conditions and the DF adjustment reflects engine deterioration with age. The steady state, TAF and DF factors used in this study were taken from the EPA *NONROAD* model default data set [142] and are shown in Appendix 2. The adjusted baseline emission factors are shown in Table 4.14.

As discussed in Section 4.1.4, diesel fuel with a sulfur content of 3000 ppm was used in the baseline emission estimates for selected equipment in the City of Seattle fleet. This higher sulfur fuel is more typical of the fuel used by construction fleets in the study area. Baseline SO_2 emission factors, shown in Table 4.14, were estimated according to the *NONROAD* model methodology shown below.

SO_2 = (BSFC * 453.6 * (1-SOx_cnv) – HC) * 0.01 * SOx_dsl * (64/32) where:

SO_2	= SO_2 emission factor in g/HP-h
BSFC	= In-use adjusted fuel consumption in lb/HP-h
453.6	= Conversion factor from lbs to grams
SOx_cnv	= Fraction of fuel sulfur converted to direct PM
HC	= In-use adjusted hydrocarbon emissions in g/HP-h
0.01	= conversion factor from weight percent to fraction
SOx_dsl	= Weight percent of sulfur in nonroad diesel
64/32	= SO_2 to sulfur molecular weight ratio

The speciation profiles, described in Section 4.2.2, are used to compile estimates for Benzene, Formaldehyde and 1,3 Butadiene.

Construction Equipment Activities

The City of Seattle has provided information on the total service/meter time logged by each of the twelve pieces of equipment for 2002.

Table 4.14 - Adjusted Exhaust and Crankcase Emission Factors for Selected City of Seattle Construction Equipment

			Exhaust Emission Factors (g/HP-h)				Crankcase Emission Factor (g/HP-h)
Equipment	**Model**	**Power (HP)**	**SO_2**	**HC**	**NO_X**	**PM**	**HC**
Backhoe Loader	590SL	99	0.212	1.196	6.167	0.858	0.024
Backhoe Loader	446B	102	0.191	0.777	6.226	0.479	0.016
Loader	921C	248	0.191	0.708	6.145	0.425	0.014
Excavator	312BL	83*	0.182	1.044	6.569	0.842	0.021
Tolt Track Excavator	9010B	186	0.164	0.724	8.021	0.493	0.014
Grader	720A	190	0.164	0.720	7.992	0.458	0.014
Tolt Grader	772BH	170	0.164	0.719	7.990	0.455	0.014
Watershed Grader	--	162	0.164	0.738	8.098	0.588	0.015
Wheel Loader	624H	160	0.191	0.775	6.218	0.464	0.015
Wheel Loader	IT 28F	120*	0.190	1.570	9.256	0.769	0.031
Asphalt Pavement Grinder	W 1000	213	0.162	0.310	5.594	0.193	0.006
Dozer	850G	99*	0.182	1.045	6.574	0.855	0.021

* Data supplied by the City of Seattle

4.2.7 Locomotive Emission Estimation Methodology

Base Quantities for Locomotives

BNSF provided its own emission estimates of NO_X, SO_2, PM, HC and CO for its fleet of line-haul and switch locomotives operating the States of Washington and Oregon. These emission estimates were based on applying fuel-based emission factors to its fleet's estimated fuel consumption, which were derived from ton-mile estimate along each route and an average fuel use factor of 760.3 ton-mile per gallon. The emissions of the additional pollutants were calculated using the speciation profiles as discussed in Sections 4.2.1.1 and 4.2.1.2.

Emission Factors for Locomotives

The fuel-based emission factors, for the pollutants of interest and representative of the entire BNSF fleet, are shown in Table 4.15 below for line-haul and switch locomotives.

Table 4.15 - BNSF Locomotive Emission Factors for Criteria Air Contaminants

Locomotive Types	Emission Factors (lb/gal)			
	NOx	SO_2	HC	PM
Line-haul	0.4931	0.036	0.0211	0.0116
Switch	0.5044	0.036	0.0506	0.0138

For the remaining pollutants not estimated by BNSF, namely VOC, $PM_{2.5}$, Benzene, Formaldehyde and 1,3 Butadiene, emission estimates were based the speciation profiles discussed in Sections 4.2.1.1 and 4.2.1.2.

Locomotive Equipment Activities

BNSF also provided the total fuel use by line-haul and switchyard locomotives. Locomotives have 2 main operational modes, idling, and under load. The fuel consumption by locomotive type provided by BNSF was further divided by operational mode based on fractional time in mode and average engine fuel consumption rates in each mode. It was assumed that line-haul locomotive spend 38% of the duty-cycle idling, and switchyard locomotives spend 59.8% of time idle [138]. Typical mode specific fuel consumption rates were provided by locomotive manufacturers and are shown in Table 4.16.

Table 4.16 -Typical Locomotive Engine Fuel Consumption by Mode

Mode	Fuel Consumption Rate (gph)	
	Idling	Under Load
Line-Haul	**4**	**116**
SwitchYard	**3**	**87**

Sources: Caterpillar [133] and GM EMD [146]

4.3 Cost Estimation

At the time that requests were made to the individual fleets for data to characterize baseline emissions, fleet contacts were also asked to provide information on annual fuel suppliers, fuel cost, and annual operating and maintenance costs. This cost data was used as a baseline against which the cost of implementing various control options could be compared. Some of the cost data obtained for this study has been cited as confidential by individual fleet operators. Therefore, fleet-supplied values for fuel and maintenance costs are omitted from this report and only furnished values of fleet fuel consumption, where available, are included. Baseline fuel consumption data, when not available, is estimated from engine power rating and assumptions about load factors and specific fuel consumption. Finally, current fuel costs are used to estimate baseline fleet fuel annual fuel costs.

Fleet baseline maintenance costs are not required for calculating the cost-effectiveness of different emission reduction alternatives; hence they are not reported here.

4.4 Baseline Emissions

4.4.1 Overall Emissions Summary

The baseline annual emission estimates are the five participating fleets are shown in Table 4.17.

Table 4.17 - Baseline Emissions Summary for Participating Nonroad Fleets

Fleets	Baseline Annual Emissions (tons per year)						
	NOX	SO_2	$PM_{2.5}$	VOC	Benzene	Formaldehyde	1,3 Butadiene
Workboats*	1,435.16	137.49	33.16	17.08	0.34	2.02	0.03
Ferries*	3,503.23	466.96	59.25	29.60	0.59	3.49	0.06
Construction Equipment*	1.92	0.28	0.14	0.21	0.00	0.03	0.00
Cruise ship***	699.99	421.63	66.66	78.00	1.56	9.20	0.16
Locomotives**	22,093.21	1,612.53	479.11	1,011.86	20.24	119.40	2.02
All fleets	27,733.51	2,638.89	638.33	1,136.75	22.73	134.14	2.27

* Baseline estimates for these fleets are for the year 2001
** Baseline estimates for this fleet is for 2002
***Baseline estimates for this fleet is for 2003

4.4.2 Workboats

For the Tidewater workboat fleet, baseline 2001 emission estimates are shown in Table 4.18.

4.4.3 Ferries

Baseline 2001 emission estimates for the WSF fleet are shown in Table 4.19.

4.4.4 Cruise Ships

Emission estimates for the Statendam cruise ship are shown in Table 2.20. Baseline emissions are shown for the Statendam assuming 5 trips per year, and for the fleet average assuming 22 cruise vessels similar to the Statendam, with 5 trips per vessel.

4.4.5 Construction Equipment

2002 emission estimates for the 12 pieces of construction equipment of the City of Seattle are shown in Table 4.21

4.4.6 Locomotives

Emission estimates for BNSF locomotives in 2002 are shown in Table 4.22 and Table 4.23. In general, the split of emissions between line-haul and switch/yard locomotives is the same for each pollutant of interest.

Table 4.18 - 2001 Baseline Emissions for the Tidewater Barge Line Workboat Fleet

Vessel	2001 Emissions (tons)							
	NOx	SO_2	$PM_{2.5}$	THC	VOC	Benzene	Formaldehyde	1,3 Butadiene
Tidewater	183.96	17.29	4.15	1.97	2.07	0.04	0.24	0.0041
Legend	118.84	11.30	2.72	1.32	1.39	0.03	0.16	0.0028
Defiance	60.90	5.98	1.45	0.74	0.78	0.02	0.09	0.0016
Chief	220.47	20.64	4.96	2.33	2.46	0.05	0.29	0.0049
Outlaw	154.95	14.62	3.52	1.68	1.77	0.04	0.21	0.0035
Hurricane	122.82	11.67	2.81	1.36	1.43	0.03	0.17	0.0029
Captain Bob	59.55	5.85	1.42	0.72	0.76	0.02	0.09	0.0015
Challenger	122.39	11.63	2.80	1.35	1.42	0.03	0.17	0.0028
Comet	81.58	7.88	1.90	0.94	0.99	0.02	0.12	0.0020
Rebel	17.22	1.96	0.49	0.30	0.32	0.01	0.04	0.0006
Liberty	108.99	10.40	2.51	1.22	1.28	0.03	0.15	0.0026
Betty Lou	32.82	3.40	0.83	0.46	0.48	0.01	0.06	0.0010
Maverick	59.20	5.82	1.41	0.72	0.76	0.02	0.09	0.0015
Invader	5.06	0.72	0.19	0.14	0.14	0.00	0.02	0.0003
Mary Gail II	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.0000
John Ackerman	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0000
Husky	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0000
James Russell	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0000
Sundial	86.40	8.32	2.01	0.99	1.04	0.02	0.12	0.0021
Fleet Total	1,435.16	137.49	33.16	16.22	17.08	0.34	2.02	0.03

Note: Totals may not add up exactly due to rounding

Table 4.19 - 2001 Baseline Emissions for the Washington State Ferry Fleet

Ferry Group	Vessel Classes	Operating Mode	Baseline Emissions (tons per year)						
			SOx	NOx	$PM_{2.5}$	VOC	Benzene	Formaldehyde	1,3 Butadiene
1	Jumbo Mk II Jumbo Mk I Super	Loading/Unloading	91.19	805.62	5.99	2.53	0.05	0.30	0.005
		Maneuvering	41.52	327.34	4.85	2.39	0.05	0.28	0.005
		Tie-up	8.64	42.60	1.18	1.21	0.02	0.14	0.002
		Underway	139.42	948.22	22.87	11.47	0.23	1.35	0.023
		Total	**280.77**	**2,123.78**	**34.88**	**17.59**	**0.35**	**2.08**	**0.035**
2	Issaquach Evergreen State	Loading/Unloading	38.24	325.95	2.77	1.40	0.03	0.17	0.003
		Maneuvering	26.85	206.03	3.19	1.70	0.03	0.20	0.003
		Tie-up	0.39	1.90	0.07	0.05	0.00	0.01	0.000
		Underway	65.19	421.18	11.03	5.42	0.11	0.64	0.011
		Total	**130.66**	**955.06**	**17.06**	**8.57**	**0.17**	**1.01**	**0.017**
3	Steel Electric Rhododendrom Passenger (Tyee)	Loading/Unloading	8.01	70.34	0.55	0.23	0.00	0.03	0.000
		Maneuvering	4.32	34.62	0.50	0.23	0.00	0.03	0.000
		Tie-up	0.03	0.16	0.01	0.00	0.00	0.00	0.000
		Underway	15.58	106.00	2.66	1.24	0.02	0.15	0.002
		Total	**27.94**	**211.12**	**3.71**	**1.71**	**0.03**	**0.20**	**0.003**
4	Passenger Only Passenger Fast Ferry	Loading/Unloading	8.00	70.53	0.54	0.22	0.00	0.03	0.000
		Maneuvering	2.90	22.67	0.35	0.17	0.00	0.02	0.000
		Tie-up	0.00	0.00	0.00	0.00	0.00	0.00	0.000
		Underway	16.69	120.05	2.72	1.33	0.03	0.16	0.003
		Total	**27.59**	**213.26**	**3.60**	**1.73**	**0.03**	**0.20**	**0.003**
Total WSF Ferries			**466.96**	**3,503.23**	**59.25**	**29.60**	**0.59**	**3.49**	**0.06**

Note: Totals may not add up exactly due to rounding. Emissions based upon published emission factors and not upon vessel measurements. Ferry groups based upon number of engines per vessel and engine horsepower.

Table 4.20 - Baseline Emissions for the Statendam Cruise Ship and Fleet Estimate in 2003

Cruise Vessel	Mode	Emissions (tons per year)						
		NOx	$PM_{2.5}$	SOx	VOC	Benzene	Formaldehyde	1,3 Butadiene
Statendam	Cruising	25.30	2.41	15.24	2.82	0.06	0.33	0.006
	Hotelling	6.52	0.62	3.93	0.73	0.01	0.09	0.001
	All Modes	31.82	3.03	19.17	3.55	0.07	0.42	0.007
Fleet Estimate	Cruising	556.56	53.00	335.24	62.01	1.24	7.32	0.124
	Hotelling	143.43	13.66	86.39	15.98	0.32	1.89	0.032
	All Modes	699.99	66.66	421.63	78.00	1.56	9.20	0.16

Note: Totals may not add up exactly due to rounding

Table 4.21 - 2001 Baseline Emissions for Selected Equipment in the City of Seattle Construction Fleet

Equipment	Model	HP	2001 Emissions (tons)						
			NOx	SO_2	$PM_{2.5}$	VOC	Benzene	Formaldehyde	1,3 Butadiene
Back-Hoe	590SL	99	0.052	0.011	0.007	0.011	0.0002	0.001	0.00002
Loader	921C	248	0.324	0.060	0.024	0.040	0.0008	0.005	0.00008
Dozer	850G	99	0.069	0.011	0.009	0.012	0.0002	0.001	0.00002
Excavator	9010B	186	0.257	0.031	0.016	0.025	0.000	0.003	0.0000
Back-Hoe	446B	102	0.072	0.013	0.006	0.010	0.0002	0.001	0.00002
Excavator	312BL	83	0.028	0.005	0.004	0.005	0.0001	0.001	0.00001
Grader	?	162	0.570	0.069	0.043	0.056	0.001	0.007	0.0001
Loader	IT28F	120	0.097	0.012	0.008	0.018	0.0004	0.002	0.00004
Grader	720A	190	0.101	0.012	0.006	0.010	0.0002	0.001	0.00002
Loader	624H	160	0.0028	0.00051	0.00022	0.0004	0.000007	0.00004	0.0000007
Grader	772BH	170	0.189	0.023	0.011	0.018	0.0004	0.002	0.00004
Pavement Grinder	W1000	213	0.162	0.028	0.007	0.010	0.0002	0.001	0.00002
Total			1.922	0.277	0.142	0.213	0.004	0.025	0.0004

Note: Totals may not add up exactly due to rounding

Table 4.22 - 2002 Locomotive Emission Estimates from BNSF

				2002 Locomotive Emissions (tons/y)*				
States	**Counties****	**Modes**	**Engine Mode**	**NOx**	**PM**	**CO**	**SO_2**	**HC**
Washington	All	Line Haul	Idling	429.87	10.11	54.57	31.38	18.39
			Full Load	20,326.91	478.18	2,580.54	1,484.02	869.80
			Total	20,756.78	488.29	2,635.11	1,515.40	888.19
		Yard	Idling	11.17	0.31	1.98	0.80	1.12
			Full Load	217.67	5.95	38.58	15.53	21.84
			Total	228.84	6.26	40.56	16.33	22.96
		All Modes	Idling	441.04	10.42	56.55	32.18	19.52
			Full Load	20,544.58	484.14	2,619.12	1,499.55	891.64
			Total	20,985.61	494.55	2,675.67	1,531.73	911.15
Oregon	All	Line Haul	Idling	22.08	0.52	2.80	1.61	0.94
			Full Load	1,043.91	24.56	132.53	76.22	44.66
			Total	1,065.99	25.08	135.33	77.83	45.61
		Yard	Idling	2.03	0.06	0.36	0.14	0.20
			Full Load	39.58	1.08	7.01	2.82	3.97
			Total	41.61	1.14	7.37	2.97	4.17
		All Modes	Idling	24.11	0.58	3.16	1.76	1.15
			Full Load	1,083.49	25.64	139.54	79.04	48.63
			Total	1,107.60	26.22	142.70	80.80	49.78
Pacific NW Total	All	Line Haul	Idling	451.94	10.63	57.37	33.00	19.34
			Full Load	21,370.82	502.74	2,713.07	1,560.24	914.46
			Total	21,822.77	513.37	2,770.44	1,593.23	933.80
		Yard	Idling	13.20	0.36	2.34	0.94	1.32
			Full Load	257.24	7.04	45.59	18.36	25.81
			Total	270.45	7.40	47.93	19.30	27.13
		All Modes	Idling	465.15	10.99	59.71	33.94	20.66
			Full Load	21,628.07	509.78	2,758.66	1,578.60	940.27
			Total	22,093.21	520.77	2,818.37	1,612.53	960.93

Note: Totals may not add up exactly due to rounding

Table 4.23 - Locomotive Emission Estimates for VOC, $PM_{2.5}$, Benzene, Formaldehyde and 1,3 Butadiene in 2002

				2002 Locomotive Emissions (tons/y)*				
States	**Counties****	**Modes**	**Engine Mode**	**VOC**	**$PM_{2.5}$**	**Benzene**	**Formaldehyde**	**1,3 Butadiene**
Washington	All	Line Haul	Idling	19.37	9.30	0.39	2.29	0.04
			Full Load	915.90	439.93	18.32	108.08	1.83
			Total	935.27	449.23	18.71	110.36	1.87
		Yard	Idling	1.18	0.28	0.02	0.14	0.00
			Full Load	23.00	5.48	0.46	2.71	0.05
			Total	24.18	5.76	0.48	2.85	0.05
		All Modes	Idling	20.55	9.58	0.41	2.42	0.04
			Full Load	938.89	445.41	18.78	110.79	1.88
			Total	959.44	454.99	19.19	113.21	1.92
Oregon	All	Line Haul	Idling	0.99	0.48	0.02	0.12	0.00
			Full Load	47.03	22.60	0.94	5.55	0.09
			Total	48.03	23.07	0.96	5.67	0.10
		Yard	Idling	0.21	0.05	0.00	0.03	0.00
			Full Load	4.18	1.00	0.08	0.49	0.01
			Total	4.39	1.05	0.09	0.52	0.01
		All Modes	Idling	1.21	0.53	0.02	0.14	0.00
			Full Load	51.21	23.59	1.02	6.04	0.10
			Total	52.42	24.12	1.05	6.19	0.10
Pacific NW Total	All	Line Haul	Idling	20.36	9.78	0.41	2.40	0.04
			Full Load	962.93	462.52	19.26	113.63	1.93
			Total	983.29	472.30	19.67	116.03	1.97
		Yard	Idling	1.39	0.33	0.03	0.16	0.00
			Full Load	27.17	6.48	0.54	3.21	0.05
			Total	28.57	6.81	0.57	3.37	0.06
		All Modes	Idling	21.76	10.11	0.44	2.57	0.04
			Full Load	990.10	469.00	19.80	116.83	1.98
			Total	1,011.86	479.11	20.24	119.40	2.02

Note: Totals may not add up exactly due to rounding.

5.0 CLEAN FUEL OPTIONS

Off-road diesel engine emissions may be reduced through the use of “clean fuels”, which include low-sulfur diesel, ultra-low sulfur diesel, natural gas (compressed or liquefied), biodiesel and other alternative fuels (methanol, ethanol and hydrogen).

- Low-sulfur diesel and ultra-low sulfur diesel (ULSD) fuels reduce the emission of inorganic sulfate particulates ($PM_{2.5}$) and SOx, which in the atmosphere are converted to acidic, $PM_{2.5}$ (respirable) sulfate aerosol. ULSD enables the use catalytic particulate-filter technology, which furthers reduces diesel engine emissions.
- Natural gas offers low emissions and potential operating cost savings but at a higher up-front infrastructure cost. LNG can be made from stranded natural gas resources or can be easily imported from low-cost producers.
- Biodiesel contains no sulfur and hence is compatible with the use high-efficiency catalytic emission-reduction technology, but it is expensive to produce and may have significant environmental impacts if produced on a large scale.
- Ethanol can be blended with diesel for combustion in a diesel engine, or used directly in a spark-ignited engine or a gas turbine. As with biodiesel, ethanol contains no sulfur and hence is compatible with the use high-efficiency catalytic emission-reduction technology, but it is expensive to produce and may have significant environmental impacts if produced on a large scale.
- Methanol can be made from stranded natural gas resources or pipeline natural gas, and from coal or waste biomass. It is readily transported and stored. It can be blended with diesel for combustion in a diesel engine, or used directly in a spark-ignited engine or a gas turbine. It can also be catalytically converted to hydrogen for use in fuel-cell vehicles.
- Hydrogen is being promoted as “the fuel of the future” but, because of its low energy density in the gaseous form, will only become practical for off-road use when cheap, liquefied hydrogen becomes readily available. It is included here because of the considerable political and media attention that is devoted to this form of energy storage. Hydrogen is already used on a large scale in petroleum refineries to make low-sulfur gasoline and diesel and ultra-low sulfur diesel so, in one sense, hydrogen already forms a significant part of the transportation fuel mix.

These different clean-fuel options will be further explored in the following sections.

5.1 Low sulfur diesel and ultra-low sulfur diesel

Low sulfur diesel and ultra-low sulfur diesel (ULSD) are required for on-road diesel-engined vehicles, as discussed in Section 3. EPA has mandated low sulfur diesel ($S < 500$ ppm) for on-road vehicles since 1994 and will require on-road ULSD by 2007. California has required transit buses to use ULSD ($S < 15$ ppm) since 2002.

These requirements will eventually be extended to off-road diesel engines – EPA has recently proposed that locomotive and marine engines use low sulfur diesel by 2007 and that all other off-road sources use ULSD by this date. The cost premium for using low sulfur diesel is estimated to be 2.5 cents/gallon and for ULSD an additional 2.3 cents/gallon. Current fuel prices are available (e.g.) at the Dept. of Energy's *Energy Information Administration* web site (http://www.eia.doe.gov/).

Ultra-low sulfur diesel (ULSD) fuel dramatically reduces harmful emissions that are hurting air quality and impacting public health. Using ULSD will contribute to dramatic reductions in harmful diesel emissions:

- The lower sulfur content produces fewer harmful emissions and enables the use of recently developed emission-reduction equipment, such as catalytic particulate filters. The use of these systems in combination with ULSD can reduce emissions of fine particles and toxic air particles by more than 90% and emissions of hydrocarbons to nearly undetectable levels.
- Even without special emission-reduction equipment, use of ULSD in diesel engines reduces harmful sulfate pollutants.

Sources of low sulfur diesel in the Pacific Northwest

There are six refineries in the Pacific Northwest – five in Puget Sound and one in Vancouver, Canada – that produce low sulfur road diesel. Two of these refineries are also presently producing ULSD; the remaining four will do so by the year 2006.

The Puget Sound refineries have a combined capacity in excess of 500,000 bbl/day (1 bbl = 1 barrel = 42 US gal). These refineries are supplied with North Slope crude oil via tankers, as well as oil from Canada through a Trans Mountain Pipe-Line feeder, and are listed below.

1. BP Cherry Point/ARCO– located approximately 11.3 km (7 miles) west of Ferndale, WA. (North of Bellingham). Has a capacity of 225,000 bbl/day. The first North Slope oil was shipped here in 1977. Currently making ULSD in their Los Angeles refinery.

2. Tesoro/Shell Anacortes Refinery – located in Fidalgo Bay, 3.2 km (2 miles) east of Anacortes (south of Bellingham). Has a capacity of 112,400 bbl/day.

3. Puget Sound Refining (Texaco) – located in Fidalgo Bay (south of Bellingham). – has a capacity of 145,000 bbl/day.

4. TOSCO Oil (Phillips 66) Refinery – located in the Straight of Georgia, north of Union Bay (16.1 km (10 miles) west/southwest of Ferndale and south of Bellingham). Total crude capacity 100,000 bbl/day. Has a capacity for 170,000+ gallons/day

(200,000+ tpy) of ULSD.[74] This product is sold in Seattle and is also available in Tacoma at a price of about 5 cents/gallon over EPA road diesel. [75] The rack prices vary according to date and location. Prices as of July 22/03 for LSD and ULSD at Ferndale were \$0.832 and \$0.900, respectively. At Tacoma on the same day the prices for LSD and ULSD were \$0.845 and \$0.895, respectively. Since Seattle is not serviced by pipeline, the prices there would be somewhat higher. [124]

5. US Oil – located in the Blair Waterway in Commencement Bay, Tacoma, south of Seattle. Total crude capacity 43,000 bbl/day. Presently produces ULSD diesel on a batch basis at approximately 10,000 bbl/month, but could ramp up to about 5,000 bbl/day (210,000 gallons/day) if there were sufficient demand. The ULSD is available from the rack in Tacoma. They also provide dyed low sulfur diesel and ULSD for off-highway and heating fuel uses.

Two of the major pipeline systems on the West Coast are the Kinder Morgan Energy Partners Pipeline (formerly the Santa Fe Pacific Pipeline) system and the Olympic Pipeline system in the Pacific Northwest. These pipelines move various petroleum products, including CARB gasoline (< 80 ppm S), Low Sulphur No.2 Oil (low sulphur diesel; < 500 ppm S), CARB diesel (as above but with < 35v% aromatics), Gas oil (< 500 ppm S), Fuel Oils (IFO 380 and IFO 180 for marine bunker market; 2.5 – 4.0% S), and No. 6 Fuel Oil (used for power generation; 0.5% and 1.0% S). [76]

The Kinder Morgan Pacific Operations uses 3,900 miles of pipeline to move more than 1 million bbl/day of refined products in Arizona, California, Nevada, Texas and Oregon (www.kne.com), while BP Pipeline's Olympic Pipeline is a 400-mile interstate system that runs along the corridor from Puget Sound (Blaine, Washington) to Portland, Oregon. Total distillate (gasoline, diesel, kerosene, jet fuel, light fuel oils) production on the USA West Coast *Petroleum Administration for Defense District V* (PADD V) during 2000 was 469,000 bbl/day. A majority of this, 361,000 bbl/day, was low sulfur (<500 ppm S) distillates.[75]

The Lower Mainland/Vancouver, Canada area is supplied by a pipeline from Edmonton, Alberta, as well as by Chevron's refinery in Burnaby. The Trans Mountain Pipeline (TMPL) transports crude oil and synthetic crude oil as well as finished products and blend stocks from the Imperial Oil and Petro-Canada refineries in Edmonton. Approximately 90% of the petroleum products used in the Lower Mainland flow, at about 3 mph, down the TMPL line. In addition, a smaller 16" x 70-mile line supplies approximately 10% of the feedstock requirements of four refineries in the Puget Sound region (TOSCO/Phillips66, ARCO, Tesoro, and Puget Sound Refining). In 1999 the TMPL pipeline mix was 55.9% light crudes, 23.5% gasoline, 16.4% distillates (diesel & jet fuels) and 4.2% MTBE. See the TMPL website for further details: www.transmountain.ca/html/western.html

The Chevron Lower Mainland plant is a "Catalytic Cracking" refinery with a capacity of 50,000 bbl/day. The primary processing units are atmospheric and vacuum distillation, catalytic cracking, reforming, alkylation, polymerization and asphalt. This Chevron refinery is presently ramping up to meet the 2006 Federal road-diesel requirements of 15 ppm S. Chevron does not supply marine bunker oils locally, only low sulphur diesel and regular diesel. Residual oils from the vacuum distillation unit are sent via barge to a refinery in Puget Sound.[77]

Some concerns about the use of LSD

- **Lubricity concerns**

In the past, concerns have been expressed about the low lubricity of ULSD, possibly leading to premature wear of fuel injection systems.

ULSD can be used in existing off-road diesel engines without any modification and the major engine manufacturers will continue to honor engine warranties when this fuel is used. Today's ULSD contains additives to ensure adequate lubricity. For example, the ULSD produced by Phillips Petroleum in Ferndale, Washington has a minimum of 3,100 grams lubricity (SBOCLE Test) in compliance with the ASTM standard for highway diesel fuels. Numerous transit bus fleets have been using ULSD since 2001. [78]

According to Shell Canada "As diesel fuel sulphur levels decrease, the risk of inadequate lubricity also increases; however, poor lubricity has been observed even in diesel fuels with very high sulphur levels. Diesel fuel lubricity is typically restored to an acceptable level by the fuel manufacturer with the use of a lubricity additive." [79]

EMD, a major manufacturer of large locomotive engines, states that low sulfur fuels are not a concern with them. Apparently some problems occurred ten years ago when switching from regular diesel (high aromatics) to CARB diesel (low aromatics). The high aromatics had caused the Buna-N seals in the fuel system to swell and harden, so that when EMD customers switched to low-aromatics CARB diesel the seals shrank and leaked. These problems only occurred in California with passenger train operators who were slow to overhaul their injectors, since EMD has used Viton™ seals in their injectors and rebuild kits since 1987.[80]

From the above we can conclude that properly formulated ULSD that meets ASTM requirements is totally acceptable for use in off-road diesel engine fuel systems provided that the fuel injectors use Viton™ seals, or that existing Buna-N seals are replaced with new ones. (Some parties who are promoting the sale of biodiesel claim that when biodiesel is mixed with ULSD it restores lubricity. But this extra expense should not be necessary.)

- **Flash Point concerns**

The marine industry may express safety concerns over the lower flash point of low sulfur diesel and ULSD. Typically the flash point for marine fuels is specified to be higher than that for highway fuels, due to the serious consequences of a fuel-related fire at sea. Most marine vessels that travel the high seas require a flash point of at least 60°C (140°F), while the minimum flash point for road diesel may be specified to be 125°F. Hence the concern by some members of the marine industry that low sulfur road diesel may not meet their safety standards.

This concern was discussed with representatives of two major diesel fuel suppliers.[129, 130] At one of the suppliers the existing flash point for their low sulfur road diesel was 144°F, while the other supplier typically ran at a 140 – 142°F flash point for their low sulfur road diesel. This same refinery typically has a flash point of 127 - 128°F for their ULSD, which exceeds the existing 125°F requirements specified by the Washington State Ferries. Apparently other refineries supply these fuels with even higher flash points.

Each diesel fuel supplier will have their own unique range of flash points for their diesel products. And fuels that are delivered over dock (via fuel barges) provide much greater flexibility in meeting user specifications than those delivered over the Olympic Pipeline. Large marine vessels are generally refueled using fuel barges. Hence major marine fuel users can include their minimum flash point in the fuel specifications and be assured that one or more suppliers will be able to meet their needs.

Emission reductions with low sulfur diesel and ULSD.

The reduction in the emissions of SOx and acidic sulfate particles will be directly proportional to the reduction of sulfur in the fuel. Hence, if low sulfur diesel (typically 350 ppm S) is substituted for regular No.2 off-road diesel (typically 2,300 ppm S), then these sulfur-related emissions will be reduced by 85%. Similarly, if ULSD (typically 10 ppm S) is substituted for regular No.2 off-road diesel, then these sulfur-related emissions are reduced by 99.6%.

SOx emission factors for diesel engines can be calculated using Lloyd's conversions[81]:

- kg/tonne fuel = 20 x fuel S content (wt.%)
- g/kWh (output) = 4.2 x fuel S content (wt.%).

The latter conversion is accurate only if the specific fuel oil consumption (SFOC) of the engine is 210 grams fuel/kWh output and therefore should be use with caution for other diesel engines. The SFOC varies from about 160 g/kWh for large, 2-stroke diesels up to 225 for small 4-strokes and also depend upon engine duty cycle. Therefore if the SFOC for the engine is unknown, it will be more accurate to base SOx emissions upon kg/tonne of fuel (1 tonne = 1000 kg).

