Reduction of Nonroad Diesel Emissions in the Lower Fraser Valley and the Rest of BC

Prepared for:

The Greater Vancouver Regional District

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Disclaimer

This report has been reviewed by representatives of the Sponsors, but the interpretation of the results of this study, as expressed in the report, is entirely the responsibility of the consultant author and does not imply endorsement of specific points of view by any or all of the Sponsors. The expressed recommendations and conclusions based on the findings are the opinion of the consultant author of the study and may or may not be supported by the study sponsors. These study sponsors include:

- Greater Vancouver Regional District
- Fraser Valley Regional District
- BC Ministry of Environment
- Clean Air Research Fund
- Canadian Petroleum Products Institute (CPPI)

CPPI Disclaimer

The Canadian Petroleum Products Institute (CPPI), one of the Sponsors, supports the study's intent to provide guidance to the GVRD, its member municipalities, the Greater Vancouver Transportation Authority and others on:

- the most promising option(s) to reduce emissions from their existing non-road heavy-duty diesel vehicles, locomotives and marine vessels and
- future purchases of non road fleet vehicles / engines and fuels.

CPPI believes this report provides a valuable resource with technical and economic data on the attributes of some of the most relevant emission reduction options for decreasing emissions from the current non road HDDV fleet vehicles. During the course of the study new methodologies were introduced to the scope of the study. CPPI has concerns about the methodologies used but wanted to maintain funding support of the study. CPPI wishes to express our appreciation for the opportunity to express our views in this disclaimer.

CPPI does not endorse the analytical methodology used to estimate the potential health effects of air quality improvements and their deemed economic value. In addition, CPPI has concerns about the methodology that applies emission-weighting factors designed to place a higher priority on some pollutants versus others. This methodology is embodied in the equation: Impact Weighted Emissions = $25*PM_{10} + NOx + VOC + CO/7 + 3*SOx$. CPPI believes that air quality can have an impact on public health, but does not believe the science is sufficiently robust to try to quantify that impact or to quantify the importance of one specific pollutant versus another. CPPI is concerned that this equation may skew the analysis and result in misleading results that may not be in the best interests of improved air quality and may not be a cost effective response to reducing HDDV emissions in the GVRD.

CPPI has summarized their concerns regarding this methodology in Appendix B and makes reference to a related report by epidemiologist, Dr. Suresh H. Moolgavkar, M.D., Ph.D to support this point of view.

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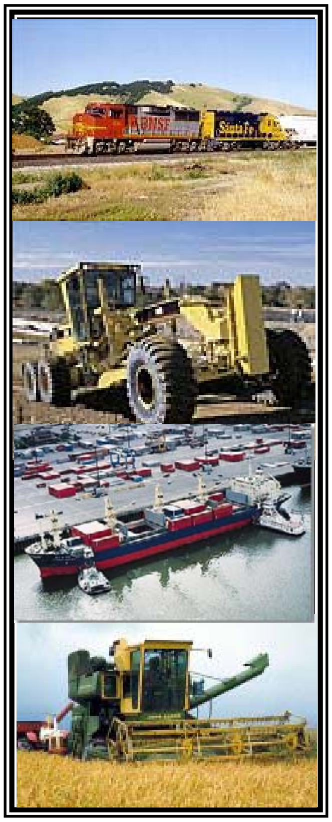
EXECUTIVE SUMMARY



Emissions from nonroad heavy-duty diesel (HDD) engines (rail, marine, construction equipment and other nonroad mobile sources) presently account for a significant part of the major pollutants (SOx, NOx, VOC, PM_{10}, CO, and NH_3) that are responsible for smog and for human health impacts in BC. During the year 2005 these nonroad emissions are expected to account for over 29% of the total emissions into the Lower Fraser Valley (LFV) of BC, which not only is the socio-economic hub of BC but also a major agricultural area.

On-road, transportation-based emissions are stringently regulated and future emissions are projected to actually decrease within the LFV. While in the past nonroad emission sources were largely uncontrolled, new HDD engines are required to meet increasingly tough emission standards which are similar to the on-road standards but which lag them by approximately 5 years. But since HDD engines may last for many years before requiring replacement, there are opportunities in the near term to reduce emissions from the existing fleets that will result in immediate societal benefits.

Also, TransLink has recently concluded the Vancouver harbour Passenger Marine Study; a study intended to explore the feasibility of this increased passenger ferry service in Vancouver Harbour. Although TransLink has no plans to implement a new passenger ferry service at this time, the current report reviewed potential emissions from four passenger ferry routes with representative fleet that were considered in the TransLink study, and compared the ferry emissions with the avoided road-commute emissions.

The objective of this project is to identify cost-effective ways to reduce emissions from three sources: nonroad HDD equipment, railway locomotives and small passenger ferries. Three areas were investigated: GVRD, FVRD1 (encompassing south-western area of FVRD) and the rest of BC. (A 2004 project for Environment Canada investigated emission reduction options within the Puget Sound/Georgia Basin area for large ocean-going vessels, cruise ships, workboats and car-carrying ferries.)

The approach used here is to estimate the net present value (NPV) cost of implementing emission reduction measures within the time frame 2005 – 2025, and then to divide these NPV costs by the associated total emission reductions over the same time period to arrive at an ERM cost-effectiveness, expressed as a cost/benefit ratio ($/tonne of avoided pollution). Nonroad HDD emissions projected to the year 2025 derive from the Canadianized version of EPA's NONROAD 2004 model and hence incorporate existing and upcoming Environment Canada regulations concerning engine emissions and fuel sulphur. Two methods are used to calculate total avoided pollution: an "impact-weighted" total and an "un-weighted" total.

Studies have shown that HDD emissions have significant health-related impacts as well as smog and visibility impacts. The health-related impacts are attributed mainly to diesel particulates (mostly $PM_{2.5}$), which in some jurisdictions are considered to be an air toxic, while smog-related impacts derive mainly from an interaction between NOx and VOC to form ozone, and with $PM_{2.5}$, SOx and NH_3 being major contributors to the "haze" portion of smog. Because of these different air pollution impacts it is necessary to use different methods to add up the individual pollution emissions to obtain total emissions. This is done by first multiplying the emission of each individual pollutant by a "weighing factor" and then summing up the total of these weighted emissions. In previous studies the total "impact-weighted" emission was obtained using the weighted sum (NOx + 3SOx + $25PM_{10}$ + VOC + CO/7). A simplified non-weighted total can also be obtained by using the sum (NOx + SOx + $PM_{2.5}$ + VOC + NH_3). While both methods are used to arrive at total (aggregate) emissions in this study, the main focus is placed on reducing impact-weighted, total HDD emissions.

(*One of the funding sponsors, the Canadian Petroleum Products Institute, CPPI, has concerns about the use of the above health-based weighting applied to specific pollutants. CPPI is of the view that the methodology has not been adequately documented nor is it supported by the available science and epidemiological data. CPPI has summarized their concerns regarding the methodology of using health based weighting factors applied to air emissions and cost effectiveness methodology in Appendix B and makes reference to a related report by epidemiologist, Dr. Suresh H. Moolgavkar, M.D., Ph.D to support this point of view. CPPI has also expressed their views in a disclaimer near the front of this report.*)

Reducing HDD emissions should be done in a cost-effective manner since these costs will, directly or indirectly, be passed on to tax payers who must weigh these societal costs against other routes for enhancing air quality in BC. Cost-effective HDD emission reduction strategies are those that provide a significant reduction in emissions at a cost lower than alternative measures.

It should be noted here that the emission reduction measures proposed here are primarily focused on advancing emission reductions that would, to a large extent, occur in any case with HDD fleet turnover. The purpose here is to explore the feasibility and costs associated with advancing the timing of these emission reductions.

Funding for this study was provided by the Greater Vancouver Regional District, the Fraser Valley Regional District, the British Columbia Ministry of Water, Land and Air Protection and by the Clean Air Research Fund.

Nonroad HDD Equipment

The BC nonroad heavy-duty diesel (HDD) equipment fleet presently (2005) consists of approximately 101,000 pieces of equipment, with 34% of these located within the GVRD and 11% within the FVRD1. The GVRD nonroad fleet is dominated by construction equipment (backhoes, front-end loaders, excavators, etc.) while the fleet within the FVRD1 and the rest of BC is mainly agricultural equipment (farm tractors, combines, etc.).

The total (unweighted) emissions from this sector during the year 2005 are projected to be 35,700 tonnes in BC, including 11,800 tonnes from the Lower Fraser Valley. In GVRD these emissions represent 14% of the total mobile-source emissions and 8.5% of the total emissions from all sources. Projected total emissions (2005 – 2025) from the nonroad HDD equipment sector are 422,000 tonnes in BC, including 146,600 tonnes from the LFV.

HDD Fleets and Study Areas

Four different fleets were investigated for the **GVRD** study area:

1. Construction and Mining Equipment
2. Agricultural Equipment
3. Industrial and Commercial Equipment
4. Other Equipment

For the **FVRD1** the major fleets are:

1. Construction and Mining Equipment
2. Agricultural Equipment
3. Other Equipment

For the **Rest of BC** the fleets investigated are:

1. Construction and Mining Equipment
2. Agricultural Equipment
3. Logging Equipment
4. Other Equipment

Emission Reduction Measures

Eleven different emission reduction options are studied for off-road equipment. Five of these are "clean fuel" options while six are technology retrofits.

1. Use of rebranded, <500 ppm S road diesel: Often #2 diesel is simply rebranded road diesel when the lower grade of diesel is not locally available. However, here we assume that a premium must be paid for using road diesel with average sulphur content of 350 ppm. It is assumed that this option is applicable over the period of 2005 until 2007, at which time the law requires it.

2. Use of rebranded, ultra-low sulphur < 15 ppm S diesel. This ULSD is presently available from at least one PNW refinery and will be a required fuel for road vehicles by 2007. Its use enables the retrofit of catalyst-based technologies that would be poisoned by higher sulphur fuels. It is assumed that this option is applicable over the period of 2007 until 2010, at which time law requires it.

3. B20: this is a blend of 20% biodiesel and 80% road diesel that is presently available in the PNW, although at a "rack-price" cost premium. It offers lower GHG, PM_{10} and VOC emissions; however, NOx emissions are increased due to the nitrogen contained within the biodiesel fuel. This blended fuel enjoys a small tax advantage over regular diesel in BC, which enhances its cost-effectiveness as a way to reduce emissions. Further reductions, of about 2 cpl, would make this an attractive fuel for fleet operators and help reduce our GHG emissions. It is assumed that this option uses 350-ppm diesel over the period of 2005 until 2007, then switches to using < 15 ppm S diesel for the period 2007 – 2025.

4. B100: 100 % biodiesel offers a 100% reduction in GHG emissions, but concurrently gives a large increase in NOx emissions. However, particulate emissions are significantly reduced. In BC there is no tax break in effect at this time for B100. It is assumed that this option is applicable over the period of 2005 to 2025.

5. *PuriNOx*: this is an emulsion consisting of 20% water, 77% diesel and 3% emulsifying agent sold by Lubrizol. This fuel has been approved by the California Air Resources Board as Tier 2 equivalent, due to its significant reduction in $PM_{2.5}$ and NOx. However, emissions of CO and VOC may actually increase (these are minor emissions from HDD engines). It is assumed that this option uses 350-ppm diesel over the period of 2005 until 2007, then switches to using < 15 ppm S diesel for the period 2007 – 2025. BC had a tax break for using this clean-fuel option, but it is no longer in effect.

6. DOC: diesel oxidation catalyst is a relatively low-cost muffler replacement that oxidizes the odorous components of diesel exhaust (VOC and the soluble organic fraction of the particulates). DOC's are widely used on diesel equipment that must operate within enclosed spaces (e.g. mines, buildings) and are applicable to all classes of nonroad HDD equipment. It is assumed that this option uses off road diesel over the period of 2005 until 2007, and then switches to using < 15 ppm S diesel for the period 2007 – 2025.

7. Passive DPF: these are catalytically regenerated diesel particulate filters, also widely used on diesel equipment that must operate within enclosed spaces. Since a high temperature (approx. 300ºC) is required to burn-off the accumulated carbon soot, they can only be used on equipment that has an adequately high exhaust temperature, which limits their use to larger engines with relatively high duty cycles (load factors). ULSD must be used to prevent catalyst poisoning. It is assumed that this option is applicable over the period of 2007 to 2025.

8. Clearaire "*Longview*": this device is representative of retrofit muffler-replacements which use fuel injection to richen the exhaust so that a catalyst can be used to reduce NOx. The NOx catalyst section is followed by a DPF section that removes VOC and PM. Again, these devices are limited to equipment that have an adequately high exhaust temperature, which limits their use to larger engines with relatively high duty cycles. Best performance is obtained using ULSD. Hence it is assumed that this option is applicable over the period of 2007 to 2025.

9. EGR: exhaust gas recirculation is used to reduce NOx emissions. It must be used in conjunction with a DPF that first removes erosive particulate. The DPF requires the use of ULSD. Again it is assumed that this option is applicable over the period of 2007 to 2025.

10. SCR: selective catalytic reduction of NOx by spraying a small amount of urea solution in front of a special NOx reduction catalyst. The catalyst is more tolerant of sulphur and of low exhaust temperatures than is that for DPF's. The European Union expects that SCR units will be required on all heavy highway diesels in the near future. They may also be retrofitted to large, nonroad diesel equipment since they are already widely used on European ferries and the technology is mature. Again it is assumed that this option is applicable over the period of 2007 to 2025.

11. NOx Adsorption: this is an emerging technology that adsorbs NOx onto a suitable substrate while the diesel engine operates in its normal lean-burn operation. When the exhaust is temporarily enriched the adsorbed NOx is catalytically reduced to N_2. Prototype "NOx-Traps" have demonstrated a 90% reduction in NOx emissions and commercial versions are expected to become

available by 2010. The NOx-Trap requires the use of ULSD. It is assumed that this option is applicable over the period of 2010 to 2025.

Engine refits are not considered for the nonroad HDD fleets for two reasons. First, new Tier 2 and Tier 3 engines generally will not fit into older equipment. Secondly, engine retrofits are an expensive way to reduce emissions and are not generally cost-effective unless some sort of government incentive program, such as California's Carl Moyer program, subsidizes the retrofit.

Table 1 summarizes the impact-weighted emission reductions (%) and the cost-effectiveness over the period 2005 – 2025 for the different options summarized above. In general, while there is a significant difference in the cost-effectiveness between individual emission reduction options, there is less difference between the cost-effectiveness of a single option when applied to different regions or to different fleets.

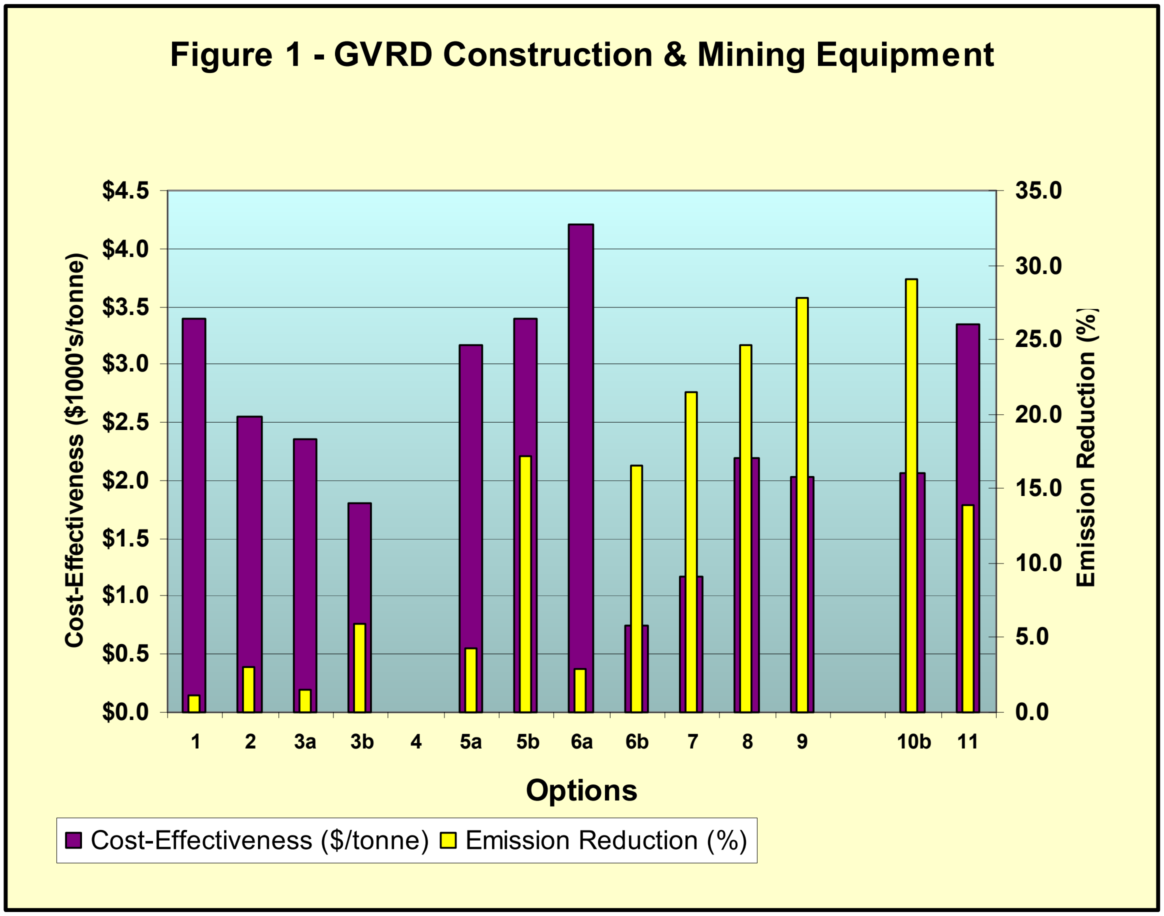
One of the objectives of this study is to identify cost-effective ways to significantly reduce nonroad HDD emissions in the near term. From Table 1 it is apparent that the major fleets within the GVRD are the Construction, and the Industrial and Commercial fleets, while in the FVRD and the Rest of BC the major fleets are Agriculture and Construction and Mining. It can be seen from the bottom half of Table 1 that there are a variety of emission reduction options (ERMs) that can reduce the weighted emissions for around $2,000 per tonne or less. The upper portion of Table 1 presents the percentage that the baseline 2005 - 2025 emission are reduced through implementing a given ERM during its period of applicability. For a fleet operator the challenge would be to identify a shortlist of ERMs that provide a significant reduction in emissions at a low or neutral cost. This process is facilitated by numerous charts in the main body of the report, and for selected fleets following Table 1 below.

While economic and regulatory instruments for encouraging the use of emission reduction options are outside the scope of this study, it should be mentioned that simple changes to federal and provincial fuel taxes can be used to encourage the use of alternative fuels, such as biodiesel, which can not only reduce the emission of the common air contaminants (SOx, CO, PM, VOC, NH_3) but also reduce GHG emissions. For hardware retrofits (e.g. diesel particulate filters) economic instruments, such as emission trading, has proven effective in some jurisdictions.

Table 1 - Summary of the Cost-Effectiveness of NonRoad HDD Equipment Emission Reduction Options

Emission Reduction Option:	1 LSD	2 ULSD	3a B20 LSD	3b B20 ULSD	4 B100	5a PNOx LSD	5b PNOx ULSD	6a DOC #2D	6b DOC ULSD	7 DPF ULSD	8 Clear-aire	9 EGR DPF	10a SCR LSD	10b SCR ULSD	11 NOx Traps
Application start year/end year	2005 2006	2007 2010	2005 2006	2007 2025	2005 2025	2005 2006	2007 2025	2005 2006	2007 2025	2007 2025	2007 2025	2007 2025	2005 2006	2007 2025	2010 2025
Region & Fleet	Percent Emission Reductions (weighted) For Time Period 2005 - 2025														
<u>GVRD</u>															
Construction & Mining	1.1	3.1	1.6	5.9	25.8	4.4	17.9	2.8	16.5	21.5	24.6	27.8	2.1	29.0	13.9
Agriculture	1.2	3.1	1.6	6.2	28.0	4.2	18.4	3.1	17.3	12.6	13.6	15.1	0.5	8.6	6.6
Industrial & Commercial	1.0	2.9	1.4	6.0	26.3	3.8	17.7	2.7	16.9	8.8	9.7	10.8	0.4	7.1	5.1
Others	0.6	1.6	0.8	3.4	14.6	2.3	10.1	1.5	9.4	12.0	13.4	15.1	0.8	12.4	7.3
<u>FVRD</u>															
Construction & Mining	1.1	3.2	1.6	6.2	27.2	4.3	18.0	2.9	17.3	19.6	22.0	24.7	1.6	22.2	11.5
Agriculture	1.2	3.1	1.6	6.2	28.0	4.3	18.4	3.1	17.3	12.5	13.4	14.9	0.5	8.4	6.6
Others	1.0	2.7	1.4	5.6	24.5	3.6	16.4	2.5	15.7	9.3	10.3	11.5	0.5	7.7	5.4
<u>Rest of BC</u>															
Construction & Mining	1.3	3.4	1.8	6.1	26.1	4.7	18.0	2.9	16.5	22.0	25.4	28.7	2.3	30.9	14.6
Agriculture	0.8	2.0	1.1	4.1	18.5	2.9	12.1	2.0	11.1	23.1	24.5	27.0	1.3	20.8	11.4
Logging	1.7	4.2	2.3	6.2	27.7	6.4	18.3	3.7	16.5	31.9	35.4	39.4	3.5	33.4	15.4
Others	1.3	3.4	1.8	6.0	26.1	4.5	17.7	2.9	16.4	15.0	16.8	18.8	1.0	13.9	8.8
	Cost Effectiveness ($1000's/Tonne Avoided Emissions)														
<u>GVRD</u>															
Construction & Mining	3.4	2.6	2.4	1.8	14.2	3.1	3.3	4.2	0.8	1.2	2.2	2.0	18.7	2.1	3.3
Agriculture	2.1	1.3	1.4	0.6	5.3	2.0	1.2	8.2	0.9	0.9	1.7	2.0	31.0	2.0	3.2
Industrial & Commercial	2.7	2.0	1.8	1.3	10.2	2.6	2.4	12.0	2.1	1.6	2.8	3.3	40.8	3.7	5.9
Others	2.8	2.1	1.9	1.4	10.7	2.6	2.6	10.9	1.9	1.5	2.7	3.1	34.6	3.4	5.6
<u>FVRD</u>															
Construction & Mining	3.1	2.3	2.2	1.6	12.5	2.9	3.0	4.9	0.8	1.3	2.4	2.4	23.7	2.7	4.3
Agriculture	2.2	1.6	1.5	1.1	8.3	2.1	2.1	8.3	1.5	1.3	2.3	2.9	32.0	3.1	5.4
Others	2.8	2.1	1.9	1.4	10.7	2.7	2.7	10.9	1.9	1.5	2.7	3.1	34.6	3.4	5.6
<u>Rest of BC</u>															
Construction & Mining	3.0	2.4	2.1	1.8	14.5	3.0	3.4	4.0	0.7	1.2	2.2	2.0	17.8	2.0	3.3
Agriculture	3.2	2.7	2.2	1.8	13.4	3.1	3.3	7.0	1.4	1.7	3.2	3.5	50.0	4.7	6.8
Logging	3.8	2.9	2.7	2.2	17.9	3.6	4.1	2.9	0.5	1.1	2.0	2.2	20.6	2.7	4.3
Others	2.7	2.2	1.9	1.7	13.6	2.8	3.2	6.6	1.2	1.4	2.4	2.7	24.0	2.8	4.9

In the figures the yellow bars represent the emission reductions, expressed as a percent of the weighted-total nonroad HDD emissions while the purple bars represent the cost-



effectiveness, expressed as a cost/benefit ratio. The greatest efficiencies will be provided by those options that provide a significant emission reduction at a low cost/benefit ratio (high yellow bar, low purple bar).