5.2 Natural Gas

There is considerable experience in using CNG in heavy-duty diesel engines. Because natural gas – mainly consisting of methane gas - readily mixes with air and has negligible sulphur content, natural gas combustion can result in lower emissions of the products of incomplete combustion, such as carbon monoxide (CO), hydrocarbons/volatile organic compounds (VOC), particulate matter (PM)) and of the oxides of sulphur (SOx).

Natural gas by itself will not ignite in a compression-ignition engine. Hence it is necessary to mix a small amount of diesel fuel along with the natural gas in order to obtain ignition, or to use spark ignition in which case it is no longer a diesel engine. Most natural gas diesel engines are dual-fuel in that they can burn either straight diesel or a mixture of diesel and natural gas. The diesel is injected under high pressure and the natural gas is blown in after the turbocharger but before the intake ports. Modern electronic engine control systems can vary the timing of the diesel injection as well as the ratio of natural gas to the charge air in order to optimize engine performance and to minimize exhaust emissions. (Older, retrofitted dual-fuel diesel engines used mechanical control systems and required considerable time and skill to tune. As a result their emissions, especially those of NOx, were often higher than desired.)

Dual-fuel engines typically use about 85% - 90% natural gas under full load, with the balance being diesel fuel. This ratio decreases as the engine load decreases. When the engine load drops below 20% - 30% of full load all of the fuel is diesel. Hence conventional dual-fuel diesel engines may not significantly reduce exhaust emissions, as compared to straight diesel engines, unless they are operated with a high duty cycle. In addition, conventional dual-fuel diesel engines need to be larger and more expensive than a regular diesel of the same power output.

These limitations of conventional dual-fuel engines are overcome with the new Westport-Cummings engines that are to be commercially available in the spring of 2004. Their 15-liter ISX-G engines are equipped with Westport's high-pressure direct-injection natural gas injector technology. This novel injection system uses a small squirt of diesel to initiate combustion within an engine cylinder; this is followed by the injection of compressed natural gas from a high-pressure, common-rail supply system. A single, co-axial injector is used for both the diesel and the compressed natural gas. Electronic controls allow the diesel and natural gas pulses to be "shaped" in order to optimize engine performance while reducing emissions. The advantage of this system is that it maintains the low-speed torque and high fuel efficiency of a diesel engine, while providing the clean-burning, low fuel-cost advantages of natural gas.[82]

This Cummings-Westport ISX truck engine has been certified by the California Air Resources Board (CARB) to emit no more than 2.4 grams/brake-horsepower hour (g/bhph) of NOx, 2 g/bhph of CO, 0.4 g/bhph VOC's, and 0.05 g/bhph of PM. Carbon dioxide emissions are about 20% less than for diesel fuel. Reduced fuel costs are expected to result in a payout time of only 2 years for these engines. However, at present the marketing thrust is for on-road diesel trucks and buses; off-road and marine applications will be phased in at a later date.[83] The above NOx emission rate for a Cummings-Westport engine is much less (73%) than the NOx emissions for a typical existing diesel engine and meet EPA's 2004 Option 2 requirements for heavy-duty truck and bus engines. Further development of these engines will no doubt lower these emissions even more.

As mentioned above, natural gas fueled diesel engines, when properly designed and operated, can result in low exhaust emissions and low fueling costs. Also, the engine life is greatly extended, as is the time between oil changes, thereby further reducing operating costs.

Fig. 5.1 LNG Fuel Tank (Ref.82)

Offsetting these lower operating costs are higher capital costs for the engine and for the associated fuel supply and fuel storage infrastructure. If a fleet is using compressed natural gas (CNG) then there will need to be one or more high-pressure (300 – 400 atmospheres) compressors and high-pressure cylinders required for storing the CNG at a centrally located fueling station. Each mobile user will need bulky, on-board, high-pressure storage cylinders that will limit the load and range of the user. The use of liquefied natural gas (LNG) is more appropriate to applications where range of operation is important. LNG requires a source of LNG, insulated LNG storage facilities at a fueling station, and insulated LNG on-board storage.

Western States Petroleum Associates argue that clean diesel (ultra-low sulphur diesel) coupled with catalytic particulate filters, provides comparable particulate emissions compared to CNG fueled buses. They quote a 2000 study by Sierra Research that concluded that the cost per ton of emissions removed was 4 – 11 times lower for clean diesel as compared to CNG.[94] There is no doubt that refiners are worried about the encroachment of natural gas into bus fleets, who traditionally have been a good market for road diesel.

Certainly a site-specific study would have to be carried out when comparing the costs and benefits of natural gas versus clean diesel alternatives. The logistics of constantly refueling with CNG may be daunting to some operators. One consultant even proposed to resolve a CNG tugboat-refueling problem by adding an additional barge, fitted with CNG cylinders.[95] The increasing availability of LNG will make the use of natural gas more attractive to vessel operators by reducing the size and weight of the fuel storage tanks and by greatly increasing the operating time between refueling.

Examples of Natural Gas Fueled Transportation.

Below are a few examples of CNG and LNG fueled sources. A recent listing of natural gas engine manufacturers and companies specializing in natural gas conversions is provided in the Natural Gas Vehicles Purchasing Guide 2003 (http://www.ngvc.org/).

- **Albion CNG Ferries**

In 1985 M.D.A. Marine Design Associates of Victoria, B.C. converted one of the Albion ferries that cross the Fraser River at Fort Langley, B.C. (M.V. Klatawa, operated by the B.C. Ministry of Transportation and Highways, now Translink) to dual-fuel (91% natural gas/9% diesel at 85% max. load). The cost in 1985, including development of shore side facilities, was CDN$347,000. Annual fuel savings were over CDN$58,000, and the Ministry calculated a total cumulative savings of CDN$541,600 in 1990 dollars from the period 1990 to 1995.[84]

Following the conversion of the M.V. Klatawa, its sister ferry M.V. Kullet, was converted from diesel to dual-fuel in 1988. The engines of this vessel operated for 60,000 hours on dual-fuel before requiring a major overhaul on the converted engines. M.D.A. also completed designs for 3 BC Ferry *Century Class* ferries (100 car/600 passenger) and for a B.C. Ministry of Transportation and Highways 80 car/250 passenger M.V. Osprey 2000. One of the *Century Class* ferries was built, but without dual-fuel since it took too long to receive Lloyd's approval. The insurance certification for dual-fuel engines has now been granted but no other vessels of this class are presently been built. The Osprey has not yet been converted at the time of this writing. [84]

The original Albion ferries operated for close to 15 years on dual-fuel retrofitted Cat 3406 engines. These ferries are expected to be refitted with new, electronic-injector Cat C12 engines that have been specially manufactured for dual-fuel. CNG is significantly cheaper than diesel – on an equivalent energy basis the difference is about 5 – 8 cents per litre, which yields a rate of return in Canada of 2 ½ - 4 years. Refueling logistics are not a problem; it takes about 5 minutes to take on about 10,000 scft of gas (equivalent to 260 litres of diesel). This is done while vehicles are being unloaded and loaded onto the ferry. The proximity of a natural gas supply pipeline is important to the feasibility of using CNG. [85]

Emissions from these early dual-fuel engines were measured during their initial operation. NOx was reduced by approximately 45%, particulates were up and methane emissions were elevated.[85] Unless an engine is especially designed for a natural gas fuel the promise of lower emission levels may not be realized. And reduced emissions of the "green house gas" CO_2 will be offset by increased methane emissions.

- **Hampton Roads Transit Authority CNG Ferry**

The Hampton Roads Transit Authority did side-by-side comparisons between two ferries, one running twin Cat 3406-G, natural gas fueled engines and the other twin Detroit Diesel 671, diesel fueled engines. Both engines have similar fuel consumption and power. Exhaust analyses showed that the natural gas engine emissions had 10 – 100 times lower particulates, 2 – 3 times lower CO, and approximately the same emissions of NOx. It was concluded that simple retrofits do not realize the full potential of CNG. There needs to be a closed loop (feedback) control using an O_2 sensor located in the engine's exhaust. This would insure correct fuel/air ratio under different load conditions, after engine tuning was carried out to optimize power and minimize emissions.[86]

- **Norwegian LNG Ships**

The Norwegian Maritime Directorate sponsored the construction of two LNG powered supply vessels built that were delivered in 2002 and 2003. Projected annual emission reductions for each vessel are 195 – 210 tpy (82 – 84%) for NOx and 2720 tpy (~ 20%) for CO_2. The extra investment is \$5.6 – \$6.7 Million \$US per vessel.[87]

- **Norwegian LNG Ferry**

The Norwegians have also been operating an LNG 100 car, 300 passenger ferry "*Glutra*" since 2000 19 hours a day, 7 days a week without any kind of interruption on a short, 35 minute round trip route. The total cost of the LNG ferry was 30% higher than a similar diesel powered ferry. The LNG fuel system is sealed off under the main deck in two separate compartments containing one LNG tank and one evaporator each. Evaporated gas is fed in double piping to the main engine at about 4 bars. [88]

The sizes of the LNG tanks are 32 m^3 (8400 gallons) each, each having enough capacity for one full truckload. Having this storage capacity aboard means that storage at the ferry berth is not necessary, thereby reducing costs and allowing the *Glutra* to be used on other routes. Refueling occurs at night and takes about 1 hour for a truckload. The truck connects to the filling station through a hatch at the shipside. [88]

- **Motive Power Co./Wabtec LNG Switching Locomotive**

Motive Power/Wabtec manufactures a 4-axle, 1200 hp switching locomotive powered by a Caterpillar G3516 SITA engine. Three interconnected LNG tanks are used for a total of 1,400 gallons of LNG. [89]

- **Burlington Northern LNG Freight Locomotives**

In the late 1980's and early 1990's BN had two freight locomotives converted to natural gas by Energy Conversion. The locomotives had a dedicated LNG tender, which was filled from a 10,000-gallon tank truck. The locomotives were used to haul unit coal trains for a period of five years, after which they were run on straight diesel. The LNG was from a facility in Vancouver, WA or from Portland. [89] The cost for the rolling stock was about $1 million ($250,000 for each locomotive conversion plus $500,000 for the LNG tender). Tests by Southwest Research Institute indicated that the NOx was reduced by 62% while the CO emissions were up somewhat. There was no change in PM (mainly lube oil emissions). [90] There was no reduction in locomotive engine power resulting from the dual-fuel conversion.

In addition, there is a spark-ignited, 100% natural gas passenger locomotive operating in California that has realized a 70% reduction in NOx. [90] Generally there will be an engine power derating when using a spark-ignited natural gas engine.

- **LNG Heavy-Duty Highway Trucks**

A "Clean Air Corridor" demonstration project will see a multi-fleet deployment of LNG-fueled trucks along Highway 401, Canada's busiest urban corridor. Initially two trucking companies will each use five heavy-duty trucks equipped with Cummings Westport 450 hp 15 liter ISXG natural gas engines in regular highway service. Enbridge Gas Distribution Inc. will source and deliver LNG to customer sites in London, Ontario and Toronto. It hoped that this demonstration would expand the use of LNG-powered heavy-duty trucks in Canada and the US.[93]

Supplies and Price of CNG and LNG in the Pacific Northwest

There is a ready supply of natural gas in the Pacific Northwest for residential and commercial use. Prices are dictated by supply and demand and with the proliferation of natural gas fueled power-generating plants the demand has increased substantially, thereby driving up prices. It is probable that in the near term off-shore LNG will be used to shore-up the supply side of the equation, as studies have shown that this is cost-effective when natural gas prices exceed about $5/MM Btu. [91] ($0.65/gal. of diesel on an equivalent energy basis.)

Compressed natural gas (CNG) is readily made and stored on-site with a compressor and a cascaded system of high-pressure storage tanks. It can also be transported short distances with tube-trailers, although the expense of this form of transportation quickly negates any cost advantage from using natural gas.

Liquefied natural gas (LNG) can be transported relatively long distances in insulated tank trailers. (The density of LNG is 610 times that of natural gas.) LNG is available from gas-supply company storage facilities, where it is liquefied and stored in order to meet peak natural gas demands, such as during winter cold snaps, or from marine import terminals. Presently there are a number of LNG import facilities proposed for the West Coast of the USA that, if approved, will come on-line during 2005 and 2006. [92]

Presently the demand for LNG as a vehicle fuel is low, but this is expected to increase in the future due to regulatory pressures and improved natural gas engines. The California demand for LNG vehicles was about 25,000 gallons/day in 2001. This is expected to increase to about 200,000 gallons per day by 2006. [92] No equivalent data is available for the Pacific Northwest.

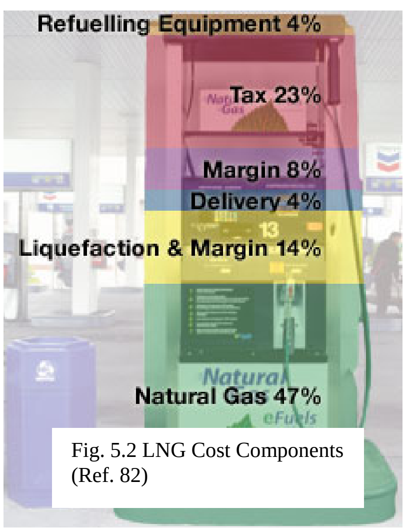


Fig. 5.2 LNG Cost Components (Ref. 82)

Figure 5.2 shows representative cost components for LNG manufactured from pipeline natural gas when LNG is selling for $1.06/gal diesel equivalent ($8.17/MM Btu). It can be seen that the price of LNG is sensitive to natural gas commodity prices. In Figure 5.2 the natural gas commodity price is given as 47% of the pump price, or $3.84/MM Btu. Clearly taxes also have a strong effect upon LNG prices. These taxes are usually much reduced for off-road users who are not expected to support the burden of highway infrastructure.

For a long-term natural gas commodity price of $5.00/MM Btu, the equivalent delivered LNG price (less taxes) would be in the order of $7.50/MM Btu, $0.61/gal LNG, or $1.06/gal diesel equivalent. If the natural gas is already liquefied then the price will be lower by approximately 10% – 15%.

Costs of Natural Gas Conversions

During the period 1998 – 2002 California's Carl Moyer program funded the installation of clean-burning natural gas engines in a total of 1,577 vehicles, at an average cost of

$18,000 per vehicle. The vehicle mix included refuse trucks, transit buses, street sweepers and school buses. In-use NOx emissions were said to be 50% lower than conventional diesel engines, and particulate emissions were 70% lower than diesel engines not equipped with particulate filters. [96]

Bachman AFV, a company specializing in natural gas conversions, estimate the average big heavy duty diesel engine conversion at about $15,000, which includes electronic sensors for maintaining the optimal fuel-air ration. All up installed costs, including high-pressure storage tanks, are in the order of $25,000 - $30,000. Diesels with electronic engine controls are easier to retrofit because sensors and controls are already in place. Typical exhaust emission reductions are NOx 50% and PM 70% - 80%. These costs can be compared with change-out to a new, heavy-duty natural gas engine, which is in the order of $50,000 - $80,000. [97]

One of the roadblocks to using natural gas in marine vessels is obtaining Lloyds and Coast Guard approval. There is a concern that natural gas is not as safe or as reliable as is diesel power. (It is interesting to note that a similar concern was expressed when steam power was first used in ships – for a period of roughly 10 years ships using steam power were required to have sails as a back-up, proven system.[31]) The Albion ferries were approved because they could instantly switch back to diesel if there was a problem with the natural gas system. But for engines using Westport's modern, high-pressure fuel injectors, this is not possible. A history of proven reliability with the Westport system and similar modern diesel engines may be necessary before approval from Lloyds and the Coast Guard is forthcoming.

5.3 Biodiesel

Biodiesel fuels are methyl or ethyl esters derived from a broad variety of renewable sources such as vegetable oil, animal fat and cooking oil. Esters are oxygenated organic compounds that can be used in compression ignition engines because their key properties are comparable to diesel fuel. Biodiesel is produced in a pure form (100% biodiesel fuel referred to as "B100" or "neat biodiesel") and may be blended with petroleum-based diesel fuel. Such biodiesel blends are designated as BXX, where the XX represents the percentage of pure biodiesel contained in the blend (e.g. "B5", "B20"). [105]

"Soy Methyl Ester" diesel ("SME" or "SOME"), derived from soybean oil, is the most common biodiesel in the United States. "Rape Methyl Ester" diesel ("RME"). Derived from rapeseed oil (canola oil), is the most common biodiesel available in Europe. Collectively, these fuels are sometimes referred to as "Fatty Acid Methyl Esters" ("FAME"). They are produced by a process called transesterification, in which various oils (triglycerides) are converted into methyl esters through a chemical reaction with methanol in the presence of a catalyst, such as sodium or potassium hydroxide. The byproducts of this reaction are glycerol and water, both of which are undesirable and need to be removed from the product along with traces of methanol., unreacted triglycerides and catalyst. Biodiesel fuels naturally contain oxygen, which must be stabilized to avoid storage problems.[105] Bayer Chemicals has recently commercialized an anti-oxidant (*Baynox*) to prevent biodiesel from turning rancid. This anti-oxidant is similar in chemical structure to vitamin E.[114]

According to the Engine Manufacturers Association, biodiesel blends up to B5 should not cause engine or fuel system problems, provided that the B100 used in the blend meets the requirements of ASTM D 6751, DIN 51606, or EN 14214. Engine manufacturers should be consulted if higher percentage blends are desired. The blends may require additives to improve storage stability and allow use in a wide range of temperatures. In addition, the conditions of seals, hoses, gaskets and wire coatings should be monitored regularly when biodiesel fuels are used. [105]

Biodiesel has a high oxygen content that results in improved combustion and much lower particulate emissions (28 – 49%). However, NOx emissions are increased (14%) as a result of the extra oxygen. A B20 (20% biodiesel/80% CARB diesel) could be produced for an additional $0.25 - $0.45 per gallon over CARB diesel. Fuel economy would be less by about 4%. [98] Raw material costs for the large-scale production of biodiesel from (say) canola oil are expected to be high and may make the product uncompetitive with other alternatives, such as Dynamotive's BioOil, described below.

USA prices for biodiesel are tabulated on a weekly basis in the Alternative Fuels Index prepared by the Energy Management Institute. [112] For July 10, 2003 the price/gal for biodiesel blends in Seattle, WA, are given as $2.12 (B100), $1.16 (B20), $0.94 (B2) and $0.91 (straight diesel). These prices are exclusive of taxes and may be net of certain subsidies.

A Danish study into the energy and CO_2 balances associated with making biodiesel from rape seed oil (canola oil) concluded that the energy value of the oil (40.7 GJ/ha) far exceeded the total actual gross energy consumption (12.2 GJ/ha) when grown at a of 3 tonnes/ha. If energy credit was taken for byproduct rape cake and rape straw, then the energy balance is even more favorable. [103]

Calculations show that, at the current USA low-sulfur (<0.05%S) distillate consumption of approximately 3 million bbl/day, approximately 70 million acres of canola would have to be cultivated to replace 20% of this fuel. But if the byproduct rape cake and rape straw were converted to BioOil, methanol or some other biofuel, which is then blended with the biodiesel, much less acreage would be required.

The San Francisco Water Transit Authority tried biodiesel (soy-based methyl-ester type from World Energy, Inc.) in a 5-month demo on their ferry M.V. *OSKI*. It reduced all emissions except NOx, which increased 24%. PM was reduced by 50 – 55%. The biodiesel was available at $1/gallon premium over CARB diesel. They then used the biodiesel fuel in conjunction with the continuous water injection (CWI) system developed by M.A. Turbo/Engine Design, Vancouver, Canada. This reduced the NOx to 12% above the diesel-fuel base line. A final report on this trial is being prepared.[99, 100] A review of the costs associated with biodiesel operation concluded that overall "there was no change in emissions, at a cost of 50% - 100% increase in operating costs". [101]

5.4 BioOil

DynaMotive Technologies Corp. in Vancouver, B.C. is developing a "BioOil" fuel that is made from agricultural or forestry residue via a flash pyrolysis process. The BioOil is a complex mixture of carbohydrates, lignum break-down products and water (about 20%), with a pH of about 3 and a heating value of about 50% that of diesel on a volume basis. The CO_2 emissions are of course GHG neutral and NOx is about 50% lower than that of diesel. The BioOil is a suitable fuel for large, low to medium speed diesels or for gas turbines. Testing has been carried out on a large, slow-speed diesel in the UK. (BioOil probably should be emulsified with diesel for smaller, high-speed diesel engines.) Projected price based upon a 200 – 400 tpd plant is about Cdn$3.85/GJ (US$0.40/gallon diesel equivalent). [102, 104]

5.5 Ethanol

Ethanol is a common alcohol product that can be made through the fermentation of corn and grain, or through conversion of waste lignocellulosic biomass (forest and agricultural residue). Ethanol is a fuel oxygenate commonly blended with gasoline to improve combustion and reduce exhaust emissions. It is also promoted as a substitute for fuels made from imported oil.

Ethanol also can be blended with diesel to make an ethanol-diesel emulsion called E-diesel, which results in reduced emissions of particulates and other compounds. An additive, such as that made by Lubrizol, should be added in order to prevent separation when moisture gets into the blend. [108]

Research is underway to burn aqueous ethanol (30% water, 70% ethanol) in a modified diesel engine while retaining the performance of a diesel engine. An electronic fuel injection system, direct-injected diesel engine was modified by adding a catalytic igniter (*Smartplug* technology). The tests indicated a 10-fold reduction in NOx emissions, a 10% increase in engine power, and a 1% improvement in SFOC. [110]

A 2001 study by Cornell University agricultural scientist David Pimental concluded that ethanol from corn was not energy efficient, in that it took 131,000 Btu to make 1 gallon, whereas the ethanol has an energy value of only 77,000 Btu. Its production also has negative impacts upon soil conservation and ground water supplies. An average automobile traveling 10,000 miles/year on E100 would need 852 gallons that would take 11 acres to grow – this is the same cropland area required to feed seven Americans. [106]

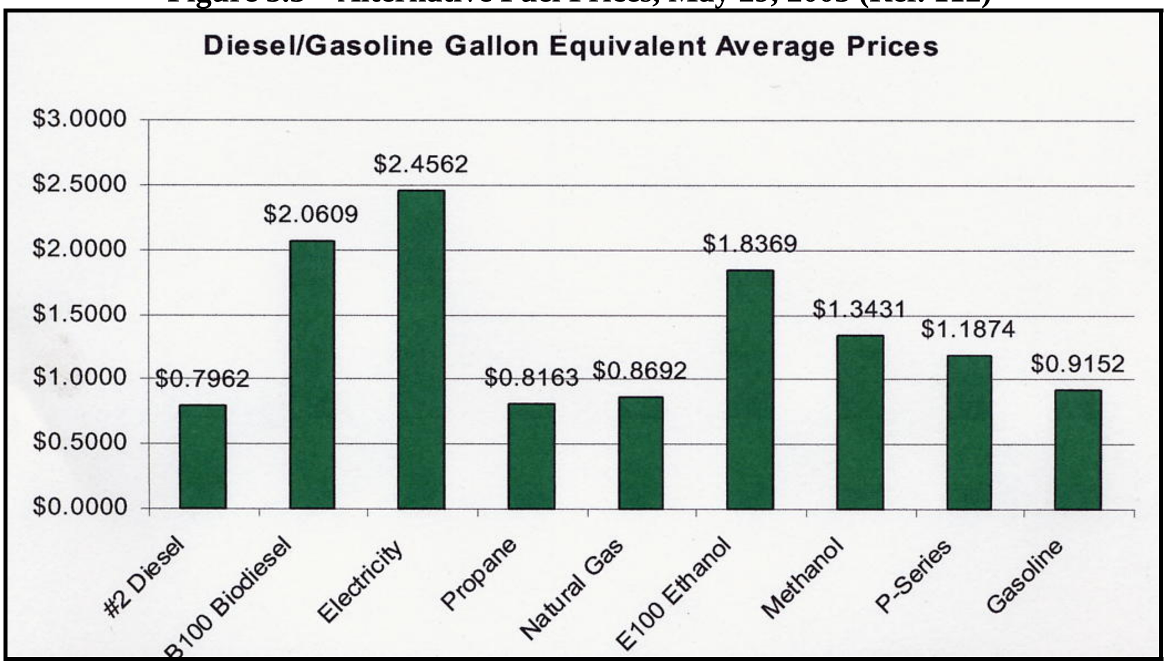
The Cornell study has been refuted by a consultant for the National Corn Growers Association, who quotes other studies which estimate a more favorable energy-out to energy-in ratio of 1.24 – 1.37. [107] It is probable that this ratio is sensitive to the assumptions that are used in its derivation. It is clear, however, that ethanol from corn will not play a significant role in reducing energy imports, as even under the most optimistic assumptions the net energy gain is not great. Biodiesel from canola, on the other hand, has an estimated energy-out to energy-in ratio of about 3.3.

Processes for producing ethanol from agricultural and forestry residues have been under development for some time and may prove to be sustainable. They have not been afforded the scale of subsidies accorded to ethanol from corn and hence are difficult to justify on an economic basis.

Recent (July 10, 2003) prices for ethanol blends in Tacoma, WA, are presented in the Alternative Fuels Index as \$1.43/gal for E100, or \$2.14/gal gasoline equivalent (\$2.43/gal diesel equivalent). [112]

The average USA price for E100 can be compared with that of other alternative fuels in Figure 5.3 (prepared by the Energy Management Institute). Agricultural-based fuels are at present significantly more expensive than fossil fuels.

Figure 5.3 – Alternative Fuel Prices, May 29, 2003 (Ref. 112)



5.6 Methanol

Methanol can be made from natural gas, coal and from agricultural and forestry residue. In principle it can also be blended with diesel if an additive, such as those formulated by Lubrizol, is used. Some testing is presently underway with methanol-diesel emulsions in

China, where they have very large reserves of coal as compared to petroleum, and where methanol from coal is seen as a promising supply of a relatively clean fuel for mobile sources.

Methanol can be burned directly in spark-ignited internal combustion engines or in gas turbines. In these applications some form of catalytic converter should be used in the exhaust system to prevent the emission of smog-forming compounds.

Methanol can also be catalytically decomposed to yield hydrogen (plus CO_2) for use in a fuel-cell vehicle, thereby marrying the high energy density of liquid methanol with the fuel efficiency of fuel cells.

5.7 Hydrogen

Hydrogen is being promoted as the “green” fuel of the future in that it can be made from a variety of non-petroleum sources, produces almost zero emissions upon combustion and can be used directly in high-efficiency fuel cells to make electricity. All of these claims are true but there are a few stones remaining on the path to the hydrogen future. One of the stones is the high cost of producing hydrogen Another obstacle is the low energy density of compressed hydrogen gas as compared to other fuels.

Hydrogen can be produced at an acceptable price only when done so on a large scale. This is already being done in petroleum refineries, where hydrogen is made from natural gas or from other sources, and is used to remove sulfur from the petroleum and to help break large molecules down into smaller, more easily burned molecules. The energy density of hydrogen improves dramatically when hydrogen is stored at low temperature in the liquid form, as is the case for natural gas.

Probably the future for hydrogen will depend upon manufacturing liquid hydrogen on a large scale and in a sustainable fashion. This could, for instance, take the form of the production of hydrogen at large coal mines, with byproduct CO_2 being injected back into the ground for permanent disposal and with the hydrogen product being pipelined to strategically located liquefaction plants. But in the near term the large-scale production of hydrogen will best be done through the steam reforming of natural gas, wherein approximately 4 molecules of hydrogen are produced for each molecule of CO_2 released to the atmosphere.

Hydrogen can be burned in diesel engines when mixed with natural gas to form “hythane”. This mixture can reduce emissions of NOx as well as of the greenhouse gas CO_2. The SunLine Transit Agency in Palm Springs, USA, has been testing hythane for several years in a Cummings L10 natural gas engine. They experienced a 43% reduction in NOx, as compared with straight natural gas, in this older, mechanically controlled engine. More recently they have been testing hythane in a newer, electronically controlled Cummings-Westport B+ engine. NOx emission reductions have been in the range of 50% - 60%, with the best results being with 20% hydrogen – 80% natural gas blend. One other B+ engine will also be run on hythane and testing of emissions versus blend ratios will continue. The goal is to maintain the power and range of the Cummings-Westport B+ engine while significantly reducing emissions. [109]

Hydrogen can also be burned in a pure form in spark-ignited engines and in gas turbines. Emissions of NOx are greatly reduced as compared to burning regular distillates (diesel or jet fuel). Preliminary testing by Ballard Power Systems indicated that a NOx emission of 0.18 g/kWh could be achieved when H_2 is burned in a large spark-ignited genset. This is a path being actively pursued by BMW and others as a way to use clean hydrogen fuel without the high cost of fuel cells.

Price of Hydrogen

The price of hydrogen is very sensitive to the scale of production. Genesis Engineering Inc. has recently estimated the production of hydrogen produced by three different technologies and at two different production rates. These are shown in table 5.1 below.

Table 5.1 – Cost of Hydrogen Production For Three Technologies ($/kg)*

Production Rate Kg/day	Electrolysis of Water	Catalytic Cracking of Methanol	Steam Reforming of Natural Gas
30 (14 Nm^3/h)	$19.37	$25.27	$32.18
4286 (2000 Nm^3/h)	$4.90	$1.98	$1.59

*Basis: Electricity at $0.06/kWh; methanol at $251/tonne; natural gas at $5.00/MM Btu. Cost includes capital amortization and other direct and indirect costs.

Since 1 kg of H_2 is equivalent to 0.984 gallons of diesel (1.120 gallons of gasoline) in energy content, it is clear from this table that hydrogen, unless produced on a very large scale from an inexpensive resource, will remain an expensive fuel.

Air Products presented hydrogen gas cost estimates vs. usage capacity for the Los Angeles area. Costs exceed $80/kg for a production of only 1000 kg/year (3 kg/day), but drop to $25/kg for a production rate of about 9000 kg/year (25 kg/day). [113] These cost estimates are in good agreement with those independently produced by Genesis Engineering Inc.

One near-term strategy for dramatically reducing the entry price of using hydrogen in mobile sources would be for existing large-scale hydrogen producers, such as petroleum refineries, to further increase their hydrogen production capacity and to then sell their excess hydrogen to a distributor for off-site sales. This strategy would reduce costs to the refinery (economies of scale) and would allow off-site sales of compressed hydrogen for about $2/kg or less.

Another existing source of low-cost hydrogen are the chloralkali plants that electrolyze salt to make chlorine and caustic soda. A byproduct of this process is waste hydrogen.

Some plants burn this hydrogen for energy; this energy could be replaced with cheap natural gas and the hydrogen used for mobile sources at a cost somewhat greater than the cost of the replaced natural gas.

5.8 Diesel Fuel Additives

Diesel fuel additives are used for a wide variety of purposes, however they can be grouped into four major categories:

- Engine Performance Additives: cetane number improvers, injector cleanliness additives, lubricity additives, smoke suppressants.
- Fuel Handling Additives: antifoam additives, de-icing additives, low temperature operability additives, drag reducing additives.
- Fuel Stability Additives: antioxidants, stabilizers, metal deactivators, dispersants
- Contaminant Control: biocides, demulsifiers, corrosion inhibitors.

Additives may be added to diesel fuel at the refinery, during distribution, or after the fuel has left the terminal. During distribution, additives may be injected prior to pipeline transit (if the fuel is distributed by pipeline), or at the terminal. When the fuel leaves the terminal, its ownership generally transfers from the refiner or marketer to the customer, who may be a reseller *(jobber)* or the ultimate user. For this reason, additives added to the fuel ***after*** it leaves the terminal are called *aftermarket additives*. [115]

Refinery Addition

Refiners have a legal requirement to provide a product that meets specifications. Beyond that, reputable refiners ensure that non-specification properties, such as stability, lubricity, and low temperature operability are suitable for the intended use.

Pour point reducers are probably the diesel fuel additives most widely used by refiners. However, their use is limited to fuel made in the wintertime and destined for regions with colder ambient temperatures.

Some refiners add one or more additives to improve fuel stability, either as a regular practice or on an "as needed" basis. Some refiners also use a cetane number improver when the additive cost is less than the cost of processing to increase cetane number. Red dye is added to high sulfur diesel fuel and may be added to tax-exempt diesel fuel at the refinery. [115]

California: A Special Case

Because of its unique diesel fuel regulations, California is a special case. California regulations restrict the aromatics content of diesel fuel in order to reduce emissions. The regulations can be met either with a low aromatics diesel (LAD) having less than 10% aromatics, or with an alternative low aromatics diesel (ALAD) formulation that gives an equivalent reduction in emissions. Many of these ALAD formulations use cetane number improvers to help achieve the necessary emissions reduction. As a result, a significant percentage of the low aromatic diesel fuel now sold in California contains some cetane number improver.

Reducing diesel aromatic content to 10% requires more severe hydrotreating than reducing sulfur content. As a result, the lubricity of some LAD may be low, so some refiners may treat the fuel with a lubricity additive. (In the rest of the U.S., hydrotreating to remove sulfur may reduce lubricity, but not enough to require a lubricity additive.)

Two diesel fuel lubricity guidelines have recently been proposed in the U.S.: the EMA guideline recommends a 3100 g minimum (SLBOCLE method) and the state of California recommends a 3000 g minimum (SLBOCLE method). There are ongoing discussions and investigations in the industry, which may lead to a specification. In the absence of a specification, each refiner sets its own standard. [115]

Distribution System Addition

When diesel fuel is distributed by pipeline, the operator may inject corrosion inhibiting and/or drag reducing additives. No additional additives are added to diesel fuel distributed by truck or marine ship or barge. [115]

Aftermarket Additives

It would be convenient for the user if a finished diesel fuel could satisfy all his or her requirements without the use of supplemental additives. Although this is often the case, some users must use additives because the low temperature conditions in their region are more severe than those for which the fuel was designed, or because of other special circumstances. Other users feel that they need a higher quality diesel than regular diesel. And, finally, there are users who regard the cost of an additive as cheap insurance for their big investment in equipment.

A large number of aftermarket additive products are available to meet these real or perceived needs. Some are aggressively marketed with testimonials and bold performance claims that seem "too good to be true." So, as with any purchase, it is wise to remember the advice, *caveat emptor* – let the buyer beware.

The EPA has a technology verification protocol for fuel additives. EPA’s certification of an additive, which is required before any fuel additive can be sold and only means that it is not harmful to the environment or to public health, should not be confused with EPA’s verification of its emission reduction effectiveness. [151]

It may be helpful to regard additives as medicine for fuel. Like medicine, an expert who has made an effort to diagnose the problem should prescribe them. And they should be used in accordance with the recommendations of the engine manufacturer and the instructions of the additive supplier. Sometimes indiscriminant use of additives can do more harm than good because of unexpected interactions. [115]

The above comments on diesel additives was excerpted for the excellent technical review in diesel fuels prepared by Chevron Products co. [115]

A common aftermarket additive is a detergent additive, which helps keep the injectors clean by reducing deposits and thereby reducing smoke emissions. [116]

Rhodia is marketing a fuel-born, cerium-based catalyst for diesel engines that are equipped with diesel particulate filters. The additive (*Eolys*) results in very low particulate emissions, less than 0.05 g/bhp-hr, while burning diesel fuel with a sulfur concentration of 368-ppm sulfur. The additive, in conjunction with a DPF, prevents the emission of the catalyst to the environment and allows EGR to be used, which further reduces the emission of NOx by approximately 35 – 40%. [117] The cost of using this additive would have to be compared with the cost of using ULSD in DPF with a fixed catalyst. If the cost differential of the 2 fuels is say 3 cents/gallon and *Eolys* is used at a concentration of 50 ppm in the fuel, then the cost of the additive must be less than 20 cents/gram ($91/lb) in order to be less expensive than using ULSD. The use of the higher sulfur diesel will of course result in greater emissions of SOx, which in the atmosphere are converted to acidic, respirable particulate.

6.0 EMISSIONS REDUCTION TECHNOLOGIES

6.1 Introduction

Much of the research for developing technology to reduce exhaust emissions from large diesel engines is directed at marine vessels. This research is being done by Scandinavian marine technology research institutes, by marine engine manufacturers in response to proposed IMO and national standards and by pollution-control equipment manufacturers. Scandinavian research is driven by the high density of marine traffic in their coastal waters and fiords and by the large contribution that these vessels make to air pollution in these areas. For instance, the relative amount of ship emissions, as compared to the total Norwegian national emissions, is about 20% for SOx and about 60% for NOx[16].

Emission reduction technology for smaller diesel engines is being driven by the stringent emission standards that are promulgated in the USA and Europe for on road diesel-engined vehicles. Much of the technology being developed for on road diesel engines is also applicable to non-road diesel engines, thereby reducing the costs associated with their development.

Technology for diesel emissions reduction can be divided into three general areas:

1. In-engine technologies, which modify the conditions of combustion, are used to reduce NOx and particulate emissions and are favored by engine manufacturers since they are relatively easy to implement. Lowering the peak combustion temperature mainly reduces NOx emissions, while particulate matter (PM) emissions are reduced by improving fuel combustion through improved fuel atomization and distribution.

2. Exhaust cleaning technologies that use some form of scrubber or reactor to remove contaminants from the exhaust stream. These technologies can remove most of the contaminants from the exhaust gases, but may be heavy, bulky and expensive and hence are not used unless needed.

3. Fuel-related technologies that yield cleaner combustion through modified or alternative fuels. These technologies have the largest potential for reducing SOx emissions by lowering the sulfur content in the fuel. They were, to a large extent, reviewed in the previous chapter.

6.2 In-Engine Methods For Reduction of Nitrogen Oxides

As was previously discussed, nitrogen oxides from diesel engines derive from two sources:

1. Oxidation of the nitrogen within the combustion air under high temperature, called thermal NOx.
2. Oxidation of the nitrogen compounds of the fuel, known as fuel NOx.

Almost all the nitrogen present in the fuel reacts with the oxygen in the air to nitrogen oxides, but this still constitutes only a small part of the total quantity of nitrogen oxides. The formation of thermal NOx depends on excess-air ratio, pressure, temperature and combustion duration. During combustion nitrogen oxide, NO, is formed first. Later, during expansion and while in the exhaust system, some of this thermal NO is converted to nitrogen dioxide, NO_2, and also to nitrous oxide, N_2O, (approx 5 and 1 per cent respectively of the original NO quantity).

The main factors affecting the emissions of nitrogen oxides are:

- The design and optimization of the engine:
  - Injection timing.

- Injection pressure (higher pressure results in smaller fuel droplets and cleaner combustion).
- Injection geometry.
- Combustion chamber design.
- Compression ratio.
- Supercharging.
- Valve timing, etc.

- Ambient conditions:
  - Humidity.
  - Atmospheric pressure.
  - Ambient Temperature.
  - Cooling water temperature (lower temperature results in less NOx).
  - Exhaust system back-pressure (higher back pressure results in more NOx).

- Fuel:
  - Cetane rating (ignitibility).
  - Nitrogen concentration (Heavy bunker contains approx. 10% – 15% more nitrogen than diesel oil).
  - Viscosity (size of fuel drops in combustion chamber).

Today's engines are mainly optimized to minimize fuel consumption. It is possible to reduce emissions of nitrogen oxides by 20-30 per cent by modifying the optimization of the engine to minimize pollution emissions. This may, however, give an increase in fuel consumption of up to 5 to 10 per cent in older engines. Some of the in-engine measures can be carried out without any increase of the manufacturing cost of the engine, as the additional costs will mainly be on the operative side. Still larger emission improvements can only be achieved through design changes leading to new engines, and usually resulting in increased engine prices.

Optimizing an engine with respect to NOx emissions and fuel consumption is a complicated task. It is not possible to select one method of the ones mentioned below and pronounce this to be the correct one. Instead, it is up to the engine manufacturer to optimize every engine type utilizing a number of measures, some of which are required to reduce operational problems created with the NOx reduction methods.

In addressing primary NOx reduction methods, Wartsila Diesel identified a number of measures that can affect the reaction temperature in the cylinder and hence influence the amount of NOx formed (the higher the temperature and the longer the residence time at high temperatures, the more thermal NOx will be formed) [18]. Among the design measures are:

- A lower air manifold temperature (more efficient inter-cooling or lower ambient temperature) results in lower combustion temperatures.

- A slower injection rate normally implies lower combustion temperatures because less fuel is injected before the piston reaches top dead center (TDC), thus yielding a lower maximum pressure.

- Retarded injection timing and changed valve timing also results in lower combustion temperatures and pressures.

- The geometry of the combustion space and the flow pattern within it may affect temperature distribution.

- A fuel with a poor ignition quality affects NOx formation.

- A lower compression ratio cuts down on the peak pressure and reduces temperature.

- Water emulsified in the fuel or introduced to the combustion space with the air or via separate nozzles will consume energy in evaporation, thus lowering the combustion temperature.

- Exhaust gas recirculation reduces NOx because the CO_2 and H_2O molecules have higher molar heat capacities and thereby dampen the combustion temperature.

In-engine measures presently being used for diesel engine emission reduction is summarized below.

- <u>Retarded Fuel Injection</u> - A later injection time leads to most of the combustion occurring after TDC. As a consequence, the maximum flame temperature in the combustion space will be lowered and the formation of nitrogen oxides will be reduced. Since this method is easily applicable and significantly reduces NOx formation, it is regarded as one of the most important tools for in-engine emission reduction. Using retarded injection exclusively leads to increased fuel consumption and increased emissions of Voc and particulate. To a certain extent the increased fuel consumption may be compensated by other measures when the engine is optimized for low emissions[19]. To re-establish low fuel consumption the compression ratio of the engine is increased, resulting in lower NOx emissions and no penalty in terms of fuel consumption[20]. Some newer engine designs are incorporating variable injection timing that allows the timing to be adjusted so as to optimize engine performance for different requirements. Electronic fuel injection control also accommodates shutting off the fuel flow to some of the cylinders during low speed operation, thereby allowing the remaining cylinders to operate more efficiently and with less pollution.

- <u>Increased Fuel Atomization</u> - Increased fuel atomization leads to better combustion; a higher indicated thermal efficiency and reduced emissions of NOx and particulate. Improved injector tips and/or increased injection pressure can accomplish better fuel atomization. Injector tip design is limited by the need for the fuel to properly mix with the combustion air. Injection pressure is limited by mechanical strength considerations of the injector pump drive train. Older engines use a maximum injection pressure of 1000 - 1200 bar while the newer designs can accommodate a pressure of 1500 bar [19]. Future designs may increase the injector pressure up to 2500 bar (36,000 psi) [21].

Modern diesel engines also use common-rail technology wherein a single, high-pressure fuel-supply system, with one or more accumulators, supplies the injectors. This system prevents low-pressure fuel from reaching the injectors, with attendant poor atomization. Common-rail fuel-supply is used in conjunction with electronic injector control to optimize performance and minimize emissions during all phases of engine operation.

- <u>Pre-injection</u> - By injecting a small quantity of fuel before the regular injection, the ignition of the main charge is facilitated and the amount of premixed fuel can be reduced. Reduced premixed fuel leads to a more modest pressure and temperature increase at the beginning of combustion, leading to a lower maximum temperature and reduced formation of nitrogen oxides. Wartsila, a leading Finnish-based medium speed engine designer, uses separate injectors and injector pumps to effect pre-injection on their medium speed VASA 46 engine and claim a nitrogen oxide reduction of 15 %. Trials by Steyr, on a high-speed diesel engine, show reductions of the emissions of nitrogen oxides by 12% - 25% using pre-injection. The use of pre-injection also allows the use of two-fuel operation, wherein a more easily ignitable fuel is used for ignition, while an inferior fuel with a lower cetane rating is used as the main fuel. (This is done, for instance, when natural gas is used as the main fuel in a diesel engine.) Because of the extra expense and the reliability considerations, pre-injection is rarely used on existing large ship engines[19]. However, the new diesel engines being introduced by major engine manufactures use electronic injection so that pre-injection should be possible.

  For older railroad locomotives EPA has estimated the cost of installing electronic engine controls that accommodate injection-pulse rate shaping to be $36,200. For a typical 3000 hp engine this cost is equivalent to $12/hp ($16/kw). Emission reductions are estimated to be 10-20% for HC, 0-10% for CO, 25-40% for NOx, 10-25% for PM and 0-2% for the BSFC (fuel consumption). [63]

- <u>Charge Air Techniques</u> - Practically all medium-speed and low-speed diesel engines use turbocharging and intercooling to yield improved fuel economy. These measures can also contribute to reductions in the emissions of nitrogen oxides and other pollutants. Large marine diesels may use seawater cooling that gives lower temperatures and hence lower nitrogen oxides emissions than if recycled engine-cooling water is used. However, over-cooling of the charge air may result in an ignition delay and hence actually increase nitrogen oxides and soot emissions. Therefore precautions have to be taken to achieve optimal charge air temperature. Over-cooling will especially present a problem during low-speed engine operation hence manufacturers may resort to using combustion air preheat.[19]

Wartsila uses a clever “Miller supercharging” strategy in their Sulzer ZA40S engines in order to reduce the temperature of the charge in the cylinder. By using a high-pressure turbocharger, and closing the intake valves before the pistons reach bottom dead center during the intake stroke, the same amount of air as before can be charged into the engine. However, the expansion before compression cools the air charge in the cylinder. Tests showed that NOx emissions could be reduced by 15 to 20 percent without any increase in fuel consumption. [5]

The puff of smoke often observed on older diesel engines during acceleration is due in part to turbo lag. One method commonly used to address this problem is to slowly increase the fueling rate following a rapid change in throttle position. Other methods to address this problem include the use of variable geometry turbocharger (VGT), multiple turbochargers, electronic matching of the turbocharger and fuel injection, or mechanical drive of the compressor (i.e., the use of a supercharger rather than a turbocharger). [63] VGTs require slightly more space and are more costly than conventional turbochargers. Over a section of the on-highway transient federal Test Procedure, particulate reductions of up to 34% have been achieved on a HDD truck engine through the use of VGT with no increase in NOx emissions.[63]

The cost for implementing VGT on a Tier 0 locomotive has been estimated by the EPA to be $25,000.[63] The engines are typically turbocharged, 2-stroke diesels of approximately 3000hp, so the unit cost would be approximately $8.30/hp ($11.00/kW).

- <u>Engine Design Changes</u> - These changes pertain to valve timing changes, combustion chamber and swirl chamber design changes, etc.

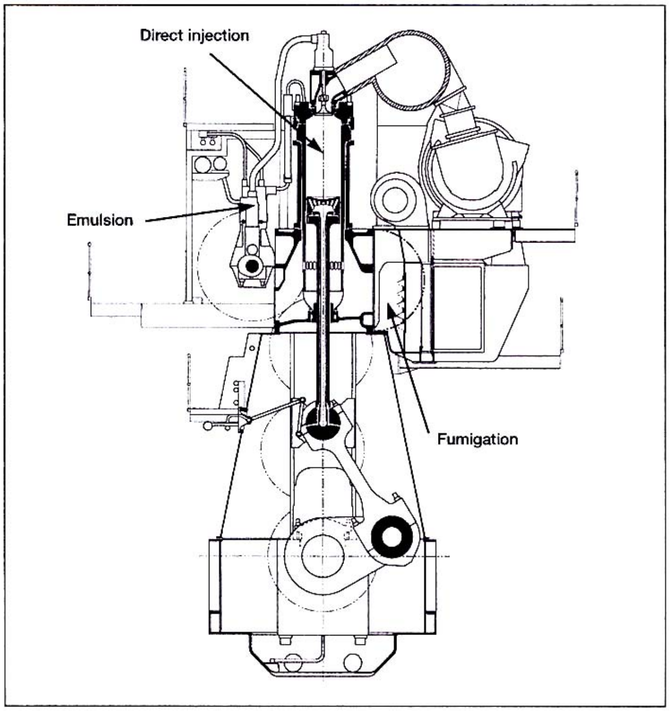
  The Electro-Motive Division of General Motors (EMD) is selling remanufacturing kits for their locomotive engines to enable them to meet the EPA Tier 1 standards. These kits can include new after-cooling system, revised pistons, camshaft and cylinder heads plus a new electronic engine control system.[73] The cost for Tier 0 injector change-out has been quoted to be in the range of $20,000 - $30,000 and for new pistons would be around $50,000. Tier 1 would probably also require electronic engine control at a cost of approximately $100,000. [127]

  Others have estimated the cost for a locomotive Tier 1 engine rebuild at approximately $183,000 and a total locomotive remanufacture at $600,000. [122]

- Cost of Retrofit Engines – Off-road diesel engines may be retrofitted with new engines that incorporate one or more of the above emission-reduction technologies, such as is done under California's Carl Moyer program. The South Coast Air Quality Management District has, over the last several years, supervised the replacement of 101 off-road, construction-equipment engines. The low-emission replacement diesel engines (Tier 2 or 3) varied from 170hp – 1045 hp and had an average cost of $174/hp ($233/kW). Similarly, 58 marine diesels were replaced with low-emission diesel engines (Tier 2) varying from 85 – 1500 hp and with an average cost of $179/hp ($240/kW). The smallest marine engine (85hp) was an auxiliary engine costing $290/hp, while the largest marine engine (1500 hp) cost $163/hp. Despite these figures, there was not a strong effect of engine size on cost per horsepower. (Data from Ref. 71).

A 2002 study on the cost for reducing emissions from ferries operating in the San Francisco bay Area used a diesel engine acquisition cost of $175/kW ($130/hp) when comparing different pollution reduction alternatives.[72] This unit cost is lower than the above, but may be applicable to a base-line scenario using "mechanical" diesels whereas the Carl Moyer replacement diesels would generally be state-of-art, electronically-controlled engines which are significantly more expensive.

6.3 Reduction of Nitrogen Oxides by Water Addition



To achieve greater NOx reductions than those achievable by internal engine modifications and tuning processes described above, techniques such as exhaust gas recirculation (EGR), direct injection of ammonia, and the addition of water to the diesel process, may be employed. They can result in reductions of NOx in the order of, or even greater, than 50%. However, some of these measures are not compatible with the use of heavy marine fuel oil, are excessively expensive, or may result in an increase in other emissions.

Figure 6.1 – DIFFERENT MODES OF WATER ADDITION

The introduction of water into the combustion chamber is a well-known NOx reduction technique. A potential problem with this process would occur if liquid water droplets impinge against the surface of the cylinder liners. In this case there would be an immediate disintegration of the lubrication oil film.[5] Therefore it is important that a water addition process be designed so that liquid water evaporates before it contacts the cylinder liners.

There are basically three ways to add water to the diesel engine combustion process: by direct injection in parallel with fuel injection, by fumigation (humidification) of the scavenge air, and by an emulsion with the fuel oil. These different processes are shown in Figure 6.1.

6.3.1 Direct Water Injection (DWI)

Wartsila NSD Switzerland started in 1993 to develop direct water injection to achieve high NOx reduction rates. The water is handled by a second, fully independent injection system, preferably under electronic control. This offers the possibilities of firstly injecting very large amounts of water without having to derate the engine and secondly, having the ability use different timing for the fuel and the water injection. Independent injection systems allow water injection to be switched on and off without influencing fuel injection.

Based upon the 4RTX54 engine tuned for low NOx emissions, Wartsila realized a NOx reduction of greater than 60% through the combination of retarded fuel injection and direct water injection at approximately 140 g/kWh. Figure 6.2 below shows the effect of tuning and water injection upon NOx emissions and upon specific fuel consumption.

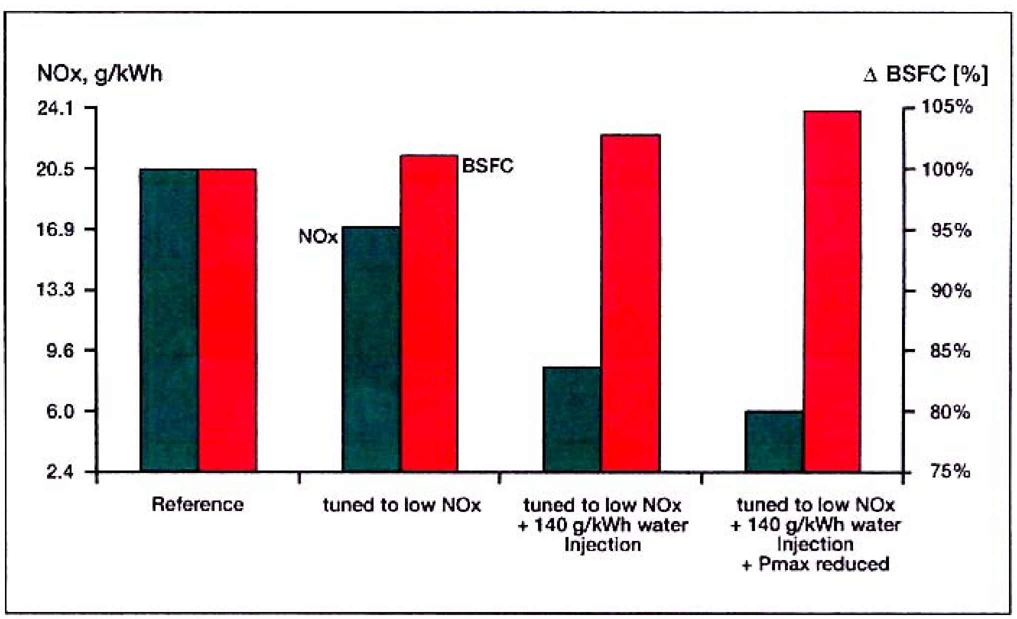


Figure 6.2 – Effect of water injection on NOx emissions (Ref.5)

It can be seen from Figure 6.2 that a dramatic reduction in NOx can be realized through a combination of DWI and engine tuning, although at the expense of an increase in fuel consumption.

The DWI package offered by Wartsila[27] for their four-stroke diesels includes the following components:

- Low-pressure module (1.7 m^3) to supply 3.5 bar water pressure to the high-pressure module, or a dual filter unit if suitable water is available.
- High-pressure module (1.7 m^3) to supply 200 – 4—bar water to the injection valves.
- Injection valves (Figure 6.3) and flow-fuse for each cylinder.
- Control unit, piping and cabling.

Figure 6.3. Wartsila DWI valve

The benefits claimed by Wartsila[27] for this DWI system include:

- NOx reductions of 50 – 60 %; typically 4 – 6 g/kWh on MDO and 5 – 7 g/kWh on HFO.
- Ratio of water to fuel typically 0.4 – 0.7.
- No negative effects upon engine components.
- Can be installed while the ship is in operation.
- Transfer to "non-water" mode at any mode. This transfer is done automatically in an engine alarm situation.
- Low capital and operating costs. ($15 - $20 US per installed kilowatt, $1.5 - $5.0 US per MWh operating cost) [28].

The downside of the DWI system is that it cannot be used at low loads (under 30% - 40% of full load). [28]

Assuming a 1000 kW marine engine running 2000 hours per year, a discount rate of 11%, and an NOx emission reduction of 50% (from 10 g/kWh down to 5 g/kWh), then the cost benefit of this technology would be in the range of $500 - $1,200 US per tonne NOx reduction.

To date Wartsila has 23 vessels, with a total of 568 cylinders and 526 MW power, equipped with DWI.[28] The main driving force behind this is the high Swedish fairway fees for polluting marine vessels. Similar technology is being developed for their large 2-stroke diesel engines. Apparently it would be difficult to directly retrofit the Wartsila

DWI system to other manufacturer's engines, as the water injector specifications must be carefully adapted to the fuel injector specifications in order to achieve the best performance tradeoff.[69]

The specifications for the water used in DWI are given[69] as:

- 5 < pH < 9
- Hardness max. 10° dH
- Chlorides < 80 mg/l
- Particles < 50 mg/l, SiO2 < 50 mg/l
- Fresh water, not contaminated by oil, grease, surfactants, etc. which may cause plugging of the filters or malfunctioning of the injectors.

EPA has estimated the cost of retrofitting domestically manufactured DWI systems on Category III marine engines. They use a cost of $24/ton for desalinated water used in marine DWI applications. [54]

Daimler-Chrysler has been experimenting with DWI in their diesel engines, using a prototype Bosch injector. The emission reduction of NOx has been dramatic. For further information see http://www.cae.wisc.edu/~rutland/research.dir/NOx_water/2000-01-2938.pdf.

Genesis Engineering expects that DWI technology will facilitate the use of "clean fuels" in diesel engines. Methanol or ethanol could be directly injected into the cylinders in order to provide combustion-air cooling as well as to provide a significant fraction of the combustion fuel.

6.3.2 Scavenge Air Humidification

Scavenge air humidification attempts to saturate the air between the turbocharger and the engine with water vapor. Different companies use different approaches:

M.A. Turbo/Engine Design's CWI System - The simplest system is that being developed by M.A. Turbo/Engine Design, called Continuous Water Injection (CWI) [29]. Here a very fine water mist is sprayed into the air intake side of the engine, typically after a turbocharger. The water injection system is automatically controlled to turn on only when the engine is under medium to high loads. NOx is reduced by up to 30% and PM by up to 50% at no increase in fuel costs or loss in engine power. In fact tests on a BC Ferry Wartsila 9R32D engine (3375 kW @ 750 rpm) have shown that the fuel consumption actually decreased by roughly 1% with CWI. Water consumption is around 30% of fuel consumption.

The CWI system has been tested on a number of vessels. The test installation cost for one Wartsila engine is quoted to be " $4,5000, for 4 engines each 360 hp at ferry *OSKI* (San Francisco) - $3,600, for 4 engines (one main Sulzer 4,500hp and three aux. Wartsila engines @ 550kw each) - $7,000. Systems operate practically maintenance free; only once in two months softener should be replaced (cost $50 for small engines and about $140 for main engines)". [29] NOx emission reduction, compared with CARB diesel, was 26% for the *OSKI*.[30]

Actual commercial, installed costs of the CWI can be expected to be considerably higher than the above quoted prototype costs. In the case of the Wartsila, which was one of two main engines on B.C. Ferry's *Queen of New Westminster*, an installed price for both engines of approximately $35,000, and annual maintenance costs of $3,500, would be more reasonable. The annualized (15 years@10%) operating cost for two engines would then be $8,100. Fuel savings at 1% would amount to $8,470 if MDO costs $220/tonne. Hence CWI has the <u>potential to reduce NOx by up to 30% and PM by up to 50% at no increase in the cost for vessel operation.</u> Long term testing is needed, however, to ascertain the cumulative effects of CWI upon engine life and reliability. Such long-term testing is now underway on the auxiliary engine of a B.C. Ferry vessel.

Wartsila's CASS System – Wartsila is developing a "Combustion Air Saturation System", or CASS, that potentially reduces NOx by up to 70% at no increase in fuel consumption. This technology will be able to reduce NOx emissions down to about 4 g/kWh.[28]

Figure 6.4 presents a schematic of the CASS concept. Water is sprayed in after the turbocharger. If necessary, the intercooler is used as a heater to evaporate most of the water. Water droplets not evaporated are removed with a demister, resulting in saturated air at 70 - 90ºC.

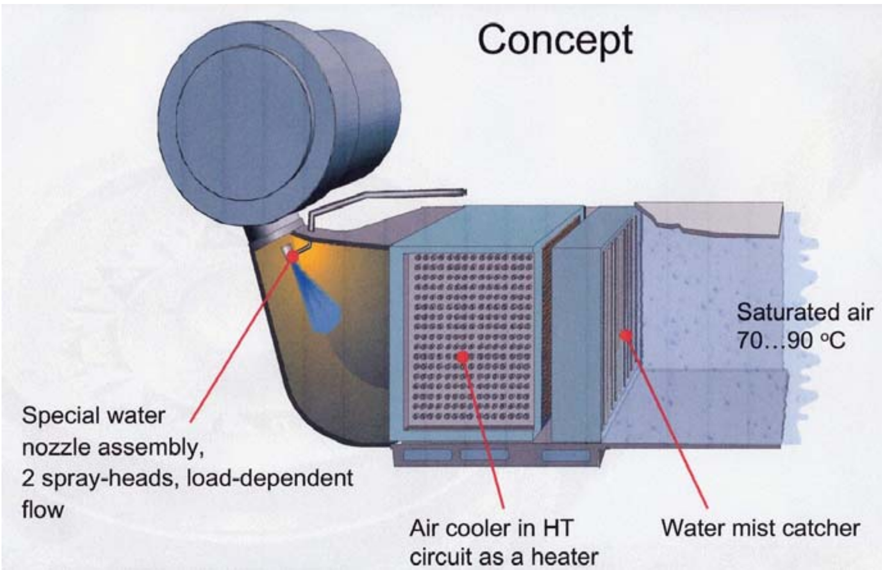


Figure 6.4. Wartsila Combustion Air Saturation System (Ref. 25)

Presumably the advantage of CASS over CWI is that the CASS system can safely achieve higher humidification levels without the fear of water droplets carrying over into the engine. The disadvantage is a higher installation cost for the demister system and the increased turbo pressure. However, the claimed 70% NOx reduction at no increase in fuel consumption makes this an upcoming technology to watch. No data is currently available to allow a $/tonne NOx reduction calculation.

6.3.3 Fuel-Water Emulsions

Both the major European marine engine manufacturers MTU (Motoren-und Turinen-Union Friedrichshafen GmbH) and MAN B&W Diesel AG depend upon fuel-water emulsions to reduce NOx emissions. Wartsila has used fuel-water emulsions but have subsequently gone over to the DWI system. Their reasons are given below.

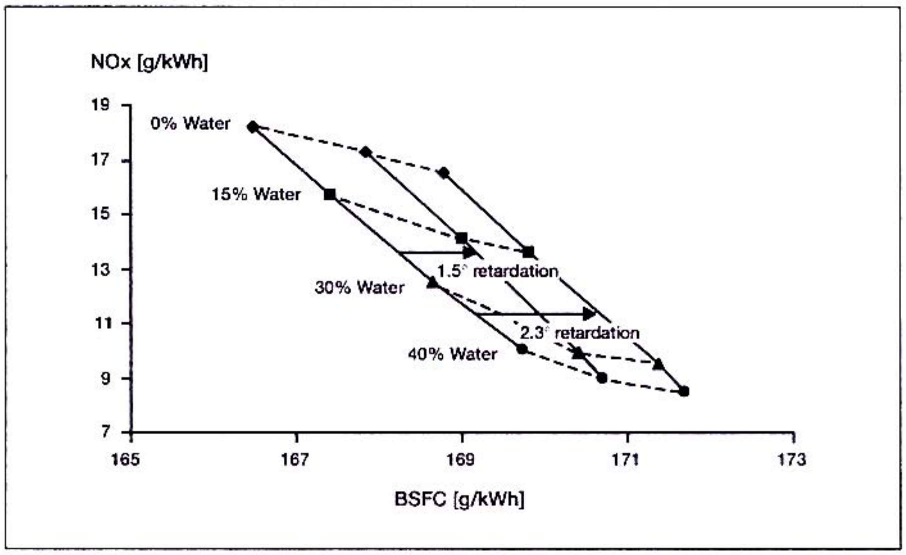
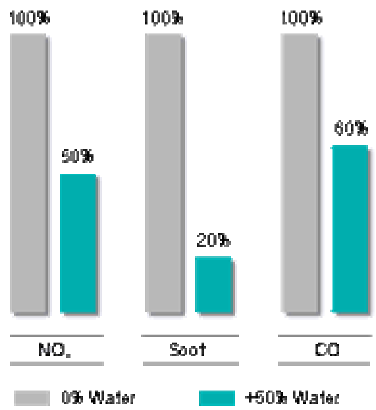


Figure 6.5. Effect of Water Content and Timing Upon NOx (Ref.5)

According to Wartsila[5], running an engine on fuel-water emulsions makes it theoretically possible to reduce NOX emissions by up to 50% with the required water quantity being about 1% for each percentage point reduction in NOx, as is shown in Figure 6.5 for 75% load. The limiting factor for fuel-water emulsions is the maximum delivery capacity of the injection pumps so that, in practice, the engine has either to be derated or the maximum achievable NOx reduction limited to about 10 – 20%. To obtain the maximum NOx reduction under full load, it may be necessary to redesign not only the injection system but also the camshaft, camshaft drive, etc. Because of these problems Wartsila developed their DWI system that was discussed in 3.3.1.