	Emission Reduction Options	Years
1	Rebranded road diesel, 350 ppm S	05 - 06
2	Ultralow sulphur diesel, 10 ppm S	07 - 10
3a	B20 biodiesel (biodiesel + LSD)	05 - 06
3b	B20 biodiesel (biodiesel + ULSD)	07 - 25
4	B100 biodiesel, 0 ppm S	05 - 25
5a	PuriNOx with LSD, 350 ppm S	05 - 06
5b	PuriNOx with ULSD, 10 ppm S	07 - 25
6a	DOC with off-road diesel (563 ppm S)	05 - 06
6b	DOC with ULSD, 10 ppm S	07 - 25
7	Passive DPF with ULSD (10 ppm S)	07 - 25
8	Cleaire "LongView" with ULSD	07 - 25
9	EGR + DPF + ULSD	07 - 25
10a	SCR + LSD (urea added to fuel costs)	05 - 06
10b	SCR + LSD (urea added to fuel costs)	07 - 25
11	NOx Adsorbers	10 - 25

Emission reductions for the ERM's are presented as a percentage of the total emissions over the period of 2005 – 2025. Hence ERM options that are applicable over only a small portion of this time span will have a relatively small emission reduction (right vertical axis of the charts).

Two of the ERM options (#4 - 100% Biodiesel and #10a – SCR + LSD) are not shown in the figures because their costs are far in excess of the other options and hence their inclusion would distort the vertical axis of the charts. (For the GVRD Construction and Mining sector the use of B100 is estimated to reduce weighted aggregate emissions by 20% but at a cost of over $18,000/tonne of avoided emissions. The expense of the SCR & LSD option is not viable because of the assumed short-term applicability of this ERM; it is replaced by the use of SCR & ULSD in 2007 (Option 10b).

The most cost-effective ERM's, at less than $2000 per tonne of weighted, avoided emission reductions are seen to be a biodiesel blend (B20), a diesel oxidation catalyst (DOC) or a diesel particulate filter (DPF), all in combination with the upcoming ULSD road diesel. If the existing taxes on colored B20 are reduced from 5.6 ¢/L down to 4.5 ¢/L then the cost of using B20 becomes cost-neutral to fleet operators and they will start using this alternative fuel, which not only reduces overall emissions by about 6% but which also reduces the emission of greenhouse gases (CO_2).

NOx adsorbers (Option 11) are not expected to become commercially available until 2010, which reduces their effectiveness in reducing weighted-total emissions over the 2005 – 2025 timeframe.

Figures 2 and 3 compare costs and emission reductions when calculated using weighted aggregate reductions and when calculated using un-weighted aggregate reductions. It can be seen that there are significant differences in the results of these two methods, with the weighted-total method generally resulting in lower costs per tonne of avoided emissions.

The proposed Canadian nonroad diesel engine regulations are expected to become final and to apply to 2006 and later engines. They will mirror the EPA Tier 2, 3 and 4 regulations. A previous study showed that if all the existing nonroad diesel equipment fleets in BC could be immediately re-engined with Tier 2 engines the smog-forming emissions, from this source, would be reduced by approximately 40 – 50%. Similarly, if the existing nonroad diesel equipment fleets in BC could be immediately re-engined with Tier 3 engines these emissions would be reduced by approximately 60 – 70%. These options were not explored in this study because they are not practical. Generally, the engines built for new Tier 2 or Tier 3 compliant nonroad HDD equipment are not retrofitable to old equipment due to changes and improvements in equipment chassis design. Hence any sort of Tier 2 or Tier 3 compliant retrofit would entail buying all new equipment. This is not cost-effective unless an old machine needs to be completely rebuilt or replaced.

Emission reductions through engine and technology retrofits are being accomplished in California through a government subsidized "Carl Moyer" program, wherein the state will pay for the incremental cost of replacing an engine with a Tier 2 or better engine.

Figure 2 - Rest of BC Agricultural Equipment (weighted)

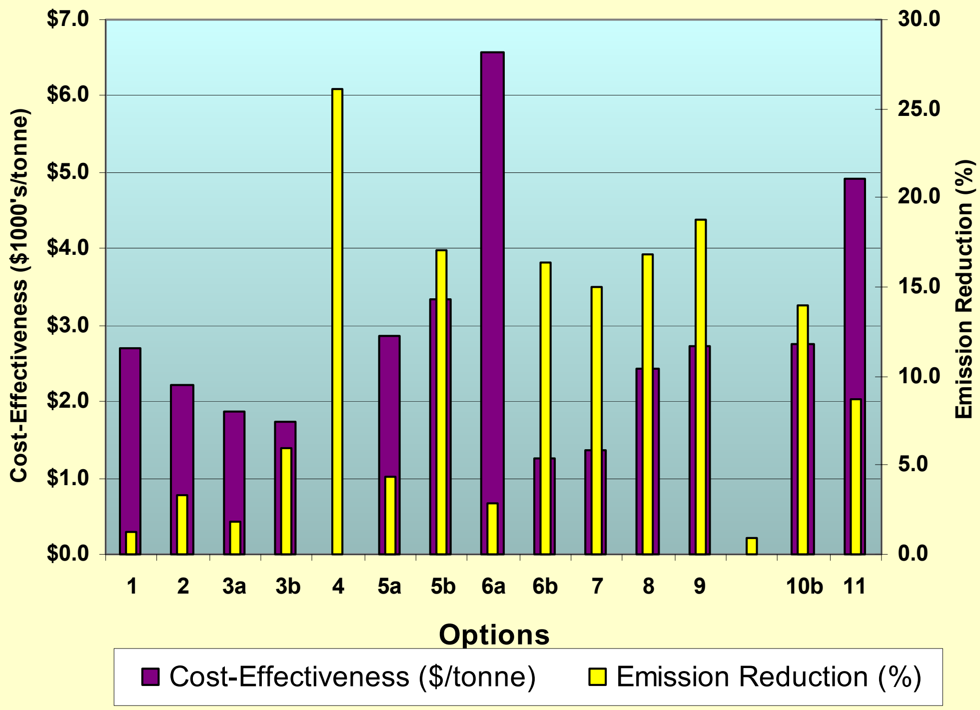
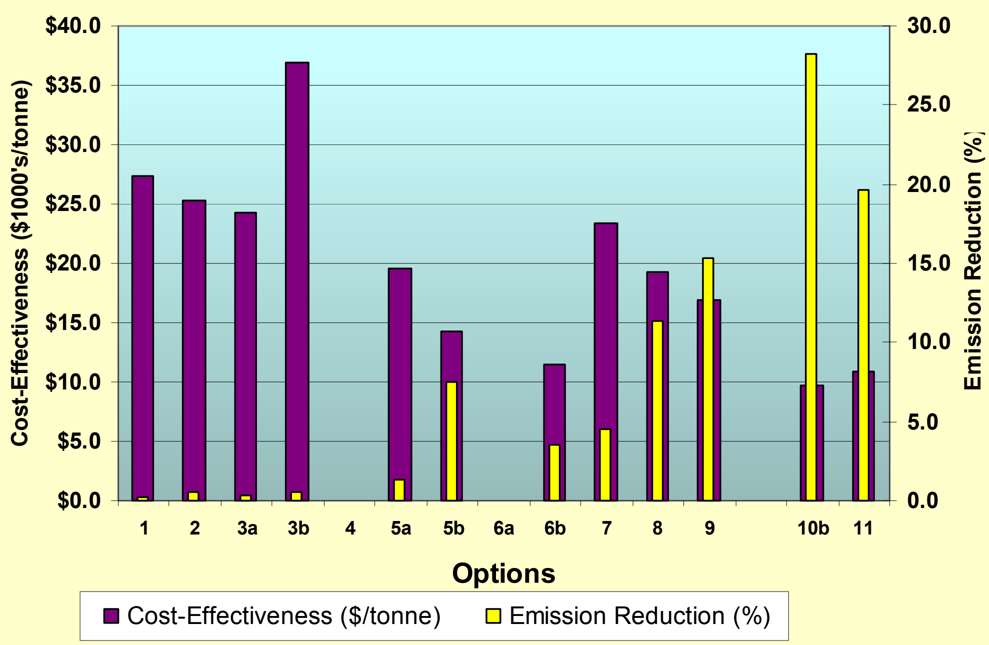


Figure 3 - Rest of BC Agricultural Equipment (unweighted)



The incremental cost is the total cost of the retrofit (engine purchase plus any special engineering to enable the new engine to be retrofitted) less the cost of simply rebuilding the existing engine. This successful program reduces NOx at a cost of about US$4,000 - $5,000/ton. (There is a cap of US$12,000/ton to prevent the program from subsidizing improvements that are not cost-effective.) The Carl Moyer program also applies to locomotives, marine vessels and other heavy-duty diesel engines.

However, in the nonroad HDD equipment sector the Carl Moyer program has mainly been applied to diesel engine powered agricultural pumps or to emission-reduction retrofits, such as diesel oxidation catalysts and diesel particulate filters. As stated above, it is generally not possible to install a new, low-emission engine into an old piece of equipment.

This study has shown that weighted aggregate emissions reductions of in the order of 20% can be achieved at a cost of around $2,000/tonne or less in the nonroad HDD equipment sector. The most cost-effective ERM's are those that can benefit from fuel tax reductions, such as B20 biodiesel, in which case the cost to the operator can be made neutral or even negative. With appropriate tax reductions clean-fuel ERM's can be combined with low-cost technology ERM's such as retrofit diesel oxidation catalysts to achieve in excess of a 25% emission reduction at a neutral cost to the operator.

On a non-weighted basis the emission reductions are generally lower and the cost/benefit ratios higher than when treated on a weighted basis. One of the most cost-effective options using this method of aggregation is the use of selective catalytic reduction (SCR). Emissions can be reduced by 29% at a fleet cost-effectiveness generally under $6,000 per avoided tonne. SCR is being successfully applied to HDD engines in Europe.

Locomotives

CN photo

The locomotive fleet operating part-time or full time within BC consists of approximately 480 locomotives (line haul and yard), with 10% of these located within the GVRD and 5% within the FVRD1. The line haul locomotives have an average power of about 3580 hp, are operational approximately 7500 hours/year and on average spend around 60% of this time idling. Yard locomotives are operational approximately 7000 hours/year and on average spend around 81% of this time idling. The line haul locomotives exhaust a large majority of the emissions coming from the railroad sector.

The total emissions in the Lower Fraser Valley from the locomotive equipment fleet during the year 2005 are estimated to be 4,272 tonnes. These emissions represent 2.3% of the total emissions in the Lower Fraser Valley from all sources. Hence these emissions are a small but not insignificant portion of the total emissions. (Emissions of coal dust from coal trains are not included here. Coal dust is a substantial railway issue, particularly outside of the LFV.) This section will explore ways to reduce locomotive exhaust emissions in the near term in a cost-effective manner. First the options for line haul locomotives will be discussed, then those for the yard engines.

It should be noted here that a *Memorandum of Understanding* between the Railway Association of Canada and Environment Canada caps railway locomotive NOx emissions in Canada. Further emission reductions would require some sort of amendment to this agreement. This MOU is presently under review by the two stakeholder parties.

Line Haul Locomotives

Possible options for the line haul locomotives include:

1. Use of ultra-low sulphur diesel (ULSD).
2. Rebuilding the engines to EPA Tier 0 emission requirements.
3. Rebuilding the engines to EPA Tier 1 emission requirements.
4. Using water injection (CWI) to reduce NOx and other emissions.
5. Using the MEC system to produce a micro-emulsion of diesel and water.
6. Replacing the muffler with a diesel oxidation catalyst (DOC).
7. Using selective catalytic reduction (SCR) to reduce NOx and other emissions.
8. Using an advanced idle reduction system (*Hotshot/Smart-Start)* to largely eliminate locomotive idling, which is normally used to keep the engine and engine fluids hot. A small auxiliary diesel engine used instead when the main engine is shut down.

Yard Engines

Options for switch engines include:

1. Use of ultra-low sulphur diesel (ULSD).
2. Rebuilding the engines to EPA Tier 1 emission requirements.
3. Using water injection (CWI) to reduce NOx and other emissions.
4. Diesel oxidation catalyst (DOC) muffler replacement.
5. Idle control (*Hotshot/Smart-Start*).
6. Hybrid rebuild (*RailPower Technologies Ltd*. diesel/battery).
7. Idle control (*Smart-Start*). An electronic system used alone to shut down and restart the locomotive engine. Not applicable to large diesel engines in cold climates.

Table 2 provides a summary of the cost-effectiveness of the different emission reduction options as applied to the various locomotive fleets. Emission reductions are given as a percent of the weighted total projected emissions over the 20-year period 2005 – 2025, while the cost-effectiveness in the net present value cost-effectiveness (NPV of total 20-year costs divided by the total, weighted emission reductions).

Table 2 - Summary of Weighted Cost-Effectiveness

Line Haul Locomotives

Region	1 ULSD	2 Tier 0 Rebuild	3 Tier 1 Rebuild	4 Water Inj.	5 MEC System	6 DOC	7 SCR	8 Hot Shot SmartStart
	Percent Emission Reduction (2005 - 2025)							
GVRD	3.1	1.6	8.4	14.6	18.0	6.3	40.6	4.1
FVRD	3.0	1.6	8.4	14.6	18.0	6.3	40.6	4.0
Rest of BC	3.5	1.5	8.3	14.5	18.4	7.0	39.9	4.1
	Cost-Effectiveness ($/tonne Avoided Emissions)							
GVRD	$2,770	$551	$628	$751	$842	$228	$1,791	($1,391)
FVRD	$2,793	$551	$630	$753	$845	$230	$1,792	($1,405)
Rest of BC	$2,342	$558	$628	$731	$803	$200	$1,743	($1,184)

Yard Locomotives

Region	1 ULSD	2 Tier 1 Rebuild	3 Water Injection	4 DOC	5 Hot Shot SmartStart	6 Hybrid	7 Smart Start
	Percent Emission Reduction (2005 - 2025)						
GVRD	3.8	8.7	14.7	8.6	29.4	50.5	65.4
FVRD	3.8	8.8	14.7	8.6	29.4	50.5	65.4
Rest of BC	4.3	8.6	14.4	9.9	28.1	50.6	-
	Cost-Effectiveness ($/tonne Avoided Emissions)						
GVRD	$1,734	$5,931	$5,105	$1,584	$1,068	$15,889	($5,026)
FVRD	$1,729	$5,918	$5,101	$1,582	$1,061	$15,906	($5,048)
Rest of BC	$1,384	$5,373	$4,633	$1,223	$970	$14,127	-

The emission reductions and costs are similar between the three different regions simply because similar assumptions were used. It can be seen that the cost for reducing emissions from yard engines is generally higher than it is for line haul engines. An exception is the early use of ULSD, in which case the costs are actually lower for the yard engines.

For line haul engines significant emission reductions are attainable at costs of less than $1000/tonne. However, the highest emission reduction that was attained by the 8 options that were studied was through the use of SCR (selective catalytic reduction), which reduced total weighted emissions by about 40% at a cost of about $1,800/tonne. In Europe SCR is being installed on HDD highway rigs and on marine vessels. Locomotive applications, if done at all, are rare and would probably also require the use of an idle control technology to prevent fouling of the catalyst during prolonged idling.

Option 8 (idling control using the *Hotshot/Smart-Start* technology) actually saves money for the railway industry. It has a negative cost/benefit ratio as shown in Table 2. (The emission reduction is relatively small, 4.4%, so that when the cost-savings from reduced fuel expenditures are divided by the emission reductions, a large negative cost/benefit ratio results.)

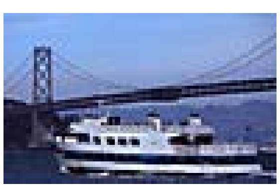
The two lowest cost options for line haul locomotives are to retrofit the idle-control system and to retrofit diesel oxidation catalysts. Some railroads are presently pursuing the former option, while latter would require incentives, perhaps similar to those of the Carl Moyer program. The use of retrofit diesel oxidation catalysts may, in some applications, require the simultaneous use of an idle control technology to prevent fouling of the catalyst during prolonged idling. Long-term testing is required in order to gain more experience with these systems.

The two lowest cost options for yard locomotives are those using idle control technology (Options 5 & 7). If the *SmartStart* idle control technology could be used year around it would provide a very significant (65%) emission reduction while at the same time substantially reducing operational costs.

A more in-depth study is required to properly evaluate the applicability of idle control technology in different regions of the Province – what fraction of the year can the *SmartStart* idle control technology be used alone and what fraction of the year would the *HotShot* system also be required to keep the engine fluids warm. The study could also investigate the emission reductions attainable and the corresponding cost-effectiveness of other retrofit technologies used in conjunction with idle control technologies, such as the use of diesel oxidation catalysts and diesel particulate filters.

It should be mentioned here that emissions from yard locomotives would generally incur a larger impact upon human health, on a per tonne basis, than will the emissions from line haul engines due to the proximity of yard locomotives and railway yards to urban centers.

Marine Alternatives to Road Transportation



Expanded passenger ferry services are the subject of continued interest in Greater Vancouver, given the potential of such services to bypass traffic bottlenecks, reduce travel times, improve reliability and attract new transit-system ridership. A 2003 study of an expanded passenger ferry system in the San Francisco Bay Area showed that emissions of NOx would increase significantly unless advanced technologies were used to reduce these emissions. It was concluded that it should be feasible to design and implement an enhanced ferry service to conform to regional transportation and air quality goals.

TransLink has recently concluded the *Vancouver Harbour Passenger Marine Study*, a study intended to explore the feasibility of this increased passenger ferry service in Vancouver Harbour. Although TransLink has no plans to implement passenger ferry service at this time, this present study has reviewed potential emissions from four passenger-ferry routes, traveled by a representative ferry fleet that was considered in the TransLink study, and has compared the forecasted ferry emissions with the avoided road-commute emissions.

Table 3 - Weighted-Contaminant Marine Passenger Transportation Analysis

Run	Displaced Land Emissions (tpy)	Emission Reduction Option						
		1	2	3	4	5	6	7
All runs	(Emissions are							
Ferry, no controls (tpy)	for the	24.8	24.8	24.8	24.8	24.8	24.8	24.8
Ferry Emission reduction (tpy	year 2005)	5.06	5.97	5.77	16.6	16.8	13.6	20.9
Cost-Effectiveness ($/tonne)		$6,135	$793	$433	$1,278	$2,048	$2,764	$809
Snug Cove - Ambleside - Waterfront		Ferry Emissions - Percent Of Displaced Vehicle Emissions						
25% occupancy	6.2	319	304	307	132	129	181	76
50% occupancy	12.4	160	152	154	66	64	90	38
75% occupancy	18.5	106	101	102	44	43	60	25
Lonsdale-Ambleside-Jericho		Ferry Emissions - Percent Of Displaced Vehicle Emissions						
25% occupancy	14.2	139	133	134	58	56	79	33
50% occupancy	28.3	70	66	67	29	28	39	17
75% occupancy	42.5	46	44	45	19	19	26	11
Deep Cove-Maplewood-Waterfront		Ferry Emissions - Percent Of Displaced Vehicle Emissions						
25% occupancy	7.7	257	245	247	106	103	145	61
50% occupancy	15.4	128	122	124	53	52	73	30
75% occupancy	23.1	86	82	82	35	34	48	20
Ioco-Maplewood-Lonsdale		Ferry Emissions - Percent Of Displaced Vehicle Emissions						
25% occupancy	12.5	158	150	152	65	64	89	37
50% occupancy	25	79	75	76	33	32	45	19
75% occupancy	37.5	53	50	51	22	21	30	12

Ferry Emission Reduction Options
1. PuriNOx water/diesel emulsion
2. Continuous Water Injection (CWI)
3. Diesel Oxidation Catalyst
4. Exhaust Gas Recirculation + Diesel Particulate Filter
5. Selective Catalytic Reduction (SCR)
6. Cleaire "Longview"
7. Natural gas (LNG, gas at US$9/MMBtu commodity price)

Table 3 summarizes the estimated increase in year 2005 emissions into the GVRD airshed for the four different routes that are studied, expressed as a percent of the displaced vehicle emissions. Seven different emission reduction options are studied for each route. For sustainable transportation alternatives the emissions into the airshed should not substantially increase. Those options that do not increase emissions, or actually reduce them, are highlighted in blue. It can be seen that rider-occupancy is an important parameter in determining whether an emission reduction option qualifies for sustainability or not.

If the passenger occupancy level is 50% or greater, Options 4 – 7 qualify in three out of the four runs. LNG looks especially attractive, even at a commodity price of US$9/MMBtu.

(It is assumed that ultra-low emission natural-gas engines, such as those under development by Cummings-Westport, are used to power the ferries in this option).

Of the four options that qualify for sustainability, SCR is widely used on ferries in Europe to reduce NOx emissions, while LNG is used on a number of vessels there, including one car ferry.

Conclusions and Recommendations

Conclusions:

- Nonroad heavy-duty diesel equipment contributes substantially to the emission inventory in BC. In 2005 this source is expected to contribute 35,700 tonnes. Within the GVRD the 2005 nonroad HDD equipment emissions would represent 14% of the mobile source emissions. Emission reductions (weighted) in the order of 20% can be achieved at a cost of approximately $2,000/tonne or less. The most cost-effective ERM's are the retrofit of a diesel oxidation catalyst, a diesel particulate filter or the use of B20 (all in conjunction with ULSD). If the taxes on coloured (off-road) B20 are reduced by 2 cents per litre (cpl), from the existing 5.6 cpl, then this fuel becomes highly attractive for fleet operators to use. Not only are the emissions of most exhaust contaminants reduced through the use of B20 but also there results a significant reduction in the emissions of greenhouse gases, thereby helping Canada to meet its Kyoto commitments.

- During 2005 railway locomotive emissions are expected to represent 2.3% of the total emissions in the Lower Fraser Valley. Hence these emissions are a small but not insignificant portion of the total emissions. On line-haul locomotives these emissions can be substantially reduced, at a cost of $1,000/tonne or less, using various retrofit technologies. Idle-reduction technologies for line locomotives that are based upon using a small auxiliary diesel engine to keep the locomotive engine fluids warm when the engine is shut down would provide a modest 4 % reduction in emissions but would actually save money for the railways through reduced fuel consumption. For yard locomotives idle control, in the form of an electronic system to shut down the engine during idling, would provide a large (65%) reduction in emissions while also significantly reducing operational costs through reduced fuel consumption. However, the use of this technology would be restricted to regions with a temperate climate where cold-starting a large diesel engine is feasible.

- Possible future TransLink fast passenger ferry systems would significantly increase emissions into the GVRD airshed if the ferries were powered with modern Tier 2 diesel engines. However, technologies are now available to reduce these potential emissions down below those of the displaced land-based transportation, at a cost of $2,000/tonne or less, thereby both improving air quality and decongesting roadways.

Recommendations:

This present study explored ways to reduce emissions from nonroad HDD equipment and from locomotives, as well as from a possible expanded TransLink passenger ferry system, and showed that there are clean-fuel and technology options available to significantly reduce these emissions at a cost of $2,000/tonne or less.

1. Tax and other incentives should be readily available for nonroad HDD operators to use clean-fuel and technology options to reduce their emissions. Special tax incentives should be put in place to reduce Canada's greenhouse gas emissions through the use of biodiesel blends. Emission reduction options should be screened for cost-effectiveness, with an upper limit placed on the cost/tonne, similar to that used in California's successful Carl Moyer program.

2. A follow-up study to this present "broad-brush" study is needed to provide operators with detailed information on sources and prices of the most cost-effective emission reduction technology, as well as their performance history under similar operating conditions.

3. A more in-depth study is required to properly evaluate the applicability of idle control technology in different regions of the Province – what fraction of the year can the *SmartStart* idle control technology be used alone and what fraction of the year would the *HotShot* system also be required to keep the engine fluids warm. The study should also investigate the emission reductions attainable and the corresponding cost-effectiveness of other retrofit technologies used in conjunction with idle control technologies, such as the use of diesel oxidation catalysts and diesel particulate filters.

4. A follow-up study is also required to identify economic instruments, as well as regulatory methods, for implementing the early introduction of clean fuels and

emission reduction technologies into the three regions that were studied (GVRD, FVRD1 and BC). In this study consideration should be given to the differences between government-managed fleets and private fleets, as the economic consequences and competitive impacts will differ.

5. Stakeholder concerns about the effect of certain emission reduction technologies upon equipment performance need to be addressed. It is recommended that pilot projects, with multi-party stakeholder funding, be initiated to demonstrate these emission reduction technologies under a wide range of actual operating conditions. These pilot projects need to be coordinated with those planned or underway in other jurisdictions and countries. (One forum for such coordination would be the *West Coast Diesel Emission Reduction Collaborative*.)

Table of Acronyms

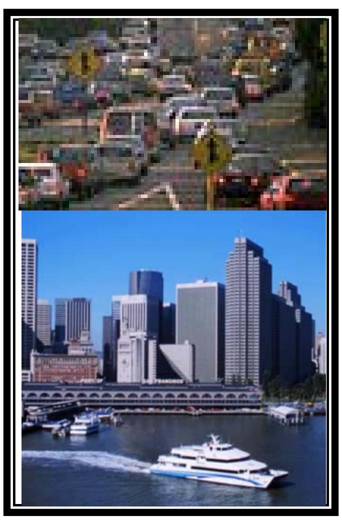
AAR	American Association of Railroads
ASTM	American Society of Testing Methods
BHP	Brake Horse Power
BTU	British thermal unit
BSFC	Brake Specific Fuel Consumption
CAC	Criteria Air Contaminants (CO, VOC, NOx, SOx, PM)
CARB	California Air Resources Board
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CWI	Continuous Water Injection
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DWI	Direct Water Injection
EMD	Electro Motive Division of General Motors
EPA	US Environmental Protection Agency
ERM	Emission Reduction Measure
FVRD1	Fraser Valley Regional District (southern portion)
G/HP-HR	Grams per horsepower-hour
G/KWH	Grams per kilowatt-hour
GE	General Electric locomotives
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)
GVRD	Greater Vancouver Regional District
GCCAB	Georgia Coast Cascade Air Basin (same as GB/PS)
HC	Hydrocarbon gases
HFO	Heavy Fuel Oil
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
ISO	International Standards Organization
KW	Kilowatts power
LFV	Lower Fraser Valley
LNG	Liquefied Natural Gas
LSD	Low sulfur diesel
MEC	MEC System (An Italian manufacturing company)
MECA	Manufacturers of Emission Controls Association
MDO	Marine Diesel Oil
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
PNW	Pacific Northwest
RAC	Railway Association of Canada
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	Tonnes per Year
ULSD	Ultra-Low Sulfur Diesel (< 15 PPM S)
VOC	Volatile Organic Compounds (includes benzene, formaldehyde and 1,3 butadiene, as well as other volatile species)
WSF	Washington State Ferry

1.0 INTRODUCTION

1.1 Background

Emissions from nonroad heavy-duty diesel (HDD) engines (rail, marine, construction equipment and other nonroad mobile sources) presently account for a significant part of the major pollutants (SOx, NOx, VOC, $PM_{2.5}$, CO, and NH_3) that are responsible for smog and for human health impacts in BC. During the year 2005 these emissions are expected to account for over 29% of the total emissions into the Lower Fraser Valley (LFV) of BC, which not only is the socio-economic hub of BC but also a major source of food produce.



On-road, transportation-based emissions are stringently regulated and future emissions are projected to actually decrease within the LFV. While in the past nonroad emission sources were largely uncontrolled, new HDD engines are required to meet increasingly tough emission standards which are similar to the on-road standards but which lag them by approximately 5 years. But since HDD engines may last for many years before requiring replacement, there are opportunities in the near term to reduce emissions from the existing fleets that will result in health benefits.

Also, TransLink has recently concluded the Vancouver harbour Passenger Marine Study; a study intended to explore the feasibility of this increased passenger ferry service in Vancouver Harbour. Although TransLink has no plans to implement a new passenger ferry service at this time, the current report reviewed potential emissions from four passenger ferry routes with representative fleet that were considered in the TransLink study, and compared the ferry emissions with the avoided road-commute emissions.

1.2 Study Area

The areas investigated in this study are the *Lower Fraser Valley* and *The Rest of BC* (BC less the *Lower Fraser Valley*.)

For purposes of this study the *Lower Fraser Valley* (LFV) is defined as a rectangular region covering approximately 9200 square kilometers, running from Bowen Island to Hope in the west-east direction and from Lions bay to the Canada-United States in the north-south direction. In terms of the Universal Mercator coordinates: 470,000 E; 630,000 E; 5,427,500 N: 5,485,000 N. This area encompasses virtually the entire Greater Vancouver Regional District (GVRD) as well as the southwestern portion of the Fraser Valley Regional District (FVRD).

A large part of the FVRD lies outside the LFV airshed, and is mostly vegetation. In this report, the portion of the FVRD that is included in the Lower Fraser Valley study area is designated as "FVRD1".

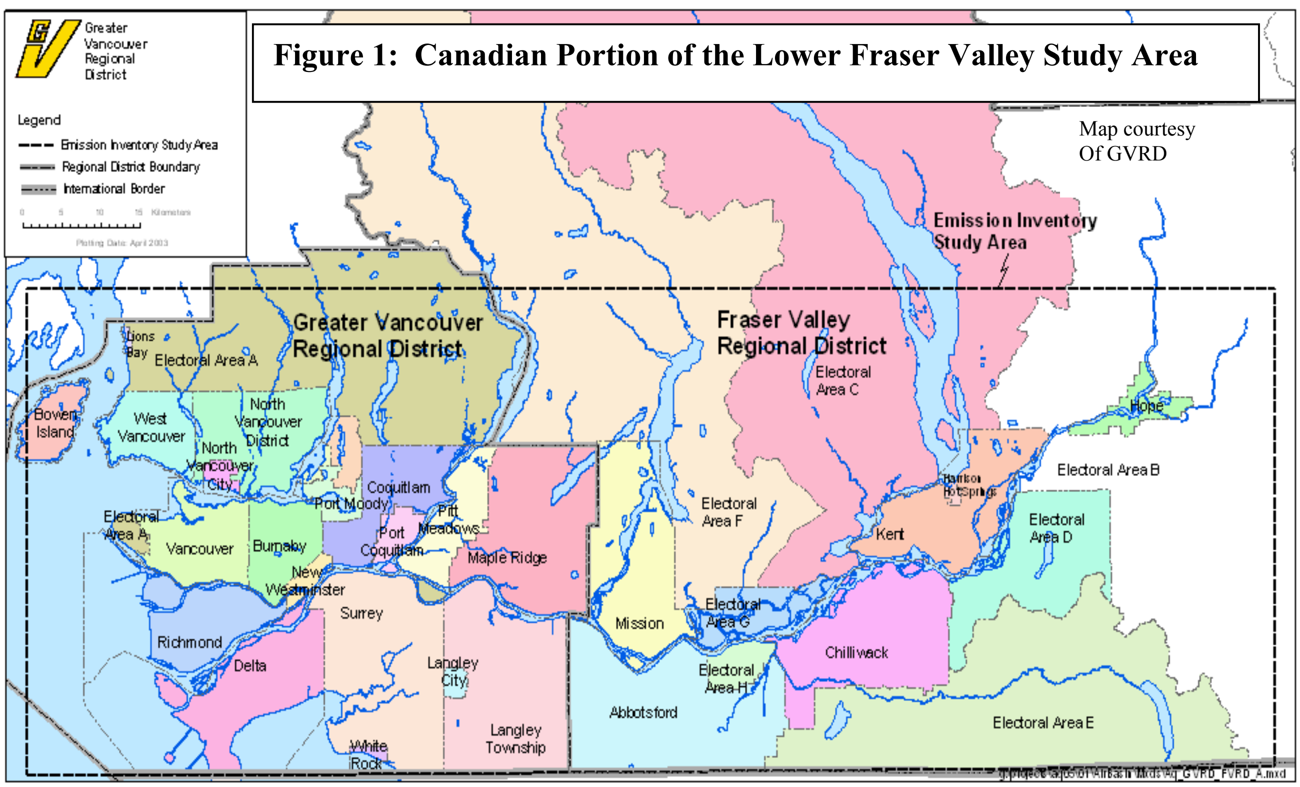


Figure 1: Canadian Portion of the Lower Fraser Valley Study Area

1.3 Study Objectives and Scope

1. The primary objective of this project is to identify cost-effective ways to reduce the nonroad HDD emissions; either through the use of clean fuels or with exhaust treatment technologies, over the time period of 2005 to 2025. First base-line emissions for the various major nonroad sources will be quantified using data derived from a Canadianized NONROAD 2004 model which incorporates the effects of existing and future Canadian nonroad HDD emission and fuel sulphur regulations Then selected emission reduction options appropriate to each of the nonroad HDD sources will be identified and their associated net present value (NPV) costs and emission reductions, for the 20-year period 2005 – 2025, will be estimated. Finally, the cost-effectiveness of each option will be calculated as a ratio of total NPV costs divided by total emission reductions ($/tonne of avoided emissions). Those options which provide a significant percentage reduction in emissions and at a low $/tonne cost will be short-listed. This study will be carried out for three distinct geographic regions in the province of BC: the GVRD, the portion of the Fraser River Regional District within the Lower Fraser Valley (LFV) airshed (FVRD1), and the rest of BC. Emission reductions from marine vessels will be excluded as theses have been studied in a previous Environment Canada study.[126]

   The emission reduction measures that will be proposed here are primarily focused on advancing emission reductions that would, to a large extent, occur in any case with future HDD fleet turnover. The purpose is to advance the timing of the emission reductions, if this can be done in a cost-effective manner.

2. Another objective will be compare emissions between possible TransLink short-haul marine transportation options and those from the existing car-based mode of transportation, and then to suggest methods for reducing the air quality impacts that may result from the marine-based options. Four conceptual routes, all of which were identified as potential service options in TransLink's *Vancouver Harbour Passenger Marine* study, will be studied:

   1. Snug Cove – Ambleside – Vancouver Waterfront.
   2. Lonsdale – Ambleside – Jericho (with direct bus service from Jericho to UBC).
   3. Deep Cove – Maplewood - Vancouver Waterfront.
   4. Ioco – Maplewood – Lonsdale.

Again, although TransLink has no plans to implement a new passenger ferry service at this time, the current report reviewed potential year 2005 emissions for the four routes listed above from a representative fleet that was considered in the TransLink study, and compared these emissions with avoided road-commute emissions for the same time period.

The methodology used will be similar to that used in a CALSTART 2003 study comparing emissions from an expanded ferry system in San Francisco with those from automobiles. [170]

The following section will provide a brief overview of diesel engine emissions.

2.0 DIESEL ENGINE EMISSIONS

2.1 Diesel Engines

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 large diesel engine burning heavy 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.

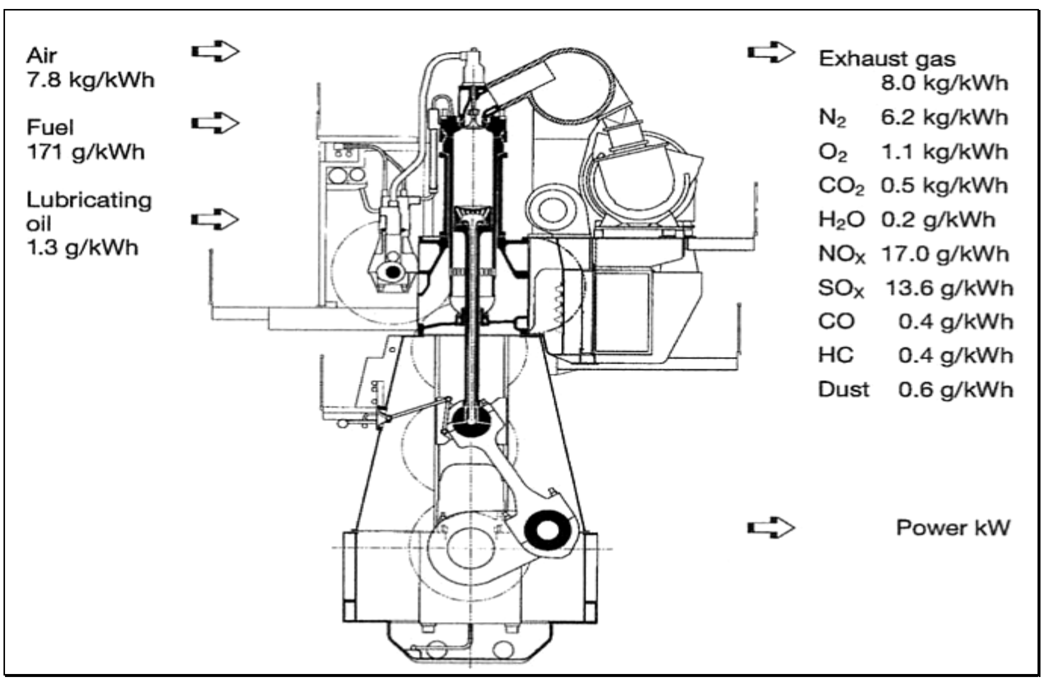


FIGURE 2.1 – TYPICAL MARINE DIESEL ENGINE EMISSIONS (Ref. 5)

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 discussed health and welfare impacts from heavy-duty diesel engines and quantified 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, may be responsible for a significant part of the carcinogenic effect.

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 defined as the total material that can be collected upon a filter and condensed under specified temperature conditions. PM_{10} is all particulate matter with a diameter of less than 10 microns, which is the approximate cut-off diameter for nasal inhalation. $PM_{2.5}$ is all 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 since they can penetrate deep into the lungs.

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.

$$CH + N_2 \Rightarrow HCN + N \quad (7)$$
$$N + O_2 \Rightarrow NO + O \quad (8)$$
$$N + OH \Rightarrow NO + H \quad (9)$$
$$C2 + N_2 \Rightarrow 2CN \quad (10)$$
$$CN + O \Rightarrow C + NO \quad (11)$$
$$CN + O_2 \Rightarrow CO + NO \quad (12)$$

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).

$$NO + HO_2 \Rightarrow NO2 + OH \quad (13)$$
$$2NO + 02 \Rightarrow 2NO_2 \quad (14)$$

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].

$$\text{Fuel S} + O_2 \Rightarrow SO_2 \quad (15)$$
$$SO_2 + O \Rightarrow SO_3 \quad (16)$$
$$2SO_2 + O2 \Rightarrow 2SO_3 \quad (17)$$

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.

$$SO_3 + H_2O \Rightarrow H_2SO_4 \quad (18)$$

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.

$$H_2SO_4 + H_2O \Rightarrow H_3O^+ + HSO_4^- \quad (19)$$

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].

3.0 DIESEL ENGINE EMISSION STANDARDS

3.1 Off-Road Heavy-Duty Diesels

3.1.1 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.

Tier 4 Standards

On May 11, 2004, the EPA signed the final rule introducing Tier 4 emission standards to be phased-in over the period of 2008-2015. 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 June 2007 for fuels used in nonroad, locomotive and marine engines
- 15 ppm effective June 2010 for nonroad fuel, and June 2012 for locomotive and 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 3.1
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)
	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 3.2.

Table 3.2
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 2008-2015. Tier 4 emissions standards are listed in Table 3.3.

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 (“family emission limits”) for emission averaging.

Table 3.3 – Proposed Tier 4 Emission Standards, g/kWh (g/bhp-h) Refs.67, 68			
Engine Power	**Year**	**NOx**	**PM**
kW < 19 (hp < 25)	2008	7.5 (5.6)	0.40 (0.30)
19≤ kW < 56 (25 ≤ hp < 75)	2013	4.7 (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)
Generators kW > 560 (hp > 750)	2011-2015	0.67 (0.50)	0.03 (0.022)
All others kW > 560 hp > 750	2011-2015	3.5 (2.34)	0.04 (0.03)

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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 3.4 for different engine categories. The Tier 4 proposal maintains the same engine useful life periods.

Table 3.4
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 less than 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 regulation

When fully phased in, annual emission reductions in the USA are estimated by the EPA at 738,000 tons of NOx and 129,000 tons of PM. By 2030, 12,000 premature deaths in the USA 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 1-3% relative to the typical retail price. For example, for a 175 hp bulldozer that costs approximately $230,000 it would cost an additional $6,900 to add the advanced emission controls and to design the bulldozer to accommodate the modified Tier 4 engine.

EPA estimated the cost of producing 15-ppm fuel to be on average 7 cents per gallon. This figure would be reduced to 4 cents by an anticipated savings in maintenance costs due to low sulphur diesel.

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. In January 2003, the EU proposed its Stage III/IV after-treatment forcing standards for nonroad engines, but the final Directive has been delayed, in part due to standards harmonization between the EU and USA authorities.

3.1.3 Canada Nonroad Diesel Engine Regulations

Canada does not have nonroad engine manufacturers – a majority of our engines come from the USA. In addition, Environment Canada has a policy that says that Canadian standards will align with USA standards.

On May 10th, 2004, the Honourable David Anderson, Minister of the Environment, announced draft regulations to help reduce smog emissions from off-road diesel engines that power construction, mining, farming and forestry machines. The regulations have been published in the Canada Gazette, Part I, for a 60-day public comment period. They are expected to become final in early 2005 and apply to 2006 and later year engines. The proposed Canadian nonroad regulations are essentially identical to the above EPA Tier 2 and 3 regulations. Environment Canada plans also to maintain alignment with the U.S. EPA 2008 (Tier 4) rules for off-road diesel engines, once these are finalized in the United States.

At present Canada does not have federal regulations that limit the sulphur content for off-road diesel. A discussion paper was published in 2003 proposing two alternatives:

1. a simple regulation requiring Canadian off-road diesel fuel to meet a 500mg/kg limit starting in 2007, reduced to 15 mg/kg starting 2010 (except for locomotive and marine diesel fuel that would remain subject to the 500 mg/kg limit).
2. a more EPA-style regulation, including the above sulphur reductions, but also with complex banking, credit and trading programs plus limited extensions for small refiners during the 2006 – 2014 transitional period.

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 3.5a - 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 3.5b - 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 3.5a shows that, except for NOx emissions, existing locomotives are generally meeting Tier 0 and Tier 1 requirements.

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. (RAC refers to the Railway Association of Canada.)

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.

RAC: Railway Association of Canada

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 3.7.

Table 3.7 — 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 Canada Locomotive Regulations

There presently are no regulations limiting diesel locomotive emissions in Canada. Instead, there exists a *Memorandum of Understanding* (MOU) between Environment Canada and the Railway Association of Canada that was signed in 1995 and is valid until 2005. It calls upon RAC to report annually on HC, CO, NOx, PM and CO2 emissions from its member companies, and includes voluntary compliance with a 115,000 tonne NOx cap. [172]

The calculation of emissions is based upon factors deriving from engine testing carried out by the American Association of Railroads and the Southwest Research Institute in the 1980's, and from duty cycle information provided by the RAC. Three sets of factors were derived, giving emissions in terms of imperial gallons of fuel for road freight, yard switcher, and passenger duty cycles. These factors are applied to fuel consumption data supplied by RAC members to give the final estimates of total emission levels.

The MOU scope and methodology are presently under review by Transport Canada, Environment Canada and by the RAC. The MOU provides a uniquely detailed record of railway locomotive emissions and has no other parallel in any other transportation sector. Since it is based upon fuel consumption, it is also directly applicable to current efforts to limit greenhouse gases. It is likely to play a prominent role in future strategy to control emissions from the railway sector. [172]

3.3 Marine Diesel Engines (U.S. EPA)

Background

Engine Categories

For the purpose of emission regulations, marine engines in the USA are divided into three categories, as listed in Table 3.8. 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 3.8 – 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 engines, on the other hand, have a bore/stroke of 320mm x 350mm and a cylinder displacement of 28.1 liters. They are Category 2 engines.

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

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 IMO 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.

Engines Category 1 and 2

Emission standards for engine categories 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 3.9 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 3.9 – 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 3.10.

Table 3.10 – "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.

4.0 PROJECTED NONROAD EMISSIONS

4.1 Locomotive Emissions

Figure courtesy of BC Rail (Now CN Rail)

Estimation of Projected Emissions

Projected locomotive emissions for the GVRD, the FVRD1 and the rest of BC are presented in Table 4.1 for the years 2005 – 2020. (The staff of GVRD and Environment Canada provided these projected emissions.)

Table 4.1 Projected Locomotive Emissions in the LFV and Rest of BC								
	2005	2010	2015	2020	2005	2010	2015	2020
GVRD (tonnes)	Line				Yard			
NOx	2,627	2,654	2,599	2,557	138	142	136	134
CO	446	450	441	434	25	26	25	25
PM10	41	42	41	40	4	4	4	4
VOC	62	63	62	61	9	9	9	8
NH3	0	0	0	0	0	0	0	0
SOx	32	32	1	1	2	2	0	0
PPM S	400	400	15	15	400	400	15	15
FVRD (tonnes)								
NOx	1,223	1,235	1,210	1,190	64	65	64	63
CO	207	210	205	202	12	12	12	12
PM10	19	19	19	19	2	2	2	2
VOC	29	29	29	28	4	4	4	4
NH3	0	0	0	0	0	0	0	0
SOx	15	15	1	1	1	1	0	0
PPM S	400	400	15	15	400	400	15	15
Rest of BC (tonnes)								
NOx	22,652	21,584	20,690	19,956	1,079	1,069	1,066	1,063
CO	3,352	3,269	3,219	3,186	305	303	302	302
PM10	364	375	391	402	36	36	36	37
VOC	891	893	899	910	101	101	102	103
NH3	3	3	3	3	0	0	0	0
SOx	401	412	16	16	19	20	1	1
PPM S	400	400	15	15	400	400	15	15
GVRD								
Total Engines	47	51	53	55	30	30	29	29
Fuel (millions of litres)	46.4	50.1	52.5	55.3	2.5	2.5	2.4	2.4
Possible SD-75/Dash 9 upgrades	9	6	3	0	0	0	0	0
FVRD								
Total Engines	22	24	25	26	14	14	14	13
Fuel (millions of litres)	21.6	23.3	24.5	25.8	1.1	1.2	1.1	1.1
Possible SD-75/Dash 9 upgrades	4	3	1	0	0	0	0	0
Rest of BC								
Total Engines	408	413	420	430	232	230	229	229
Fuel (millions of litres)	400	408	418	432	19	19	19	19
Possible SD-75/Dash 9 upgrades	78	51	25	0				

(Note to Rest of BC Locomotive Emission Projection. Source: Draft Base Case Emission Forecast, Nov. 2004 version, Environment Canada, Hy-Hien Tran. For purposes of this study GVRD and BCWLAP have adjusted Environment Canada's 2015 and 2020 Rail SOx emission forecast to reflect Canada's proposed "Regulations Amending the Sulphur in Diesel Fuel Regulations introducing 15 mg/kg in 2012 for locomotive diesel fuel.)

Table 4.2 provides estimates of the total locomotive emissions for the period 2005 – 2025. The projected emission estimates listed in Table 4.1 were curve-fitted (least-mean squares regression analysis) and then integrated over the 20-year period 2005 - 2025. ($PM_{2.5}$ is assumed to be 97% of PM_{10} emissions.) In the case of SOx there is a step-change in fuel sulphur concentration occuring during the year 2012 due to federal fuel regulations, which mandate < 15 ppm S diesel commencing at that time. In this case the total SOx emissions were estimated by first curve-fitting the fuel consumption data of Table 4.1 and then integrating in parts using estimated fuel sulphur levels, also shown in Table 4.1.