MTU – claims that the fuel-water emulsion system offers advantages in a small installation package, maximum effects can be obtained at partial load, low maintenance



costs, no increase in exhaust back pressure and no increase in specific fuel consumption. A side benefit is a large reduction in soot emissions. The new system does not affect starting characteristics or behavior under load acceptance or load shedding conditions compared to a pure diesel unit. The only condition for use of this technology on MTU Series 396 8-, 12-, and 16-cylinder engines with split-circuit cooling system is the necessity for a flushing cycle after running on emulsion. This takes only up to 5 minutes and is activated automatically at 20% load.

Figure 6.6 – MTU Water Emulsion

Figure 6.6 shows the reduction in emissions that are attainable when using an emulsion of 2/3 fuel and 1/3 water.[31]

MAN – MAN has adopted fuel-water emulsion (FWE) injection in combination with variable injection timing at part load as the most suitable measure to cut NOX emissions from their medium-speed diesel engines. Emulsification has the advantage that it uses the lowest amount of water for a given NOx reduction requirement. The other advantage is a large reduction in soot emissions as compared to either DWI or intake air humidification [32]. Since 2000 four RoRo vessels equipped with 12V 48/60 type medium speed diesel engines with FWE (max 20% water) are in operation. (The fresh water content is limited to 20% because it has to be produced onboard.) By simultaneously retarding injection at engine loads below 80% and using 20% FEW, NOx is reduced from 14.5 g/kWh (1996/97 status) down to 6.7 g/kWh.[32] No cost data is given by MAN for using FEW system.

Lubrizol Emulsion Additives

The Lubrizol Corp markets its PuriNOx emulsion which contains about 20% water, 80% diesel and somewhat less that 1% additives. The PuriNOx product is manufactured by fuel marketers and distributors, who mix Lubrizol's proprietary additives with diesel fuel to form a stable product that has the appearance of thick milk.[33] Emission reductions measured in a 8-cylinder, 34.5-litre engine are 15% NOx, 14% THC, 9% CO and 51% PM.[34]

The Port of Houston has been experimenting with the PuriNOx fuel emulsions for 2 years in five yard-trucks and 1.5 years in 2 yard-cranes. They have experienced a 25 – 30% reduction in NOx and a 30 – 50% reduction in PM. These reductions are considered to be cost effective at a cost of $7,500/ton of emissions.[35]

Typical emission reductions with PuriNOx are 20% for NOx and 50% for PM. Typical fuel cost premium in the USA is about $0.15 per gallon over the rack price for diesel (currently around $1.00 per gallon). However, since the emulsion is 20% water by weight

(18% by volume) there is a 10% to 15% volumetric increase in fuel consumption. The net effect is a 20% to 25% increase in fuel costs to achieve the reductions in emissions noted above.

The San Francisco Water Transit Authority has also tried PuriNOx during a 3-month trial in a Cat diesel. They noticed 37% reduction in NOx emissions and a 42% PM reduction. The cost premium over CARB diesel was $0.16/gallon.[30]

In B.C.'s Lower Mainland the Chevron Burnaby refinery was slated to be the PuriNOx manufacturer and distributor. The capacity was expected to be in the order of 20 – 25 million gallons per year (70,000 – 90,000 TPY).[33]

Diesel can also be emulsified with methanol or ethanol. Lubrizol markets their E-diesel, a blend of ethanol and diesel, as an alternative transportation fuel and claim lower emission levels of particulates. No cost or performance data is available for these emulsions. They certainly have potential for significantly reducing emissions from existing engines.

Cost of Using FWE

Assume a 1000 kW diesel engine with a SFOC of 200 g/kWh, a nominal NOx emission rate of 12 g/kWh, which is reduced 30% using FWE.

- Fuel used: 230 kg/h, approx. 90 US gallons.
- Cost of additive: At $0.16/gal is approx. $14.40/h
- NOx reduction: from 12 kg/hr to 8.4 kg/hr (3.6 kg/h)
- Cost/benefit: $4/kg (<u>$4,000/tonne NOx reduction</u>)

It can be seen from this hypothetical example that FWE incurs a significant cost due to the expense to the Lubrizol additive.

Practical Aspects of Water Addition

A practical consideration in the use of water addition for reducing NOx emissions is the volume and mass of water that must be stored along with the fuel. In marine vessels this water may be stored in fresh-water tanks or made continuously from seawater.

For diesel locomotives the water storage requirement would be more difficult. A separate tank-car would probably be required in order to minimize the logistical problems of taking on fresh water. For instance, if water were used at a 0.5:1 ratio in a 2000 hp (1490 kW) engine with a SFOC of 208 g/kWh, then the water consumption under full load would be about 7.5 tonnes/day. A 50 tonne (net) tank car would be needed to meet the requirements of approximately 2 weeks of normal operation.

Off-road construction equipment may be able to fit a separate fresh water tank somewhere, or to use a diesel-water emulsion and to refuel more frequently. Generally this class of equipment is routinely serviced once per day.

6.4 Reduction of Nitrogen Oxides by Exhaust Gas Recirculation

Another NOx reduction option measure is EGR (Exhaust Gas Recirculation). Here a portion of the exhaust gases are recycled back to the engine charge air, thereby diluting it and reducing peak combustion chamber temperatures. Some laboratory research has demonstrated NOx reductions of 10 % to 30% with only a marginal increase in fuel consumption. Higher NOx reductions will generally significantly increase fuel usage. EGR has not been used on large ships because of complications caused by ship's consumption of residual fuels. These complications are caused mainly by acidic soot deposits which would damage the turbocharger and which cause increased smoke emissions. Remedial actions are usage of a high quality fuel or exhaust gas particulate removal, both significantly increasing the operational costs and, for the latter, strongly affecting system complexity and availability. Cost of EGR is expected to be similar to that for water-in-fuel emulsions if no particulate scrubbing/filtration is required. The necessity for a higher quality fuel will further increase costs.

EGR is being used in heavy-duty diesel vehicles, which typically have smaller, high-speed diesel engines and which burn relatively low-sulphur diesel. In most cases an intercooler lowers the temperature of the recirculated gases. The cooled recirculated gases, which have a higher capacity than air and which contains less oxygen than air, lower combustion temperature in the engine and thereby reduce NOx formation. Diesel particulate filters are often an integral part of any low-pressure EGR system, ensuring that large amounts of particulate matter are not recirculated to the engine.

EGR systems are capable of achieving 40% NOx reduction. The cost for retrofitting EGR on a typical bus or truck engine is about $13,000 - $15,000 US. Over 400 EGR systems have been installed on bus engines in Europe. EGR retrofit systems are now being installed in the USA on solid waste collection vehicles, buses and some city-owned vehicles. Technology demonstration programs have been conducted in Houston, TX and Los Angeles, CA. Additional demonstration programs are being planned in the San Francisco Bay area; Sacramento, CA; and Washington, DC.[36]

The Manufacturers of Emission Controls Association (MECA) instituted a test program at Southwest Research Institute to investigate the performance of a variety of commercially available exhaust emission control technologies with standard No.2 diesel (368 ppm sulphur), low-sulphur diesel (54 ppm sulphur) and, in limited cases, with zero sulphur diesel. A 1998 12.7 liter Detroit Diesel, 400 HP Series 60 engine with electronic injection timing was used as the test bed. EGR was incorporated onto the engine for some of the testing. Figure 6.7 shows the effect of EGR alone and EGR in combination with different particulate filters, using the heavy-duty engine transient US Federal Test procedure (FTP).

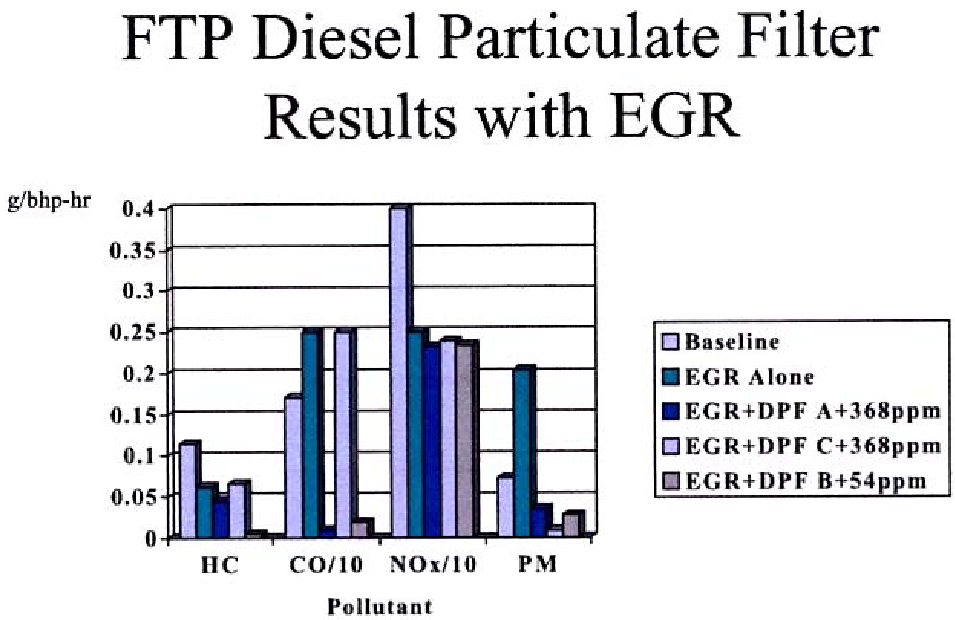


Figure 6.7 – EGR and DPF (Ref.37)

The results of the testing show that EGR alone will decrease NOx by 38%, but at the expense of increasing CO and particulate emissions. With the addition of a commercially available, self-regenerating catalytic diesel particulate filter, NOx was reduced by approximately 40% and particulate emissions reduced to less than 0.05 g/bhp-hr on both fuel containing 368 ppm sulphur and 43 ppm sulphur.

The diesel particulate filters tested in the MECA study were cylindrical in shape, about 10” diameter and 12” long. This size would be typical for engines with displacements ranging from approximately 7 – 13 liters.[37] These units can be installed as muffler replacements if space limitations are a problem.

DPF maintenance is required when the backpressure increases above a predetermined level. In, practice this filter cleaning is needed approximately every 2,000 hours and takes about 2 hours.[37] EGR, combined with DPF, can be expected to incur a fuel penalty in the order of 3 - 5%.

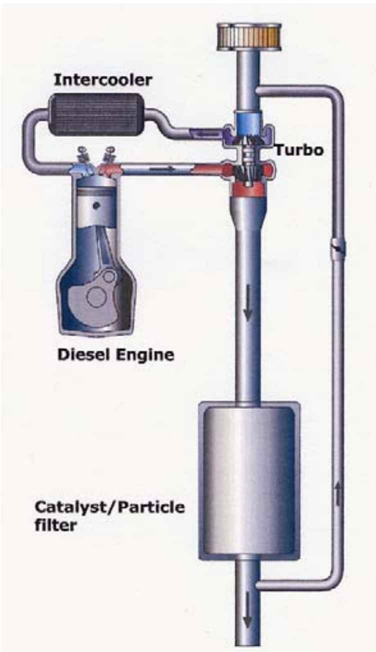
According to MECA, the average cost of a DPF is about $7,500 US. [36] The cost of retrofitting a 400 hp diesel with EGR is estimated to be $13,000 - $15,000US. [36]

Example: Small Diesel - Estimated Cost-Benefit For EGR + DPF

- Assume a 400 hp diesel engine with a NOx reduction of 1.5 g/bhp-hr and with 2000 operating hours per year, the annual NOx reduction would be 1.2 tonnes.

- Assuming a 4% fuel economy penalty, a SFOC of 200 g/kWh and diesel costing $1.00/gallon, then the additional fuel cost would be $1,800/year.
- Assuming a total installed cost of $15,000, capitalization of 7% (capital recovery factor = 0.1424) and annual maintenance/replacement costs of $1000, then the total annual cost would be $4,936, or $4,100/tonne NOx.

Figure 6.8 (Ref. 41)



Johnson Matthey is marketing an EGRT ™ system for NOx and particulate reduction. They claim greater than 40% NOx reduction, and greater than 90% reduction in CO, HC and PM. A specially formulated catalyst converts some of the NO in the exhaust to NO_2, which then oxidizes the soot collected in the filter, thereby regenerating the filter. A control module, programmed with engine mapping to optimize the system, is important to prevent plugging of the catalyst filter. The use of ULSD is recommended for maximum emission reduction and filter regeneration. Over 1200 on-road installations have proven the durability of their system, which is approved by the engine manufacturers and which therefore maintains the engine warranty.[41]

Figure 6.8 shows the EGRT ™ low-pressure EGR system. A cooler can be fitted onto the recycle line to further reduce NOx. The whole system is quite compact and can be retrofitted into a typical city transit bus. The filter is approximately 13” in diameter and 30” long.

The installed cost for a EGRT ™ for say a 12.7-liter Detroit Diesel 400 hp Series 60 would be in the order of $20,000 - $23,000, with the price being reduced based on the total number of units (>20). The expected service life is at least 5 years, with filter ash cleaning about once per year, or every 60,000 – 100,000 mile of operation. The increase in fuel consumption is expected to be less than 2%. The cost effectiveness of this technology ranges from $950/ton NOx to $1,600/ton NOx.[45, 46]

A 2002 study for the San Francisco Water Transit Authority to look at technologies to reduce emissions from ferries concluded that EGR, while being suitable for engines under about 500 hp, are not yet fully developed for the larger marine diesels.[38]

Wartsila has investigated EGR for their large marine engines and concluded that there are too many problems because of fouling and corrosion due to the burning of heavy fuel oil. To avoid these problems they use “internal recirculation” to keep a portion of the burned gases within the combustion chamber by reduced scavenging ports and smaller turbochargers. The temperature within the combustion chamber is then reduced down to the level it would be without internal recirculation by using direct water injection.[5]

Wartsila is now achieving up to 70% NOx reduction (down to 5 g/kWh) with their *Water Cooled Residual Gas* system through a combination of internal EGR, direct water injection and RT-flex (common rail and variable exhaust valve timing).[25]

The EGR system is very effective for NOx reduction in medium-sized, clean burning, natural-gas engines. Wartsila has shown that the NOx emission can be reduced from over 8 g/kWh down to less than 2 g/kWh. This is, however, at the expense of an increase in fuel consumption of about 4% (Figure 6.9). Depending upon the duty cycle of the engine, this may be a lees expensive option than using SCR to dramatically reduce NOx.

At this stage of development external EGR technology is probably limited to construction equipment and workboats burning low sulphur diesel (ULSD) and to larger engines burning natural gas.

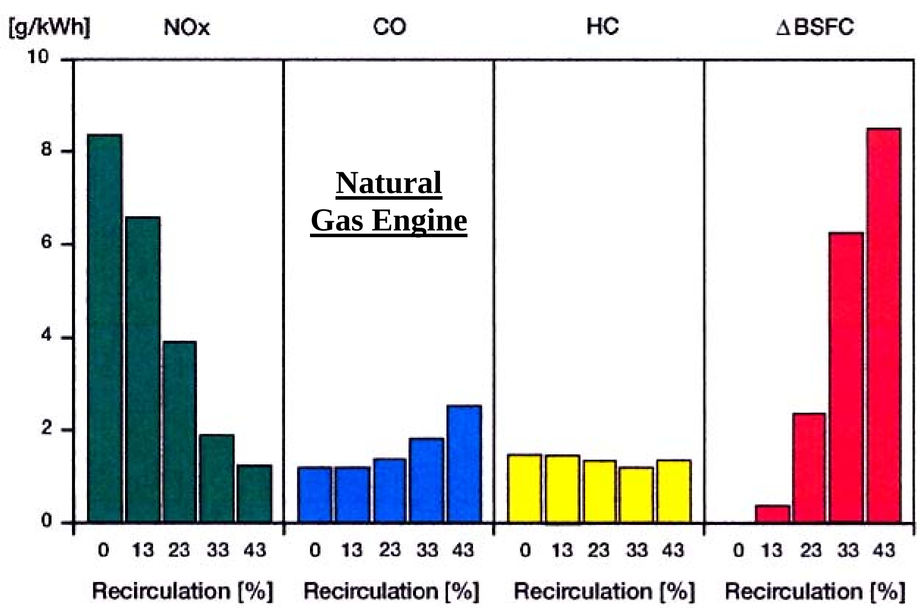


Figure 6.9. Effect of EGR on Emissions and Fuel Consumption (Ref. 5)

6.5 Selective Catalytic Reduction (SCR) For NOx Control

SCR of NOx using ammonia or urea has been used for many years in stationary and marine diesel applications, and also for gas turbine NOx control. The first marine SCR units were installed in 1989 and 1990 on two Korean 30,000 metric ton marine carriers. The ship operator was seeking a permit from the Bay Area Air Quality Management District to allow the reduced-emission ships to dock there. Both ships were powered by MAN B&W 8 MW diesel engines. The ammonia SCR systems were designed for 92% NOx reduction and were granted operation and docking permits. Since that time numerous vessels have been fitted with various SCR NOx reduction systems, primarily in Europe. [38]

The catalysts employed for SCR units are typically vanadium pentoxide embedded in titanium dioxide, and additionally are often dosed with tungsten trioxide and molybdenum trioxide to optimize the catalytic properties. Such catalysts are termed "full-contact catalysts", in contrast to "coated catalysts" in which a porous carrier material is coated with the catalytic material.[5] The operating temperature range for various catalysts are given as 175ºC - 250ºC for platinum catalysts, 300ºC - 450ºC for vanadium catalysts and 350ºC - 600ºC for zeolite catalysts.[38]

Ammonia (NH_3) and urea ($CO(NH_2)_2$) have turned out to be the only commercially applicable reducing agents. Both chemicals are widely used as a source of nitrogen in agricultural applications and therefore are readily available at a reasonable price. Ammonia gas is more difficult to handle and to store, whereas urea is used in a water solution, typically at around 40% by weight. As a solution it has a pH of 9 – 11 and a relatively low toxicity. When it is heated urea decomposes to ammonia – this process requires 2 – 3 meters in the hot exhaust pipe.

Diesel exhaust is at a fairly low temperature (250ºC - 400ºC) and the presence of sulphur trioxide (SO_3) poses a limitation on the temperature range in which the SCR system can operate. For exhaust temperatures below about 300ºC (the exact value dependent upon the concentration of ammonia and SO_3, as well as the porosity of the catalyst surface), the

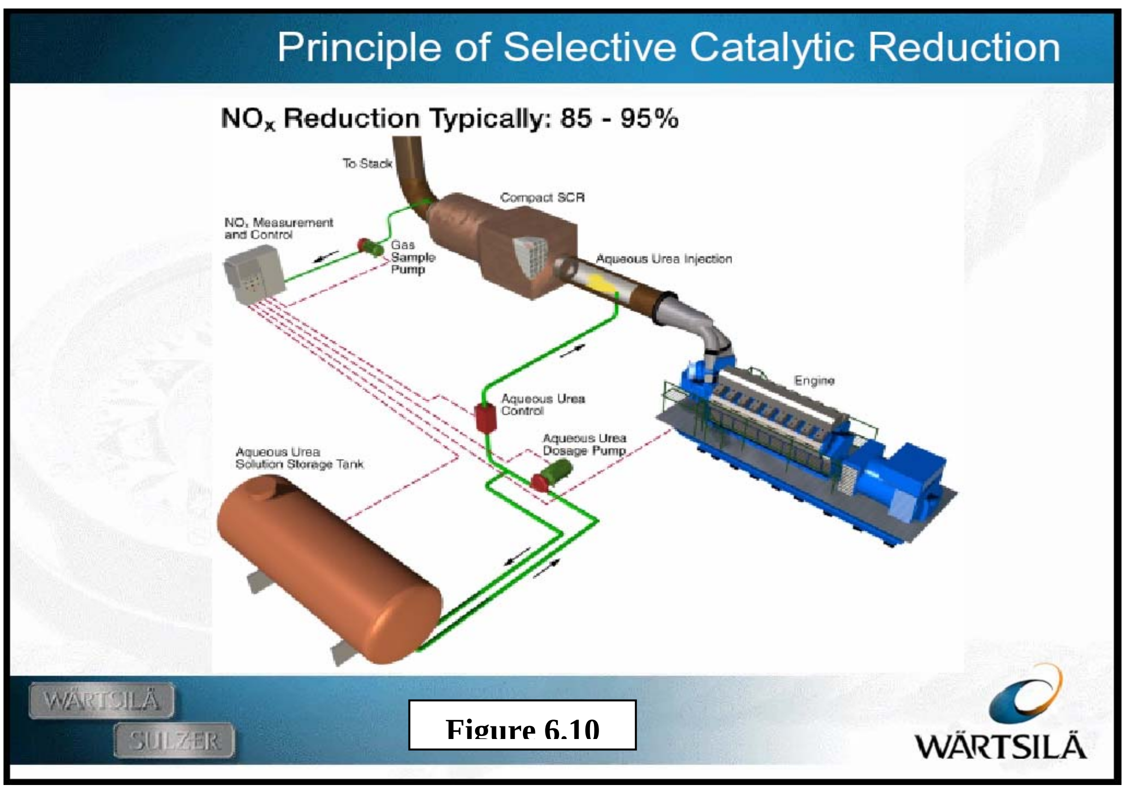
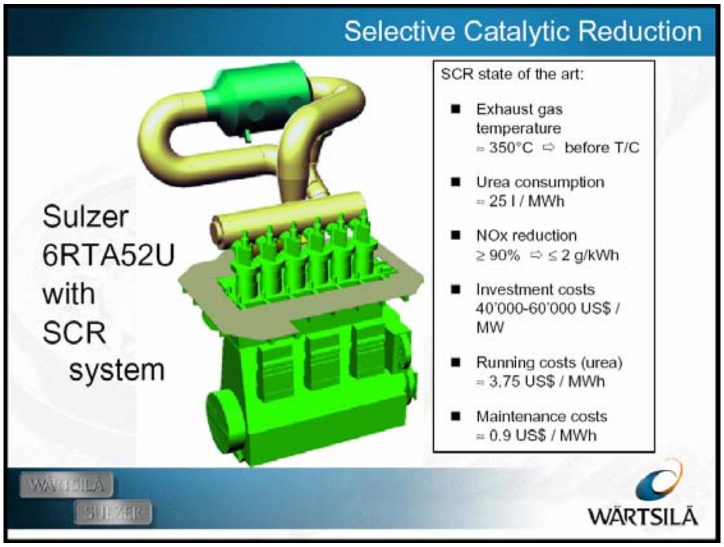


Figure 6.10

ammonia and SO_3 combine to form ammonium sulfate. Ammonium sulfate is an adhesive and corrosive aerosol that can foul the catalyst. At temperatures above 500ºC, ammonia starts to burn in the oxygen-rich exhaust gas, therefore the temperature window for an SCR unit is in the region of about 320ºC - 480ºC, with an optimal temperature of approximately 350ºC. [5]

Figure 6.10 presents a schematic of a SCR system installed on a 4-stroke diesel engine.[25] (For a low-speed 2-stroke diesel the catalyst is usually installed before the turbocharger.) The rate of urea addition in this Wartsila system is controlled by the amount of NOx measured in the exhaust stream (feed-back control system). Feed-forward control is also used.



SCR has been successfully used on diesel engines burning low quality fuel oil with a sulphur content of 3.5%. For 2-stroke diesels Wartsila has developed their "Compact SCR", which combines an SCR unit and silencer, together with built-in soot blowers. This system is shown in Figure 6.11.

Figure 6.11 – Wartsila Compact SCR System (Ref. 25)

The SCR reactor housing, including insulation, has a volume of about 2 – 5 m^3 per MW engine power (depending upon the catalyst, which is dependent upon fuel quality). The size is more or less independent of the input NOx concentration. The exhaust backpressure imposed by the SCR plant is typically between 15 and 25 mbar. If the SCR is only to be used intermittently, then a burner is absolutely necessary to heat the catalyst before the engine is started. Otherwise ammonium sulfate deposits will inevitably plug the catalyst. [5]

Hug Engineering, who have supplied about 70% of the SCR units in use in Europe, use an engine load signal to control the amount of urea injected into the exhaust. This allows a much faster response than would be attainable if only feedback control was used. Figure 6.12 shows how this control system follows the load for a ferry installation, where there are frequent large transients in engine load.

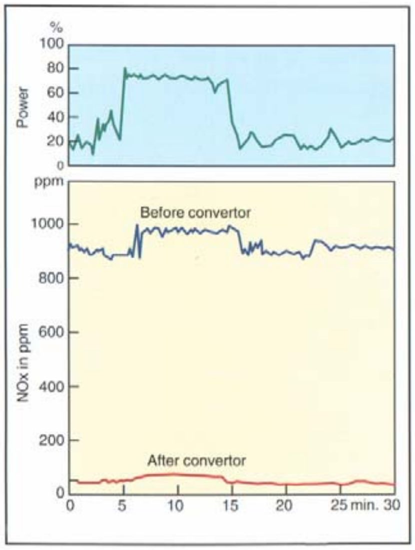


Figure 6.12. Transient Response of SCR (Ref. 42)

For smaller diesel engines, MECA estimated the cost of SCR at about $17,500 - $40,000 for engines in the 100 – 200 hp range, and about $18,500 - $50,000 for engines in the 300 – 500 hp range. [38]

Due to the high installed cost of SCR systems, their cost-effectiveness is highly dependent upon their annual operating hours and upon the degree of NOx removal. RJM Corporation has estimated the cost-effectiveness of using their RJM ARIS system on a 2,336 hp, stationary 4-stroke diesel with 687 ppm NOx.[43] The capital cost is estimated to be $157, 600 for 90% NOx removal, $150,000 for 75% NOx removal, and $142,000 for 50% NOx removal. Table 6.1 below shows the resulting cost-effectiveness vs. operating hours.

Table 6.1 – SCR Cost-Effectiveness for NOx Removal
(2,336 HP stationary diesel, ref. 43)

Hours/year of operation	90% NOx Reduction ($ per ton reduced)	75% NOx Reduction ($ per ton reduced)	50% NOx Reduction ($ per ton reduced)
1,000	$3,130	$3,422	$4,654
2,000	$1,763	$1,909	$2,475
4,000	$1,080	$1,183	$1,436
8,000	$738	$775	$916

The uncontrolled emissions are given as 101 tons per year for 8000 hours per year operation. This is equivalent to 8.7 g/bhp-hr and 6.6 g/kWh.

Wartsila recently investigated the different machinery concepts for 12,000 DWT RoRo vessels.[44] The most competitive design was a single Wartsila 64 medium speed diesel engine with SCR. Figure 6.13 shows that the annual cost of SCR is a small, but significant, part of the total annual machinery costs (approximately 7%). (Not shown are the all the other costs – vessel costs, crewing costs, licensing and insurance costs, port fees, etc.)

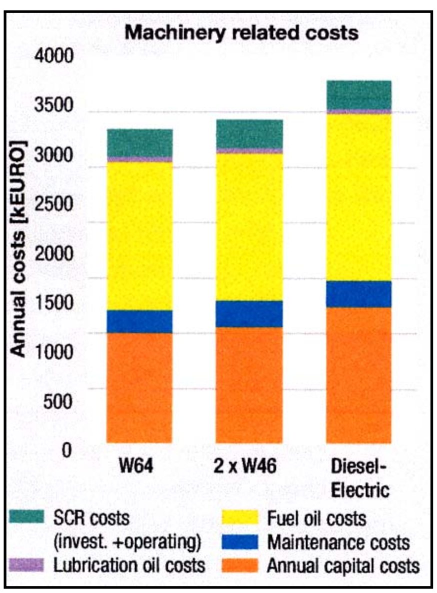
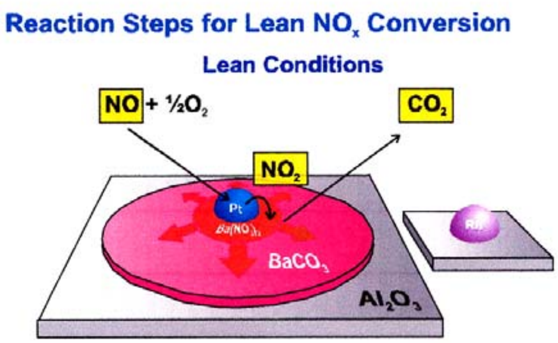


Figure 6.13. Annual Machinery Costs for RoRo Operation (Ref. 44)

6.6 NOx Adsorbers for NOx Reduction

NOx adsorbers are the newest control technology being developed for diesel NOx control. The technology was originally developed for lean-burn, low-emission gasoline engines but is now being adapted for use in diesel engines. The adsorbers are incorporated into a catalyst wash coat and chemically bind NOx during normal lean (oxygen-rich) engine operation. After the adsorber capacity is saturated the system is regenerated. The released NOx is catalytically reduced during a short period of rich engine operation, using a conventional 3-way catalytic converter. The reactions are shown schematically in Figures 6.14 & 6.15 (From Ref. 46).



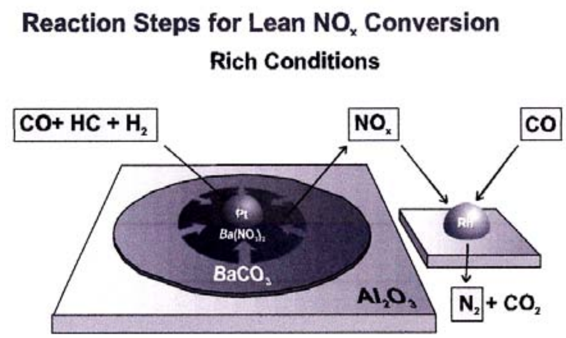


Figure 6.14

Figure 6.15

The NO is adsorbed and chemically binds with barium carbonate ($BaCO_3$) to form barium nitrate ($Ba(NO_3)_2$). During regeneration the diesel exhaust gas is rich in CO and unburned hydrocarbons. Theses chemicals reduce $Ba(NO_3)_2$ back to $BaCO_3$, in the process releasing NOx. In a downstream 3-way catalytic converter the NOx is reduced by the rich exhaust gases to nitrogen (N_2).

The regeneration step during lean/rich modulation typically lasts a few seconds. Various methods are used to attain rich conditions:

- Intake air throttling
- Exhaust gas recirculation
- Post-combustion fuel injection.

The technology has demonstrated NOx conversion efficiencies of in excess of 90%. [46] The catalyst is, however, susceptible to sulphur poisoning and hence ULSD must be used as a fuel. Emerachem is developing a system that includes up-stream sulphur "trap" to obviate this problem. [47] (The same company is commercializing a NOx removal system (SCONOx) for stationary gas turbine power plants, where the sulphur concentration in the fuel is extremely low. [48]) Because rich exhaust conditions must be periodically induced for adsorber regeneration, there will be a fuel-economy penalty of 1% - 3%, depending upon the NOx concentration in the exhaust (high NOx requires more frequent regeneration).