Table 4.2 Projected Locomotive Emissions 2005 - 2025 (tonnes)				
GVRD		Line Haul	Yard Engines	Total Emissions
	NOx	51,920.0	2,734.4	54,654.4
	CO	8,810.0	503.4	9,313.4
	PM_{10}	791.5	73.3	864.9
	VOC	1,236.0	171.6	1,407.6
	NH3	4.0	0.0	4.0
	SOx	256.7	13.0	269.7
FVRD				
	NOx	24,166.0	1,269.0	25,435.0
	CO	4,100.0	233.8	4,333.8
	PM_{10}	368.6	33.6	402.2
	VOC	572.0	79.6	651.6
	NH3	2.0	0.0	2.0
	SOx	119.5	6.0	125.5
Rest of BC				
	NOx	415,426.9	21,335.1	436,762.0
	CO	64,581.4	6,050.6	70,632.0
	PM_{10}	7,556.9	699.7	8,256.6
	VOC	18,022.0	2,048.0	20,070.0
	NH3	53.9	6.1	60.0
	SOx	2,134.0	100.4	2,234.3

Estimation of Fleet Size

Locomotive fleet size and fleet fuel consumption for the different regions and for the province are also shown in Table 4.1. Although there is expected to be a significant increase in the volume of rail freight, this is not reflected in the increase in the number of line haul locomotives. Older locomotives instead are being replaced with much more powerful locomotives so that on a tonne-kilometer basis less are required. The newer locomotives are also more fuel-efficient and have lower atmospheric emissions. The bottom of Table 4.1 also shows one estimate of the number of older locomotives that may qualify for upgrades through rebuilds or replacements.

Section 8 will investigate possible ways to reduce locomotive emissions, over the 2005 – 2025 time period, through the early introduction of various clean-fuel and emission-reduction technologies.

4.2 Nonroad Equipment Emissions

GVRD provided estimates of future nonroad equipment emissions that they derived using a “Canadianized” version of the EPA NONROAD 2004 model. Estimates were tabulated in Excel worksheets for the LFV in 5-year increments for the years 2000 – 2025. Environment Canada supplied the same data for BC outside of the LFV area. A program was written in *Visual Basic for Applications* to integrate this data over the period 2005 – 2025 using "Bode's Rule", which is a 5-point version of the closed Newton-Cotes integration formulas.

The total base-line emissions for GVRD, FVRD1 and the rest of BC over the period 2005 – 2025 are tabulated in Tables 4.3 – 4.5 below. Annual nonroad emission estimates for three major fleets for the years 2005, 2010, 2010, 2020 and 2025 are presented in Table 4.6 and also further in the report (Tables 7.17 – 7.19) wherein rich detail is provided on potential reduction of annual emissions through implementation of different emission reduction strategies. (The SOx emissions assume 563-ppm sulphur in fuel up to 2010, 15-ppm sulphur thereafter.)

Table 4.3 GVRD NonRoad HDD Equipment - Total Emissions (tonnes) 2005 - 2025

Emission Species	Construction & Mining	Agriculture	Industrial & Commercial	Others	GVRD Total
NOx	64,287	10,924	21,119	3,373	99,702
SOx	384	50	100	15	548
PM10	4,660	1,020	1,757	267	7,705
VOC	6,664	1,086	2,400	356	10,506
CO	30,335	6,250	10,849	1,622	49,056
NH_3	105	13	28	4	150
Sum (less CO)	75,960	13,062	25,351	4,008	118,381

Table 4.4 FVRD NonRoad HDD Equipment - Total Emissions (tonnes) 2005 - 2025

Emission Species	Construction & Mining	Agriculture	Others	FVRD Total
NOx	6,823	13,168	3,486	23,477
SOx	42	60	73	175
PM10	576	1,227	288	2,092
VOC	796	1,310	395	2,501
CO	3,677	7,541	1,786	13,004
NH_3	11	16	5	32
Sum (less CO)	8,231	15,745	4,239	28,215

Table 4.5 Rest of BC NonRoad HDD Equipment - Total Tonnes 2005 - 2025

Emission Species	Construction & Mining	Agriculture	Logging	Others	Rest of BC Total
NOx	66,328	132,013	17,804	16,290	232,434
SOx	606	756	215	146	1,724
PM10	4,577	11,371	1,245	1,183	18,376
VOC	6,703	12,569	1,718	1,647	22,637
CO	29,678	62,807	7,130	7,960	107,575
NH_3	109	155	36	26	326
Sum (less CO)	78,186	156,522	20,980	19,258	274,946

It can be seen from these tables that the construction sector dominates the GVRD nonroad HDD emissions, whereas the agriculture sector dominates both in the FVRD1 and in the rest of BC.

Table 4.6 shows that emissions are generally projected to decrease with time due to cleaner fuels and modern low-emission engines being phased in. (These projections were kindly provided by the GVRD and Environment Canada, as mentioned previously.)

Table 4.6 - Projected Emissions for Selected NonRoad Fleets (tonnes/year)

Nonroad Equipment Fleet & Region	2005	2010	2015	2020	2025
GVRD					
Construction & Mining					
NOx	5562.9	4576.6	2997.1	1814.0	1412.2
SOx	183.7	5.5	5.2	5.1	5.4
PM10	416.8	350.5	227.8	113.7	66.3
VOC	520.3	402.6	310.5	253.3	232.8
CO	2609.3	2283.8	1409.9	770.3	512.9
NH3	4.2	4.7	5.2	5.8	6.3
FVRD					
Agricultural Equipment					
NOx	893.4	811.5	667.9	505.3	407.3
SOx	28.6	0.8	0.9	0.8	0.9
PM10	111.4	86.5	58.7	35.4	20.0
VOC	118.2	84.7	59.5	43.3	36.4
CO	621.1	513.7	369.2	240.1	147.6
NH3	0.7	0.7	0.8	0.9	0.9
Rest of BC					
Logging Equipment					
NOx	2356.0	1502.6	685.9	203.6	113.5
SOx	122.9	1.6	1.3	1.1	1.0
PM10	151.5	113.1	49.5	9.4	4.3
VOC	171.3	111.4	68.7	55.6	51.8
CO	794.4	633.8	270.8	81.7	54.5
NH3	2.0	1.9	1.8	1.7	1.6

Section 7 will investigate cost-effective ways to reduce these emissions, over the 2005 – 2025 time period, through the early introduction of various clean-fuel and emission-reduction technologies.

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). (It should be noted here that some of the historical fuel prices cited in this section have recently increased significantly.)

- 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 particulate less than 2.5 microns in diameter) 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 of high-efficiency catalytic emission-reduction technology, but it is expensive to produce and may also 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. It, along with dimethyl ether, may well be the fuels of choice in the future.
- 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 by the EPA to be US2.5 cents/gallon and for ULSD an additional US2.3 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 significant 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, the use of ULSD in diesel engines reduces harmful sulfate and $PM_{2.5}$ emissions. This is discussed further in this section.

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+ US 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 (US)/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 US$0.832 and US$0.900, respectively. At Tacoma on the same day the prices for LSD and ULSD were US$0.845 and US$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 US 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 Shell Canada, 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 (now called Terasan) 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 563 ppm S in BC), then these sulfur-related emissions will be reduced by 38%. Similarly, if ULSD (typically 10 ppm S) is substituted for regular No.2 off-road diesel, then these sulfur-related emissions are reduced by 98%.

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).

California's strategy for reducing marine vessel emissions includes requiring vessels to switch to cleaner fuels while in port. Ships switching from 2.1% S bunker to marine distillate (MDO with 0.2% S) are expected to see a 60% reduction in PM, a 6-10% reduction in NOx and a 90% reduction in SOx emissions. Similarly, harbour craft switching from #2 diesel to CARB (road) diesel are expected to experience a 10-25% reduction in PM, a 6% reduction in NOx and about a 90% reduction in SOx. [159]

The EPA, in a study testing the effect of fuel sulphur on nonroad HDD particulate emissions, came up with a relationship between particulate emissions (g/hp-hr) and fuel sulphur (g/hp-hr) of 0.16. The testing was carried out using #2 diesel (0.28% S) and road diesel (0.035% S) on 9 different pieces of equipment dating from 1991 to 1997. The average PM reduction was 17.4%. [160]

A more recent study in Bangkok[161] related increases in diesel fuel sulphur to increases in vehicular emissions, using a base line of 150-ppm sulphur diesel. Hydrocarbon emissions increased 45% with 350 ppm S diesel and 94% with 500 ppm S diesel. NOx increased 0% with 350 ppm S diesel and 5% with 500 ppm S diesel. Particulate emissions increased 16% with 350 ppm S diesel and 33% with 500 ppm S diesel.

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 expected.)

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 may 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 will become commercially available in 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.

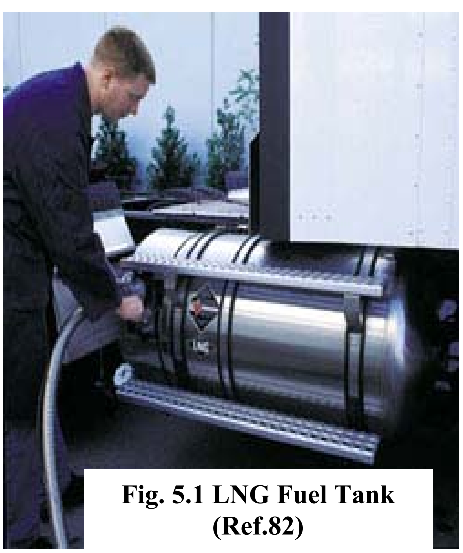


Fig. 5.1 LNG Fuel Tank (Ref.82)

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 emission reductions 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 also 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 were 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] However, with the recent approval of a bridge crossing over the Fraser River the two small ferries will not be required and the expensive engine replacements will not proceed.

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.

- **<u>Hampton Roads Transit Authority CNG Ferry</u>**

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]

- **<u>Norwegian LNG Ships</u>**

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, as compared with diesel-fueled vessels, are 195 – 210 tpy (82 – 84%) for NOx and 2720 tpy (~ 20%) for CO_2. The extra investment was US$5.6 – US$6.7 Million 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 US 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 US 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 US 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 US$1 million (US$250,000 for each locomotive conversion plus US$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.

- **<u>LNG Heavy-Duty Highway Trucks</u>**

  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] These large truck engines are also suitable for use on small passenger ferries, which typically use two engines to provide reliable propulsion.

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 US$5/MM Btu. [91] (US$0.65/USgal. 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 US gallons/day in 2001. This is expected to increase to about 200,000 US 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 US$1.06/gal diesel equivalent (US$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 US$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 US$5.00/MM Btu, the equivalent delivered LNG price (less taxes) would be in the order of US$7.50/MM Btu, US$0.61/gal LNG, or US$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 US$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 US$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 US$25,000 - US$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 US$50,000 - US$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]

The current specification in the World Wide Fuel Charter specifies a limit of 5% v/v biodiesel for current engines and zero biodiesel for 2007+ engines. There is a concern about the equality standards for biodiesel and as a consequence some engine manufacturers are unwilling to warranty biodiesel use. This may change in coming years. The biggest draw back to biodiesel is the cost and the poor flow properties. Cloud points are impacted even at low biodiesel concentrations. [183]

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 US$0.25 - US$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 December 16, 2004 the price (US$/US gallon) for biodiesel blends in Seattle, WA, are given as $2.70 (B100), $1.49 (B20), $1.21 (B2) and $1.37 (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 US$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/USgallon 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] However, to date there has been little or no published information regarding engine emissions and performance using this emulsion. Some fuel marketers (Esso, Shell, Petro-Canada) will not market a diesel ethanol blend because of safety concerns. [183]

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]

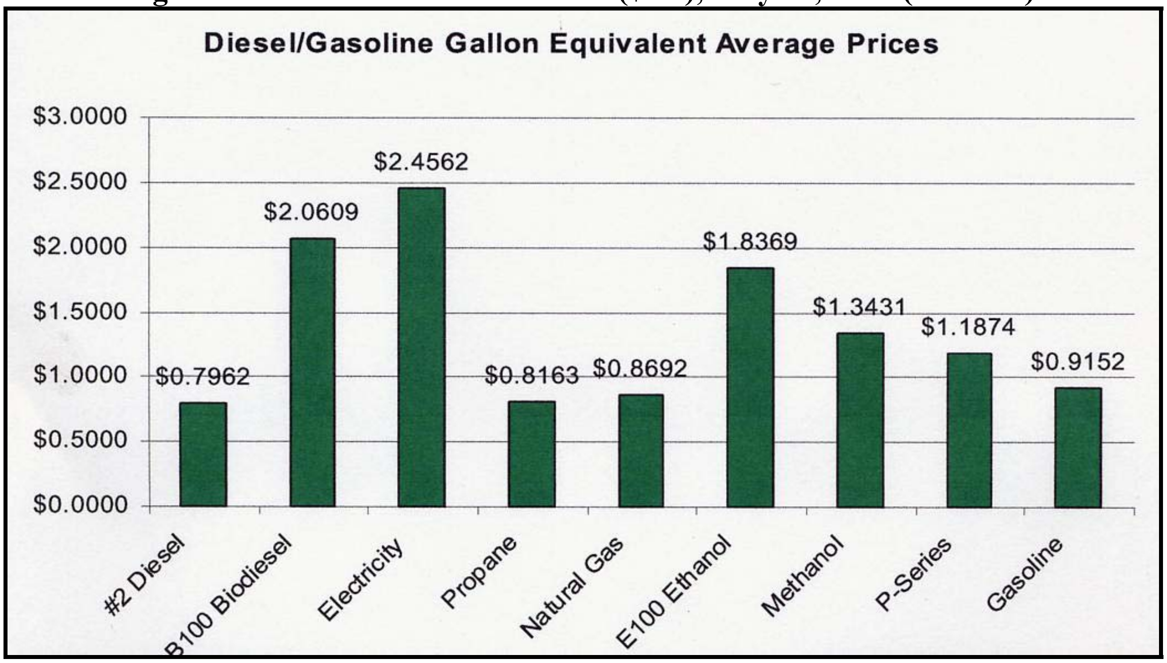
The Cornell study has been refuted by a consultant for the National Corn Growers Association, who quotes other studies which estimate a more favorable energy-out to energy-in ratio of 1.24 – 1.37. [107] It is probable that this ratio is sensitive to the assumptions that are used in its derivation. It 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 (US$/US gal) 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 much more expensive than fossil fuels.

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



* Cost for biodiesel given on a basis of equivalent gallons of diesel with the same energy content.
Cost for other energy media given on a basis of equivalent gallons of gasoline with the same energy content.

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 source of a relatively clean fuel for vehicles and mobile equipment.

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 fuel storage 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 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 (US$/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 US$0.06/kWh; methanol at US$251/tonne; natural gas at US$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 US$80/kg for a production of only 1000 kg/year (3 kg/day), but drop to US$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 US$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 contractual specifications, as well as government fuel sulphur limits. 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 US/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 (US$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 Background

Emission reduction technology for small and medium-sized 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.

Engines and retrofits that have been certified by the US EPA and by the California Air Resources Board are listed on their respective websites:
(www.epa.gov/otaq/retrofit/retroverifiedlist.htm and
http://www.ard.ca.gov/diesel/verdev/level3.htm).

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 catalyst to reduce contaminants from the exhaust stream. These technologies can remove most of the contaminants from the exhaust gases, but some may be heavy, bulky and expensive and hence the technologies should be chosen with care.

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].

  Recent testing by Environment Canada on a Caterpillar 3306 mechanical injection engine showed that retarding the fuel injection timing by 9 degrees resulted in a direct reduction in NOx of 48% and THC of 33%; however, CO, CO_2 and PM were increased by 51%, 9% and 35%, respectively. Measured power was also reduced by 2.6%.[163] 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.

Another approach being used to improve fuel atomization is through the use of micro-emulsions of fuel and water. The idea is that rapid heating of the encapsulated micro-droplets of water will cause an explosive atomization of the larger fuel droplets into smaller droplets. This will improve combustion and reduce the emission of diesel soot. [164] This atomization process will be discussed in more detail in a further section.

- Pre-injection - 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 US$36,200. For a typical 3000 hp engine this cost is equivalent to US$12/hp (US$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]

- Charge Air Techniques - 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 US$25,000.[63] The engines are typically turbocharged, 2-stroke diesels of approximately 3000hp, so the unit cost would be approximately US$8.30/hp (US$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 US$20,000 - US$30,000 and for new pistons would be around US$50,000. Tier 1 would probably also require electronic engine control at a cost of approximately US$100,000. [127]

  Others have estimated the cost for a locomotive Tier 1 engine rebuild at approximately US$183,000 and for a total locomotive remanufacture at US$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 US$174/hp (US$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 US$179/hp (US$240/kW). The smallest marine engine (85hp) was an auxiliary engine costing US$290/hp, while the largest marine engine (1500 hp) cost US$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 US$175/kW (US$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.

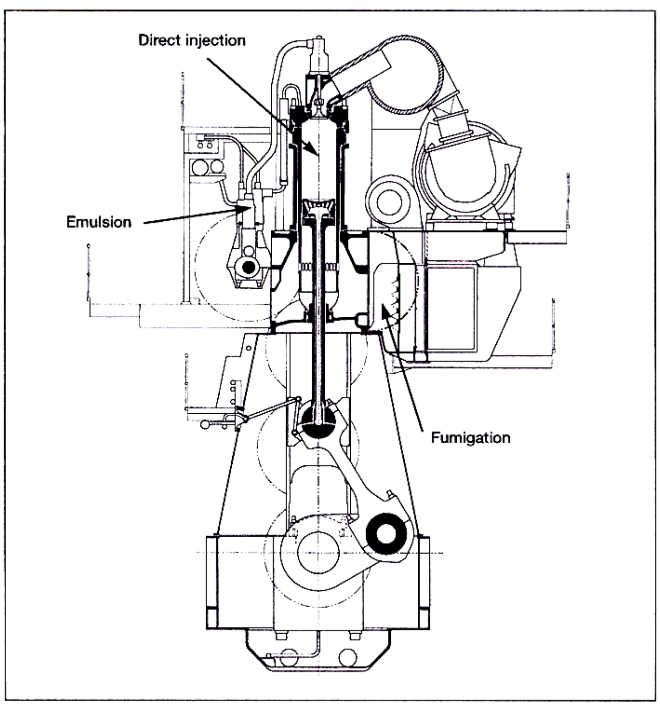


Figure 6.1 – **DIFFERENT MODES OF WATER ADDITION**

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

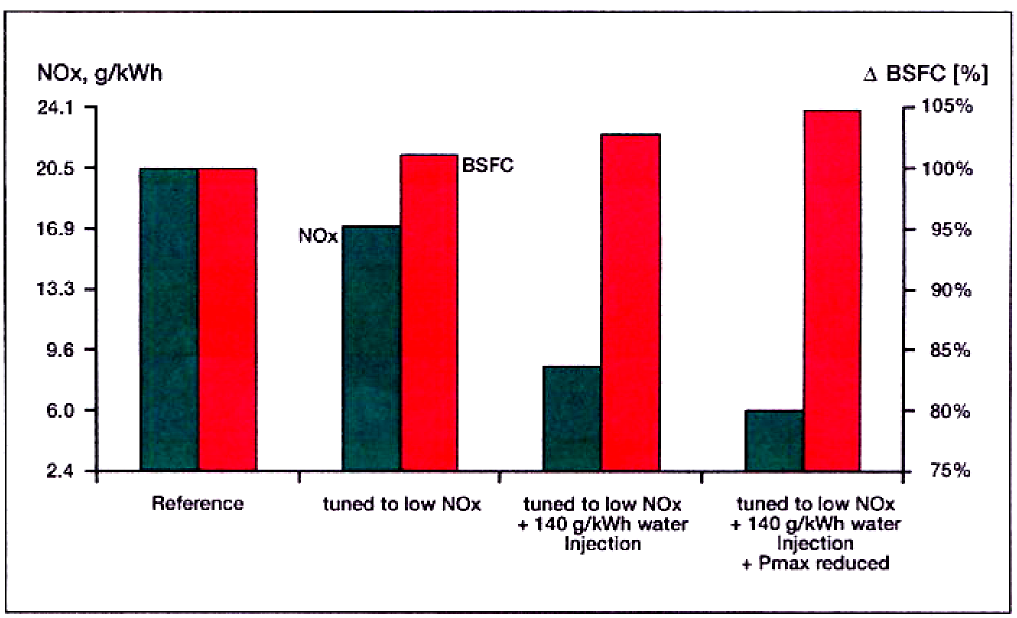


Figure 6.2 – Effect of water injection on NOx emissions (Ref.5)

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.

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 (BSFC is the “Brake Specific 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 US$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 load, as measured by the manifold pressure. NOx is reduced by up to 30% and PM by up to 20% 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 wide variety of vessels. Systems operate practically maintenance free and are claimed to reduce exhaust gas temperatures by up to 25ºC, minimize thermal stresses and carbon buildup on the engine components and decreases engine maintenance costs by 25%. [166]

For B.C. Ferry's *Queen of New Westminster*, which has four main engines and three auxiliary engines, the installed price for all seven engines is quoted to be US$90,000 and annual costs for water and water filter cartridges are estimated to be US$3,700. Savings in fuel (at US$460/tonne) is estimated to be US$48,200/year and savings in maintenance at US$13,000/year, giving a total annual savings of US$61,200.[166] The simple *pay-back period* for this retrofit would then be $90,000/($61,200 - $3700) = 19 months. Long term testing has been carried out on the auxiliary engine of a B.C. Ferry vessel.

Transport Canada Water Injection System - Transport Canada, in cooperation with Environment Canada, have been recently experimenting with a computer controlled water injection system installed on a Caterpillar 3406 diesel engine. [163] The water injectors are derived from an AC Delco fuel injection system and spray a fine mist of water in close to the intake valves, using a pressure of about 60 psig. With a water injection rate of 34% of the fuel rate they measured (IMO Marine cycle ISO 8178-4 E3) a maximum NOx reduction of 28%, although PM increased 18% and SFOC increased by 0.7%.

This system was then installed and tested on the cargo vessel *MV Cabot*, which has a weekly run between Montreal and St. John. This vessel is equipped with a 7300 hp V12 Pielstick main engine that runs on a blend of MDO and Bunker C HFO. Baseline testing by Environment Canada showed that NOx emissions from this vessel are well in excess of IMO limits. [163]

Testing was carried out both with heavy fuel oil (IFO 180) and with lighter marine distillate oil (MDO). The findings are summarized by Transport Canada's Transportation Development Centre[165]:

- Both NOx and PM are load dependent; specific emissions decrease with engine load.
- NOx reduction is a function of water/fuel ratio and engine load: Maximum reduction was 30% at 0.75 max. continuous rating and 100% Water/Fuel (W/F) ratio.
- PM increases with both W/F ratio and fuel type. A 70% - 90% increase was measured when using IFO180 at high W/F ratios. But when on MDO the PM values decreased slightly at high W/F ratios. This difference is ascribed to sulphate formation during combustion.
- A similar increase in CO with water injection was measured when operating on IFO180. No increase was noted with MDO fuel.
- Water injection has no effect upon fuel consumption.

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.

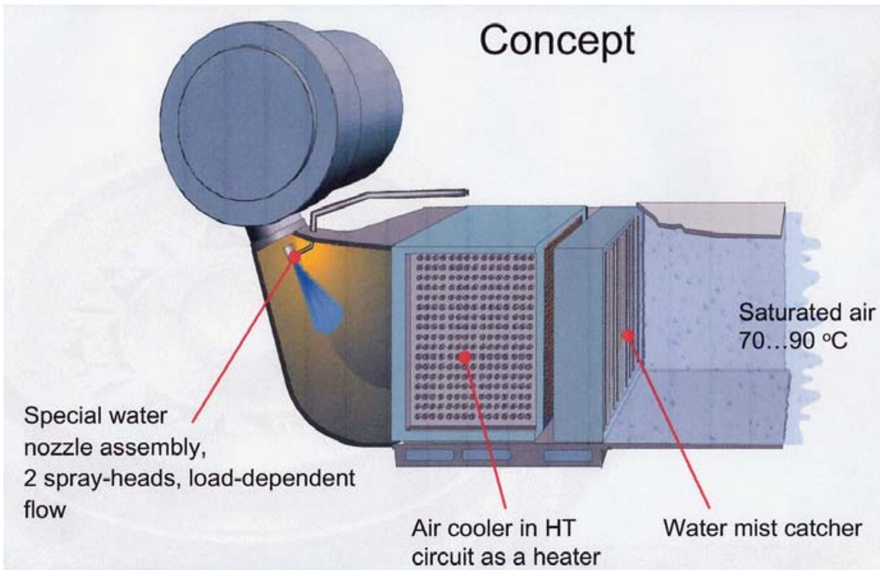


Figure 6.4. Wartsila Combustion Air Saturation System (Ref. 25)

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.