The NOx adsorber technology is not yet mature, but initial commercial offerings can be expected to coincide with the 2007 ULSD road diesel requirements.

6.7 Diesel Oxidation Catalysts (DOC) for THC and CO Reduction

The diesel oxidation catalyst is the only catalyst technology that has demonstrated required robustness and durability with presently available on-road diesel fuels and is commercially established in a large number of diesel systems. The diesel oxidation catalyst promotes the oxidation of THC and CO with up to 90% efficiency, as well as the soluble organic fraction of diesel particulates. The catalyst also promotes the oxidation of SO_2 to SO_3, which leads to the generation of sulfate particles and which may actually increase the total particulate emissions (PM) despite the decrease in the soluble fraction. These catalysts are therefore designed to be selective in order to obtain a compromise between high THC and soluble particulate activity and acceptable low SO_2 activity. [38] The performance of the DOC is greatly enhanced by using low sulfur road diesel. [36] For a fuller discussion of this topic the reader is invited to peruse the EPA website http://www.trucks.doe.gov/research/fuel/decse-oxidation.html.

Under EPA's urban bus rebuild/retrofit program, five manufacturers have certified DOC's as providing at least 25% reduction in PM emissions for in-use diesel buses. Certification data also indicates that DOC's achieve substantial reductions in CO and THC emissions. [36]

The DOC's can be combined with engine tuning to reduce NOx, by tuning the engine for low NOx and then using a DOC to control the accompanying increase in CO, THC and PM. [36]

The benefits of DOC include the oxidation of toxic, non-regulated, hydrocarbon-derived emissions, such as aldehydes and PAH's, as well as elimination of the diesel odor. DOC's have been installed in over 250,000 off-road vehicles around the world for over 30 years. Over 1.5 million DOCs have been installed on heavy-duty highway trucks in the USA since 1994. These systems operate reliably and trouble free for hundreds of thousand of miles.[36]

The cost of DOC varies according to engine power. For a muffler replacement on a 100 – 200 hp engine the cost is about $1250. This increases to about $1750 for a 300 – 500 hp engine. [38] It is probable that the average installed cost will be significantly higher than these estimates.

<u>Cost-Effectiveness for THC and PM Reduction on a Work Boat Diesel</u>

The DOC technology is appropriate for construction equipment and for small workboats and the auxiliary engines of larger vessels such as ferries, provided that they burn road diesel in place of MDO. The cost-effectiveness can be estimated as below.

- Assume a 400 hp diesel engine with THC and soluble organic fraction (SOF) reduction of 0.8 g/bhp-hr and with 2000 operating hours per year, the annual reduction would be 0.64 tonnes.
- Assuming that the workboat must use road diesel, instead of MDO, with an extra cost of $5/tonne and a SFOC of 200 g/kWh, then the additional fuel cost would be $600/year.
- Assuming a total installed cost of $2,500, capitalization of 7% (capital recovery factor = 0.1424) and annual maintenance/replacement costs of $250, then the total annual cost would be $1,210, or <u>$1,880/tonne of THC and SOF</u>.

6.8 Diesel Filters for Particulate Reduction

Diesel Particulate filters (DPF) are commercially available for smaller 4-stroke diesel engines that burn low-sulfur road diesel. They are easily plugged by the impurities present in heavy fuel oil and bunker oils. Figure 6.16 is a schematic of a DPF.

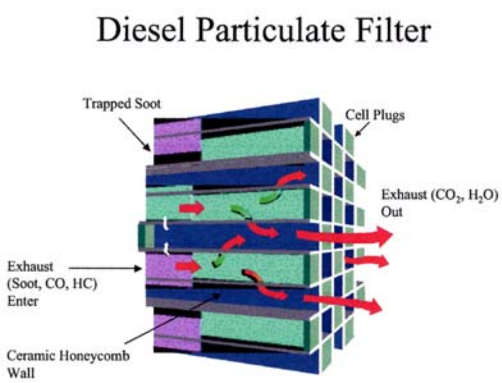


Figure 6.16. DPF (Ref. 46)

In the figure, particulate-laden exhaust enters the filter from the left. Because the cells of the filter are capped at the downstream end, exhaust cannot exit the cell directly. Instead, exhaust gas passes through the porous walls of the filter cells and particulate matter is deposited on the upstream side of the cell walls. Cleaned exhaust gas exits the filter to the right. Removal efficiencies of over 90% can be achieved.

Many techniques can be used to regenerate a diesel particulate filter. Some of these techniques are used together in the same system to increase regeneration efficiency. The major regeneration techniques are shown below.[36]

- Catalyst-based regeneration using a catalyst applied to the surfaces of the filter. A base or precious metal coating applied to the surface of the filter reduces the ignition temperature necessary to oxidize accumulated particulate matter.

- Catalyst-based regeneration using an upstream oxidation catalyst to convert NO to NO_2. The NO_2 then adsorbs on the collected particulate substantially reducing the temperature required to regenerate the filter.
- Fuel-borne catalysts to reduce the temperature necessary to oxidize accumulated particulate matter.
- Air-intake throttling in one or more cylinders can increase the exhaust temperature.
- Post top-dead-center (TDC) fuel injection. Injecting small amounts of fuel in the cylinders after TDC results in a small amount of unburned fuel in the engine's exhaust, which can then be oxidized in the particulate filter to combust accumulated particulate matter.
- On-board fuel burners or electrical heaters upstream of the DPF, or electrical heating coils within the DPF.
- Off-board electrical heaters – blow hot air through the filter system.

Other regeneration methods currently being investigated include the use of plasma to convert NO to NO_2, and the use of microwave energy to help burn off the collected soot.

The experience with catalyzed filters indicates that there is a virtually complete elimination of odor and in the soluble organic portion of the particulate. However, some catalysts may increase sulfate emission by oxidizing SO_2 to SO_3. Companies selling catalyzed filters have reformulated their catalysts to reduce sulfate emissions to acceptable levels. The use of ULSD will also mitigate this problem.

A recent study of catalyzed soot filters by the University of Utah demonstrated 95% - 98% filtration efficiency in removing particulate matter, 72% - 89% efficiency in total hydrocarbons and 49% - 92% reductions in CO during various transient tests.[49]

Diesel particulate filters are widely used both on-road and off-road. They have been installed on off-road equipment since 1986, with over 20,000 active and passive systems being installed either as OEM or as retrofits worldwide. Some of the off-road systems have been in use for over 15,000 hours or over 5 years and are still in use. [36]

As noted in a previous section, DPF can be combined with exhaust gas recirculation (EGR) to achieve NOx reductions of over 40% and PM reductions of over 90%. Engines equipped with selective catalytic reduction (SCR) and DPF can achieve NOx reductions of 75% - 90% and PM reductions of over 90%. Retuning the engine to minimize NOx, and then using the DPF to control the extra particulate emissions can also achieve combined NOx and PM reductions. [36]

The diesel particulate filters are quite compact and can be designed to replace the existing muffler, although some form of exhaust gas reheat may be needed for a self-cleaning catalytic system, which require a temperature of 200ºC to 280ºC. [38]

DPF unit costs are around $7,500. [36] Installed cost will be higher, depending upon the degree of modifications required. The Washington Metropolitan Area Transit Authority budgeted $4.6 million to retrofit between 208 and 282 Detroit Diesel engined buses. [36] This works out to $16,300 - $22,000 per bus but probably includes research testing and administrative overhead costs.

Little or no information is available on the operating costs for a DPF. It has been reported that the City of Seattle's DPF-equipped diesels are expected to only require a biannual cleaning, costing in the order of $300 ($100 for shop labor + $200 for cleaning charges).[152] However, this is for a fleet with exemplary attention to maintenance and fuel quality. It is expected that most off-road DPF applications will encounter physical shock loadings, and abuse from contaminated diesel, that will result in more maintenance. Annual maintenance in the order of 5% -10% of the cost of the DPF can be expected for general off-road applications.

Cost-Effectiveness for Particulate Reduction on a Work Boat Diesel

The DPF technology is appropriate for construction equipment and for small workboats and the auxiliary engines of larger vessels such as ferries, provided that they burn ULSD road diesel. The cost-effectiveness can be estimated as below.

- Assume a 400 hp diesel engine with particulate reduction of 0.8 g/bhp-hr and with 2000 operating hours per year, the annual PM reduction would be 0.64 tonnes.
- Assuming that the workboat must use ultra-low sulfur road diesel (ULSD), instead of MDO, with an extra cost of $15/tonne and a SFOC of 200 g/kWh, then the additional fuel cost would be $1,800/year.
- Assuming a total installed cost of $10,000, capitalization of 7% (CRF = 0.1424) and annual maintenance/replacement costs of $800, then the total annual cost would be $4,020, or $6,290/tonne PM.

Much of this cost is due to the use of ULSD, which also results in about 0.15 TPY less SOx emissions to the atmosphere due to its much lower sulfur content as compared to MDO (<15 ppm S vs. an assumed 1,300 ppm S for MDO).

6.9 Hybrid Power Systems

Hybrid power systems typically use a small genset (diesel or gasoline engine) in combination with storage batteries. The batteries provide the extra power boost that is needed during relatively short periods of acceleration and/or heavy load. Hybrid power systems are presently appearing in light duty vehicles. Manufacturers presently find them a feasible option, as compared to fuel cell power, for achieving very low emissions and excellent fuel economy. Hybrid power systems are also appropriate to low duty-cycle rail switching engines.

Rail Power is marketing their retrofit, hybrid-powered rail yard switcher technology that will allow older 750 – 2000 hp locomotives, which are being replaced with more powerful and modern engines, to be converted to switchers that meet EPA's Tier Two emission standards. They have been demonstrating a modified switcher that they call the *Green Goat*. The retrofit consists of an 80 – 100 hp low-emission diesel engine, a large battery pack and an electronic control system.

The advantages of the *Green Goat* are said to be:

- Instant on-power
- Field maintainable
- Large reduction in operating costs (45% less fuel, lube oil, etc.)
- Much lower switch yard noise levels
- Cost – estimated to be $650,000 - $750,000, as compared to about $1.1 million for a new switcher.
- Low emissions (NOx and PM reduced 80% - 90%). Complies with California's 2005 emission requirements.

A smaller version of the *Green Goat*, called the *Green Kid*, is also planned. [119]

6.10 Gas Turbine Engines

Gas turbines offer a high power output from a low weight, compact package. Their emissions are lower than those from a diesel engine. However, they are not as fuel efficient as a diesel engine and they must use a more expensive distillate (marine gas oil or jet fuel). Therefore, they are generally used where their low-weight and high-power attributes are important – aircraft and military warships – but have also been used in the past in railroad locomotives where their power output was important for line-haul applications.

Recently gas turbines are appearing on cruise ships, where they are used in combination with conventional diesel-electric gensets. The diesel-electric gensets provide the fuel economy required for cruising, while the gas turbine driven genset provides low-emission hoteling power as well as extra power maneuvering and for getting up to cruising speed. The reduced weight and volume of this package also offers greater flexibility in where it is located, as well as freeing up capacity for more paying passengers.

The General Electric LM2500+ is being used in cruise ship applications. It has a maximum output of 30,200 kW. Typical emission factors, when on 0.1% S MGO, are NOx = 4.5 g/kWh, PM = 0.17 g/kWh and SOx = 0.55 g/kWh.

No cost data is available for this engine. Therefore it's installed cost is derived from that of a 5,000 kW turbine, or a 5,000 kW diesel, installed in a 400-passenger ferry (ref. 72), using the 2/3 power-law to scale-up. The estimated costs for a 30.2 MW gas turbine is $10.5M and for a 30.2 MW diesel is $3.6 M. Therefore the extra cost for the turbine is roughly $6.9M. It can be assumed that the annual maintenance costs are approximately the same for both engines. The gas turbine requires marine gas oil (MGO), which is assumed to cost $305/tonne, as compared with IFO 180 at $185/tonne.

6.11 Idle Reduction Technologies

Large diesel engines, especially those in locomotives, can reduce their fuel costs and exhaust emissions by shutting down during extended periods of idling. For instance, the General Motors EMD locomotives that are equipped with their EM2000 control system can be fitted with an automatic engine start/stop system that monitors engine and locomotive parameters and automatically shuts down when idling for a certain period of time. For mainline locomotives this may save 1800 hours of idling time ands 5400 – 7200 gallons of fuel per year.

EPA recognized idle reduction technologies are listed on their website (http://www.epa.gov/otaq/retrofit/idlingtech.htm). Included is the technology by Kim Hotstart Manufacturing Co. and by ZTR Control Systems. [120, 121]

The *Hotstart Diesel Driven Heating System* (DDHS) uses a compact, diesel-engine generator to heat the locomotive's engine coolant and oil, keep the batteries charged and powers the cab heaters during cold weather. The auxiliary Lister-Petter 3 cylinder diesel can be mounted on the walkway or inside the car body where space allows, the package is 24x49x33" and weighs approximately 1000 lbs. The price of this system is $27,600. [120]

ZTR's *Smart-Start* system is a microprocessor technology that automatically manages the shutdown and restart of locomotives while parked idling. It continually monitors existing conditions against a preprogrammed set of values. This system monitors the following operating conditions: reverser and throttle position, air brake cylinder pressure, engine coolant and ambient air temperature, and battery voltage and charging amperage. This technology cost $7,500. [121]

These technologies are being marketed together as the *Hotstart-Smartstart Package*. [120]

The *Smart-Start* system was installed on several of Burlington Northern – Santa Fe's locomotives as early as the late 1980's. It was found at that time that they required a lot of maintenance and required batteries that were in superb condition. Its cost-effectiveness was minimal and, by itself, could not be used in cold weather. However, it is now being reconsidered for use in combination with the 40 hp *Hotstart* system on some of the short-haul locomotives (e.g. the GP38, GP39-2 and the GP40) where there is adequate space. Apparently there is insufficient space in the newer 4000 hp engines, such as the EMD 570. [122]

7.0 CONSTRUCTION EQUIPMENT EMISSION REDUCTIONS AND COSTS

7.1 Introduction

The construction equipment "fleet" consists of 12 pieces of equipment, out of a total of 375 pieces of off-road diesel-engined equipment that are owned by the City of Seattle. The City dispenses fuel from their own fueling facilities, using ULSD since the HDD on-road fleet, which may use catalytic particulate filters and oxidation catalysts, uses the same fuel.

Annual fuel consumption for this fleet is estimated to be 13,416 gallons based upon reported values for annual engine hours for each piece of equipment and assumed values for load factors and specific fuel consumption (Section 4).

In general, construction equipment will use either off-road, high-sulfur diesel or rebranded road diesel, depending upon what is locally available. Fuel additives may be used but this first should be discussed both with the equipment supplier and the fuel supplier in order to determine if the additive is compatible with the engine and fueling systems, and if it is not already included in the fuel package.

Clean fuel options that are available for use in construction equipment are rebranded road diesel (LSD and ULSD), biodiesel, and fuel-water emulsions such as Lubrizol's PuriNOx. Biodiesel has been discussed in Section 5.2. It has higher NOx emissions, compared with off-road diesel, and is more expensive than ULSD. Its use may well be justified for reducing emissions of greenhouse gases but not for reducing emissions of the pollutants of interest in this study.

Technological, after-market emission-reduction options include diesel oxidation catalysts (DOC), diesel particulate filters (DPF) and exhaust gas recirculation (EGR). The existing engines may also be replaced with newer, low-emission engines. This option was not explored for construction equipment because it is expensive and, since construction equipment only operates for a rather limited time each year, the cost per unit of operating time would be high.

The following section will estimate the emission reduction and costs associated with each of the options mentioned above. It is assumed that a reduction in VOC includes those in benzene, formaldehyde and 1,3-butadiene. Therefore 90% reduction in VOC will imply a 90% reduction in these three species. The results will be summarized in Table 7.1, which will also show changes in annual operating costs and will show the estimated cost effectiveness ($/ton of pollution reduction).

Annualized capital costs are based upon a discount rate of 7% and an amortization period of either 10 years or 15 years, depending upon the expected service life of the equipment. Annual maintenance costs are assumed to be either 5% of installed capital or 10% of installed capital, depending upon the robustness of the equipment. In the case of catalytic-containing equipment it is conservatively assumed that off-road abuse, and probable exposure to contaminated fuel will shorten the service life and increase the maintenance of these devices as compared to on-road applications. Readers may wish to estimate annual costs based upon different assumptions than those used in this study. This can easily be done using the cost summary table at the end of this section.

7.2 Construction Equipment Emission Reduction Options

1. Baseline

For the base case it is assumed that the fleet uses 3000-ppm sulfur off-road diesel that costs $0.80/gallon. This price is a typical rack price and does not include taxes and delivery costs. These extra costs will be approximately the same for each fuel option and hence will not factor into changes in fueling costs between the different options.

- Annual fuel cost = 13,416 gpy x $0.80/gal = $10,733
- NOx = 1.922 tpy
- SOx = 0.276 tpy
- PM2.5 = 0.125 tpy
- VOC = 0.213 tpy

2. Low Sulfur Diesel (LSD)

Assume 500 ppm S diesel at a rack price of $0.845/gallon (approximately 5 cents per gallon over the rack price for off-road diesel in Tacoma).

- Annual fuel cost = 13,416 gpy x $0.845/gal = $11,336 (increase of $603/year)
- Change in SOx = 0.276 – 0.046 = 0.23 tpy (total pollution reduction).
- Cost effectiveness = $603/0.23 = **$2,622/ton**.

3. Ultra-low Sulfur Diesel (ULSD)

Assume 5 ppm S diesel at a rack price of $0.895/gallon.

- Annual fuel cost = 13,416 gpy x $0.895/gal = $12,007 (increase of $1274/year)
- Change in SOx = 0.276 tpy (assumed total pollution reduction; no credit taken for a probable small PM and VOC reduction.)
- Cost-effectiveness = $1274/0.276 = **$4,624/ton**.

4. Fuel-Water Emulsion + Low Sulfur Diesel

Assume *PuriNOx* is used with an all-up premium of $0.16/gal over diesel and no increase in infrastructure. This option is assumed to provide a 37% reduction in NOx, 42% in PM and no change in VOC.

- Annual fuel cost = 13,416 gpy x $1.005/gal = $13,483 (increase of $2,750/year)
- Change in SOx = 0.23 tpy
- Change in NOx = 0.37 x 1.922 = 0.711 tpy
- Change in PM2.5 = 0.42 x 0.125 = 0.0525 tpy
- Total pollution reduction = 1.04 tpy
- Cost-effectiveness = $2,750/1.04 = **$2,645**

5. Low Sulfur Diesel + Diesel Oxidation Catalysts (DOC)

Diesel oxidation catalysts are usually retrofitted as replacement “mufflers”. They are compact and inexpensive, but require a low sulfur diesel to prevent poisoning of the catalyst.

Assume the DOC costs $1250 and has an installed price of $2,500. VOC’s are reduced 90% and $PM_{2.5}$ is reduced 25%. The DOC has an average life of 10 years, with an assumed annual maintenance costs of 5% of the installed cost. Amortization is 7% over 10 years; capital recovery factor is 0.1424.

- Installed capital cost = 12 x $2,500 = $30,000
- Amortization = 0.1424 x $30,000 = $4272
- Maintenance = 0.05 x $30,000 = $1500
- Added cost of LSD = $603
- Total increase in annual costs = $6,375

- Reduction in SOx (use of LSD) = 0.23 tpy
- Reduction in VOC = 0.90 x 0.213 = 0.192 tpy
- Reduction in PM2.5 = 0.25 x 0.125 = 0.031 tpy
- Total emission reduction = 0.453 tpy
- Cost-effectiveness = $6375/0.453 = **$14,060/ton**

6. Ultra-low Sulfur Diesel + Diesel Particulate Filter (DPF)

A catalytic diesel particulate filter requires the use of ULSD to ensure its self-regenerating capabilities. A DPF can act as a replacement muffler on construction equipment.

Assume that the capital cost of a DPF follows the usual 2/3-power law for equipment cost versus equipment capacity, and that the cost for a DPF for a 400 hp engine is $7,500. The capital cost for construction equipment with an average 153 hp engine is then $3,950.

Assume an installed price of $5,000 and annual maintenance of 10%. (While the assumed annual maintenance cost for diesel particulate filters (10% of the installed price of the DPF) is higher than that actually experienced by the City of Seattle fleet (3% - 4%), it is expected to apply to off-road construction equipment where fueling and maintenance procedures are not so carefully followed and where contaminated fuel will require more frequent servicing and replacement of the filter.)

Assume there is a 95% reduction in PM2.5 and a 80% reduction in VOC.

- Installed capital cost = 12 x $5,000 = $60,000
- Amortization = 0.1424 x $60,000 = $8544
- Maintenance = 0.10 x $60,000 = $6,000
- Added cost of ULSD = $1274
- Total increase in annual costs = $15,818

- Reduction in SOx (use of ULSD) = 0.276 tpy
- Reduction in PM2.5 = 0.95 x 0.125 = 0.119 tpy
- Reduction in VOC = 0.80 x 0.213 = 0.170 tpy
- Total emission reduction = 0.565 tpy
- Cost-effectiveness = **$27,992/ton**

7. Ultra-low Sulfur Diesel + Exhaust Gas Recirculation (EGR) + DPF

Exhaust gas recirculation requires a filter to remove diesel particulates (soot) that may damage the engine. Compact EGR/DPF packages are available for off-road equipment from companies such as Johnson-Matthey.

Assume that the capital cost of a EGR/DPF follows the usual 2/3-power law for equipment cost versus equipment capacity, and that the cost for a EGR/DPF for a 400 hp engine is $20,000. The capital cost for construction equipment with an average 153 hp engines is then $10,535. Assume an installed price of $12,000 and annual maintenance of 5%. Assume there is a 95% reduction in PM2.5 and VOC, and a 40% reduction in NOx.

- Installed capital cost = 12 x $12,000 = $144,000
- Amortization = 0.1424 x $144,000 = $20,506
- Maintenance = 0.05 x $144,000 = $7,200
- Fuel (2% increase, ULSD) = $1300
- Total annual cost increase = $29,000

- Reduction in SOx = 0.276 tpy
- Reduction in NOx = 0.4 x 1.922 = 0.769 tpy
- Reduction in PM2.5 = 0.95 x 0.125 = 0.119 tpy
- Reduction in VOC = 0.95 x 0.213 = 0.202 tpy
- Total emission reduction = 1.366 tpy
- Cost-effectiveness = **$21,228/ton.**

8. Low Sulfur Diesel + *PuriNOx* + Diesel Oxidation Catalyst

This option includes both a fuel-water emulsion to reduce emissions of NOx and a DOC to reduce PM and VOC emissions. LSD is required for the DOC.

Assume NOx is reduced by 37%, VOC by 90% and PM by 56.5% (42% by PuriNOx and 25% reduction of the remainder by the DOC). Costs will be a combination of these options.

- Installed capital cost = 12 x $2,500 = $ 30,000
- Annualized DOC = $4,272
- Maintenance = $1,500
- Fuel (ULSD) = $2,750
- Total annual cost increase = $8,522

- Reduction in SOx (ULSD) = 0.23 tpy
- Reduction in NOx = 0.37 x 1.922 = 0.71 tpy
- Reduction in PM = 0.565 x 0.125 = 0.071 tpy
- Reduction in VOC = 0.90 x 0.213 = 0.192 tpy
- Total emission reduction = 1.203 tpy
- Cost-effectiveness = $8,522/1.203 = **$7,090/ton**.

17.1 Comparison of Emission Reduction Options

The seven emission reduction options are summarized in Table 7.1 below.

It can be seen that the most cost-effective options are the two clean-fuel options (options 1 & 2), and the use of a fuel-water emulsion (option 3). Somewhat more expensive, but achieving a higher (47%) reduction in emissions is the use of a combination of low sulfur diesel, *PuriNOx* and the diesel oxidation catalyst (option 7).

The hardware options (4,5 & 6) are effective in reducing emissions but at a much higher cost, pushing their cost-effectiveness well over $10,000 per ton of pollution removed.

Not shown here is the rapidly maturing DeNOx technology, which will remove most of the NOx at a cost expected to be somewhat higher than that for the catalytic diesel particulate filters.

Table 7.1 - Comparison of Emission Reduction Options for Construction Equipment*

Control Option	Installed Cost	Capital Amortize	Increased Maintenance	Added Fuel Cost	Total Annual Cost	Emission Reduction (Tons per year)					Cost-Effectiveness $/ton
						SOx	NOx	PM2.5	VOC	Total	
1. LSD	-	-	-	$603	$603	0.23	-	-	-	0.23	$2,622
2. ULSD	-	--	-	$1,274	$1,274	0.276	-	-	-	0.276	$4,624
3. LSD + *PuriNOx*	-	-	-	$2,750	$2,750	0.276	0.711	0.052	-	1.04	$2,645
4. LSD + DOC	$30,000	$4,272	$1,500	$603	$6,375	0.23	-	0.031	0.191	0.453	$14,060
5. ULSD + DPF	$60,000	$8,544	$6,000**	$1,274	$15,810	0.276	-	0.119	0.170	0.565	$27,990
6. ULSD + EGR/DPF	$144,000	$20,500	$7,200	$1,300	$29,000	0.276	0.769	0.119	0.202	1.366	$21,230
7. LSD + DOC + PuriNOx	$30,000	$4,272	$1,500	$2,750	$8,522	0.23	0.71	0.071	0.191	1.203	$7,090
Base-Line Costs and Emissions	n/a	n/a	n/a	$10,733	n/a	0.276	1.922	0.125	0.213	2.536	n/a

* Representative construction equipment fleet includes 12 pieces of equipment selected from the City of Seattle's total fleet.

** While the assumed annual maintenance cost for diesel particulate filters (10% of the installed price of the DPF) is higher than that actually experienced by the City of Seattle fleet (3% - 4%), it is expected to apply to general construction equipment where fueling and maintenance procedures are not so carefully followed and where contaminated fuel may require more frequent servicing and replacement of the filter.

8.0 LOCOMOTIVE EMISSION REDUCTIONS AND COSTS

8.1 Introduction

The representative locomotive "fleet" consists of 53 line-haul and 14 yard engines operated by BNSF in the Pacific Northwest (Washington and Oregon) and does not include the transcontinental stock. The average rating of the line-haul engines is 2121 hp, while that of the yard engines is 1164 hp. Baseline emissions and fuel costs are based upon the fleet using #2 diesel with 0.254% sulfur and costing $0.80/gal. Estimated annual fuel consumption is given in Table 8.1 below (Total fuel consumption data supplied by BNSF. Levelton Engineering estimated the split between idling and full load fuel consumption using EPA duty-cycle data.)

Figure 8.1 - Estimated Annual Locomotive Fuel Consumption

			2002 Fuel Consumed (gallons)		
States	**Counties****	**Modes**	**Idling**	**Full Load**	**Total**
Washington	All	Line Haul	1,743,541	82,446,227	84,189,768
		Yard	44,300	863,090	907,390
		All Modes	**1,787,841**	**83,309,317**	**85,097,158**
Oregon	All	Line Haul	89,542	4,234,129	4,323,671
		Yard	8,054	156,926	164,980
		All Modes	**97,596**	**4,391,055**	**4,488,651**
Pacific NW Total	All	Line Haul	1,833,083	86,680,356	88,513,439
		Yard	52,354	1,020,016	1,072,370
		All Modes	**1,885,437**	**87,700,372**	**89,585,809**

Locomotives typically have large two-stroke, turbo-charged, medium-speed diesel engines that power electrical generators that in turn supply electricity to the drive motors. The engines operate at one of eight discrete steady-state operational points, or "throttle notches", in addition to a dynamic braking mode and an idling mode. The duty cycles assigned to these 10 modes of operation vary somewhat according to manufacture, railroad association, or government authority, and whether the locomotive is freight (line haul) or switch (yard). [65] The line-haul locomotives spend approximately 38% of their time idling, whereas the yard locomotives may spend approximately 60 % of their time idling. [63] The size of add-on pollution reduction equipment is subject to restrictions due to the spacing of railroad tracks and the dimensions of railroad tunnels. The locomotives may have a service life of 40 years or more, but during this period of time may be remanufactured 5 – 10 times. [62]

Emission reduction options that will be explored in the is chapter include rebuilding the engines to EPA's Tier 0 or to Tier 1 emission standards, using road diesel (rebranded low-sulfur diesel, LSD), using water injection (CWI), using diesel oxidation catalysts

(DOC), using self-regenerating, catalytic diesel particulate filters (DPF), using exhaust gas recirculation (EGR) in combination with DPF, using liquefied natural gas carried in an insulated tank car (tender), using idle-control technologies, and using hybrid, diesel-battery technology for yard switchers.

The following section will estimate the emission reduction and costs associated with each of the options mentioned above. It is assumed that a reduction in VOC includes those in benzene, formaldehyde and 1,3-butadiene. Therefore 90% reduction in VOC will imply a 90% reduction in these three species. The results will be summarized in Table 8.3, which will also show changes in annual operating costs and will show the estimated cost effectiveness ($/ton of pollution reduction).

8.2 Emission Reduction Options for Locomotives

1. Baseline

For the base case it is assumed that the fleet uses off-road #2 diesel with a sulfur content of 0.254% sulfur and a rack price of $0.80/gallon. This price is a typical rack price and does not include taxes and delivery costs. These extra costs will be approximately the same for each fuel option and hence will not factor into changes in fueling costs between the different options.

- Annual fuel costs = $0.80/gal x 89,585,809 = $71.67 M

Table 8.2 summarizes the estimated annual emissions for the two classes of locomotives.

Table 8.2 Base Line Locomotive Emissions (tons/year)

	SOx	NOx	PM2.5	VOC
Line Haul	1593.2	21,823	513.4	983.3
Yard	19.3	270.4	7.4	28.6
Total	1612.5	22,093.4	520.8	1,012

2. Rebuild to Tier 0 – Total Fleet

Assume all engines can meet Tier 0 if converted using new diesel injection systems at a cost of approximately $30,000 per locomotive. [127] Assume that the resulting emissions are 90% of Tier 0, unless this is higher than existing BNSF emissions, in which case the existing BNSF emission factors are used. Further assume that the capital is amortized over 10 years and that there is no change in maintenance costs or in fuel costs.

The change in costs and emissions are shown in Table 8.2. This option reduces NOx emissions by 6, 193 tpy (28%) at an annual cost of $286,200. The cost effectiveness of this option is therefore $46.21/ton of pollution reduction.

3. Rebuild to Tier 1 – Total Fleet

Assume all engines can meet Tier 1 if converted using new pistons, injectors, and electronic engine control at a cost of $190,000/engine. [122, 127] Assume that the resulting emissions are 90% of Tier 1, unless this is higher than existing BNSF emissions, in which case the existing BNSF emission factors are used. Further assume that the installed capital is amortized over 15 years, that maintenance costs increase 2 ½% of installed capital due to the added complexity of the electronics and associated engine sensors, and that fuel consumption is reduced 1% due to better engine control.

The change in costs and emissions are shown in Table 8.3. This second option reduces NOx emissions by 9,673 tpy (44%) at an annual cost of $1,644,000. The cost effectiveness of this option is therefore $170/ton of NOx reduction.

4. Use Low-Sulfur Road Diesel (LSD) – Total Fleet

Assume 350 ppm S diesel at a rack price of $0.845/gallon. Assume that SOx emissions are reduced the same amount as the reduction of fuel sulfur (86.2%), and that particulate emissions are reduced by 5% due to the reduced sulfur. Assume no change in maintenance costs (there should be a reduction in these costs due to the cleaner fuel).

The annual fuel cost then increases by $4,036,000/year. Total emissions are reduced by 1,416 tpy. The cost-effectiveness of this option (Table 8.3) is $2,850/ton of pollution reduction.