Humid Air Motor (HAM) System – a variation of CASS is the HAM system promoted by MAN B&W and others. Seawater is used in a humidification chamber to completely saturate and cool the hot scavenge air. The saturated air then passes through a fresh-water-rinsed demister before entering the intake valves of the engine. The advantage of HAM is that operating costs are low since seawater is used for the humidification process. NOx reductions of up to 70% are achievable with this system. [155]

HAM has been demonstrated on the 2700 passenger, 540 vehicle M/S Mariella Ferry operating between Sweden and Finland. NOx emission reductions of up to 70% have been confirmed in these trials and have resulted in reduced fairway fees. The HAM unit for the 6-MW diesel engine is 4m long x 1.4 m diameter (6.2 m^3). Three more HAM units are on order from the manufacturer, Muntners. [154,156]

Cost for HAM have been quoted as US$32/kW installed, with operating costs of about US$1/kW-year. [157,158]

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 use 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.

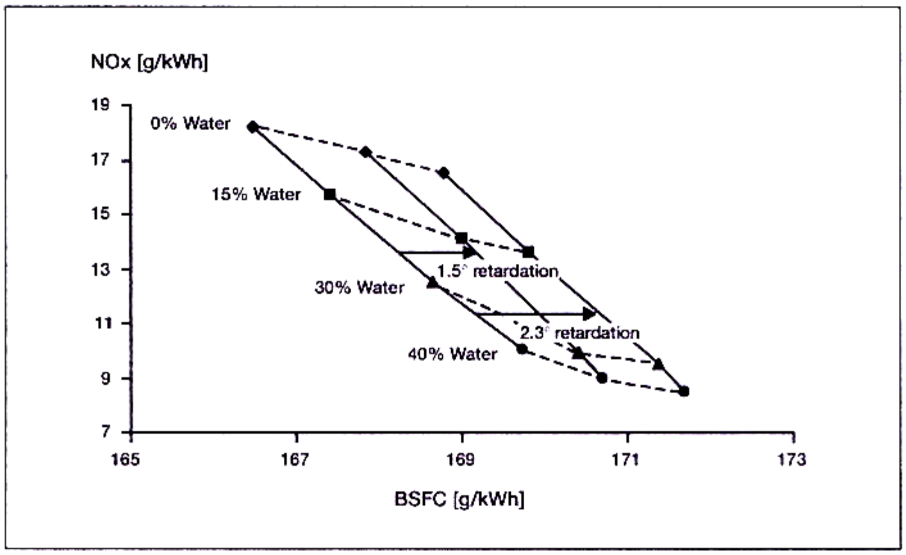


Figure 6.5. Effect of Water Content and Timing Upon NOx (Ref.5)

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 6.3.1.

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

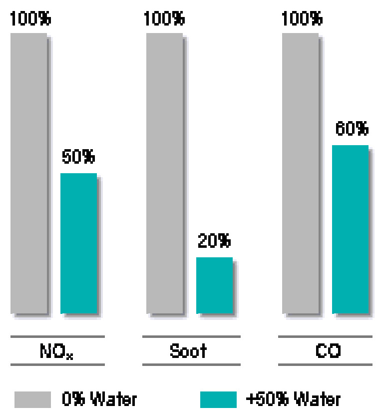


Figure 6.6 – MTU Water Emulsion

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 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. The MAN emulsion, unlike the Lubrizol system discussed below, is prepared mechanically and does not require a surfactant to maintain the water droplets in suspension. With respect to modifications to the engine system, the manufacturer suggests that it may be necessary to increase the size of the fuel pumps in order to increase their volumetric flow rate.

According to a study by Polar Design Associates, NOx emissions may be reduced by 1% for each 1% water in the fuel oil (i.e., 50% water and 50% fuel oil gives a reduction of 50% NOx), fine particulate can be reduced up to 80%, THC by 30% to 50% and CO by 20% to 50%. These benefits came at an expense of 1.5% increase in specific fuel consumption. [167]

MEC System – MEC System is an Italian company [168] that has been testing their *Turbo-Transducer* system of micro-emulsifying HFO fuel oil, in which pressurized water and fuel are mixed in cavitation chambers surrounded by high magnetic fields created by permanent magnets. The high fluid velocities and magnetic fields are claimed to cause a vortex phenomena that results in micro-droplets of water totally surrounded by a film of oil. The size of these micro-droplets is claimed to be in the order of 0.5 – 0.15 microns in diameter, as compared with 5 – 10 microns for other emulsions. When droplets sprayed by the fuel injectors enter the combustion chambers they are further divided by an explosive vaporization effected by the rapid heating of the water. [164]

Testing of the MEC system was carried out aboard the cruise ship *Veendam* during 2002 when the vessel was burning a heavy fuel oil (IFO 380). This vessel is equipped with Sulzer/Wartsila 12ZAV40 engines that were retrofitted at a cost of approximately US$70,000. Measurements were done following the RINA protocol in accordance with Annex VI – Test cycle E2 for diesel electric ships. "Drastic" smoke reduction started at a water/fuel ratio of 10%. With a water/fuel ratio of 23% the smoke was reduced by over 75%, CO by 27% and NOx by 22%. Engine efficiency (CO2 reduction) improved by 6%, the exhaust temperature was reduced by 10 deg. C after the turbochargers and fuel consumption was reduced by over 2%. [164]

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 US$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 US$0.15 per gallon over the rack price for diesel (currently around $1.37 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 US $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 US gallons per year (70,000 – 90,000 TPY). [33] However, due to the large amount of effort required to comply with 2007 ULSD regulations, this initiative has apparently been delayed.

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 Fuel Water Emulsion (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 US$0.16/gal is approx. $14.40/h
- NOx reduction: from 12 kg/hr to 8.4 kg/hr (3.6 kg/h)
- Cost Effectiveness: US$4/kg (US$4,000/tonne NOx reduction)

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 US$13,000 - US$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 brands of particulate filters (A, B & C), using the heavy-duty engine transient US Federal Test procedure (FTP).

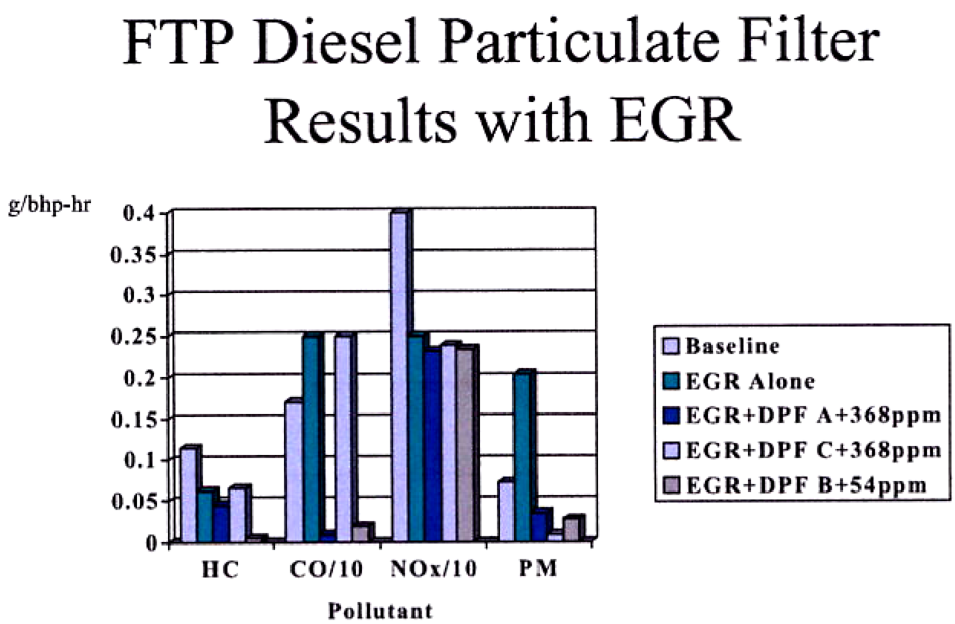


Figure 6.7 – EGR and DPF (Ref.37)

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 US$7,500. [36] The cost of retrofitting a 400 hp diesel with EGR is estimated to be US$13,000 - US$15,000. [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 US$1.00/gallon, then the additional fuel cost would be US$1,800/year.

- Assuming a total installed cost of US$15,000, capitalization of 7% (capital recovery factor = 0.1424) and annual maintenance/replacement costs of US$1000, then the total annual cost would be US$4,936, or US$4,100/tonne NOx.

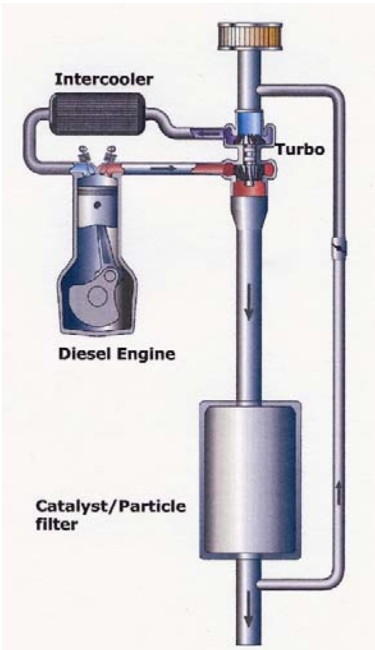


Figure 6.8 (Ref. 41)

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 US$20,000 - US$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 US$950/ton NOx to US$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.

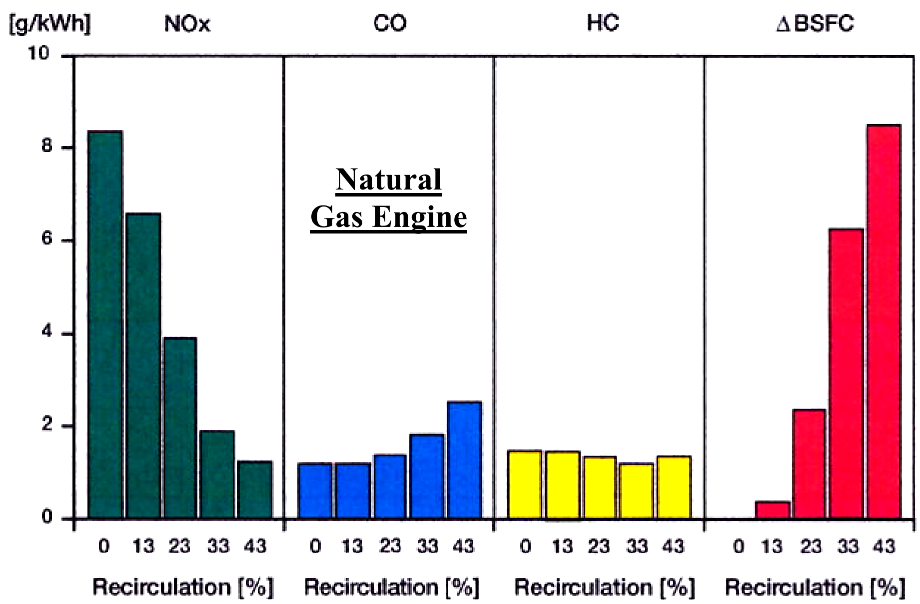


Figure 6.9. Effect of EGR on Emissions and Fuel Consumption (Ref. 5)

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.

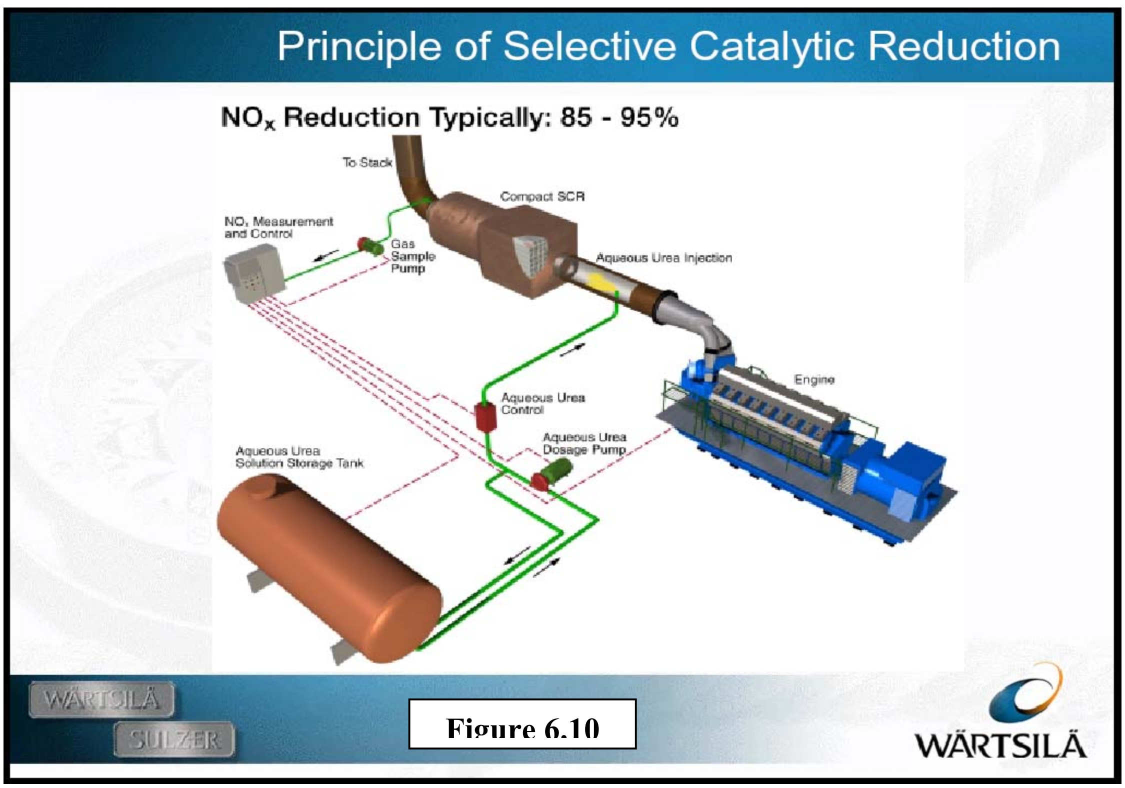
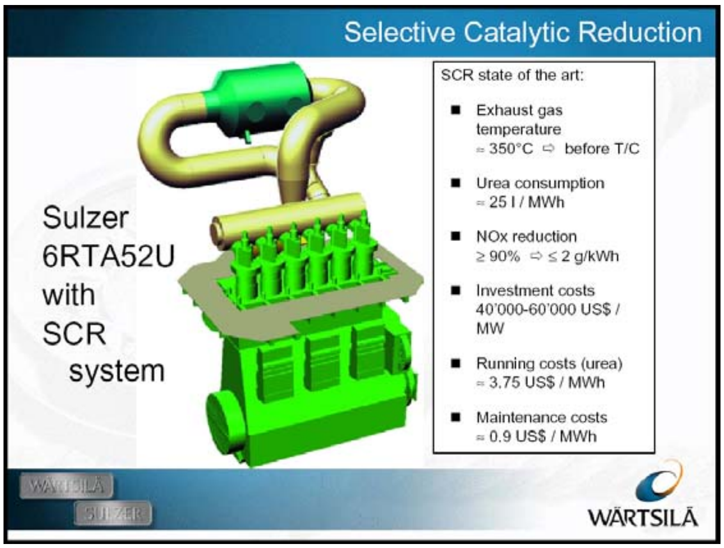


Figure 6.10

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 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.

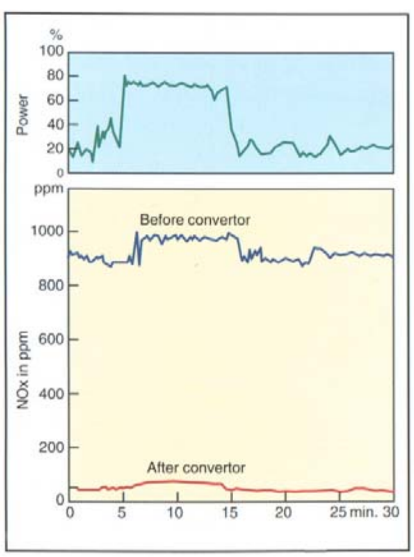


Figure 6.12. Transient Response of SCR (Ref. 42)

For smaller diesel engines, MECA estimated the cost of SCR at about US$17,500 - US$40,000 for engines in the 100 – 200 hp range, and about US$18,500 - US$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 US$157, 600 for 90% NOx removal, US$150,000 for 75% NOx removal, and US$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 (US$ per ton reduced)	75% NOx Reduction (US$ per ton reduced)	50% NOx Reduction (US$ 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.)

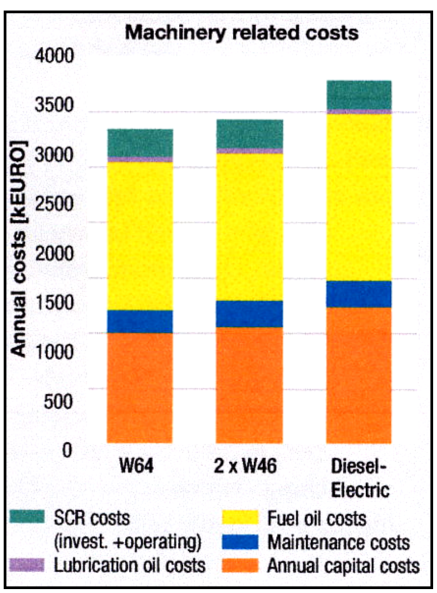


Figure 6.13. Annual Machinery Costs for RoRo Operation (Ref. 44)

Starcrest Consulting, in their evaluation of technologies for reducing emissions during the upgrading of the New York/New Jersey harbor, assumed a cost of US$50 - US$70/hp for SCR. The size of the SCR was quoted as being 2 ½ times the engine displacement and the operating temperature range was given as 260º C to 450ºC, with the higher temperature required for higher sulphur fuels. A reliable NOx sensor is needed to monitor in real time the amount of NOx in the exhaust. One problem identified with SCR is that their operation is easy to bypass by shutting off the flow of urea. Therefore some sort of NOx monitor would be required to insure proper operation. [169]

The CALSTART team, in their evaluation of emission reduction options for an expanded San Francisco Bay area ferry system, used a SCR cost of US$71/kW and an operating cost of US$20/kW-year. In addition, they assumed a 1% fuel penalty. NOx was expected to be reduced by 80%, THC by 75%, CO by 75% and PM by 40%. [170]

6.6 Catalytic Reduction of NOx with Diesel

Another approach being used to catalytically reduce NOx to nitrogen is to use diesel instead of urea as the reducing agent. Such a system is presently available from Cummins as a CARB-verified commercial product (see http://www.cleaire.com/). The diesel is sprayed in front of the NOx catalytic converter, where it is partially oxidized and thereby provides an increase in temperature to promote the NOx reduction reaction. Either a diesel particulate filter (DPF) or a diesel oxidation catalyst (DOC) then follows the NOx catalyst.

In the case of the NOx catalyst/DPF combination, NOx reduction is quoted[162] to be in the range of 25% - 35% (lower part of range in cold duty cycles and higher part of range for hotter duty cycles), PM and VOC reductions of 85%+ (tests show 90% - 95% reductions) and CO reduction of 85%+ (tests show virtual elimination of CO emissions). The system works on everything from 5.9L up; above 15L (about 425 hp) the systems can be manifolded together. For much smaller systems (below 100 – 125 hp; e.g. smaller backhoe/loaders and skid-steer loaders) a DOC is recommended, as there is not enough heat in the exhaust for a DPF to regenerate itself. The duty cycle requirement for the NOx catalyst/DPF combination is > 260 deg. C for > 25% of the operating cycle. [162]

The cost for a NOx catalyst/DPF combination is quoted as US$14,500 plus installation, with a total installed cost in the range of US$18K - US$19K. Increased fuel consumption is approximately 3% and ULSD is required to obtain the CARB-verified emission reductions. Higher sulphur diesel (up to 500 ppm) can be used but the emission reductions will not be as great as with ULSD. The system includes an electronic controller that automatically adjusts diesel injection depending upon engine conditions. Periodic filter cleaning is required; Cummins West charges US$400/filter/cleaning. It is recommended having clean filters on the shelf so that a rapid (30 minute) filter replacement can occur. [162]

6.7 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).

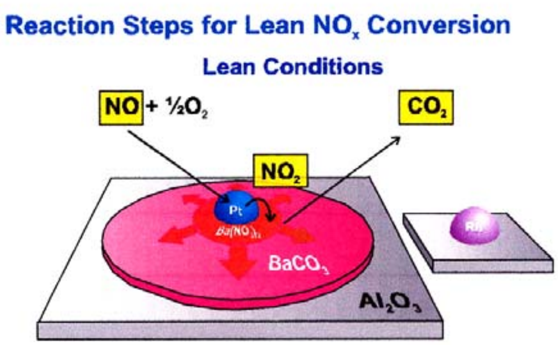


Figure 6.14

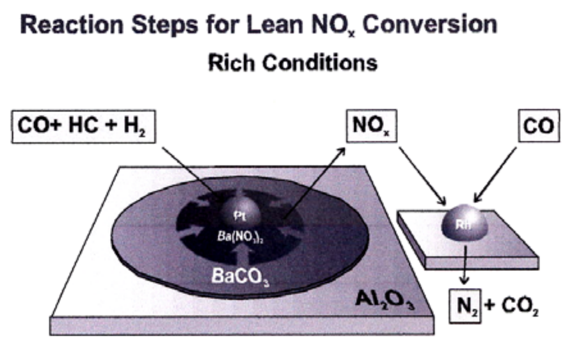


Figure 6.15

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.

6.8 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 US$1250. This increases to about US$1750 for a 300 – 500 hp engine. [38] It is probable that the average installed cost will be significantly higher than these estimates.

More recent experience in California places the price of DOC for on-road HDD at US$700 - US$6,500, with an average price of US$3,100 installed (US$12.40/hp, US$16.70/kW). Maintenance is estimated at about US$80/year (2.6% installed capital). [171]

6.9 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 heavier fuel oils. Figure 6.16 is a schematic of a DPF.

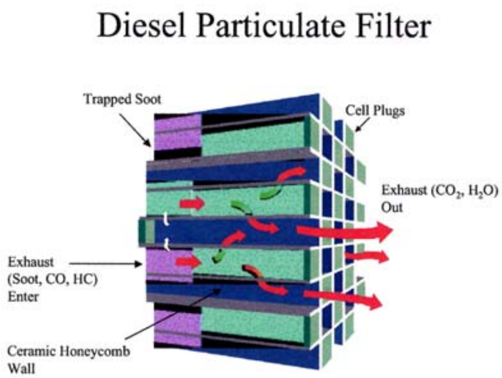


Figure 6.16. DPF (Ref. 46)

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] A more recent study by Starcrest Consulting suggested that passive self-cleaning filters require an operating temperature peaking up into 300º C - 400º, with lower temperatures possible through the use of ultra low sulphur fuels which in turn enable the use of highly active catalysts. A study of port cargo handling equipment in Oakland showed that the exhaust temperature on their yard tractors were too low for passive filters, whereas their use on top-lifts was okay. [169]

The California Air Resources Board conducted a study into the suitability of passive filters for HDD garbage trucks. Two of their verified DPF's required an average temperature of 225ºC with 10% of the duty cycle above 300ºC, and a temperature of 260ºC for 40% of the duty cycle. Approximately 32% of the 1994 – 2002 fleet was expected to be able to use passive DPF's. Recent installed price, including a backpressure monitor, was about US$5,300 (US$21/hp, $28/kW). [171] Active DPF's, being developed by SUVA in Europe, use extra fuel to periodically heat the exhaust up to a temperature where the collected soot is burned off. They cost about US$12,000 installed, [171] and incur a 2% fuel penalty. [169]

CALSTART, in their analysis of the cost of reducing emissions from the proposed expansion of the San Francisco Bay area ferry system, used an installed cost of US$20/kW and an operating cost of US$18/kW-year plus a 1% fuel penalty. Emission reductions were taken as 90% for PM, 92% for THC, 85% for CO and 3% for NOx. [170]

MECA quotes 2002 DPF unit costs of around US$7,500.[36] Installed cost will be higher, depending upon the degree of modifications required. The Washington Metropolitan Area Transit Authority budgeted US$4.6 million to retrofit between 208 and 282 Detroit Diesel engined buses. [36] This works out to US$16,300 - US$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 US$300 ($100 for shop labor + $200 for cleaning charges).[152] However, this is for a fleet with exemplary attention to maintenance and fuel quality. Cummins West apparently charges US$400/filter/cleaning.[162] 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.

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.

RailPower Technologies Ltd. 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.[119]

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 US$650,000 - US$750,000, as compared to about US$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 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 and 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 US$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 US$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 NONROAD EQUIPMENT EMISSION REDUCTIONS

This section identifies cost-effective emission reduction measures (ERM's) for nonroad HDD equipment (construction, agriculture, mining, logging, etc.) in three regions: Greater Vancouver Regional District (GVRD), Fraser Valley Regional District 1 (FVRD) and for the Rest of BC.

7.1 Methodology

A template worksheet (Table 7.1 below) was created in the Excel nonroad emissions inventory workbooks that the staff of GVRD and Environment Canada provided. This template facilitated the calculation of the cost-effectiveness of different clean fuel options and different technology options. The GVRD workbooks derived from NONROAD 2004 model and contained detailed listings of equipment emissions, populations, average horsepower, annual fuel, load factors, etc. for each horsepower class, equipment category and equipment class for GVRD, FVRD1 and for all of BC. The NONROAD 2004 model accounts for the EPA Tier 1 – 4 new engine regulations that were discussed in a previous section.

Because of the large amount of data and the complexity of this analysis, several programs were written in *Visual Basic for Applications* (VBA) in order to enable the computations. Total base-line emissions for each pollution species (NOx, SOx, PM_{10}, VOC, NH_3 and CO) for each non-road equipment fleet within each study region for the years 2005 – 2025 were first calculated. Next, the total (aggregated) emission reductions for each pollution species, each non-road equipment fleet, each study region and each ERM for the years 2005 – 2025 were calculated, based upon the assumptions listed in Table 7.2 The total (2005 – 2025) emission reductions for each pollution species were then summed using two different methods.

1. Weighted: each species is multiplied by the following weights and then the results are summed (NOx = 1, SOx = 3, PM_{10} = 25, VOC = 1 and CO = 1/7)
2. Non-weighted: each species is simply added up (NOx = 1, SOx = 1, $PM_{2.5}$ = 1, VOC = 1, NH_3 =1 and CO = 0). CO is excluded because it does not contribute directly to smog and haze and because its morbidity effects are felt only in high-density automobile traffic locations.

The emissions were aggregated as above in order to be consistent with previous GVRD studies. In the weighted aggregates the magnitude of the weights used are reflective of what are felt to be the relative environmental impact of the associated species, with diesel particulate matter (PM_{10}) receiving the highest weight because of its suspected strong relation to human morbidity. However, the weighting used in this and other studies are open to controversy. It is difficult to separate out the contribution of individual pollutant species when conducting epidemiological studies into the effects of air pollution on human health. The non-weighted aggregates (second method) are somewhat reflective of the smog-forming potential of the total emissions, although again this is open to debate.

<u>CPPI disclaimer</u>:

One of the funding sponsors of this study, the Canadian Petroleum Products Institute (CPPI) has concerns about the validity of the health-based weighting factors that were applied to the air emissions and which impacted the cost effectiveness calculations. These weighting factors are expressed in the equation: Impact Weighted Emissions = $25*PM_{10} + NOx + VOC + CO/7 + 3*SOx$.

This study indicates that the derivation of the relationship between the different pollutants reflected in this equation is based on the relative importance of the different pollutants on a health base relationship and associated risk factors. CPPI believes there is no comprehensive documentation of the basis of this methodology.

CPPI understands that the health impacts of all pollutants are not equal, but believes the current scientific data is inadequate to place a significant higher priority on one pollutant versus another. If the wrong relationship is assumed, the prioritization of the air pollutant reduction measures could be impacted and the derived air quality improvement strategy could be misleading. CPPI has summarized their concerns regarding the methodology of using health based weighting factors applied to air emissions and cost effectiveness methodology in Appendix B and makes reference to a related report by epidemiologist, Dr. Suresh H. Moolgavkar, M.D., Ph.D to support this point of view.

Table 7.1 - Template & Assumptions Used For Calculating the Cost-Effectiveness of NonRoad Equipment ERM's

Emission Reduction Option:	BaseLIne	1	2	3a	3b	4	5a	5b	6a	6b	7	8	9	10a	10b	11
Fuel Factors																
Fuel consumption factor	1	1	1	1	1	1	1	1	1	1	1	1.03	1.02	1	1	1.02
Fuel cost (US$/gallon)	1.57	1.63	1.7	1.67	1.77	2.58	1.78	1.85	1.57	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Baseline fuel cost (US$/gal)	1.57	1.57	1.63	1.57	1.7	1.65	1.57	1.7	1.57	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Fuel Taxes (CAD $/L)	0.07	0.07	0.07	0.056	0.056	0.03	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Fuel Sulphur (PPM)	563	350	10	280	8	0	350	10	563	10	10	10	10	350	10	10
Installed Cost: US$=A+B(HP)	A=	0	0	0	0	0	0	0	2071	2071	1333	0	8824	24000	24000	8824
	B=	0	0	0	0	0	0	0	2.857	2.857	18.67	61.67	21.18	40	40	21.18
Maintenance (% installed capital)		0	0	0	0	0	0	0	5	5	5	3	5	5	5	5
Application (>Horse Power)		0	0	0	0	0	0	0	0	0	115	115	100	150	150	100
Application(> Load Factor)		0	0	0	0	0	0	0	0	0	0.4	0.4	0.3	0.3	0.3	0.3
First Year of Usage	y_m	2005	2007	2005	2007	2005	2005	2007	2005	2007	2007	2007	2007	2005	2007	2010
Last Year of Usage	y_n	2006	2010	2006	2025	2025	2006	2025	2006	2025	2025	2025	2025	2006	2025	2025
Penetration Rate (%)	P	100	100	100	100	100	100	100	50	50	25	25	25	25	25	25
Last Year Reduction (% Initial)	EndReduct	100	100	100	50	50	100	50	100	50	50	50	50	100	100	50
Initial Emission Reductions (%)																
(Negative indicates increase)																
NOx		0	0	-2	-2	-10	24	24	0	0	0	25	40	75	90	90
SOx		38	97	50	98	100	38	97	0	97	97	97	97	38	97	97
PM_{10}		8	13	12	12	47	30	30	30	30	90	85	90	40	40	25
VOC		10	15	20	20	67	-79	-79	70	70	80	90	80	75	75	25
CO		10	15	11	11	48	22	22	70	70	70	90	70	75	75	25
NH_3		10	15	11	11	48	22	22	70	70	70	90	70	-100	-100	25
	BaseLine															
Emission Reductions (TPY)	**2005 - 2025**															
NOx																
SOx																
PM_{10}																
VOC																
CO																
NH_3																
% Reduction (weighted)																
NPV Costs (Y2005)																
Total NPV (Millions $CAD)																
Cost-Effectiveness (1000$/tonne)																
NOx																
SOx																
PM_{10}																
VOC																
CO																
NH_3																
Total (weighted)																
Total (unweighted)																

Other Assumptions		
Discount Rate (%)	7	
Amortization Period (years)	10	
Exchange Rate (CAD$/USA$)	1.25	
1 US.gallon =	3.785411784	L

Weightings	
NOx	1
SOx	3
PM_{10}	25
VOC	1
CO	0.14

Location of data in inventory-data sheets				
Data	**Column**	**Sector**	**Codes****	**Total Row**
NOx	11	Recreational vehicles	01	596
SOx	13	Construction and mining	02	597
PM_{10}	15	Industrial	03	598
VOC	8	Lawn & garden - residential	040	599
CO	10	Lawn & garden - commercial	041	600
NH_3	32	Agriculture	05	601
Population	33	Commercial	06	602
Activity(hr/y)	34	Logging	07	603
Fuel (L/y)	35	Airport support	08	604
Horsepower	36	Recreational Marine	82	605
Load factor	38	Underground mining	09	606
Sector Code**	4	Other oil field equipment	10	607
Region	**Code**	Railway maintenance	85	608
GVRD	1	SectorTotals		609
FVRD	2			

**Note: Sector Codes are *String Variables*

The net present values (NPV) of the ERM's deployed during the period of 2005 to 2025 were then calculated based upon the cost and discounting assumptions presented in Table 7.2. The discount rate used generally will be the sum of the interest rate, the inflation rate and some sort of index of investment risk. For current economic conditions a discount rate that is commonly (e.g. US EPA) used for environmental analysis is 7%. (Tables 7.14 – 7.16 explore the sensitivity of ERM cost-effectiveness for selected fleets using discount rates of 0%, 7% and 14%.)

In Table 7.1 costs are initially calculated using US$ and then converted to CDN$ using the current exchange rate, as most costs are given in the literature in terms of US$. Costs for fuel are derived from recent fuel commodity price, or "rack price", to which the applicable fuel taxes are added.

Cost-effectiveness is then calculated as a cost/benefit ratio, wherein the total costs (2005 Net Present Value basis) are divided by the total (2005 – 2025) reduction (tonnes) of either weighted emissions or non-weighted emissions.

Description of Assumptions in Table 7.2

The assumptions used to estimate the cost-effectiveness of the nonroad HDD ERM's are listed in Table 7.2 below for the different options that will be described in the next section. These assumptions are defined below:

- Fuel consumption factor: the factor by which fuel consumption increases due to the use of an ERM. Fuel consumption will increase for those ERMs that require temporary exhaust enrichment, and for EGR. (Fuel consumption is not shown to increase for the use of a PuriNOx diesel-water emulsion because the consumption of this fuel is already based upon diesel equivalent gallons.)
- Fuel cost: based upon readily available USA commodity prices or "rack prices" currently applicable to the PNW. These prices are difficult or impossible to obtain for BC, however, the use of PNW commodity prices is thought to be appropriate since these fuels readily move both ways across the Canada-USA border.
- Baseline cost: the cost of the fuel that would normally be used instead of the ERM fuel.
- Fuel Taxes: Off-road fuel taxes applicable in BC – typically 3¢/L provincial and 4¢/L federal excise tax. See http://www.rev.gov.bc.ca/ctb/publications/bulletins/mft_005.pdf for further details. The federal excise tax is not applicable to B20 but is applicable to B100.
- Fuel Sulphur (ppm): this will typically be less than the federally mandated maximum sulphur limits. Here 350 ppm is used for LSD and 10 ppm for ULSD.
- Installed cost: Is assumed to be a linear function of the horsepower of the engine. The coefficients "A" and "B" in the model ($ = A + B x HP) are curve-fitted to literature cost data, which usually is quoted in $USA.
- Maintenance: annual maintenance costs assumed to be a % of the installed ERM cost.

- Application (>Horse Power): Some ERM's are limited to equipment that have an adequately high exhaust temperature, which limits their use to larger engines with relatively high duty cycles (load factors).
- Application (>Load Factor): As above.
- First & Last Year of Usage: the assumed early-introduction period of the ERM.
- Penetration Rate (%): the rate that an ERM is introduced into the nonroad HDD fleets; generally 100% for fuels and <100% for technology-based ERM's.
- Last Year Reduction (% Initial): Accounts for the reduction in ERM efficacy over the years due to a nonlinearity between control efficiency and specific emissions.
- Initial Emission Reductions (%): The assumed reduction in emissions of the different pollution species caused by usage of the ERM. Based upon literature values.
- Discount rate: the interest rate used in the discounted cash flow analysis to determine the net present value (2005 dollars) of the different ERM's.
- Amortization Period: the time over which a technology-based ERM is amortized. The model also assumes that the ERM is replaced after the amortization period.
- Exchange Rate: currently about 1.25 $CAD/$USA.
- Weightings: use to weight the reduction of each pollution species in order to arrive at an impact-weighted aggregate reduction.

These assumptions were used in Excel-VBA modeling to arrive at total emissions, emission reductions, NPV and cost-effectiveness for each ERM in each fleet and in each of the three study areas (GVRD, FVRD and the rest of BC).

Table 7.2 - Assumptions Used to Calculate the Cost-Effectiveness of Emission Reduction Measures

Emission Reduction Option:	BaseLIne	1	2	3a	3b	4	5a	5b	6a	6b	7	8	9	10a	10b	11
		LSD	ULSD	B20/LSD	B20/ULSD	B100	PNOx/LSD	PNOx/ULSD	DOC/#2	DOC/ULSD	DPF/ULSD	Clearare	EGR/DPF	SCR/LSD	SCR/ULSD	NOx Traps
Fuel Factors																
Fuel consumption factor	1	1	1	1	1	1	1	1	1	1	1	1.03	1.02	1	1	1.02
Fuel cost (US$/gallon)	1.57	1.63	1.7	1.67	1.77	2.58	1.78	1.85	1.57	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Baseline fuel cost (US$/gal)	1.57	1.57	1.63	1.57	1.7	1.65	1.57	1.7	1.57	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Fuel Taxes (CAD $/L)	0.07	0.07	0.07	0.056	0.056	0.03	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Fuel Sulphur (PPM)	563	350	10	280	8	0	350	10	563	10	10	10	10	350	10	10
Installed Cost: US$=A+B(HP)	A=	0	0	0	0	0	0	0	2071	2071	1333	0	8824	24000	24000	8824
	B=	0	0	0	0	0	0	0	2.857	2.857	18.67	61.67	21.18	40	40	21.18
Maintenance (% installed capital)		0	0	0	0	0	0	0	5	5	5	3	5	5	5	5
Application (>Horse Power)		0	0	0	0	0	0	0	0	0	115	115	100	150	150	100
Application(> Load Factor)		0	0	0	0	0	0	0	0	0	0.4	0.4	0.3	0.3	0.3	0.3
First Year of Usage	y_m	2005	2007	2005	2007	2005	2005	2007	2005	2007	2007	2007	2007	2005	2007	2010
Last Year of Usage	y_n	2006	2010	2006	2025	2025	2006	2025	2006	2025	2025	2025	2025	2006	2025	2025
Penetration Rate (%)	P	100	100	100	100	100	100	100	50	50	25	25	25	25	25	25
Last Year Reduction (% Initial)	EndReduct	100	100	100	50	50	100	50	100	50	50	50	50	100	100	50
	FFLAG	0	0	0	1	0	0	1	0	1	0	0	0	0	1	0
Initial Emission Reductions (%)																
Negative (grey) indicates increase.																
NOx		0	0	-2	-2	-10	24	24	0	0	0	25	40	75	90	90
SOx		38	97	50	98	100	38	97	0	97	97	97	97	38	97	97
PM_{10}		8	13	12	12	47	30	30	30	30	90	85	90	40	40	25
VOC		10	15	20	20	67	-79	-79	70	70	80	90	80	75	75	25
CO		10	15	11	11	48	22	22	70	70	70	90	70	75	75	25
NH3		10	15	11	11	48	22	22	70	70	70	90	70	-100	-100	25
Other Assumptions																
Discount Rate (%)	7															
Amortization Period (years)	10															
Exchange Rate (CAD$/USA$)	1.25															
Weightings			Note: Diesel prices are from the AFI dated Nov.18, 2004													
NOx	1															
SOx	3															
PM_{10}	25															
VOC	1															
CO	0.14															

7.2 Emission Reduction Options Studied

Eleven different emission reduction options were studied for off-road equipment. Five of these are “clean fuel” options while six are technology retrofits.

1. Use of rebranded, <500 ppm S road diesel: Often #2 diesel is simply rebranded road diesel when the lower grade of diesel is not locally available. However, here we assume that a premium must be paid for using road diesel with average sulphur content of 350 ppm. It is assumed that this option is applicable over the period of 2005 until 2007, at which time the law requires it.

2. Use of rebranded, < 15 ppm S diesel. This ULSD is presently available from at least one PNW refinery and will be a required fuel for road vehicles by 2007. Its use enables the retrofit of catalyst-based technologies that would be poisoned by higher sulphur fuels. It is assumed that this option is applicable over the period of 2007 until 2010, at which time law requires it.

3. B20: this is a blend of 20% biodiesel and 80% road diesel that is presently available in the PNW, although at a “rack-price” cost premium. It offers lower CO_2, PM_{10} and VOC emissions; however, NOx emissions are increased due to the nitrogen contained within the biodiesel fuel. This blended fuel enjoys a small (1.4¢/L) tax advantage over regular diesel in BC. It is assumed that this option uses 350-ppm diesel over the period of 2005 until 2007, then switches to using < 15 ppm S diesel for the period 2007 – 2025.

4. B100: 100 % biodiesel offers a 100% reduction in GHG emissions, but concurrently gives a significant increase in NOx emissions. However, particulate emissions are significantly reduced. In BC there is only the federal 4¢/L tax exemption, with no provincial tax break in effect at this time for B100. It is assumed that this option is applicable over the period of 2005 to 2025.

5. *PuriNOx*: this is a water/diesel emulsion prepared using an expensive emulsifying agent sold by Lubrizol. No capital equipment costs are incurred to obtain a significant reduction in NOx and PM_{10} emissions. However, emissions of CO and VOC increase. It is assumed that this option uses 350-ppm diesel over the period of 2005 until 2007, then switches to using < 15 ppm S diesel for the period 2007 – 2025.

6. DOC: diesel oxidation catalyst is a relatively low-cost muffler replacement that oxidizes the odorous components of diesel exhaust (VOC and the soluble organic fraction of the particulates). DOC’s are widely used on diesel equipment that must operate within enclosed spaces (e.g. mines, buildings) and are applicable to all classes of nonroad HDD equipment. It is assumed that this option uses off road 563-ppm diesel over the period of 2005 until 2007, and then switches to using < 15 ppm S diesel for the period 2007 – 2025.

7. Passive DPF: these are catalytically regenerated diesel particulate filters, also widely used on diesel equipment that must operate within enclosed spaces. Since a high temperature (approx. 300ºC) is required to burn-off the accumulated carbon soot, they can only be used on equipment that has an adequately high exhaust temperature, which limits their use to larger engines with relatively high duty cycles (load factors). ULSD must be used to prevent catalyst poisoning. It is assumed that this option is applicable over the period of 2007 to 2025.

8. Clearaire “*Longview*”: this device is representative of retrofit muffler-replacements which use fuel injection to richen the exhaust so that a catalyst can be used to reduce NOx. The NOx catalyst section is

followed by a DPF section that removes VOC and PM. Again, these devices are limited to equipment that have an adequately high exhaust temperature, which limits their use to larger engines with relatively high duty cycles. Best performance is obtained using ULSD. Hence it is assumed that this option is applicable over the period of 2007 to 2025.

9. EGR: exhaust gas recirculation is used to reduce NOx emissions. It must be used in conjunction with a DPF that first removes erosive particulate. The DPF requires the use of ULSD. Again it is assumed that this option is applicable over the period of 2007 to 2025.

10. SCR: selective catalytic reduction of NOx by spraying a small amount of urea solution in front of a special NOx reduction catalyst. The catalyst is more tolerant of sulphur and of low exhaust temperatures than is that for DPF's. The European Union expects that SCR units will be required on all heavy highway diesels in the near future. They may also be retrofitted to large, nonroad diesel equipment since they are already widely used on European ferries and the technology is mature. Again it is assumed that this option is applicable over the period of 2007 to 2025.

11. NOx Adsorption: this is an emerging technology that adsorbs NOx onto a suitable substrate while the diesel engine operates in its normal lean-burn operation. When the exhaust is temporarily enriched the adsorbed NOx is catalytically reduced to N_2. Prototype "NOx-Traps" have demonstrated a 90% reduction in NOx emissions and commercial versions are expected to become available by 2010. The NOx-Trap requires the use of ULSD. It is assumed that this option is applicable over the period of 2010 to 2025.

Engine refits were not considered for the nonroad HDD fleets for two reasons. First, new Tier 2 and Tier 3 engines generally will not fit into older equipment. Secondly, engine retrofits are a very expensive way to reduce emissions and are not cost-effective unless some sort of government incentive program, such as California's Carl Moyer program, subsidizes the retrofit.

7.3 Cost-Effectiveness Comparison of Emission-Reduction Options

The cost-effectiveness of the 11 different ERMs for the time period 2005 – 2025 was applied to the major nonroad fleets within each of the three study areas.

Four different fleets were investigated for the **GVRD** study area:

1. Construction and Mining Equipment (Table 7.3)
2. Agricultural Equipment (Table 7.4)
3. Industrial and Commercial Equipment (Table 7.5)
4. Other Equipment (Table 7.6)

For the **FVRD** the major fleets are:

1. Construction and Mining Equipment (Table 7.7)
2. Agricultural Equipment (Table 7.8)
3. Other Equipment (Table 7.9)

For the **Rest of BC** the fleets investigated are:

1. Construction and Mining Equipment (Table 7.10)

2. Agricultural Equipment (Table 7.11)
3. Logging Equipment (Table 7.12)
4. Other Equipment (Table 7.13)

An inspection of the equipment populations for the three different regions reveals that the nonroad equipment population within GVRD is dominated by smaller construction equipment, whereas for the LFV and the rest of BC agricultural equipment and logging equipment dominate the nonroad HDD sector.

Both the weighted cost-effectiveness and the un-weighted cost-effectiveness of the different ERM's applied to these regions and fleets are presented in Tables 7.3 – 7.13 below. Note that the listed emission reductions are for the period 2005 – 2025. In some instances the ERM's result in an <u>increase</u> in the emission of certain pollution species; these increases are shaded in gray. Following these tables are charts (Figures 7.1 – 7.11) summarizing the impact-weighted cost-effectiveness and percent emission reduction data. Tables 7.14 – 7.16 then show the sensitivity of ERM cost-effectiveness on the assumed discount rate (0%, 7% and 14%) for selected fleets (GVRD Construction and Mining Equipment, FVRD Agricultural Equipment, and Rest of BC Logging Equipment). Finally, Tables 7.17 – 7.19 track the ERM emission reductions (tonnes/year), for the above selected fleets, in 5-year increments over the period 2005 – 2025. These three tables are useful for giving the reader a feel for which and when ERM's "kick-in" and provide significant emission reductions, relative to baseline emissions.

In the figures below the yellow bars represent the emission reductions, expressed as a percent of the total impact-weighted nonroad HDD emissions for the different options, while the purple bars represent the cost-effectiveness, expressed as a cost/benefit ratio. The greatest efficiencies will be provided by those options that provide a significant emission reduction at a low cost/benefit ratio (high yellow bar, low purple bar).

Emission reductions for the ERM's are presented as a percentage of the total emissions over the period of 2005 – 2025. Hence ERM options that are applicable over only a small portion of this time span will have a relatively small emission reduction (right vertical axis of the charts).

Two of the ERM options (#4 - 100% Biodiesel and #10a – SCR & LSD) are not shown in the Figures because their costs are far in excess of the other options and hence their inclusion would distort the vertical axis of the charts. (For the GVRD Construction and Mining sector the use of B100 is estimated to reduce weighted total emissions by 20% but at a cost of over $18,000/tonne of avoided emissions. The expense of the SCR & LSD option is not viable because of the assumed short-term applicability of this ERM; it is replaced by the use of SCR & ULSD in 2007 (Option 10b).

The most cost-effective ERM's, at less than $2000 per tonne of weighted, avoided emission reductions are seen to be a biodiesel blend (B20), a diesel oxidation catalyst (DOC) or a diesel particulate filter (DPF), all in combination with the upcoming ULSD road diesel. It can also be observed that cost-effectiveness of an ERM is somewhat fleet and region dependent.