5. Rebuild to Tier 0 and use LSD – Total Fleet

This option is a combination of 2 & 4. The increase in annual costs is $4,322,000 and the total emission reduction (Table 8.2) is 7,609 tpy. Therefore the cost effectiveness of combining these two options is $568/ton of pollution reduction.

6. Rebuild to Tier 1 and use LSD – Total Fleet

This option is a combination of 3 & 4. The increase in annual costs is $5,680,000 and the total emission reduction (Table 8.3) is 11,090 tpy. Therefore the cost effectiveness of combining these two options is $512/ton of pollution reduction.

7. Use Water Injection and use LSD – Total Fleet

Continuous water injection (CWI) is a relatively low cost method to reduce NOx emissions by approximately 30%, and fuel consumption by about 1%. Up to 50% by weight water is used to effect this NOx reduction. A special water tank will be required to carry the necessary extra water.

Assume an installed cost of $15,000 for the CWI system and $20,000 for the water tankage, both being amortized at 7% over a 15-year period. Assume that water costs $2/tonne and that the extra maintenance is 5% of installed capital. The increase in annual costs (LSD plus hardware) is then $4,220,000/year.

Assume that NOx is reduced by 30%, particulate by 30% and SOx by 86.2%. The total pollution is then reduced by 8,184 tpy. The cost-effectiveness of this option is therefore $516/ton, as shown in Table 8.3.

8. Use Diesel Oxidation Catalysts and LSD – Total Fleet

Diesel oxidation catalysts (DOC) are a relatively low cost method to reduce the emissions of the soluble portion of diesel particulate and to reduce the VOC emissions. They can be retrofitted as a replacement "muffler".

Assume that the installed cost of a DOC is $10,000, maintenance is 10% of this and that amortization is 7% over 10 years. Assume that VOC is reduced by 90%, particulate matter by 35% and SOx by 86.2%.

The increase in annual costs is then $4,198,000 and the reduction in emissions is 2,483 tpy. Therefore the cost-effectiveness of this approach is $1,690/ton of emission reduction (Table 8.3).

9. Use DOC plus CWI plus LSD – Total Fleet

Options 7 & 8 are combined in this case to give an increase in annual costs of $5,115,000/year and an emission reduction of 9,110 tpy. As shown in Table 8.3, the cost effectiveness of this package is $561/ton of emission reduction.

10. Use Exhaust Gas Recirculation plus DPF plus ULSD – Total Fleet

Exhaust gas recirculation (EGR) can be used to reduce NOx emissions if particulates are removed with a diesel particulate filter (DPF). The latter requires the use of ultra-low sulfur diesel (ULSD) in order to prevent poisoning of the catalyst in the DPF. A typical system is that manufactured by Johnston-Matthey.

Assume that the installed capital cost of EGR/DPF is $20,000 for a 400 hp engine, and that this cost varies according to the 2/3-power rule for capital cost versus capacity. The cost for an average, 2121 hp line haul locomotive is then $60, 820 and for an average 1164 hp yard locomotive is $40,800. Further assume that fuel consumption increases by 2% due to the EGR, amortization is 7% over 10 years, maintenance is 5% of installed capital and ULSD has a rack price of $0.895/gallon. The total annual cost increase is then estimated to be $10,857,000.

Assume that SOx is reduced by 99.61%, NOx by 40%, VOC by 95% and particulate matter by 95%. The total emission reduction is then 11,899 tpy and the cost-effectiveness of this approach is $912/ton of emission reduction.

11. Use Liquefied Natural Gas – Line Haul Locomotives

Line haul locomotives have been converted to liquefied natural gas (LNG) service so that some cost data is available. A special insulated tender is required to carry the LNG. The dual fuel conversion injects a small amount of diesel to start combustion. Gasified LNG then enters the combustion chamber to furnish most of the energy required to push the piston down. During full power most of the energy will come from the natural gas while under idle most of the energy derives from the diesel fuel. The use of natural gas is found to not only reduce emissions but also to reduce engine maintenance and lube oil requirements, as well as to increase the time between engine rebuilds. The LNG option studied here would be implemented using dual-fuel technology that results in no derating of engine power.

Assume that the cost of a duel-fuel conversion is $250,00 per engine, the cost of a LNG tender is $500,000 and that on the average one tender will serve two locomotives. Further assume that the diesel is LSD and that the average ratio of LNG: diesel is 80:20 based upon their energy content. Assume capital is amortized at 7% over 15 years, maintenance is 5%, and that the decrease in costs in engine rebuilds and lube oil can be prorated from operating data from dual-fuel ferries. [84] The total annual cost increase (less fuel) is then $3,754,000.

For natural gas with a commodity price of $5.00/MM Btu the equivalent rack price for LNG is $0.93/gallon diesel equivalent (gde). Annual fuel costs in this case would increase by $10,047,000 and the total annual operating cost increase would be $13,800,000. But if natural gas drops to $4.00/MM Btu the equivalent LNG rack price would be \$0.78/gde and the annual fuel cost would actually decrease by \$1,550,000 to give net increase in annual operating costs of \$2,204,000.

The cost-effectiveness of using LNG is extremely sensitive to the commodity price of natural gas. At \$5.00/MM Btu the cost-effectiveness is \$802/ton of emission reduction, whereas at \$4.00/MM Btu the cost-effectiveness is \$128/ton of emission reduction.

12a. Use Idle Control – Line Haul Locomotives

An effective way to reduce idling emissions and fuel consumption is to use a system similar to the Hotstart-Smartstart package that was discussed in Section 6.11. The Hotstart system uses a small, 40 hp, EPA Tier 2 diesel to warm and circulate the locomotive's fluids and to keep the batteries charged, while the Smart start system stops and starts the locomotive's engine as required. EPA Tier 2 standards (non-road engines manufactured during 2004) are 7.5 g/kWh for NOx + NMHC (non-methane hydrocarbon) and 0.60 g/kWh for PM.

Assume that the price of this package is \$35,000 and that the installed cost is \$51,000. Further assume that the 40 hp diesel operates at 70% full load and has a SFOC of 250 g/kWh, whereas the average line-haul locomotive engine burns 4 gph while idling. The annual cost for the 53 line-haul locomotives is estimated to be \$432,000/year (amortized at 7% over 15 years and a 5% maintenance charge).

The avoided fuel costs can be estimated using a fuel consumption reduction of 1.7 gph for 458,270 idling hours per year and at \$0.80/gallon to be \$623,250/year. Therefore the net cost savings per year is \$191,000.

Net emission reductions are estimated to be 420 tpy. Therefore the cost-effectiveness of this approach is estimated to be -\$456/ton of pollution reduction. In other words, operating costs can be reduced along with a reduction in emissions.

12b. Use Idle Control – Yard Locomotives

The Hotstart-SmartStart package is somewhat bulky and may not be amenable to retrofitting on all of the smaller locomotives. However, for purposes of this study it is assumed that idle control can be used on both the line haul locomotives and the smaller yard locomotives.

Again assume that the price of the package is \$35,000 and that the installed cost is \$51,000. Further assume that the 40 hp diesel operates at 70% full load and has a SFOC of 250 g/kWh, whereas the average yard locomotive engine burns about 3 gph while idling. The annual cost for the 14 yard locomotives is estimated to be $114,000/year (amortized at 7% over 15 years and a 5% maintenance charge).

The avoided fuel costs can be estimated using a fuel consumption reduction of 0.7 gph for 17,450 idling hours per year and at $0.80/gallon to be $9,773/year. Therefore the net cost for yard engine idling control per year is $104,000.

Net emission reductions are estimated to be 13.4 tpy. Therefore the cost-effectiveness of this approach is estimated to be $7,800/ton of pollution reduction. This cost is much higher than that estimated for implementing idling reduction on line-haul engines because of lower fuel savings.

13a. Re-Power with Hybrid Power System – Yard Locomotives

A hybrid diesel-battery system takes advantage of the fact that yard locomotives spend a large fraction of their time in the idle mode of operation. As discussed in Section 6.9, Rail Power will convert small locomotives to hybrid power at a cost of approximately $700,000/locomotive. The replacement engine is a 100 hp Tier 2 engine with a SFOC of about 250 g/kWh.

If the 100 hp hybrid diesel engines operate at an average of 70% full capacity and on low sulfur road diesel, the annual net fuel savings are estimated to be $758,00 for the 14 switchers. The net increase in operating cost is $314,000/year.

The net emission reduction for the 14 yard locomotives is estimated to be 311 tpy. Therefore the cost-effectiveness of this approach is $1,020/ton.

13b. Compare Hybrid Power System with Tier 1 Rebuild – Yard Locomotives

The cost-effectiveness of converting a locomotive to hybrid power can be compared with the cost-effectiveness of rebuilding it to Tier 1 requirements. The net increase in installed cost of a hybrid, as compared to a Tier 1 rebuild, is approximately $200,000 per locomotive. The annualized cost for 14 yard locomotives is $307,000/year and the annual fuel savings, per Section 13a, is $758,000. Therefore the net savings per year are $450,000.

The net emission reduction for hybrid switchers as compared to a Tier 1 rebuilt yard locomotives is 281 tpy. Therefore the net cost-effectiveness of hybrid switchers, as compared to a Tier 1 rebuilt yard locomotives, is -$1,605/ton.

In other words, hybrid conversion results not only in lower costs but also produces fewer emissions then do a Tier rebuilt yard locomotives.

8.3 Comparison of Locomotive Emission Reduction Options

The locomotive emission reduction options that were explored in this study are summarized in Table 8.3 below. For all locomotives the most cost-effective options are to rebuild the engines so that they meet EPA Tier 0 or Tier 1 standards. These options significantly reduce emissions of NOx, especially Tier 1, which reduces NOx by 44%.

Another very cost-effective option is to install an idle-control system (Hotshot heater plus Smart-Start idle control) on line haul locomotives to reduce their emissions and fuel consumption during idling. This option actually has a negative cost-effectiveness, meaning that money is saved through its implementation.

The use of liquefied natural gas (LNG) on line haul locomotives is very cost-effective if the commodity price of natural gas is $4/MM Btu or less. This option also provides the greatest reduction in total emissions. When North Slope gas or offshore LNG becomes available at a price of less than $4/MM Btu, this option will be a serious contender to reduce operating costs and to minimize emissions.

For yard engines rebuilding to Tier 0 or to Tier 1 standards are cost-effective. However, converting a locomotive to hybrid power (diesel/battery) is seen (Option 13) to be much more economical and cost-effective than rebuilding it to Tier 1 requirements. There are large savings in fuel costs available with the hybrid system.

The short-list for line haul locomotives would have to include Options 5 (remanufacture to Tier 1 plus use road diesel), Option 6 (water injection plus using road diesel) and Option 11 (idle control).

For switchers the short-list would be Option 6 (water injection plus using road diesel) and Option 12 (convert to hybrid power).

Table 8.3 - Comparison of Emission Reduction Options for Locomotives*

Control Option	Installed Cost ($1,000)	Capital Amortize ($1,000)	Increased Maintenance ($1,000)	Added Fuel Cost ($1,000)	Total Annual Cost Increase ($1,000)	Emission Reduction (Tons per year)					Cost-Effectiveness $/ton
						SOx	NOx	$PM_{2.5}$	VOC	Total	
1.Engine rebuild Tier 0	2,010	286	-	-	286	-	6,193	-	-	6,193	$46
2.Engine rebuild Tier 1	12,730	1,398	318	-72	1,644	-	9,673	-	-	9,673	$170
3. Low sulfur diesel	-	-	-	4,036	4,036	1,390	-	26.4	-	1,416	$2,850
4. Tier 0 + LSD	2,010	286	-	4,036	4,322	1,390	6,193	26	-	7,609	$568
5. Tier 1 + LSD	12,730	1,398	318	3,964	5,680	1,390	9,673	26	-	11,089	$512
6. Water Injection (CWI) + LSD	2,345	258	117	3,278	4,220	1,390	6,628	156	-	8,174	$516
7. Diesel Oxidation Catalyst (DOC) + LSD	670	95.4	67	4,036	4,198	1,390	-	182	911	2,483	$1,690
8. CWI + DOC + LSD	3,015	331	181	4,036	5,115	1,390	6,628	182	911	9,111	$561
9. EGR + DPF + ULSD	3,794	540	190	10,127	10,857	1,606	8,837	495	961	11,900	$912
10a. LNG dual fuel (line haul only; natural gas at $5/MM Btu	26,500	2,910	844	10,047	13,800	1,549	15,276	128	246	17,200	$802
10b. LNG dual fuel (line haul only; natural gas at $4/MM Btu	26,500	2,910	844	-1,550	2,204	1,549	15,276	128	246	17,200	$128
11a. Idle control (line haul only)	2,703	297	135	-623	-191	19.0	385	4.9	10.8	420	-$456
11b. Idle control (yard engine only)	714	78.4	35.7	-9.8	104	0.8	11.2	1.1	0.3	13.4	$7,815
12. Hybrid yard engines	9,800	1,076	-	-758	318	19.0	259	6.7	26.3	311	$1,022
13. Hybrid compared to rebuild to Tier 1 (Yard locomotives only)	2,800	307	-	-758	-450	19.0	228	10.3	23.9	281	-$1,605
Base-Line Annual Costs and Emissions - Total	n/a	n/a	n/a	71,760	n/a	1,612	22,093	521	1,012		

9.0 WORKBOAT EMISSION REDUCTIONS AND COSTS

9.1 Introduction

The workboat study fleet consists of 19 vessels owned and operated by the Tidewater Barge Lines on the Columbia River. These vessels typically have two large diesel engines for propulsion and may also have one or more smaller diesel gensets to provide power for lighting and electronics. Workboats are built to a Coast Guard classification system whereby the allowable tonnage is based upon vessel dimensions (volume). Therefore, care must be taken so that any modification made to reduce emissions does not increase the volume of the vessel, which would require a costly reclassification of the workboat.

Available clean-fuel emission reduction options include switching from off-road diesel to low-sulfur road diesel (LSD) and using biodiesel. However, the latter “green” fuel was not included in this study because of its high cost and increase in NOx emissions.

Applicable technology options studied include continuous water injection (CWI) for NOx control, diesel oxidation catalysts (DOC) for particulate and VOC reduction, diesel particulate filter (DPF) for particulate and VOC reduction, exhaust gas recirculation (EGR) for NOx reduction, NOx Adsorbers and PuriNOx (diesel-water fuel emulsion for NOx reduction).

Other technologies, such as selective catalytic reduction (SCR) of NOx, and liquefied natural gas (LNG), were not included because their bulk may well exceed the vessel’s classification limits. Engine tuning, where the injector timing is retarded to reduce NOx emissions, was not included because although this initiative reduces NOx by 20 – 30%, it also increases the emissions of soot (15 – 25%) and VOC (10 – 25%). [63]

The following section will estimate the emission reduction and costs associated with each of the options mentioned above. It is assumed that a reduction in VOC includes those in benzene, formaldehyde and 1,3-butadiene. Therefore 90% reduction in VOC will imply a 90% reduction in these three species. The results will be summarized in Table 9.1, which will also show changes in annual operating costs and will show the estimated cost effectiveness ($/ton of pollution reduction).

Annualized capital costs are based upon a discount rate of 7% and an amortization period of either 10 years or 15 years, depending upon the expected service life of the equipment. Annual maintenance costs are assumed to be either 5% of installed capital or 10% of installed capital, depending upon the robustness of the equipment. In the case of catalytic-containing equipment it is conservatively assumed that off-road abuse, and probable exposure to contaminated fuel will shorten the service life and increase the maintenance of these devices as compared to on-road applications. Readers may wish to estimate annual costs based upon different assumptions than those used in this study. This can easily be done using the cost summary table at the end of this section.

9.2 Workboat Emission Reduction Options

The various control options for the main engines will first be studied; these will then be followed by the different options for the smaller auxiliary engines (gensets.)

9.2.1 Main Engines

1. Baseline

For the base case it is assumed that the workboats uses 3000-ppm sulfur off-road diesel that costs $0.80/gallon. This price is a typical rack price and does not include taxes and delivery costs. These extra costs will be approximately the same for each fuel option and hence will not factor into changes in fueling costs between the different options. The annual fuel consumption was reported to be 6,603,283 gallons. This is further delineated into main engine fuel and auxiliary engine fuel based upon estimated engine hours, load factors and a SFOC of 210 g/kWh for the main engines and 243 g/kWh for the auxiliary engines, to give a fuel consumption of 58,491,000 gpy for the main engines and 753,900 gpy for the auxiliary engines.

- Annual fuel cost = 5,849,000 gpy x $0.80/gal = $4,679,000
- NOx = 1,325 tpy
- SOx = 121.8 tpy
- $PM_{2.5}$ = 29.11 tpy
- VOC = 13.95 tpy

2. Low Sulfur Diesel (LSD)

Assume 350 ppm S diesel at a $0.845/gallon. Further assume that this clean fuel reduces particulate emissions by 5% as compared with off-road, #2 diesel.

- Increased fuel cost = $263,125/year
- SOx reduction = 107.6 tpy
- $PM_{2.5}$ reduction = 1.46 tpy
- Total emission reduction = 109 tpy

The cost-effectiveness of switching to LSD is therefore estimated to be $2,413/ton of pollution reduction, reducing SOx emissions by 88.3%. SOx have negative health effects and are often responsible for regional atmospheric haze.

3a. Continuous Water Injection (CWI) plus LSD

CWI is an economical technology for reducing NOx emissions, while LSD greatly reduces SOx emissions.

Assume that the installed cost of CWI is $20,000 per vessel, amortization is 7% over 15 years, maintenance is 5% of installed cost and 50:50 fuel-water is used with water costing $2/tonne. Assume that CWI provides a 1% reduction in fuel consumption while reducing NOx and $PM_{2.5}$ by 30%.

The annual increase in costs is then estimated to be $98,478 for amortization and maintenance, and $213,700 for LSD fuel. Therefore the total annual cost increase is $312,180.

The emission reductions are estimated to be 398 tpy NOx, 8.73 tpy $PM_{2.5}$, and 107.6 tpy SOx. Therefore the cost-effectiveness of this option is calculated to be $608/ton of emission reduction.

3b. Continuous Water Injection (CWI) plus Off-Road Diesel

This option does not incur the high cost of using LSD. SOx emissions remain at 121.8 tpy.

The total annual cost increase is estimated to be $51,685, while the corresponding emission reduction is 406 tpy. Therefore the cost-effectiveness is $127/ton of emission reduction (mainly NOx).

4. Diesel Oxidation Catalyst (DOC) plus LSD

Diesel oxidation catalysts act as muffler replacements and are an effective technology for reducing emissions of VOC and the soluble portion of particulate emissions.

Assume that the installed cost of DOC is $4,000/engine which is amortized at 7% over 10 years and which has a maintenance cost of 5% of installed capital. Assume that VOC is reduced by 90% and PM by 25% due to the DOC. SOx is reduced 88% because of the ULSD.

The increase in annual costs for the main engines in the fleet is estimated to be $292,400, as shown in Table 9.1. Total emission reduction is 129 tpy, therefore the cost-effectiveness of this option is estimated to be $2,270/ton of pollution reduction. This is a relatively expensive option because it does nothing to reduce the 1,325 tpy of NOx emissions.

5. Diesel Particulate Filter (DPF) plus ULSD

Diesel particulate filters are very effective in reducing emissions of particulates and VOC. Their small size allows them to be retrofitted, as a replacement muffler, in workboats. However, ULSD must be used to prevent premature catalyst fouling.

Assume an installed cost of $20,000/engine (using the 2/3 power rule to scale from a 400 hp engine to an average ferry engine of 1362 hp), amortization at 7% over 10 years and maintenance of 10% of installed capital. The increase in annual costs is then estimated to be $740,000.

Assume that particulate emissions are reduced by 95% and VOC by 80%. SOx are reduced 99.8% because of the ULSD. Total emission reduction is 60.4 tpy and the cost-effectiveness of this option is calculated to be $4,613/ton of pollution reduction. As for Option 4, this is a relatively expensive option because it does nothing to reduce the 1,325 tpy of NOx emissions.

6. Exhaust Gas Recirculation (EGR) plus DPF plus ULSD

Exhaust gas recirculation requires a filter to remove diesel particulates (soot) that may damage the engine. Compact EGR/DPF packages are available for off-road equipment from companies such as Johnston-Matthey.

Assume that the capital cost of an EGR/DPF follows the usual 2/3-power law for equipment cost versus equipment capacity, and that the cost for a EGR/DPF for a 400 hp engine is $20,000. The capital cost for a workboat, with a main engine with an average of 1362 hp, is then $45,000 per engine. Assume amortization of 7% over 10 years and that maintenance is of 5% of capital. Further assume there are a 95% reduction in PM2.5 and VOC, and a 40% reduction in NOx. SOx are reduced 99.8% because of the ULSD. The EGR/DPF system is assumed to increase fuel consumption by about 2%.

The increased annual cost of this option is estimated to be $989,400 and the total emission reduction is 692.6 tpy (Table 9.1). Therefore the cost-effectiveness of this option is $1,428/ton of emission reduction.

7. NOx Adsorbers plus ULSD

NOx adsorption technology is still in the demonstration stage and cost data is not available. However, when the technology matures it may be viable for workboat emission reduction and hence it will be studied here. NOx “traps” are sensitive to sulfur poisoning and hence require ULSD for their use.

Assume that the installed cost of a NOx trap is similar to that for the EGR/DPF system previously studied, amortization and maintenance are the same, and that there is a 2%

fuel penalty due to the need for periodic fuel-rich pulses to regenerate the NOx trap. The annual costs will then be the same as the previous case ($989,000).

Assume that NOx is reduced by 90%, VOC by 95% and PM by 25%. SOx are reduced 99.8% because of the ULSD. The total emission reduction is therefore 1,335 tpy and the cost-effectiveness of this emerging technology will be $741/ton of emission reduction.

8. Fuel-Water Emulsion (PuriNOx) plus LSD

PuriNOx emulsions can reduce NOx emissions with no up-front capital expenditures required. However, the added cost of this fuel may not make it a cost-effective choice for emission reduction.

Assume that PuriNOx demands a $0.16/gallon premium over the rack price of diesel and that this option yields a 37% reduction in NOx and a 42% reduction in PM. SOx are reduced 99.8% because of the ULSD.

The increase in annual fuel cost is estimated to be $1,199,000 and the reduction in emissions is 610 tpy. The cost effectiveness of using the PuriNOx/ULSD emulsion is $1,965/ton of emission reduction.

9.2.2 Auxiliary Engines

On the average there will be two auxiliary engines per vessel, with each engine having an average power of approximately 160 hp. The total fuel consumption of the auxiliary engines is 754,183 gpy.

1. Baseline

Assume 3000 ppm S diesel at $0.80/gallon. The annual fuel cost is then $603,346.

- NOx emissions are 110.14 tpy
- SOx emissions are 15.7 tpy
- PM2.5 emissions are 4.05 tpy
- VOC emissions are 3.13 tpy.

2. Use Low Sulfur Diesel (LSD)

Assume LSD with 350 ppm S and a rack price of $0.845/gallon. The annual fuel cost increases by $33,940 to $637,300.

Assume SOx reduction corresponds to the reduction in fuel sulfur (88%) and that PM emissions are reduced by 5%. Total emission reduction is therefore 14.1 tpy and the cost-effectiveness of this option is $2,410/ton of emission reduction (mainly SOx).

3. Continuous Water Injection plus LSD

Assume that the installed cost for CWI on the auxiliary engines is $10,000/vessel, amortization is 7% over 15 years and maintenance is 5% of installed capital. Fuel consumption is decreased by 1% using CWI. The increase in annual costs is then $82,260.

Assume that NOx and PM emissions are reduced by 30%, and SOx emissions by 88%. The decrease in emissions is then 48.1 tpy and the resulting cost-effectiveness of this option is $1,710/ton of pollution avoidance.

4. Diesel Oxidation Catalysts plus LSD

Assume that the installed cost of the DOC is approximately $2,000 per engine; amortization is 7% over 10 years and maintenance is 5% of installed capital. The increase in annual costs due to using DOC and LSD is then $48,560.

Assume that VOC is reduced by 90% and particulate by 25%. SOx are reduced 88% because of the LSD. Total emissions are then reduced by 17.6 tpy. The cost-effectiveness of this option is calculated to be $2,760/ton of emission reduction as summarized in Table 9.1.

5. Diesel Particulate Filters plus ULSD

Assume that the installed cost of the DPF is approximately $4,100 per engine; amortization is 7% over 10 years and maintenance is 10% of installed capital. The increase in annual costs due to using DPF and ULSD is then $109,400.

Assume that PM is reduced by 95% and VOC by 80%. SOx are reduced 99.8% because of the ULSD. Total emissions are then reduced by 21.7 tpy. The cost-effectiveness of this option is calculated to be $5,040/ton of emission reduction, as summarized in Table 9.1.

6. CWI plus DOC plus LSD

This option effectively reduces NOx, VOC and SOx by combining options 2, 3 & 4.

The increase in annual cost is $96,900, while the reduction in emissions is estimated to be 51.6 tpy (Table 9.1). Therefore the cost-effectiveness is estimated to be $1,880/ton of emission reduction.

9.3 Comparison of Emission Reduction Options for Workboats

The emission reduction options that were studied for the main engines and the auxiliary engines of the workboat fleet are summarized in Table 9.1 below.

The most cost-effective option ($127/ton) for the main engines is the use of continuous water injection (CWI) to reduce NOx emissions. The next most cost-effective option ($608/ton) is the use of continuous water injection (CWI) to reduce NOx emissions and the use of low sulfur diesel (LSD) to reduce SOx emissions. The third most cost-effective option ($1,428/ton) is the use of exhaust gas recirculation (EGR) to reduce NOx emissions, the use of diesel particulate filters (DPF) to reduce particulate emissions and the use of ultra-low sulfur diesel (ULSD) to reduce SOx emissions.

For the auxiliary engines, which emit only 8.9% s much as do the main engines, the most cost effective option is to use continuous water injection (CWI) to reduce NOx emissions, either with off-road diesel or with LSD. However, these options cost considerably more than those for the main engines. Therefore it would be better to reduce emissions first from the main engines.

Table 9.1 - Comparison of Emission Reduction Options for Workboats*

Control Option	Installed Cost ($1,000)	Capital Amortize ($1,000)	Increased Maintenance ($1,000)	Added Fuel Cost ($1,000)	Total Annual Cost Increase ($1,000)	Emission Reduction (Tons per year)					Cost-Effectiveness $/ton
						SOx	NOx	$PM_{2.5}$	VOC	Total	
Main Engines											
(Main Engine Baseline)	-	-	-	4,679	-	121.8	1,325	29.11	13.95	1,490	
1. Use LSD	-	-	-	263	263	107.6	-	1.46	-	109.0	$2,413
2. CWI + LSD**	380	41.7	19	252	312	107.6	397.5	8.73	-	513.8	$608
3. CWI + #2 Diesel**	380	41.7	19	-9.0	51.7	-	397.5	8.73	-	406.2	$127
4. DOC + LSD	152	21.6	7.6	263	292	107.6	-	8.73	12.55	128.9	$2,270
5. DPF + ULSD	760	108	76	556	740	121.6	-	27.6	11.16	160.4	$4,613
6. EGR/DPF + ULSD	1,710	244	85	660	989	121.6	530.1	27.6	13.25	692.6	$1,428
7. NOx Trap + ULSD***	1,710	244	85	660	989	121.6	1,192	7.28	13.25	1,334	$741
8. PuriNOx with LSD	-	-	-	1,199	1,199	107.6	490.2	12.2	-	610.1	$1,965
Auxiliary Engines											
(Auxiliary Baseline)	-	-	-	603.3	-	15.7	110.1	4.0	3.13	133.0	
1. Use LSD	-	-	-	33.94	33.94	13.9	-	0.20	-	14.1	$2,410
2. CWI + LSD**	190	20.9	9.5	51.90	82.26	13.9	33.0	1.2	-	48.1	$1,710
3. DOC + LSD	76	10.8	3.8	33.94	48.56	13.9	-	1.0	2.7	17.6	$2,759
4. DPF + ULSD	156	22.2	15.6	71.65	109.41	15.5	-	3.8	2.4	21.7	$5,042
5. CWI + DOC + LSD**	266	31.7	13.3	51.90	96.88	13.9	33.0	2.0	2.7	51.6	$1,878

* Representative workboat fleet consists of 19 vessels from the Tidewater Barge Lines operating on the Columbia River.
** Cost of the water used in the CWI process is included in the cost of the fuel.
*** Not commercially available. Costs are assumed to be the same as those for EGR/DPF.

10.0 FERRY EMISSION REDUCTIONS AND COSTS

10.1 Introduction

The ferry fleet consists of 29 vessels operated by Washington Sate Ferries in the Puget Sound area. The vessels vary in power from that of a small ferry, powered by two 67 hp John Deere engines, up to the largest ferry, which is equipped with four 4000 hp EMD diesels.

The emission reduction options that will be explored in this section include two clean fuel options (low-sulfur, rebranded road diesel and natural gas) and five technology options (continuous water injection, diesel oxidation catalysts, diesel particulate filters, direct water injection, and selective catalytic reduction of NOx). . It is assumed here that a reduction in VOC includes those in benzene, formaldehyde and 1,3-butadiene. Therefore 90% reduction in VOC will imply a 90% reduction in these three species. The results will be summarized in Table 10.2, which will also show changes in annual operating costs and will show the estimated cost effectiveness ($/ton of pollution reduction).

10.2 Ferry Emission Reduction Options

1. Baseline

In order to facilitate the calculation of the cost-effectiveness of different emission reduction options, the vessels were classified into 4 separate groups, based upon their engine size and number of engines. Table 10.1 shows the number of vessels in each group, average engine horsepower and annual fuel consumption and the baseline emissions for each vessel grouping. Fuel consumption and emissions are given in this table in terms of metric tons (tonnes) per year. (There are 1.10 short tons per metric ton.)

The baseline fuel consumption of this fleet is 19,239,285 gallons/year of 3500 ppm S off-road diesel with an assumed price of $0.80/gallon. This price is a typical rack price and does not include taxes and delivery costs. These extra costs will be approximately the same for each fuel option and hence will not factor into changes in fueling costs between the different options. Therefore the annual baseline fuel cost is estimated to be $15,390,000.

Table 10.1 - Ferry Baseline Emissions and Fuel Consumption (tonnes/year)					
Group Designation:	**1**	**2**	**3**	**4**	Total
No.of vessels in group *	9	9	7	4	29
Main Engines					
Engines per vessel	4	2	2	4	
Total number	36	18	14	16	84
Average horsepower	3,097	2,411	1,175	964	
Average fuel (tpy)	637	216	99	248	
Vital Generators					
Total number	5	6	n/a	n/a	11
Average horsepower	148	168	n/a	n/a	
Average fuel (tpy)	41	13	n/a	n/a	
Ship Service Generators					
Total number	14	15	9	6	44
Average horsepower	592	366	224	124	
Average fuel (tpy)	70	25	7	18	
Emergency Generators					
Total number	9	9	5	n/a	23
Average horsepower	462	210	186	n/a	
Average fuel (tpy)	23	10	2	n/a	
Others					
Total number	8	8	4	n/a	20
Average gal/year	62.18	46.62	21.96	n/a	
Baseline Emissions (tpy)					
Fuel Sulfur (PPMw)	3500	3500	3500	3500	3500
SOx	254.71	118.53	25.35	25.03	423.62
NOx	1,926.66	866.42	191.52	193.47	3,178.07
PM2.5	31.64	15.47	3.37	3.27	53.75
VOC	15.96	7.78	1.55	1.57	26.85
Benzene	0.32	0.16	0.03	0.03	0.54
Fomaldehyde	1.88	0.92	0.18	0.18	3.17
1,3 Butadiene	0.03	0.02	0.00	0.00	0.05
Total Emissions/Group	2,231	1,009	222	224	3,686

Group One Classes	Group two Classes	Group three Classes	Group Four Classes
Jumbo Mk II	Issaquach	Steel Electric	Only (Po)
Jumbo Mk I	Evergreen State	Rhododendrom	Po Fast
Super		Passenger (Tyee)	

(Note that baseline emissions are estimated using literature values for emission factors and not upon actual measured vessel emissions.)