On an un-weighted aggregate emissions basis those ERM's that result in a large NOx reduction will be most cost-effective simply because NOx is the main component of diesel engine exhaust. Hence selective catalytic reduction of NOx (SCR) is seen to have the lowest cost of emission avoidance (typically $6000/tonne or less).

The implications of implementing the different ERM's will be discussed in more detail in Section 10.

Table 7.3 - GVRD Construction & Mining - Cost-Effectiveness of Emission Reduction Options															
Emission Reduction Option:	**1**	**2**	**3a**	**3b**	**4**	**5a**	**5b**	**6a**	**6b**	**7**	**8**	**9**	**10a**	**10b**	**11**
	LSD	**ULSD**	**B20/LSD**	**B20/ULSD**	**B100**	**PNOx/LSD**	**PNOx/ULSD**	**DOC/#2**	**DOC/ULSD**	**DPF/ULSD**	**Clearare**	**EGR/DPF**	**SCR/LSD**	**SCR/ULSD**	**NOx Traps**
Year 2005 - 2025															
Emission Reductions (tonnes)															
NOx	0	0	-219	-930	-5,552	2,623	11,163	0	0	0	7,581	12,130	2,092	33,278	18,966
SOx	126	229	166	280	601	126	277	0	277	123	123	123	31	187	44
PM_{10}	66	193	98	409	1,918	246	1,022	184	1,022	1,519	1,434	1,519	63	741	281
VOC	102	263	203	955	3,758	-803	-3,774	530	3,344	2,095	2,357	2,095	140	2,336	505
CO	515	1,429	567	2,417	12,577	1,134	4,833	2,694	15,379	7,386	9,497	7,386	789	9,304	1,737
NH_3	1	3	1	8	39	2	16	4	52	39	50	39	-2	-67	12
Weighted % Reduction	**1.1**	**3.1**	**1.6**	**5.9**	**25.8**	**4.4**	**17.9**	**2.8**	**16.5**	**21.5**	**24.6**	**27.8**	**2.1**	**29.0**	**13.9**
NPV Costs (Y2005)															
Total NPV (Millions $CAD)	$7.43	$15.21	$7.13	$20.66	$705.65	$26.01	$112.28	$23	$24	$48	$104	$109	$75	$116	$90
Cost-Effectiveness (1000$/tonne)															
NOx	ND	ND	-$32.6	-$22.2	-$127.1	$9.9	$10.1	ND	ND	ND	$14	$9	$36	$3	$5
SOx	$59.0	$66.5	$43.0	$73.8	$1,174.3	$206.3	$405.1	ND	$86	$392	$847	$883	$2,449	$620	$2,049
PM_{10}	$113.2	$79.0	$72.5	$50.6	$367.8	$105.7	$109.9	$126	$23	$32	$73	$72	$1,188	$156	$319
VOC	$73.1	$57.9	$35.1	$21.6	$187.8	-$32.4	-$29.8	$44	$7	$23	$44	$52	$539	$50	$178
CO	$14.4	$10.6	$12.6	$8.5	$56.1	$22.9	$23.2	$9	$2	$7	$11	$15	$95	$12	$52
NH_3	$8,747	$5,558	$7,635	$2,529	$18,313	$13,916	$6,872	$5,170	$460	$1,234	$2,075	$2,779	-$34,921	-$1,720	$7,550
Weighted Total	**$3.4**	**$2.6**	**$2.4**	**$1.8**	**$14.2**	**$3.1**	**$3.3**	**$4.2**	**$0.8**	**$1.2**	**$2.2**	**$2.0**	**$18.7**	**$2.1**	**$3.3**
Unweighted Total	$25.4	$22.3	$28.9	$29.1	$999.6	$11.9	$12.9	$32.5	$5.1	$12.9	$9.1	$6.9	$32.4	$3.2	$4.5

Notes: 1. Emission reductions are for the period 2005 – 2025.
2. "ND" in the cost-effectiveness-fields means that the value was not derived because there was zero emission reduction for that species.

Note: "ND" in the cost-effectiveness-fields means that the value was not derived because there was zero emission reduction for that species.

Table 7.4 - GVRD Agriculture - Cost-Effectiveness of Emission Reduction Options

Emission Reduction Option:	1	2	3a	3b	4	5a	5b	6a	6b	7	8	9	10a	10b	11
	LSD	ULSD	B20/LSD	B20/ULSD	B100	PNOx/LSD	PNOx/ULSD	DOC/#2	DOC/ULSD	DPF/ULSD	Clearare	EGR/DPF	SCR/LSD	SCR/ULSD	NOx Traps
Year 2005 - 2025															
Emission Reductions (tonnes)															
NOx	0	0	-29	-158	-906	352	1,896	0	0	0	585	936	81	1,579	1,557
SOx	16	29	21	36	78	16	36	0	36	7	7	7	1	6	2
PM_{10}	14	41	22	89	419	54	222	40	222	183	173	183	4	60	37
VOC	19	47	38	156	630	-150	-617	99	547	177	199	177	8	123	41
CO	101	271	111	498	2,572	222	997	528	3,172	707	910	707	40	582	183
NH_3	0.11	0.35	0.12	1.03	4.89	0.24	2.07	0.58	6.58	2.02	2.60	2.02	-0.07	-2.07	0.61
Weighted % Reduction	**1.2**	**3.1**	**1.6**	**6.2**	**28.0**	**4.2**	**18.4**	**3.1**	**17.3**	**12.6**	**13.6**	**15.1**	**0.5**	**8.6**	**6.6**
NPV Costs (Y2005)															
Total NPV (Millions $CAD)	$0.96	$1.95	$0.92	$2.62	$89.65	$3.35	$14.23	$9.75	$9.89	$6.27	$12.26	$16.77	$6.74	$10.23	$13.78
Cost-Effectiveness (1000$/tonne)															
NOx	ND	ND	-$31.3	-$16.6	-$98.9	$9.5	$7.5	ND	ND	ND	$21	$18	$83	$6	$9
SOx	$59.0	$66.1	$43.0	$72.0	$1,153.9	$206.4	$395.5	ND	$275	$944	$1,847	$2,526	$7,004	$1,717	$5,593
PM_{10}	$66.2	$48.0	$42.4	$29.5	$214.2	$61.8	$64.0	$242	$45	$34	$71	$92	$1,525	$170	$372
VOC	$50.3	$41.3	$24.2	$16.8	$142.4	-$22.3	-$23.1	$99	$18	$35	$62	$95	$820	$83	$333
CO	$9.5	$7.2	$8.3	$5.3	$34.9	$15.1	$14.3	$18	$3	$9	$13	$24	$166	$18	$75
NH_3	$8,748	$5,559	$7,635	$2,532	$18,344	$13,917	$6,880	$16,903	$1,503	$3,096	$4,711	$8,285	-$99,830	-$4,945	$22,461
Weighted Total	**$2.2**	**$1.6**	**$1.5**	**$1.1**	**$8.3**	**$2.0**	**$2.0**	**$8.2**	**$1.5**	**$1.3**	**$2.3**	**$2.9**	**$32.4**	**$3.1**	**$5.4**
Unweighted Total	$19.4	$16.8	$17.9	$21.5	$422.7	$12.4	$9.3	$70.3	$12.3	$17.2	$12.8	$12.9	$71.5	$5.8	$8.4

Table 7.5 - GVRD Industrial and Commercial - Cost-Effectiveness of Emission Reduction Options															
Emission Reduction Option:	**1**	**2**	**3a**	**3b**	**4**	**5a**	**5b**	**6a**	**6b**	**7**	**8**	**9**	**10a**	**10b**	**11**
	LSD	**ULSD**	**B20/LSD**	**B20/ULSD**	**B100**	**PNOx/LSD**	**PNOx/ULSD**	**DOC/#2**	**DOC/ULSD**	**DPF/ULSD**	**Clearare**	**EGR/DPF**	**SCR/LSD**	**SCR/ULSD**	**NOx Traps**
Year 2005 - 2025															
Emission Reductions (tonnes)															
NOx	0	0	-55	-302	-1,730	660	3,629	0	0	0	868	1,389	131	2,542	2,282
SOx	32	59	42	73	155	32	72	0	72	12	12	12	2	11	4
PM_{10}	22	66	33	152	702	83	380	62	380	225	213	225	5	80	45
VOC	35	94	71	343	1,343	-280	-1,355	185	1,201	296	333	296	12	227	72
CO	153	454	168	861	4,341	336	1,722	802	5,479	884	1,136	884	48	800	228
NH_3	0.22	0.71	0.24	2.17	10.21	0.48	4.34	1.15	13.82	3.85	4.95	3.85	-0.13	-4.19	1.18
Weighted % Reduction	**1.0**	**2.9**	**1.4**	**6.0**	**26.3**	**3.8**	**17.7**	**2.7**	**16.9**	**8.8**	**9.7**	**10.8**	**0.4**	**7.1**	**5.1**
Unweighted % Reduction	0.4	0.9	0.4	1.0	1.8	1.9	10.7	1.0	6.5	2.1	5.6	7.6	0.6	11.3	9.5
NPV Costs (Y2005)															
Total NPV (Millions $CAD)	$1.91	$3.96	$1.83	$5.48	$186.34	$6.67	$29.79	$22.18	$23.99	$9.44	$18.61	$24.79	$11.41	$18.17	$20.67
Cost-Effectiveness (1000$/tonne)															
NOx	ND	ND	-$33.3	-$18.1	-$107.7	$10.1	$8.2	ND	ND	ND	$21	$18	$87	$7	$9
SOx	$59.2	$67.6	$43.2	$75.4	$1,204.3	$207.1	$413.8	ND	$333	$789	$1,555	$2,071	$6,232	$1,592	$4,647
PM_{10}	$85.9	$59.5	$54.9	$36.0	$265.4	$80.1	$78.3	$357	$63	$42	$88	$110	$2,283	$226	$461
VOC	$53.7	$42.2	$25.8	$16.0	$138.8	-$23.8	-$22.0	$120	$20	$32	$56	$84	$976	$80	$286
CO	$12.5	$8.7	$10.9	$6.4	$42.9	$19.8	$17.3	$28	$4	$11	$16	$28	$236	$23	$91
NH_3	$8,747	$5,556	$7,634	$2,524	$18,251	$13,915	$6,858	$19,296	$1,736	$2,452	$3,758	$6,436	-$88,491	-$4,334	$17,593
Weighted Total	**$2.7**	**$2.0**	**$1.8**	**$1.3**	**$10.2**	**$2.6**	**$2.4**	**$12.0**	**$2.1**	**$1.6**	**$2.8**	**$3.3**	**$40.8**	**$3.7**	**$5.9**
Unweighted Total	$21.3	$18.2	$20.1	$20.8	$406.1	$13.5	$11.0	$90.0	$14.5	$17.8	$13.1	$12.9	$76.6	$6.4	$8.6

Table 7.6 - GVRD Other Sectors - Cost-Effectiveness of Emission Reduction Options

Emission Reduction Option:	1	2	3a	3b	4	5a	5b	6a	6b	7	8	9	10a	10b	11
	LSD	ULSD	B20/LSD	B20/ULSD	B100	PNOx/LSD	PNOx/ULSD	DOC/#2	DOC/ULSD	DPF/ULSD	Clearare	EGR/DPF	SCR/LSD	SCR/ULSD	NOx Traps
Year 2005 - 2025															
Emission Reductions (tonnes)															
NOx	0	0	-6	-27	-160	70	327	0	0	0	201	325	43	741	516
SOx	3	6	4	7	15	3	7	0	7	3	3	3	1	4	1
PM_{10}	2	6	3	13	60	7	33	5	33	47	45	48	1	19	9
VOC	3	8	6	28	110	-22	-111	15	99	56	63	57	3	51	14
CO	15	41	16	76	386	32	151	76	481	230	295	231	18	254	58
NH_3	0.02	0.07	0.02	0.23	1.07	0.05	0.46	0.11	1.46	1.03	1.32	1.04	-0.04	-1.47	0.32
Weighted % Reduction	**0.6**	**1.6**	**0.8**	**3.4**	**14.6**	**2.3**	**10.1**	**1.5**	**9.4**	**12.0**	**13.4**	**15.1**	**0.8**	**12.4**	**7.3**
NPV Costs (Y2005)															
Total NPV (Millions $CAD)	$0.19	$0.40	$0.18	$0.58	$19.42	$0.65	$3.13	$0.73	$0.83	$1.67	$3.44	$4.08	$2.01	$3.39	$3.47
Cost-Effectiveness (1000$/tonne)															
NOx	ND	ND	-$30.7	-$21.2	-$121.5	$9.3	$9.6	ND	ND	ND	$17	$13	$47	$5	$7
SOx	$59.4	$69.6	$43.4	$79.5	$1,272.9	$207.9	$436.6	ND	$115	$549	$1,132	$1,331	$3,454	$902	$2,849
PM_{10}	$97.9	$69.9	$62.7	$44.1	$322.1	$91.4	$95.9	$136	$25	$35	$77	$86	$1,406	$176	$370
VOC	$66.6	$53.2	$32.0	$20.4	$177.0	-$29.5	-$28.1	$50	$8	$30	$54	$72	$678	$66	$253
CO	$12.9	$9.7	$11.2	$7.6	$50.3	$20.5	$20.7	$10	$2	$7	$12	$18	$113	$13	$59
NH_3	$8,745	$5,552	$7,633	$2,513	$18,126	$13,913	$6,828	$6,421	$565	$1,619	$2,597	$3,928	-$48,690	-$2,308	$10,814
Weighted Total	**$3.0**	**$2.3**	**$2.1**	**$1.6**	**$12.5**	**$2.7**	**$2.9**	**$4.6**	**$0.8**	**$1.3**	**$2.4**	**$2.5**	**$23.5**	**$2.6**	**$4.5**
Unweighted Total	$23.9	$21.2	$26.7	$27.3	$787.5	$11.3	$12.3	$36.4	$5.9	$15.7	$11.0	$9.5	$42.2	$4.2	$6.4

Table 7.7 - FVRD Construction & Mining - Cost-Effectiveness of Emission Reduction Options

Emission Reduction Option:	1	2	3a	3b	4	5a	5b	6a	6b	7	8	9	10a	10b	11
	LSD	ULSD	B20/LSD	B20/ULSD	B100	PNOx/LSD	PNOx/ULSD	DOC/#2	DOC/ULSD	DPF/ULSD	Clearare	EGR/DPF	SCR/LSD	SCR/ULSD	NOx Traps
Year 2005 - 2025															
Emission Reductions (tonnes)															
NOx	0	0	-23	-99	-592	281	1,190	0	0	0	719	1,151	189	2,858	1,765
SOx	14	25	18	31	66	14	30	0	30	13	13	13	3	17	4
PM_{10}	8	23	12	51	236	29	126	22	126	163	154	163	6	72	30
VOC	12	32	25	114	449	-97	-450	64	398	213	240	213	13	215	51
CO	60	167	66	294	1,515	131	587	312	1,869	763	981	763	71	880	183
NH_3	0.09	0.30	0.10	0.89	4.20	0.20	1.78	0.49	5.67	3.97	5.10	3.97	-0.20	-6.20	1.21
Weighted % Reduction	**1.1**	**3.2**	**1.6**	**6.2**	**27.2**	**4.3**	**18.0**	**2.9**	**17.3**	**19.6**	**22.0**	**24.7**	**1.6**	**22.2**	**11.5**
NPV Costs (Y2005)															
Total NPV (Millions $CAD)	$0.81	$1.66	$0.78	$2.25	$76.90	$2.83	$12.24	$3.21	$3.31	$5.64	$11.79	$13.55	$8.80	$13.55	$11.18
Cost-Effectiveness (1000$/tonne)															
NOx	ND	ND	-$33.2	-$22.7	-$129.8	$10.1	$10.3	ND	ND	ND	$16	$12	$47	$5	$6
SOx	$59.0	$66.5	$43.0	$73.7	$1,173.6	$206.4	$404.4	ND	$109	$450	$941	$1,081	$3,113	$787	$2,498
PM_{10}	$103.0	$71.0	$65.9	$44.5	$325.9	$96.1	$96.8	$146	$26	$35	$76	$83	$1,462	$189	$368
VOC	$65.9	$51.8	$31.6	$19.8	$171.4	-$29.2	-$27.2	$50	$8	$26	$49	$64	$673	$63	$220
CO	$13.6	$9.9	$11.8	$7.7	$50.7	$21.6	$20.8	$10	$2	$7	$12	$18	$124	$15	$61
NH_3	$8,747	$5,558	$7,635	$2,529	$18,313	$13,916	$6,872	$6,568	$584	$1,421	$2,310	$3,413	-$44,386	-$2,186	$9,272
Weighted Total	**$3.1**	**$2.3**	**$2.2**	**$1.6**	**$12.5**	**$2.9**	**$3.0**	**$4.9**	**$0.8**	**$1.3**	**$2.4**	**$2.4**	**$23.7**	**$2.7**	**$4.3**
Unweighted Total	$24.0	$20.8	$25.3	$23.7	$496.6	$12.5	$13.7	$37.3	$5.9	$14.5	$10.5	$8.8	$41.9	$4.3	$6.0

Table 7.8 - FVRD Agriculture - Cost-Effectiveness of Emission Reduction Options

Emission Reduction Option:	1	2	3a	3b	4	5a	5b	6a	6b	7	8	9	10a	10b	11
	LSD	ULSD	B20/LSD	B20/ULSD	B100	PNOx/LSD	PNOx/ULSD	DOC/#2	DOC/ULSD	DPF/ULSD	Clearare	EGR/DPF	SCR/LSD	SCR/ULSD	NOx Traps
Year 2005 - 2025															
Emission Reductions (tonnes)															
NOx	0	0	-35	-190	-1,093	425	2,285	0	0	0	700	1,120	97	1,880	1,860
SOx	20	36	26	44	94	20	43	0	43	8	8	8	1	7	3
PM_{10}	17	49	26	107	504	65	267	49	267	217	205	217	5	71	44
VOC	23	57	46	188	760	-182	-744	119	659	212	239	212	10	147	49
CO	122	328	134	601	3,104	269	1,203	637	3,827	847	1,089	847	49	694	218
NH_3	0.13	0.42	0.15	1.25	5.90	0.29	2.50	0.70	7.95	2.44	3.13	2.44	-0.08	-2.48	0.74
Weighted % Reduction	**1.2**	**3.1**	**1.6**	**6.2**	**28.0**	**4.3**	**18.4**	**3.1**	**17.3**	**12.5**	**13.4**	**14.9**	**0.5**	**8.4**	**6.6**
NPV Costs (Y2005)															
Total NPV (Millions $CAD)	$1.12	$1.90	$1.08	$1.82	$68.60	$3.93	$9.92	$11.72	$6.89	$5.25	$10.76	$14.05	$7.68	$7.94	$9.85
Cost-Effectiveness (1000's$/tonne)															
NOx	ND	ND	-$30.4	-$9.6	-$62.8	$9.2	$4.3	ND	ND	ND	$15	$13	$79	$4	$5
SOx	$57.2	$53.3	$41.7	$41.6	$731.1	$200.2	$228.2	ND	$159	$657	$1,347	$1,759	$6,660	$1,111	$3,323
PM_{10}	$64.4	$38.8	$41.2	$17.1	$136.2	$60.1	$37.1	$241	$26	$24	$53	$65	$1,466	$112	$225
VOC	$48.8	$33.3	$23.4	$9.7	$90.3	-$21.6	-$13.3	$98	$10	$25	$45	$66	$781	$54	$199
CO	$9.2	$5.8	$8.0	$3.0	$22.1	$14.6	$8.2	$18	$2	$6	$10	$17	$158	$11	$45
NH_3	$8,485	$4,481	$7,406	$1,461	$11,622	$13,499	$3,970	$16,818	$867	$2,154	$3,436	$5,769	-$94,922	-$3,200	$13,339
Weighted Total	**$2.1**	**$1.3**	**$1.4**	**$0.6**	**$5.3**	**$2.0**	**$1.2**	**$8.2**	**$0.9**	**$0.9**	**$1.7**	**$2.0**	**$31.0**	**$2.0**	**$3.2**
Unweighted Total	$18.8	$13.5	$17.4	$12.4	$268.6	$12.0	$5.4	$70.0	$7.1	$12.1	$9.4	$9.0	$68.2	$3.8	$5.0

Table 7.9 - FVRD Other Sectors - Cost-Effectiveness of Emission Reduction Options

Emission Reduction Option:	1	2	3a	3b	4	5a	5b	6a	6b	7	8	9	10a	10b	11
	LSD	ULSD	B20/LSD	B20/ULSD	B100	PNOx/LSD	PNOx/ULSD	DOC/#2	DOC/ULSD	DPF/ULSD	Clearare	EGR/DPF	SCR/LSD	SCR/ULSD	NOx Traps
Year 2005 - 2025															
Emission Reductions (tonnes)															
NOx	0	0	-9	-47	-271	107	564	0	0	0	157	252	27	472	404
SOx	5	10	7	12	25	5	12	0	12	2	2	2	0	2	1
PM_{10}	3	10	5	24	109	13	59	10	59	40	38	40	1	14	8
VOC	6	15	11	53	209	-44	-211	29	187	52	59	52	2	40	13
CO	24	72	27	134	680	54	269	128	855	163	209	163	10	151	41
NH_3	0.04	0.12	0.04	0.35	1.66	0.08	0.71	0.19	2.25	0.77	0.98	0.77	-0.03	-0.87	0.23
Weighted % Reduction	**1.0**	**2.7**	**1.4**	**5.6**	**24.5**	**3.6**	**16.4**	**2.5**	**15.7**	**9.3**	**10.3**	**11.5**	**0.5**	**7.7**	**5.4**
NPV Costs (Y2005)															
Total NPV (Millions $CAD)	$0.31	$0.65	$0.30	$0.89	$30.37	$1.09	$4.85	$3.17	$3.42	$1.60	$3.17	$4.19	$1.92	$3.05	$3.49
Cost-Effectiveness (1000's$/tonne)															
NOx	ND	ND	-$33.4	-$19.0	-$112.1	$10.2	$8.6	ND	ND	ND	$20	$17	$72	$6	$9
SOx	$59.1	$67.4	$43.1	$75.2	$1,200.4	$207.0	$412.8	ND	$291	$669	$1,324	$1,746	$4,968	$1,275	$3,969
PM_{10}	$89.4	$61.9	$57.2	$37.9	$278.4	$83.5	$82.3	$325	$58	$40	$84	$105	$2,001	$216	$449
VOC	$56.5	$44.4	$27.1	$16.7	$145.4	-$25.0	-$23.0	$110	$18	$31	$54	$80	$879	$76	$276
CO	$12.8	$9.0	$11.2	$6.6	$44.7	$20.4	$18.1	$25	$4	$10	$15	$26	$194	$20	$85
NH_3	$8,747	$5,556	$7,634	$2,525	$18,260	$13,915	$6,860	$16,864	$1,522	$2,089	$3,215	$5,453	-$70,679	-$3,509	$14,914
Weighted Total	**$2.8**	**$2.1**	**$1.9**	**$1.4**	**$10.7**	**$2.6**	**$2.6**	**$10.9**	**$1.9**	**$1.5**	**$2.7**	**$3.1**	**$34.6**	**$3.4**	**$5.6**
Unweighted Total	$21.9	$18.8	$21.2	$21.5	$429.1	$13.3	$11.5	$82.5	$13.3	$17.0	$12.4	$12.1	$63.4	$5.8	$8.2

Table 7.10 - Rest of BC Construction & Mining - Cost-Effectiveness of Emission Reduction Options