2. Use Low Sulfur Diesel (all engines)

Assume that all engines burn rebranded road diesel with a sulfur content of 350 ppm S and a rack price of $0.845/gallon. Further assume that SOx emissions are proportional to the fuel sulfur and that the cleaner fuel results in 5% less particulate emissions.

As summarized in Table 10.2, the increase in annual fuel costs is $870,000 and the reduction in emissions (mainly SOx) is 383.9 tpy. Therefore the cost-effectiveness of using road diesel (LSD) is $2,057/ton of emission reduction.

3. Continuous Water Injection (main engines) + LSD (all engines)

Continuous Water Injection (CWI) is one of the technologies available for reducing NOx emission from larger diesel engines.

Assume that all engines burn rebranded road diesel with a sulfur content of 350 ppm S and a rack price of $0.845/gallon. Assume that the installed price of CWI is $40,000, $25,000 and $30,000 for Group 1, Group 2&3 and Group 4 vessels, respectively. Assume that the equipment is amortized at 7% over 15 years and that annual maintenance is 5% of the installed cost. Further assume that water costs $2/tonne and is used 50:50 with the diesel, and that CWI provides an overall 1% reduction in fuel consumption. These assumptions result in a net annual cost increase of $962,000.

It is assumed that NOx and PM are reduced by 30% on the main engines and PM reduced by 5% on all other engines. These assumptions result in a total emission reduction of 1,405.6 tpy and a cost-effectiveness of $684/ton of emission reduction, as shown in Table 10.2.

4. Diesel Oxidation Catalysts + CWI (main engines) + LSD (all engines)

Diesel oxidation catalysts (DOC) are effective in reducing emissions of VOC's and the soluble portion of diesel particulate, whereas CWI reduces NOx emissions and LSD reduces SOx emissions.

Assume that all engines burn rebranded road diesel with a sulfur content of 350 ppm S and a rack price of $0.845/gallon. Assume that the installed price of DOC is $10,000, $8,000, $6,000 and $5,000 for Group 1, Group 2, Group 3 and Group 4 main engines, respectively. Assume that the DOC equipment is amortized at 7% over 10 years and that annual maintenance is 10% of the installed cost. (The CWI assumptions are the same as those listed in the previous option.) These assumptions result in a net annual cost increase of $1,234,000.

It is assumed that NOx is reduced by 30%, VOC by 90% and PM reduced by 50% on the main engines and that PM is reduced by 5% on all other engines. These assumptions result in a total emission reduction of 1,435 tpy and a cost-effectiveness of $783/ton of emission reduction, as shown in Table 10.2.

5. Direct Water Injection (main engines) + LSD (all engines)

Direct Water Injection (DWI) is a technology available from Wartsila that can reduce NOx emissions by 50% and particulate by 30%. Typical installed price is given as $20/kW. [28]

Assume that all engines burn rebranded road diesel with a sulfur content of 350 ppm S and a rack price of $0.845/gallon. Assume that the installed price of DWI is $46,180, $35,960, $17,520 and $14,380 for Group 1, Group 2, Group 3 and Group 4 main engines, respectively. Assume that the DWI equipment is amortized at 7% over 15 years and that annual maintenance is 5% of the installed cost. Further assume that water used in DWI costs $2/tonne and is used 50:50 with the diesel. These assumptions result in a net annual cost increase of $1,433,000.

It is assumed that NOx is reduced by 50% and PM reduced by 30% on the main engines and that PM is reduced by 5% on all other engines. These assumptions result in a total emission reduction of 2,053 tpy and a cost-effectiveness of $698/ton of emission reduction, as shown in Table 10.2.

6. Selective Catalytic Reduction (main engines) + LSD (all engines)

Selective Catalytic Reduction (SCR) is an extremely effective, but somewhat bulky and expensive technology for reducing emissions of NOx.

A survey of cost data from various published sources indicate that the installed cost of SCR is about $90/kW for the main engines. An EPA analysis [54] assumes that urea costs $0.3173/kg and that it is used at a rate of 7.5% of the fuel consumption rate, and that maintenance is 7.5% of capital. These assumptions result in a net annual cost increase of $4,488,100.

It is assumed that NOx is reduced by 90% and PM reduced by 30% on the main engines and that PM is reduced by 5% on all other engines. These assumptions result in a total emission reduction of 3,037 tpy and a cost-effectiveness of $1,341/ton of emission reduction, as shown in Table 10.2.

7. Liquefied Natural Gas (main engines) + LSD (auxiliary engines)

Ferries and other vessels have been converted to compressed natural gas (CNG), duel-fuel service so that some cost data is available. Typically the cost for converting to duel-fuel, using CNG, is about $210/kW. It is assumed that the cost for using liquefied natural gas (LNG) will be slightly higher (e.g. $220/kW) due to the requirement for an LNG vaporizer.

The dual fuel conversion injects a small amount of diesel to start combustion. Gasified LNG then enters the combustion chamber to furnish most of the energy required to push the piston down. During full power most of the energy will come from the natural gas while under idle most of the energy derives from the diesel fuel. For ferryboats, which spend a significant proportion of their total operating time loading and unloading passengers and vehicles, the energy ratio of natural gas to diesel is approximately 60:40.[126] The use of natural gas is found to not only reduce emissions but also to reduce engine maintenance and lube oil requirements, as well as to increase the time between engine rebuilds.

Assume that the LNG duel-fuel conversion costs $220/kW and can be amortized over 15 years at 7%, maintenance is 5% of one-half of the total installed price and that costs savings in lube oil and engine rebuilds can be prorated from those presented by MDA for the Albion ferries. [126] The installed cost is then estimated to be $30,636,000 and the net increase in annual costs (less fuel) equals $3,019,000.

From literature data the emission reductions for the main engines are assumed to be 60% for NOx, 72% for PM, 50% for VOC and for SOx 100% on 60% of the fuel and 90% on the remaining 40% diesel portion of the fuel. The emission reduction for the auxiliary engines is assumed to be due to the SOx related to the reduction in fuel sulfur (90% reduction). These assumptions result in a total emission reduction of 2,432 tpy.

For a natural gas commodity price of $5.00/MM Btu the cost of LNG is approximately $0.93/gde (gallon diesel equivalent). Assuming low sulfur diesel at $0.845/gallon the annual fuel cost for the main engines is $14,963,000 and for the auxiliaries is $2,146,000. The increase in annual fuel costs is therefore $1,719,000 and the total increase in operating costs is $4,738,000. This results in cost-effectiveness for LNG duel-fuel of $1,948/ton of pollution reduction, when natural gas costs $5.00/MM Btu.

Similar cost-effectiveness estimates can be carried out for natural gas at $4.00/MM Btu (LNG costing $0.78 gde) and for natural gas at $3.00/MM Btu (LNG at $0.64/gde). In these cases the estimated cost-effectiveness of LNG duel-fuel reduces to $1,330/ton and $753/ton, respectively.

10.3 Comparison of Ferry Emission Reduction Options

The 6 emission reduction options that were considered for reducing emissions from ferries are summarized in Table 10.2 below. Also shown, for purposes of comparison at the bottom of the table, are the annual fuel costs and emissions (tons per year).

The most cost effective technologies appear to be those involving the addition of water to reduce NOx emissions (Options 2,3&4). SCR provides the greatest total emission reduction (82%) but at approximately twice the cost per ton of emission reduction.

LNG provides significant reductions in emissions, even for the 60:40 natural gas/diesel ratio assumed in this study, but at a high installed capital cost that increases the cost per ton of pollution reduction well above the more economical options.

Table 10.2 - Comparison of Emission Reduction Options for Ferries*

Control Option	Installed Cost ($1,000)	Capital Amortize ($1,000)	Increased Maintenance ($1,000)	Added Fuel Cost** ($1,000)	Total Annual Cost Increase ($1,000)	Emission Reduction (tons per year)					Cost-Effectiveness $/ton
						SOx	NOx	$PM_{2.5}$	VOC	Total	
1. LSD (main engines & auxiliaries)	-	-	-	870	870	420.1	-	3.0	-	423	$2,057
2. CWI (mains) + LSD (all engines)	855	93.9	42.8	825	962	420.1	970.5	15.0	-	1,406	$684
3.CWI + DOC (mains) + LSD (all engines)	1,523	189	110	825	1,124	420.1	970.5	24.6	19.2	1,435	$783
4. DWI (mains) + LSD (all engines)	2,785	306	139	988	1,433	420.1	1,618	15.0	-	2,053	$698
5. SCR (mains) + LSD (all engines)	12,533	1,422	940	2,126	4,488	420.1	2,912	15.0	-	3,347	$1,341
6a.LNG (mains) + LSD (all engines). Natural gas at $5.00/MM Btu	30,636	3,364	-345	1,719	4,738	444.4	1,941	35.2	10.9	2,432	$1,948
6b. LNG (mains) + LSD (all engines). Natural gas at $4.00/MM Btu	30,636	3,364	-345	216	3,235	444.4	1,941	35.2	10.9	2,432	$1,330
6c. LNG (mains) + LSD (all engines). Natural gas at $3.00/MM Btu	30,636	3,364	-345	-1,188	1,831	444.4	1,941	35.2	10.9	2,432	$753
Baseline cost & emissions				15,390		466.8	3,502	59.2	29.6	4,058	-

* Ferry fleet consists of 29 vessels owned by Washington State Ferry and operating in the Puget Sound area.
** Cost of the water used in the CWI and DWI processes and urea used in the SCR process is included in the cost of the fuel.

11.0 CRUISE SHIP EMISSION REDUCTIONS AND COSTS

11.1 Introduction

As discussed in Section 4, the cruise ship “fleet” is based upon a representative vessel and upon known annual visits by 22 different vessels to the Port of Seattle. Cruise ships typically have several large medium-speed diesel gensets which produce the electrical power needed to drive electric propulsion motors, maneuvering thruster motors, navigation gear and hoteling requirements. The fuel used in these ships is usually an intermediate fuel oil (IFO 180) with a sulfur content of 2.4%. Some of the newer vessels are incorporating gas-turbine driven gensets, which burn much cleaner marine gas oil (MGO) and which provide significantly lower emissions than do the more common diesel-powered gensets burning IFO 180.

An alternative fuel to IFO 180 is marine diesel oil (MDO), which has much lower sulfur content than does IFO 180. The MDO fuel usually is specified to meet ISO 8217 standards with a minimum flash point of 60°C. In some instances MDO may simply be rebranded, low-sulfur road diesel. However, not all fuel suppliers can supply road diesel with a minimum flash point of 60°C, especially if only small lots are requested.

Prices for marine fuels are available on the Internet and are quoted in US$/metric ton. As of August 13, 2003 the price in the PNW for IFO 180 was $185/tonne, for MDO was $275/tonne and for MGO was $305/tonne. In addition to these costs there will be other minor costs, such as barging costs. But these added costs will be similar for the different marine fuels and hence will not be considered in this study.

Cruise ships spend much of their time moored at dock with two or more of their diesel gensets providing hoteling power for the ship (lighting, heating, air-conditioning, electronics, etc.). Any emission reduction study must investigate ways to reduce these hoteling emissions, which typically occur in the core area of a city.

Emission reduction options that are studied in this report include using MDO instead of IFO 180, using continuous water injection (CWI) to reduce NOx, using direct water injection (DWI) to reduce NOx, using a gas turbine to reduce all emissions, using selective catalytic reduction (SCR) to reduce NOx and using shore power to reduce hoteling emissions.

The following section will estimate the emission reduction and costs associated with each of the options mentioned above. It is assumed that a reduction in VOC includes those in benzene, formaldehyde and 1,3-butadiene. Therefore 90% reduction in VOC will imply a 90% reduction in these three species. The results will be summarized in Table 11.1, which will also show changes in annual operating costs and will show the estimated cost effectiveness ($/ton of pollution reduction).

11.2 Cruise Ship Emission Reduction Options

1. Baseline – All Modes

Assume 2.4%-sulfur, IFO 180 fuel oil is burned by all engines and that this fuel costs $185/tonne. Annual fuel consumption for the 22-vessel fleet operating within Washington is estimated to be 1,632.6 tonnes while hoteling and 6,335 tonnes while cruising, based upon a fleet average SFOC of 208.3 g/kWh and upon the assumptions presented in Section 4.

The annual fuel costs for the fleet of 22 vessels is then 7,968 tonnes x $185/tonne = $1,474,000.

The baseline emissions in Section 4 are listed for SOx as 421.6 tpy, for NOx 700.0 tpy, for PM2.5 are 66.7 tpy and for VOC as 78.0 tpy.

2a. Use MDO Fuel – All Modes

Assume that MDO fuel costs $275/tonne and that it contains 0.13% sulfur. The increase in fuel costs for the fleet is then $717,080/year.

Assume that SOx emissions are reduced in proportion to the fuel sulfur content and that PM is reduced 10% because of the cleaner fuel. The total emissions are therefore reduced by 405.5 tpy and the cost-effectiveness of this option is $1,769/ton of emission reduction (mainly SOx).

2b. Use MDO Fuel – Hoteling Only

Using the same assumptions as above, the increase in fuel cost for the 1,633 tonnes of fuel burned while hoteling amounts to $146,930, while the decrease in emissions is estimated to be 83.0 tpy. Therefore the cost-effectiveness of this hoteling option is $1,838/ton of emission reduction.

3. Use Continuous Water Injection – All Modes

Continuous water injection (CW) is a relatively low cost method for reducing NOx emissions.

Assume that CWI is installed on all engines at a cost of $60,000/vessel, that the equipment is amortized at 7% over 15 years and that annual maintenance is 5% of the installed cost. Further assume that water costs $2/tonne and is used 50:50 with the diesel, and that CWI provides an overall 1% reduction in fuel consumption. These assumptions result in a net annual cost increase of $212,130.

Assume that NOx and PM2.5 are reduced by 30%. The total emission reduction is then 230 tpy and the cost-effectiveness of this option is $922/ton of emission reduction.

4a. Use Continuous Water Injection + MDO – All Modes

The use of CWI & MDO reduces both NOx and SOx emissions.

The cost assumptions are the same as those for options 2a and 3 above. The total annual cost increase (Table 11.1) will be $922,040 and the emission reduction will be 644.3 tpy. Therefore the cost effectiveness of this option is $1,430/ton.

4b. Use Continuous Water Injection + MDO – Hoteling Only

Assume that CWI is installed only on the two engines that are used for hoteling, and that the installed cost per vessel is $40,000. Other CWI/MDO assumptions were presented in option 3 above.

The annual cost is estimated to be $286,333 and the associated emission reduction is 131.9 tpy. Therefore the cost effectiveness of this hoteling option is $2,170/ton.

5a. Use Direct Water Injection + MDO – All Modes

Direct Water Injection (DWI) is a technology available from Wartsila that can reduce NOx emissions by 50% and particulate by 30%. Typical installed price is given as $20/kW. [28]

Assume that all engines burn MDO with a sulfur content of 0.13% S and a price of $275/tonne. Assume that the installed price of DWI is $89,250 per engine for the two V12's and $60,000 per engine for the two V-8's. Assume that the DWI equipment is amortized at 7% over 15 years and that annual maintenance is 5% of the installed cost. Further assume that water used in DWI costs $2/tonne and is used 50:50 with the diesel. These assumptions result in a net annual cost increase of $1,782,435.

It is assumed that NOx is reduced by 50% and PM reduced by 30%. These assumptions result in a total emission reduction of 762.1 tpy and a cost-effectiveness of $2,339/ton of emission reduction, as shown in Table 11.1.

5b. Use Direct Water Injection + MDO – Hoteling Only

It is assumed that DWI is installed only on the two V-8 engines. Other assumptions are listed above in option 5a. The total annual cost of this option is estimated to be $572,070 and the reduction in emissions is 156.2 tpy, therefore the cost-effectiveness is calculated to be $3,664/ton of emission reduction while hoteling.

6. Use a Gas Turbine + MGO – All Modes

The use of a gas turbine was discussed in Section 6.10. This power source can offer dramatic reductions in weight and in emissions, as compared to a diesel engine, but at a higher capital and annual fuel cost.

We assume that the incremental cost of the gas turbine is $6.91M, that this cost is annualized over 15 years at 7%, that maintenance is the same as that for diesel engines of the same capacity and that the gas turbine burns 0.13% sulfur MGO (marine gas oil) costing $305/tonne with a SFOC (specific fuel oil consumption) of 220 g/kWh, as compared with a SFOC for the diesel engines of 208.3 g/kWh. These assumptions result in a total annual cost of $17,777,000.

Assuming gas turbine emission factors of 4.5 g/kWh for NOx, 0.174 g/kWh for PM2.5, 0.0059 g/kWh for VOC and that the SOx reduction is equivalent to the fuel sulfur reduction, the total emission reduction is estimated to be 1,105 tpy. Therefore the cost-effectiveness of using a gas turbine for emission reduction in the Puget Sound region is calculated to be $16,090/ton of emission reduction.

6a. Use Selective Catalytic Reduction + MDO – All Modes

Selective Catalytic Reduction (SCR) is an extremely effective, but large and expensive technology for reducing emissions of NOx. It requires the use of a low sulfur, such as MDO fuel to prevent poisoning of the catalyst

A survey of cost data from various published sources indicate that the installed cost of SCR is about $90/kW for the main engines. An EPA analysis [54] assumes that urea costs $0.3173/kg and that it is used at a rate of 7.5% of the fuel consumption rate, and that maintenance is 7.5% of capital. Assuming that SCR is installed only on the two V-12 engines, which are then used exclusively within the Puget Sound area, the installed cost is estimated to be $782,800/vessel. These assumptions result in a net annual cost increase of $3,536,000 for the entire 22-vessel fleet that visits the Port of Seattle, as detailed in Table 11.1.

It is assumed that NOx is reduced by 80% and PM reduced by 30% on the main engines and that PM is reduced by 5% on all other engines. These assumptions result in a total emission reduction of 999 tpy and a cost-effectiveness of $3,999/ton of emission reduction.

6b. Use Selective Catalytic Reduction + MDO – Hoteling Only

Assume that SCR is installed only on the two V-8 engines at a cost of $550,000/vessel. Other cost assumptions are given in option 6a above. The total increase in annual costs for 22 vessels is $2,140,000 and the reduction in emissions is 204.6 tpy. Therefore the cost effectiveness of this option, if used only during the hoteling mode of operation, is estimated to be $10,258/ton of emission reduction.

7. Use Shore Power – Hoteling Only

Shore power is an effective way to reduce cruise ship emissions within an urban core, however, part of the emission reductions will be offset by the emissions that are produced elsewhere during generation of the replacement electricity. If the utility's main source of power is from hydroelectric sources or from advanced-cycle gas turbines equipped with high-efficiency SCR's, then the emission offsets will be minimal.

Shore power has been studied elsewhere[15] for emission reduction in the Port of Vancouver. The cost for two terminals was estimated to be $22M, with an additional cost of $0.5M/vessel for internal modifications. For purposes of this study we assume that these costs are also applicable to the Port of Seattle and that 22 vessels share the two terminals. Further assume that capital is amortized over 15 years at 7%, maintenance is 2% of installed capital and electricity is 50 mils ($0.05/kWh).

The annual electrical energy cost is estimated to be $391,800 while the avoided fuel cost (IFO 180 at $185/tonne) is $302,030. Therefore the net energy cost is only $89,800/year. However, the high capital costs that are shared among 22 vessels result in an annual cost increase to the fleet of $2,945,000.

If it is assumed that there are no emission off-sets then the total emission reduction is 259.5 tpy and the cost-effectiveness of this hoteling option is $11,353 per ton of emission avoidance.

11.3 Comparison of Cruise Ship Emission Reduction Options

The emission reduction options discussed above are summarized in Table 11.1 below.

The lowest capital cost option is to switch to the use of MDO while in the Puget Sound area, this reduces SOx emissions by 94% and total emissions by 32% at a cost of $1,770/ton. The most cost-effective option is to use continuous water injection (CWI) while in the Puget Sound area, this reduces NOx emissions by 30% and total emissions by 18% at a cost of $922/ton. No SOx reduction is realized when CWI is used without also using a cleaner fuel. When CWI is used with MDO fuel total emissions are reduced by 644 tons (51%) at a cost of $1,431/ton.

Direct water injection used in conjunction with MDO is also cost-effective ($2,340/ton) but the technology, while readily available for Wartsila marine diesels, may be a more difficult retrofit for engines made by other manufacturers.

The use of a gas turbine yields the greatest emission reductions, 1,105 tons or 87%, but at a high capital cost ($152 M above the cost of equivalent diesel engines) and high fuel cost ($17.8 M above the cost of using diesel engines and IFO 180). However, a gas turbine is a small, low-weight package that may well result in more revenue-generating passenger capacity, thereby offsetting its greater costs.

SCR provides almost the same emission reduction as gas turbines, but at a much lower cost ($17.2M vs. $152M). The cost-effectiveness of SCR is $3,630/ton and the total emission reduction is 79%.

The most cost-effective options for Cruise Ship emission reduction within the Puget Sound area are the use of MDO with or without CWI and the use of DWI on those marine diesel engines that accommodate it. SCR looks attractive if large emission reductions are desired at a cost well below that of using a gas turbine. A more in-depth study would be required to assess the trade-offs between emission reductions, operating costs and passenger capacities.

It can be seen that the use of shore power to reduce hoteling emissions (option 7) is expensive ($22M installed capital and $2.9M annual cost for the 22 vessel fleet). However, the hoteling emissions of 259 tons/year are eliminated in an urban core area through the use of shore power. A much more cost effective approach is the use of MDO with or without CWI and the use of DWI on those marine diesel engines that accommodate it. The implementation of SCR solely to reduce hoteling emissions is not cost-effective and is not recommended.

Table 11.1 - Comparison of Emission Reduction Options for Cruise Ships*

Control Option	Installed Cost ($1,000)	Capital Amortize ($1,000)	Increased Maintenance ($1,000)	Added Fuel Cost** ($1,000)	Total Annual Cost Increase ($1,000)	Emission Reduction (tons per year)					Cost-Effectiveness $/ton
						SOx	NOx	$PM_{2.5}$	VOC	Total	
1a. MDO – all modes	-	-	-	717	717	399	-	6.7	-	406	$1,769
1b. MDO – hoteling only	-	-	-	145	145	81.7	-	1.3	-	83.0	$1,838
2. CWI – all modes	1,320	145	66	1.2	212	-	210	20.0	-	230	$922
3a. CWI + MDO - all modes of operation	1,320	145	66	711	922	399	210	35.5	-	644	$1,431
3b. CWI + MDO – hoteling only	880	97	44	146	286	81.7	43.0	7.3	-	132	$2,170
4a. DWI + MDO - all modes of operation	6,567	721	328	733	1,782	399	350	13.3	-	762	$2,339
4b. DWI + MDO – hoteling only	2,640	290	132	150	572	81.7	71.7	2.7	-	156	$3,664
5. Gas Turbine - all modes of operation	152,000	16,680	-	1,093	17,773	398	586	44.0	77.8	1,105	$16,100
6a. SCR + MDO - all modes of operation	17,222	1,891	861	871	3,623	399	560	40.0	-	999	$3,628
6b. SCR + MDO - hoteling only	12,100	1,328	605	207	2,140	81.7	115	7.9	-	205	$10,458
7. Shore Power - hoteling	22,000	2,415	440	89.8	2,946	86.4	143	13.6	16.0	259	$11,353
Baseline fuel cost & emissions – all modes				1,474		422	700	66.7	78.0	1,267	

* Cruise ship fleet consists of 22 vessels that visit the Port of Seattle.
** Cost of the water used in the CWI and DWI processes and urea used in the SCR process is included in the cost of the fuel.

12.0 DISCUSSION and CONCLUSIONS

This section will summarize the technology and clean-fuel options available for the different fleets of non-road, diesel-engined mobile sources.

12.1 Construction Equipment Options

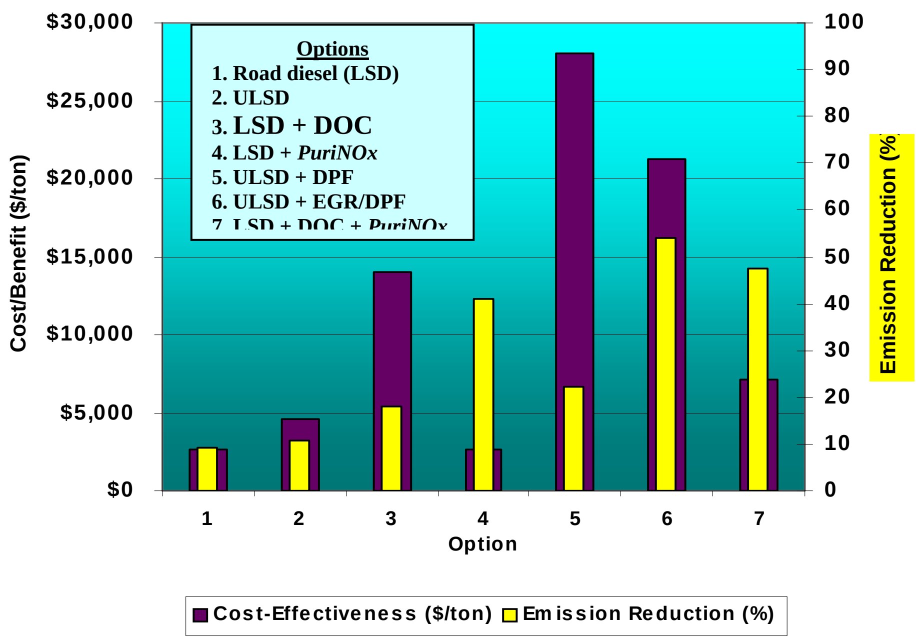
The construction equipment used as a representative study "fleet" in this study consists of 12 pieces of equipment, out of a total of 375 pieces of off-road diesel-engined equipment, that are owned by the City of Seattle. The City dispenses fuel from their own fueling facilities, using ULSD since the HDD on-road fleet, which may use catalytic particulate filters and oxidation catalysts, uses the same fuel. However, for this study it is assumed that a more representative fuel for construction equipment would be high-sulfur (3,000 ppm S) off-road diesel.

The cost-effectiveness, expressed as a cost/benefit ratio, and the percent emission reduction provided by these different options are illustrated in Figure 12.1 below. The best options give the greatest emission reduction (yellow bars) with the least cost (purple bars). It is apparent that options 1, 2, 4 & 7 are the most cost-effective (least cost/benefit ratios) options while options 4, 6 and 7 provide the greatest emission reduction.

Options 1 and 2, using low-sulfur diesel (LSD) and ultra-low sulfur diesel (ULSD), are two of the most cost-effective options but with little reduction in overall emissions.

Option 4, using a *PuriNOx* emulsion of water and low-sulfur diesel, provides both a low cost/benefit ratio and a large emission reduction. Similarly, Option 7 (LSD/PuriNOx +

Figure 12.1 - Construction Equipment Options



diesel oxidation catalyst) provides both a low cost/benefit ratio and a large emission reduction.

Option 6, the combination of exhaust gas recirculation (EGR) and diesel particulate filter (DPF) plus ULSD fuel, gives the greatest emission reduction but at a very high cost.

From this analysis it would appear that the most cost-effective choices for construction equipment consist of combinations of low-sulfur diesel (to reduce SOx emissions), *PuriNOx* (to reduce emissions of NOx and particulates) and diesel oxidation catalysts (to reduce VOC emissions).

S2 Locomotive Options

The locomotive "fleet" consists of 53 line-haul and 14 yard engines operated by BNSF in the Pacific Northwest (Washington and Oregon) and does not include the transcontinental stock. The average rating of the line-haul engines is 2121 hp, while that of the yard engines is 1164 hp. Baseline emissions and fuel costs are based upon the fleet using #2 diesel with 0.254% sulfur and costing $0.80/gal.

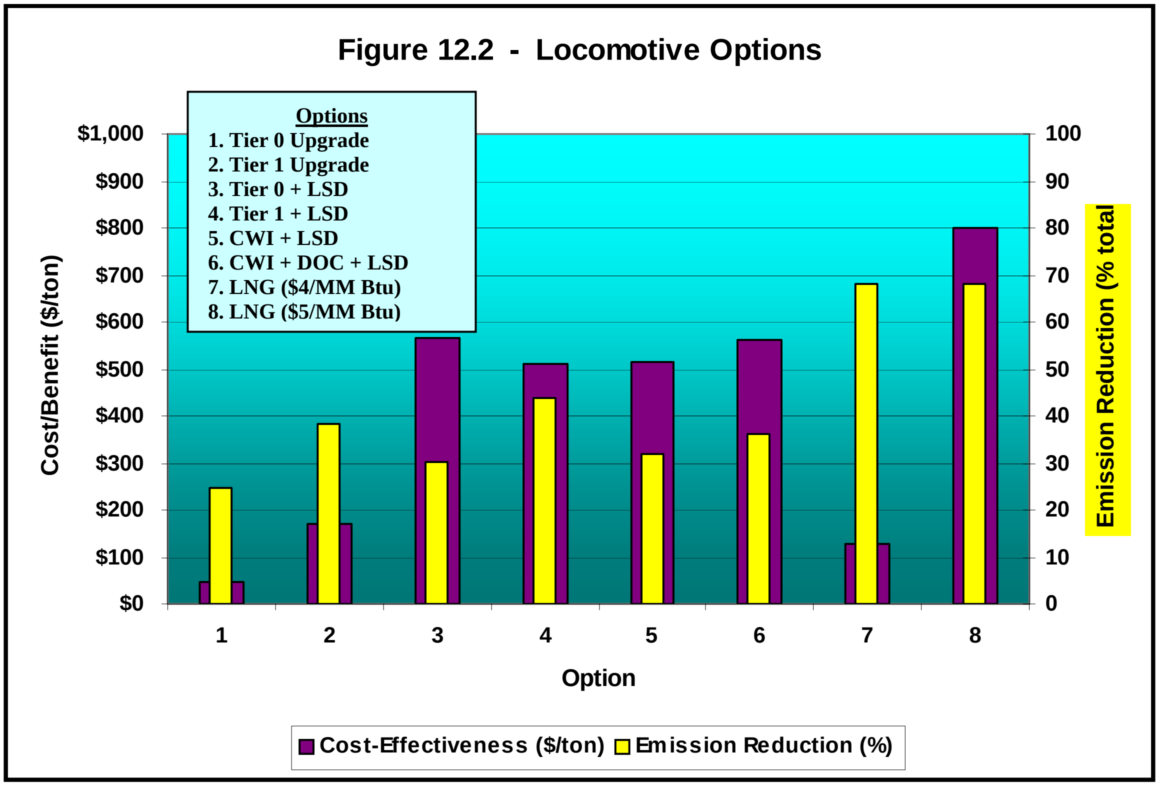
Table 8.1 in Section 8 presented a detailed summary of costs and emission reductions for the different options that were investigated and compared these values with those representative of locomotives operating in the Pacific Northwest.

Figure 12.2 compares the cost-effectiveness ($/ton of emission reduction) and the percent emission reduction for the different options. These options were applied to line-haul and yard engines except for the LNG options, which were applied only to those on line-haul.

The engine upgrades (Tier 0 and Tier 1) are cost-effective and produce significant reductions in NOx emissions. Similarly, Option 7 (using LNG duel-fuel in line-haul locomotives) is cost-effective if natural gas is available at a commodity price of $4/MM Btu. But if natural gas is only available at a commodity price of $5/MM Btu or higher, which may be the case until less expensive, offshore LNG becomes available, than LNG is not cost-effective (Option 8). The LNG option would be implemented using dual-fuel technology that results in no derating of engine power.

Not shown in Figure 12.2 is the Hotstart/SmartStart idle-control system for locomotives, which actually has a negative cost-effectiveness for line-haul locomotives (-$456/ton of idling emission reduction) and an idling emission reduction of 82%. This package greatly reduces fuel consumption during idling and therefore actually saves enough money on reduced fuel consumption to pay for the installation! However, the Hotstart system is not cost effective for the smaller yard engines ($7,815/ton of idling emission reduction), even though an 84% idling emission reduction is realized, due to much lower net fuel savings (lower operational time plus smaller engines).

For yard engines a viable option is the conversion of the locomotive to hybrid, diesel-battery power. A hybrid system takes advantage of the fact that yard locomotives spend a



large fraction of their time in the idle mode of operation. As discussed in Section 8, a hybrid replacement has a cost-effectiveness of $1,022/ton of emission reduction and reduces yard emissions by over 95%. However, if the cost of converting a yard engine to hybrid power is compared with the cost of rebuilding the engine to Tier 1 standards, then the cost-effectiveness becomes -$1,605. In other words, converting to hybrid power incurs a much lower annual cost than does rebuilding to Tier 1. Also, an emission reduction of 86% is realized over that obtained from the Tier 1 rebuild.

12.3 Workboat Options

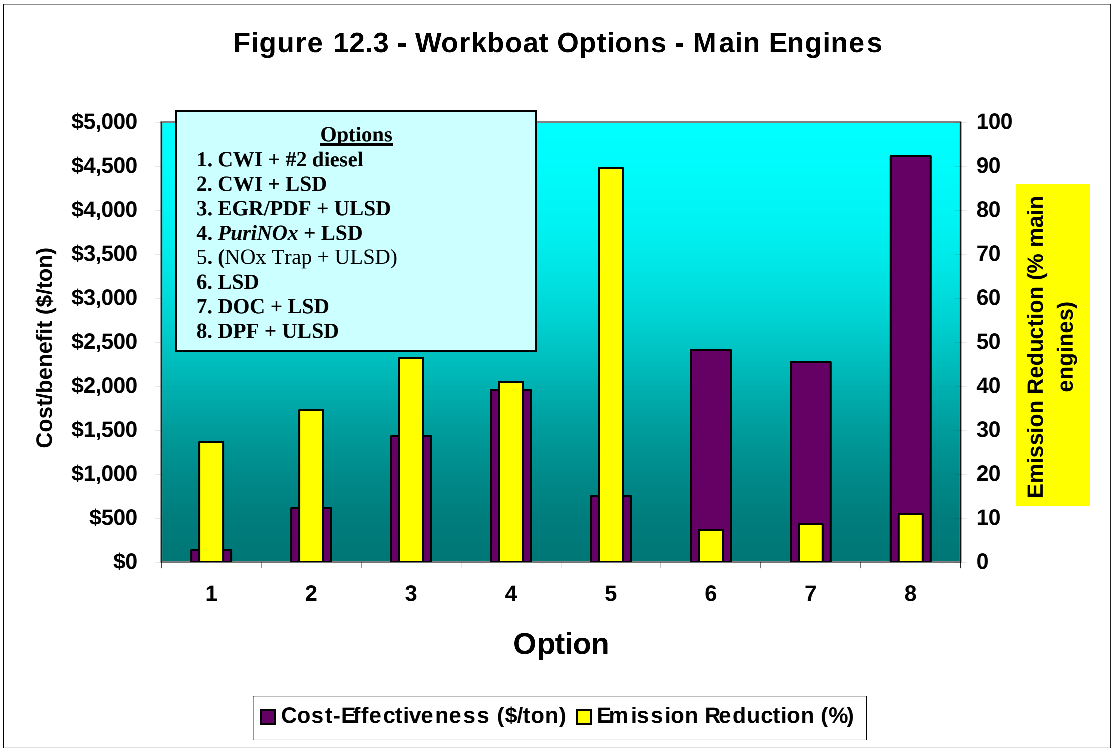
The representative workboat fleet that formed the basis of this study consists of 19 vessels owned and operated by the Tidewater Barge Lines on the Columbia River. These vessels typically have two larger, medium-speed diesel engines for propulsion and may also have one or more smaller, high-speed diesel gensets to provide power for lighting and electronics.

For purposes of this study to estimate the baseline emissions it is assumed that workboats in the PNW will generally use an off-road diesel averaging 3000 ppm S.

The emission reduction options that were considered for the **main engines** are:

1. Use continuous water injection (CWI) with the off-road diesel to reduce NOx emissions.
2. Use CWI with LSD to reduce NOx and SOx emissions.
3. Use exhaust gas recirculation (EGR) and diesel particulate filters (DPF) with ULSD to reduce NOx, particulate matter and SOx emissions.
4. Use a water-diesel emulsion (*PuriNOx*) with LSD to reduce emissions of NOx, particulates and SOx.
5. Use a "NOx Trap" to remove NOx from the exhaust (these are still in the prototype stage but are expected to become commercially available within a few years; their use requires ULSD to prevent poisoning of the catalyst).
6. Switch from off-road diesel to LSD to reduce SOx emissions.
7. Use diesel oxidation catalyst (DOC) in combination with LSD to reduce emissions of VOC compounds and the soluble portion of diesel particulates.
8. Use diesel particulate filters to reduce particulate emissions and VOC emissions.

The cost-effectiveness ($/ton of total pollution reduction) and percent emission reduction for these different options is shown in Figure 12.3.

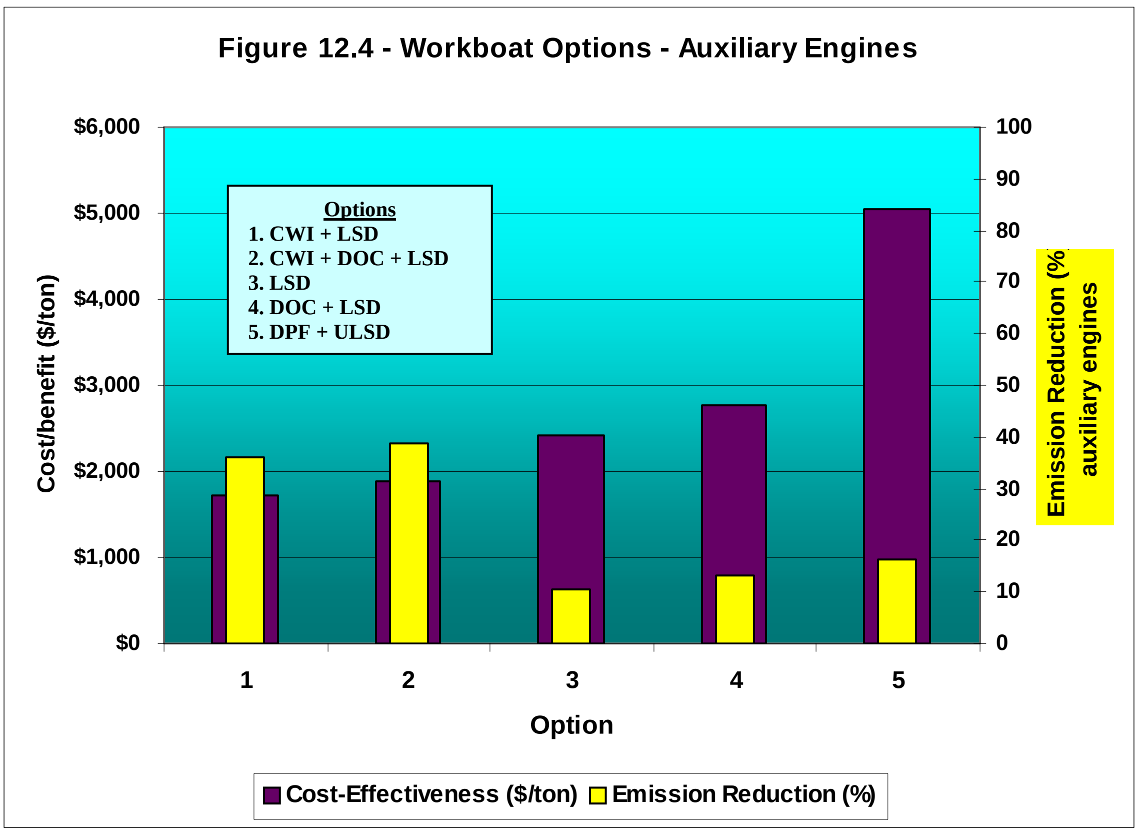


From Figure 12.3 it can be seen that the options with the lowest cost/benefit ratio are the first five, while the greatest emission reductions are afforded by options 2, 3, & 4. (Option 5 the catalytic "NOx trap" provides the greatest emission reduction at the most favorable cost/benefit ratio, but this technology is not yet commercially available at the time of this writing.)

The first three options are the most cost-effective of those commercially available. Option 3 – the EGR/DPF system (commercially available from Johnson-Matthey) - appears to yield a good compromise between effectiveness and emission reduction.

Engine-replacements were not included in this study because of their extremely high cost. They would not be cost-effective unless supported by a program similar to California's Carl Moyer program.

The five options that were considered for the auxiliary engines of the workboats are



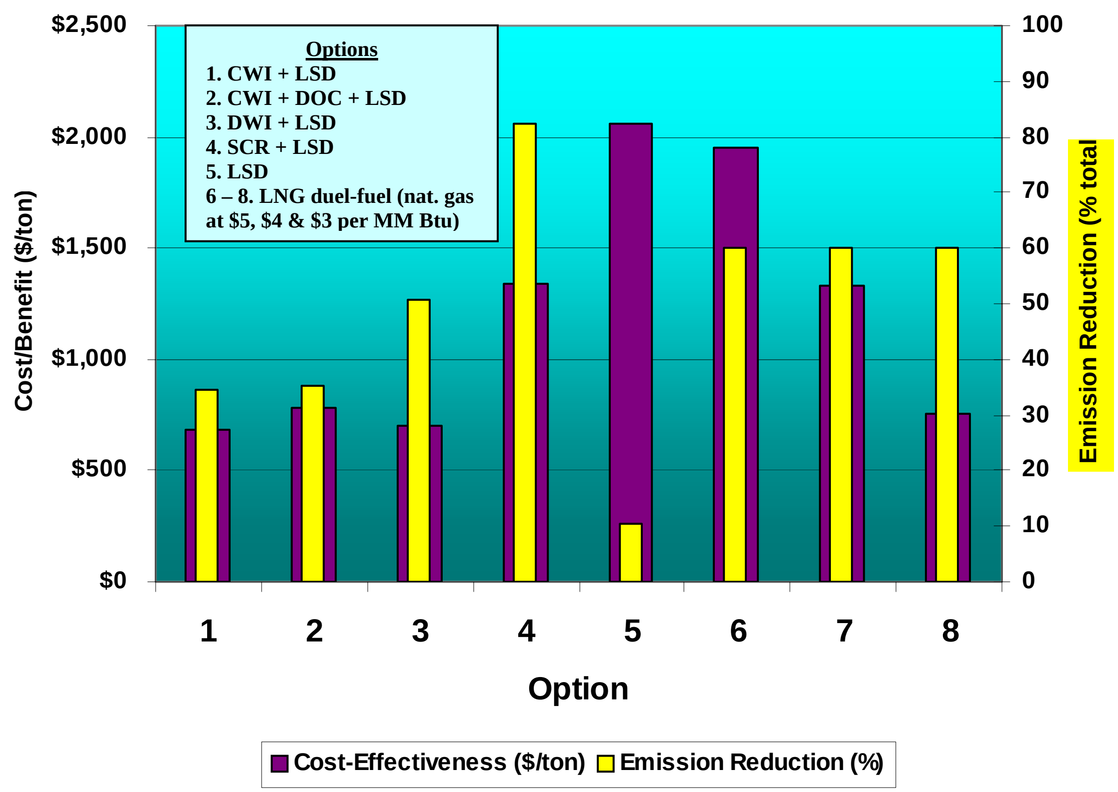
shown in Figure 12.4 below. The two most cost-effective options are seen to be using CWI with LSD to reduce NOx and SOx emissions, and CWI with DOC and LSD to reduce emissions of NOx, VOC, particulates and SOx. The other three options, by themselves, have a greater cost/benefit ration and a lower emission reduction.

12.4 Ferry Options

The representative ferry fleet that is used as a basis for this study consists of 29 vessels operated by Washington Sate Ferries in the Puget Sound area. The vessels vary in power from that of the smallest ferry, powered by two 67 hp John Deere engines, up to the largest ferry, which is equipped with four 4,000 hp EMD diesels. The ferries typically burn high-sulfur (3,500 ppm S) off-road diesel.

The different emission reduction options that were studied for ferry engines are shown in Figure 12.5. The different technological options are applied to the main engines only, while the use of low sulfur diesel (LSD) was applied to all engines.

Figure 12.5 - Ferry Options



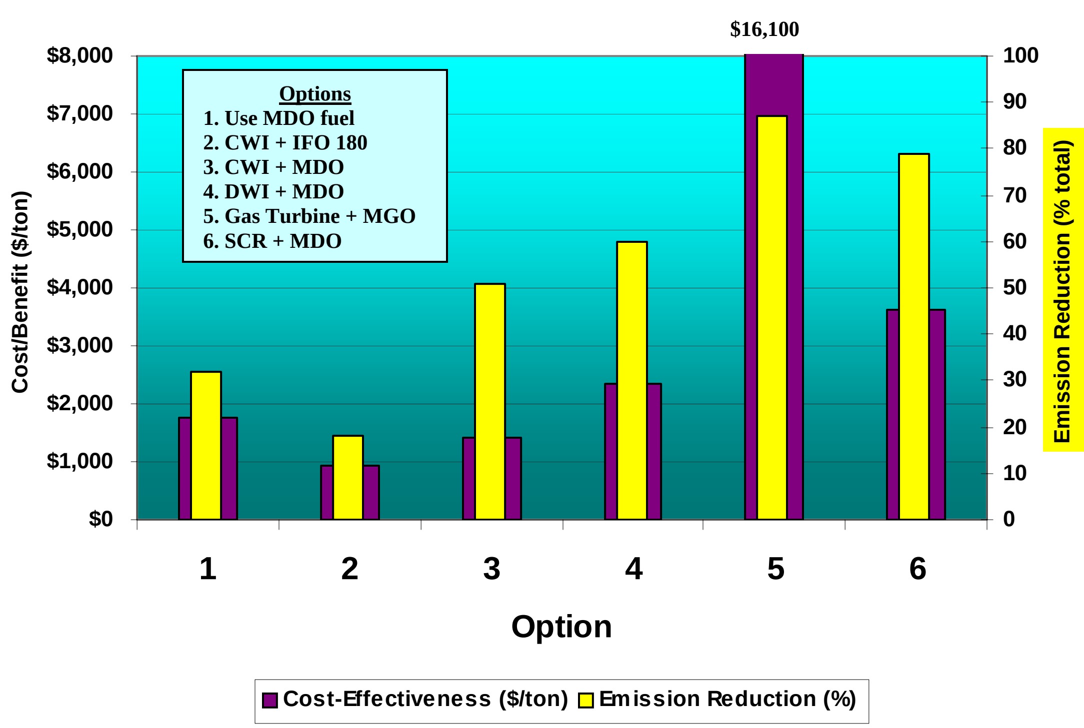
The most cost-effective options are the first four, and LNG duel-fuel conversion of the main engines, if natural gas is available at $3/MM Btu (option 8). Selective catalytic reduction (SCR), option 4, provides the greatest emission reduction (over 80%), but at a higher cost/benefit ratio than does thee use of direct water injection (DWI), option 3. However, DWI is a Wartsila technology that may not be retrofitable to all other marine engines. Therefore options 1,2 & 4 will be most generally applicable to ferries.

12.5 Cruise Ship Options

The cruise ship “fleet” that is used in this study is based upon a representative vessel and upon an annual visit by 22 different vessels to the Port of Seattle. Cruise ships typically have several large medium-speed diesel gensets which produce the electrical power needed to drive electric propulsion motors, maneuvering thruster motors, navigation gear and hoteling requirements. The fuel used in these ships is usually an intermediate fuel oil (IFO 180) with a sulfur content of 2.4%.

The emission-reduction options that are applicable to all modes of vessel operation and which were included in this study are the use of marine diesel oil (MDO, 0.13% S), continuous water injection (CWI) alone or with MDO, direct water injection (DWI) with MDO, an alternate new-engine gas turbine burning marine gas oil (MGO, 0.13% S), and selective catalytic reduction of NOx (SCR) with MDO fuel.

Figure 12.6 - Cruise Ship Options - All Modes of Operation



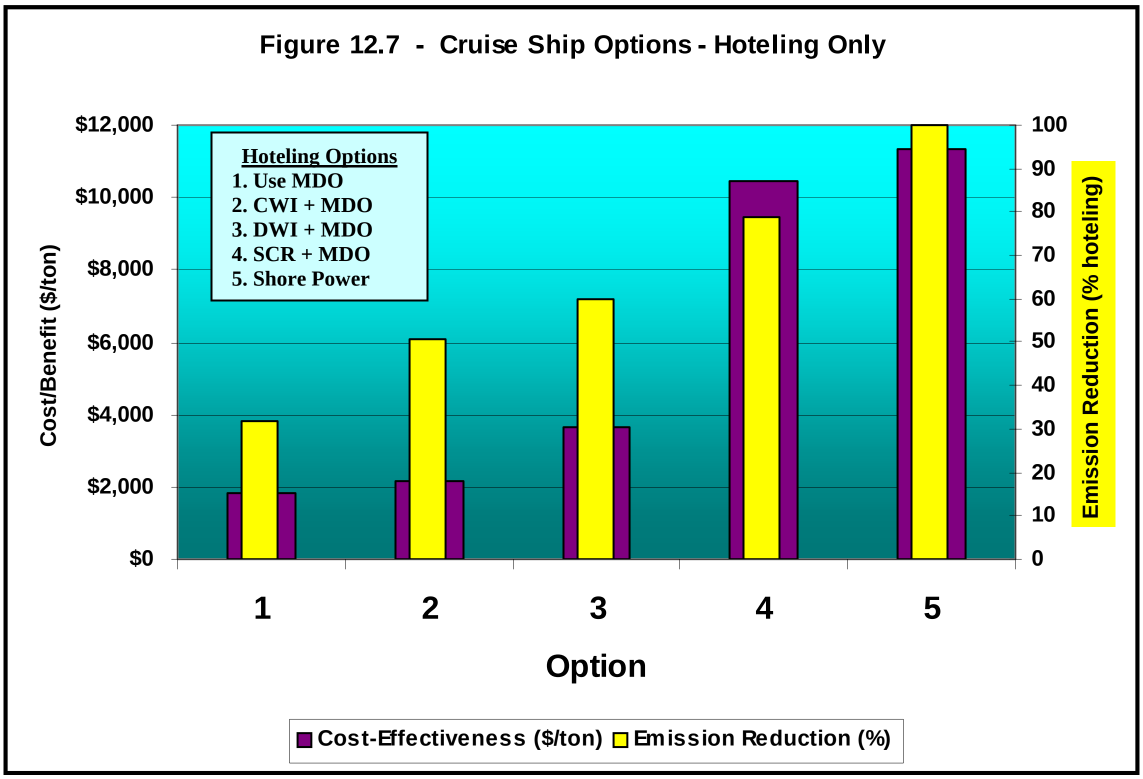
These different options are shown in Figure 12.6. It can be seen that the first four options are the most cost-effective, while the last two provide the greatest emission reduction.

The use of a gas turbine solely for emission reduction in the Puget Sound region is very expensive ($16,100 per ton of emission reduction) but does reduce total emissions by 90%. The relatively low weight and small size of the gas turbine, as compared to diesel engines of the same power output, may increase the capacity of a cruise ship for paying passengers and thereby offset the increased operating costs.

The use of selective catalytic reduction (SCR) of NOx reduces emissions by 80% at a cost/benefit ratio of $3,600/ton of emission reduction. SCR is bulky, however, and may decrease the passenger capacity of cruise-ships although it is widely used on ferries in Scandinavia.

The use of continuous water injection (CWI) or direct water injection (DWI), in conjunction with MDO, are the most cost-effective options when used for all modes of vessel operation and can reduce emissions by 50% - 60%.

Figure12.7 shows the five options that were studied for use in reducing emissions from hoteling only. Their cost/benefit ratio will be higher than if the same options are applied to all modes of operation, since capital expenditures will be almost the same while tons of emission reduction will be less because baseline emissions are less for hoteling than for total vessel operation.



The three most cost-effective options are again seen to be using MDO alone or with some form of water injection for NOx reduction. Shore power appears to reduce hoteling emissions by 100% if no offset is made for somewhat increased emissions within the shore-based power grid.

12.6 Conclusions

Five different families of non-road, heavy-duty diesel-engined (HDD) mobile sources were studied in order to identify cost-effective ways to reduce their emissions of emissions.

- For HDD construction equipment the use of a water-diesel emulsion such as *PuriNOx* can reduce total emissions by over 40% when used in conjunction with low sulfur diesel. The cost-effectiveness is estimated to be $2,600/ton of emission reduction for this option.

- For locomotives (mix of line-haul and yard engines) operated in the Pacific Northwest the most cost-effective emission reduction strategies are to rebuild the engines to Tier 0 or to Tier 1 NOx emission standards. These options have a low cost/benefit ratio of $46/ton and $170/ton, respectively. The most expensive option considered (using liquefied natural gas in converted duel-fuel engines on the line-haul locomotives) reduces total emissions by almost 70% at a cost of $802/ton, when the natural gas commodity price is $5/MM Btu, or $128/ton when the natural gas commodity price is $4/MM Btu.

- For workboats, such as barge tugs, the cost-effectiveness for effective emission reduction options for the main engines varied from $127/ton (using continuous water injection, CWI, with existing #2 diesel to give a 27% emission reduction) up to $1,430/ton (using exhaust gas recirculation, EGR, with diesel particulate filters, DPF, and low sulfur diesel to give a 46% emission reduction). Other technologies resulted in higher costs and with lower emission reductions.

- Emission reduction options applied to the auxiliary engines of workboats were less cost-effective, with costs in the order of $2,500/ton of emission reduction for two technologies (CWI + ULSD, and CWI + DOC + ULSD) that provide for 30% – 40% total emission reduction. Other technologies resulted in nearly double the cost ($5,000/ton) and with much lower emission reductions.

- Ferry emissions can be reduced by 82 % at a cost of $1,300/ton of reduction through the use of selective catalytic reduction (SCR) of NOx. However, less costly technologies are available, albeit with lower emission reductions. The use of continuous water injection along with low sulfur diesel will, for instance, reduce emissions by35% at a cost of $684/ton of emission reduction. Liquefied natural gas burned in duel-fuel converted diesel engines only looks cost-effective if the commodity price of natural gas is less than $4 per million Btu’s.

- For cruise ships operating within Puget Sound six different technologies were studied that would reduce emissions both while cruising and while hoteling (moored at dock). The options providing significant emission reductions at low cost were the use of continuous water injection along with MDO (marine diesel oil), which cost $1,400/ton of emission reduction and gave a 51% total reduction, and the use of direct water injection along with MDO, which cost $2,300/ton of emission reduction and which gave a 60% total reduction in emissions. The use of MDO in place of fuel oil (IFO 180) is a positive move, with an emission reduction of 32% at a cost of $1,800/ton.

- If only the hoteling emissions from cruise ships are to be reduced this can be done using the same options as those applicable to all modes of operation, since similar engines are used. In addition, the cruise ships can hook-up to shore power, as some do in Alaska. However, while this option results in the greatest emission reduction (nearly 100%) it does so at a cost of $11,000/ton of emission reduction. Other options, such as those described above, can reduce hoteling emissions by up to 60% at a cost of $3,700/ton or less. They are probably best implemented for reducing exhaust emissions both during hoteling and during cruising, since this provides the least cost per ton of emission reduction.

12.7 Recommendations

This study compared the different emission reduction options, for five different families of non-road HDD mobile sources, based upon their cost-effectiveness (cost per ton of total emission reduction) and upon their percentage of emission reduction. Emissions of SOx, NOx, PM, VOC, formaldehyde, benzene and 1,3-butadiene were lumped together as "total emissions", even though the health effects of these different species vary widely. Therefore the current, commonly-used methodology is heavily weighted toward NOx and SOx reduction, because the rating criteria are based on total tons of emission reduction per dollar spent, instead of upon toxicity reduction, which may favor PM or VOC reductions.

An improved method of comparison recently developed by Genesis Engineering is to multiply the emission of each species by an index, whose magnitude is proportional to the toxicity of that species, and then to sum the resulting values to obtain a health-effect-weighted total. In this way technology that is effective in reducing toxic species, such as diesel particulate or some of the components of VOC, would be more favored over technologies that only are good at reducing the emissions of less toxic compounds. Monies spent upon pollution reduction would thereby provide a greater benefit to society.

It is therefore recommended that this study be extended to also estimate the toxicity-weighted cost-effectiveness for the different emission reduction strategies discussed above. These toxicity-weighted values of cost-effectiveness can then be compared with the values that were estimated in this study. Strategies to cost-effectively reduce air toxics may well differ from those that are cost-effective for reducing the smog-related pollutants. Air quality managers should have both sets of cost indices available in order to help them guide optimal emission-reduction initiatives.

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14.0 APPENDICES

Appendix 1: Sample Calculations for Ferry Fuel Split by Operation Mode and Route

<u>Vessel Spokane: Edmonds/Kingston</u>

Main Engine Operating Modes	Load Factors (fractions)*	Operating Time (fractions)*	Proration Factors**	Fuel Allocation Factors***
Loading/Unloading	0.1	0.4348	0.0435	0.1574
Maneuvering	0.3	0.1435	0.0430	0.1558
Underway	0.45	0.4217	0.1898	0.6868
Tie-up	--	--	--	--
		Factor Total	0.2763	1.0000

* Based on WSF survey
** Product of load factor and operating time
*** Fraction of proration factor for given mode to total

<u>Vessel Sealth: Ancortes/San Juans and Faunt/SW/Vashon</u>

Route	Daily In-service Time (hours/d)*	Days Served in Route in 2001	Total In-service Time (hours)	Fraction of In-service Time per Route
Ancortes/San Juans	960	228	3,648	0.8244
Faunt/SW/Vashon	1,260	37	777	0.1756
		Total	4,425	1.0000

* Based on WSF survey and excludes tie-up time

Route 1: Ancortes/San Juans

Main Engine Operating Modes	Load Factors (fractions)*	Operating Time (fractions)*	Fraction of Route In-service Time	Fuel Allocation Factors for Route
Loading/Unloading	0.160	0.3229	0.8244	0.0426
Maneuvering	0.475	0.1302	0.8244	0.0510
Underway	0.865	0.5469	0.8244	0.3900
Tie-up	--	--	--	--
* Per WSF survey			Factor Total	0.4836

Route 2: Faunt/SW/Vashon

Main Engine Operating Modes	Load Factors (fractions)*	Operating Time (fractions)	Fraction of Route In-service Time	Fuel Allocation Factors for Route
Loading/Unloading	0.10	0.3175	0.1756	0.0056
Maneuvering	0.60	0.2381	0.1756	0.0251
Underway	0.89	0.4444	0.1756	0.0695
Tie-up	--	--	--	--
			Factor Total	0.1001

* Per Vessel Issaquah

Fuel Split by Route

Routes	Fuel Allocation Factors for Route	Fractional Fuel Split by Route
Anacortes/San Juans	0.4836	0.8285
Faunt/SW/Vashon	0.1001	0.1715
Total	0.5837	1.0000

Appendix 2: Emission Factors Used for Selected City of Seattle Construction Equipment

Table A2-1: Steady State Exhaust Emission Factors for Selected City of Seattle Construction Equipment

Equipment	Model	SCC	Model Year	Technology Type/Tier	Exhaust Emission Factors (lb/HP-h)			
					BSFC*	HC	NO_X	PM
Backhoe Loader	590SL	2270002066	1999	1	0.408	0.521	5.599	0.473
Backhoe Loader	446B	2270002066	1999	1	0.367	0.338	5.652	0.280
Loader	921C	2270002066	2000	1	0.367	0.309	5.577	0.252
Excavator	312BL	2270002036	1997	0	0.408	0.990	6.900	0.722
Tolt Track Excavator	9010B	2270002036	1995	0	0.367	0.680	8.380	0.402
Grader	720A	2270002048	1992	0	0.367	0.680	8.380	0.402
Tolt Grader	772BH	2270002048	1996	0	0.367	0.680	8.380	0.402
Watershed Grader	--	2270002048	1991	0	0.367	0.680	8.380	0.402
Wheel Loader	624H	2270002066	2002	1	0.367	0.338	5.652	0.280
Wheel Loader	IT 28F	2270002066	1995	0	0.367	0.680	8.380	0.402
Asphalt Pavement Grinder	W 1000	2270002054	1997	1	0.367	0.309	5.577	0.252
Dozer	850G	2270002069	1995	0	0.408	0.990	6.900	0.722

* Brake specific fuel consumption

Table A2-2: Transient Adjustment Exhaust Emission Factors for Selected City of Seattle Construction Equipment

Equipment	Model	SCC	Equipment Median Life	Adjustment Factors			
				BSFC	HC	NO_X	PM
Backhoe Loader	590SL	2270002066	4667	1.18	2.29	1.10	1.97
Backhoe Loader	446B	2270002066	4667	1.18	2.29	1.10	1.97
Loader	921C	2270002066	4667	1.18	2.29	1.10	1.97
Excavator	312BL	2270002036	4667	1.01	1.05	0.95	1.23
Tolt Track Excavator	9010B	2270002036	4667	1.01	1.05	0.95	1.23
Grader	720A	2270002048	4667	1.01	1.05	0.95	1.23
Tolt Grader	772BH	2270002048	4667	1.01	1.05	0.95	1.23
Watershed Grader	--	2270002048	4667	1.01	1.05	0.95	1.23
Wheel Loader	624H	2270002066	4667	1.18	2.29	1.10	1.97
Wheel Loader	IT 28F	2270002066	4667	1.18	2.29	1.10	1.97
Asphalt Pavement Grinder	W 1000	2270002054	4667	1.00	1.00	1.00	1.00
Dozer	850G	2270002069	4667	1.01	1.05	0.95	1.23

			Deterioration Factors			
Equipment	**Model**	**SCC**	**$S_{PM\ adj}$**	**HC**	**NO_X**	**PM**
Backhoe Loader	590SL	2270002066	0.097	1.002	1.001	1.025
Backhoe Loader	446B	2270002066	0.087	1.002	1.001	1.027
Loader	921C	2270002069	0.087	1.002	1.002	1.031
Excavator	312BL	2270002036	0.083	1.004	1.002	1.042
Tolt Track Excavator	9010B	2270002066	0.075	1.015	1.007	1.148
Grader	720A	2270002036	0.075	1.008	1.004	1.078
Tolt Grader	772BH	2270002048	0.075	1.007	1.004	1.017
Watershed Grader	--	2270002066	0.075	1.034	1.017	1.340
Wheel Loader	624H	2270002048	0.087	1.000	1.000	1.000
Wheel Loader	IT 28F	2270002066	0.087	1.008	1.004	1.081
Asphalt Pavement Grinder	W 1000	2270002048	0.074	1.005	1.003	1.060
Dozer	850G	2270002054	0.083	1.006	1.003	1.057

Table A2-3: Deterioration Exhaust Emission Factors for Selected City of Seattle Construction Equipment

* $S_{PM\ adj}$ is the sulfur adjustment factor for particulate