Emission Reduction Option:	1	2	3a	3b	4	5a	5b	6a	6b	7	8	9	10a	10b	11
	LSD	ULSD	B20/LSD	B20/ULSD	B100	PNOx/LSD	PNOx/ULSD	DOC/#2	DOC/ULSD	DPF/ULSD	Clearare	EGR/DPF	SCR/LSD	SCR/ULSD	NOx Traps
Year 2005 - 2025															
Emission Reductions (tonnes)															
NOx	0	0	-227	-958	-5,728	2,720	11,501	0	0	0	8,077	12,923	2,261	35,923	20,215
SOx	247	427	325	448	1,077	247	443	0	443	169	169	169	62	286	21
PM_{10}	67	193	101	401	1,899	251	1,004	187	1,004	1,552	1,466	1,552	69	767	284
VOC	101	262	203	962	3,777	-801	-3,800	528	3,367	2,220	2,497	2,220	148	2,511	537
CO	510	1,416	561	2,361	12,317	1,122	4,722	2,667	15,024	7,546	9,702	7,546	823	9,568	1,758
NH_3	1	3	1	8	40	2	17	5	54	42	54	42	-2	-73	13
Weighted % Reduction	**1.3**	**3.4**	**1.8**	**6.1**	**26.1**	**4.7**	**18.0**	**2.9**	**16.5**	**22.0**	**25.4**	**28.7**	**2.3**	**30.9**	**14.6**
NPV Costs (Y2005)															
Total NPV (Millions $CAD)	**$7.7**	**$15.8**	**$7.4**	**$21.5**	**$733.6**	**$27.0**	**$116.7**	**$22.1**	**$22.9**	**$49.7**	**$107.5**	**$111.9**	**$78.8**	**$121.3**	**$92.3**
Cost-Effectiveness (1000$/tonne)															
NOx	ND	ND	-$32.7	-$22.4	-$128.1	$9.9	$10.1	ND	ND	ND	$13	$9	$35	$3	$5
SOx	$31.3	$37.0	$22.8	$48.0	$680.8	$109.5	$263.4	ND	$52	$295	$637	$663	$1,269	$424	$4,326
PM_{10}	$115.3	$81.8	$73.8	$53.5	$386.3	$107.6	$116.3	$118.3	$23	$32	$73	$72	$1,143	$158	$326
VOC	$76.2	$60.3	$36.6	$22.3	$194.2	-$33.8	-$30.7	$41.9	$7	$22	$43	$50	$532	$48	$172
CO	$15.1	$11.2	$13.2	$9.1	$59.6	$24.1	$24.7	$8.3	$2	$7	$11	$15	$96	$13	$53
NH_3	$8,747	$5,558	$7,635	$2,529	$18,313	$13,916	$6,872	$4,757	$423	$1,186	$1,997	$2,671	-$33,583	-$1,654	$7,255
Weighted Total	**$3.0**	**$2.4**	**$2.1**	**$1.8**	**$14.5**	**$3.0**	**$3.4**	**$4.0**	**$0.7**	**$1.2**	**$2.2**	**$2.0**	**$17.8**	**$2.0**	**$3.3**
Unweighted Total	$18.7	$18.0	$18.6	$25.3	$727.1	$11.2	$12.8	$31.0	$4.7	$12.6	$8.8	$6.6	$31.1	$3.1	$4.4

Table 7.11 - Rest of BC Agriculture - Cost-Effectiveness of Emission Reduction Options

Emission Reduction Option:	1	2	3a	3b	4	5a	5b	6a	6b	7	8	9	10a	10b	11
	LSD	ULSD	B20/LSD	B20/ULSD	B100	PNOx/LSD	PNOx/ULSD	DOC/#2	DOC/ULSD	DPF/ULSD	Clearare	EGR/DPF	SCR/LSD	SCR/ULSD	NOx Traps
Year 2005 - 2025															
Emission Reductions (tonnes)															
NOx	0	0	-201	-1,144	-6,508	2,416	13,727	0	0	0	10,499	16,799	1,681	38,917	29,271
SOx	177	303	233	312	763	177	309	0	309	105	105	105	34	150	10
PM_{10}	111	293	166	669	3,164	416	1,672	309	1,672	3,844	3,630	3,844	138	1,849	789
VOC	125	310	251	1,009	4,082	-991	-3,985	652	3,531	3,274	3,683	3,274	242	3,248	744
CO	637	1,599	701	3,083	15,975	1,402	6,165	3,315	19,617	14,858	19,103	14,858	1,123	17,510	4,002
NH_3	1	2	1	5	24	1	10	3	32	22	29	22	-1	-30	7
Weighted % Reduction	**0.8**	**2.0**	**1.1**	**4.1**	**18.5**	**2.9**	**12.1**	**2.0**	**11.1**	**23.1**	**24.5**	**27.0**	**1.3**	**20.8**	**11.4**
Unweighted % Reduction	**0.3**	**0.6**	**0.3**	**0.5**	**0.9**	**1.3**	**7.5**	**0.6**	**3.5**	**4.6**	**11.4**	**15.3**	**1.3**	**28.2**	**19.7**
NPV Costs (Y2005)															
Total NPV (Millions $CAD)	**$11**	**$23**	**$11**	**$32**	**$1,089**	**$39**	**$174**	**$62**	**$68**	**$168**	**$348**	**$412**	**$281**	**$431**	**$341**
Cost-Effectiveness (1000$/tonne)															
NOx	ND	ND	-$53.6	-$28.0	-$167.3	$16.3	$12.7	ND	ND	ND	$33	$25	$167	$11	$12
SOx	$63.6	$76.7	$46.4	$102.5	$1,426.3	$222.4	$562.6	ND	$220	$1,599	$3,304	$3,913	$8,165	$2,871	$33,144
PM_{10}	$101.3	$79.3	$64.8	$47.8	$344.1	$94.5	$104.0	$200.7	$41	$44	$96	$107	$2,040	$233	$432
VOC	$89.6	$75.0	$43.0	$31.7	$266.7	-$39.7	-$43.6	$95.0	$19	$51	$95	$126	$1,160	$133	$458
CO	$17.6	$14.5	$15.4	$10.4	$68.1	$28.1	$28.2	$18.7	$3	$11	$18	$28	$250	$25	$85
NH_3	$20,784	$13,570	$18,140	$6,438	$46,246	$33,066	$17,492	$21,764	$2,147	$7,549	$12,134	$18,477	-$274,485	-$14,291	$50,557
Weighted Total	**$3.2**	**$2.7**	**$2.2**	**$1.8**	**$13.4**	**$3.1**	**$3.3**	**$7.0**	**$1.4**	**$1.7**	**$3.2**	**$3.5**	**$50.0**	**$4.7**	**$6.8**
Unweighted Total	$27.4	$25.9	$24.3	$38.5	$761.2	$19.6	$14.9	$64.9	$12.4	$23.6	$19.5	$17.2	$134.5	$9.8	$11.1

Table 7.12 - Rest of BC Logging - Cost-Effectiveness of Emission Reduction Options															
Emission Reduction Option:	1	2	3a	3b	4	5a	5b	6a	6b	7	8	9	10a	10b	11
	LSD	ULSD	B20/LSD	B20/ULSD	B100	PNOx/LSD	PNOx/ULSD	DOC/#2	DOC/ULSD	DPF/ULSD	Clearare	EGR/DPF	SCR/LSD	SCR/ULSD	NOx Traps
Year 2005 - 2025															
Emission Reductions (tonnes)															
NOx	0	0	-91	-258	-1,684	1,090	3,096	0	0	0	2,454	3,927	922	9,459	5,271
SOx	84	147	111	158	373	84	157	0	157	71	71	71	22	107	12
PM_{10}	24	65	35	109	545	89	272	66	272	612	578	612	30	260	100
VOC	33	78	66	244	1,005	-261	-964	171	854	787	886	787	64	792	176
CO	156	409	171	564	3,095	342	1,128	812	3,588	2,677	3,442	2,677	306	2,984	575
NH_3	0	1	0	3	14	1	6	2	18	16	20	16	-1	-24	4
% Reduction (weighted)	**1.7**	**4.2**	**2.3**	**6.2**	**27.7**	**6.4**	**18.3**	**3.7**	**16.5**	**31.9**	**35.4**	**39.4**	**3.5**	**33.4**	**15.4**
NPV Costs (Y2005)															
Total NPV (Millions $CAD)	**$3.42**	**$6.35**	**$3.28**	**$7.26**	**$258.68**	**$11.95**	**$39.43**	**$5.58**	**$4.34**	**$17.95**	**$37.33**	**$45.34**	**$38.02**	**$47.67**	**$34.72**
Cost-Effectiveness (1000$/tonne)															
NOx	ND	ND	-$36.1	-$28.1	-$153.6	$11.0	$12.7	ND	ND	ND	$15.2	$11.5	$41.2	$5.0	$6.6
SOx	$40.6	$43.1	$29.6	$45.8	$693.3	$142.0	$251.4	ND	$27.7	$251.9	$523.8	$636.1	$1,710.2	$444.8	$2,884.5
PM_{10}	$144.5	$98.0	$92.5	$66.8	$475.1	$134.9	$145.2	$84.7	$16.0	$29.3	$64.6	$74.1	$1,267.6	$183.7	$348.7
VOC	$103.3	$81.8	$49.6	$29.7	$257.3	-$45.8	-$40.9	$32.5	$5.1	$22.8	$42.1	$57.6	$595.0	$60.2	$197.6
CO	$21.9	$15.5	$19.2	$12.9	$83.6	$34.9	$35.0	$6.9	$1.2	$6.7	$10.8	$16.9	$124.3	$16.0	$60.4
NH_3	$8,752	$5,573	$7,639	$2,582	$18,885	$13,924	$7,015	$2,728	$243	$1,158	$1,873	$2,925	-$35,608	-$1,962	$7,729
Total (weighted)	**$3.8**	**$2.9**	**$2.7**	**$2.2**	**$17.9**	**$3.6**	**$4.1**	**$2.9**	**$0.5**	**$1.1**	**$2.0**	**$2.2**	**$20.6**	**$2.7**	**$4.3**
Total (unweighted)	$24.3	$22.0	$27.1	$28.7	$1,095.5	$12.0	$15.4	$23.5	$3.4	$12.2	$9.4	$8.4	$36.7	$4.5	$6.2

Table 7.13 - Rest of BC Other Sectors - Cost-Effectiveness of Emission Reduction Options															
Emission Reduction Option:	**1**	**2**	**3a**	**3b**	**4**	**5a**	**5b**	**6a**	**6b**	**7**	**8**	**9**	**10a**	**10b**	**11**
	LSD	**ULSD**	**B20/LSD**	**B20/ULSD**	**B100**	**PNOx/LSD**	**PNOx/ULSD**	**DOC/#2**	**DOC/ULSD**	**DPF/ULSD**	**Clearare**	**EGR/DPF**	**SCR/LSD**	**SCR/ULSD**	**NOx Traps**
Year 2005 - 2025															
Emission Reductions (tonnes)															
NOx	0	0	-49	-231	-1,353	587	2,771	0	0	0	1,161	1,854	235	3,826	2,879
SOx	59	102	78	106	258	59	105	0	105	24	24	24	6	29	4
PM_{10}	17	49	25	102	481	64	254	47	254	271	256	271	8	99	51
VOC	25	63	49	230	906	-194	-909	128	806	350	393	349	16	284	84
CO	122	360	135	624	3,198	269	1,248	642	3,972	1,258	1,618	1,257	91	1,270	311
NH_3	0	1	0	2	10	0	4	1	13	7	8	7	0	-8	2
Weighted % Reduction	**1.3**	**3.4**	**1.8**	**6.0**	**26.1**	**4.5**	**17.7**	**2.9**	**16.4**	**15.0**	**16.8**	**18.8**	**1.0**	**13.9**	**8.8**
NPV Costs (Y2005)															
Total NPV (Millions $CAD)	**$1.74**	**$3.65**	**$1.67**	**$5.13**	**$173.94**	**$6.10**	**$27.90**	**$9.22**	**$10.00**	**$9.97**	**$20.09**	**$25.02**	**$11.42**	**$18.90**	**$21.09**
Cost-Effectiveness (1000$/tonne)															
NOx	ND	ND	-$34.2	-$22.2	-$128.5	$10.4	$10.1	ND	ND	ND	$17	$13	$49	$5	$7
SOx	$29.4	$35.7	$21.4	$48.3	$675.5	$102.8	$265.3	ND	$95	$416	$838	$1,045	$1,913	$663	$5,643
PM_{10}	$102.7	$74.0	$65.8	$50.5	$362.0	$95.9	$109.9	$194.4	$39	$37	$78	$92	$1,463	$192	$412
VOC	$71.0	$57.7	$34.1	$22.3	$192.0	-$31.5	-$30.7	$72.2	$12	$28	$51	$72	$700	$67	$251
CO	$14.2	$10.1	$12.4	$8.2	$54.4	$22.6	$22.3	$14.4	$3	$8	$12	$20	$125	$15	$68
NH_3	$8,746	$5,555	$7,633	$2,520	$18,208	$13,914	$6,847	$8,767	$771	$1,528	$2,396	$3,843	-$48,020	-$2,297	$10,548
Weighted Total	**$2.7**	**$2.2**	**$1.9**	**$1.7**	**$13.6**	**$2.8**	**$3.2**	**$6.6**	**$1.2**	**$1.4**	**$2.4**	**$2.7**	**$24.0**	**$2.8**	**$4.9**
Unweighted Total	$17.3	$17.1	$16.2	$24.9	$608.8	$11.8	$12.6	$52.7	$8.5	$15.5	$10.9	$10.0	$43.2	$4.5	$7.0

Figure 7.1- GVRD Construction & Mining Equipment

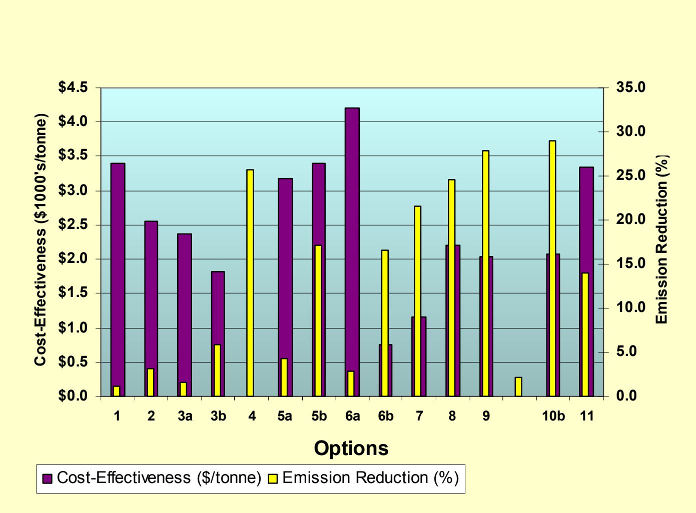
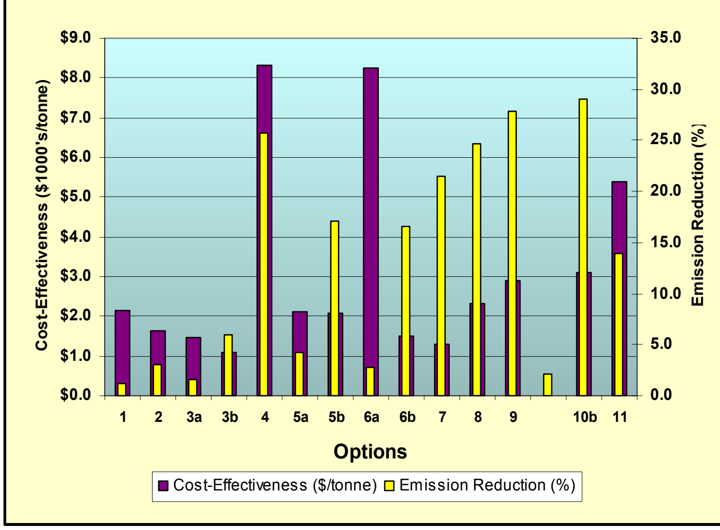


Figure 7.2 - GVRD Agricultural Equipment



	Emission Reduction Options	Years
1	Rebranded road diesel, 350 ppm S	05 - 06
2	Ultralow sulphur diesel, 10 ppm S	07 - 10
3a	B20 biodiesel (biodiesel + LSD)	05 - 06
3b	B20 biodiesel (biodiesel + ULSD)	07 - 25
4	B100 biodiesel, 0 ppm S	05 - 25
5a	PuriNOx with LSD, 350 ppm S	05 - 06
5b	PuriNOx with ULSD, 10 ppm S	07 - 25
6a	DOC with off-road diesel (563 ppm S)	05 - 06
6b	DOC with ULSD, 10 ppm S	07 - 25
7	Passive DPF with ULSD (10 ppm S)	07 - 25
8	Cleaire "LongView" with ULSD	07 - 25
9	EGR + DPF + ULSD	07 - 25
10a	SCR + LSD (urea added to fuel costs)	05 - 06
10b	SCR + LSD (urea added to fuel costs)	07 - 25
11	NOx Adsorbers	10 - 25

Figure 7.3- GVRD Industrial & Commercial Equipment

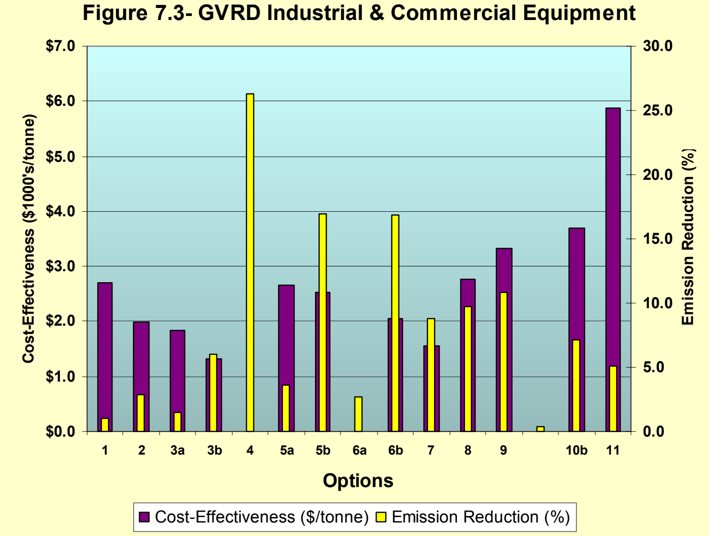
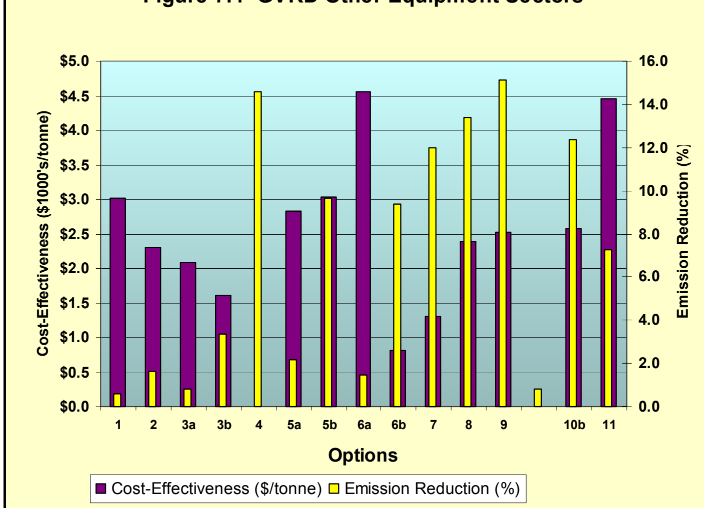
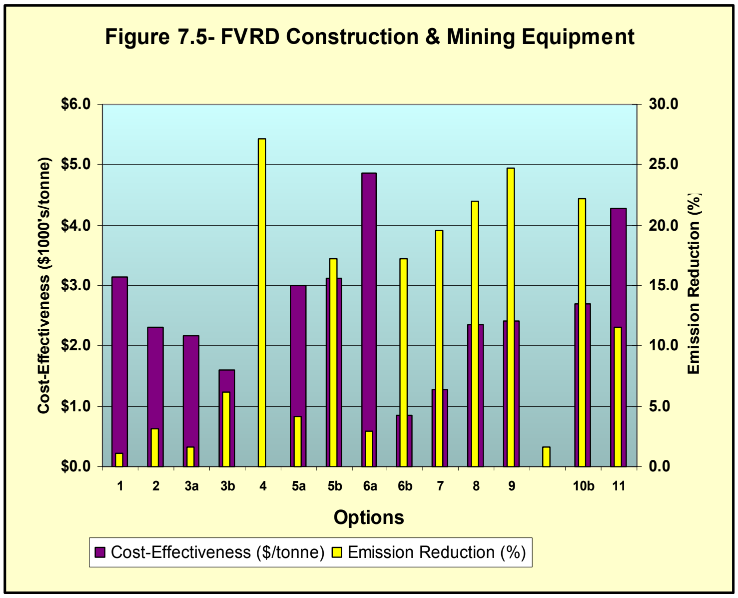
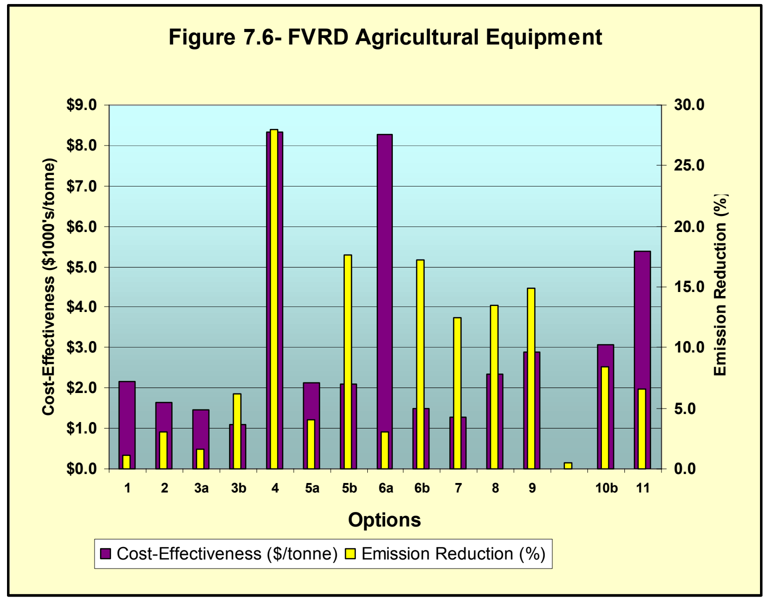
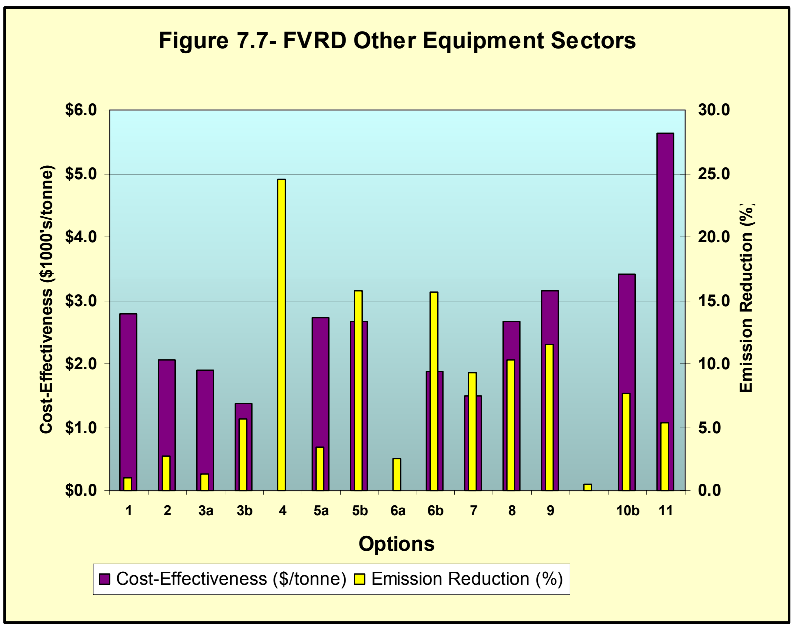


Figure 7.4- GVRD Other Equipment Sectors









	Emission Reduction Options	Years
1	Rebranded road diesel, 350 ppm S	05 - 06
2	Ultralow sulphur diesel, 10 ppm S	07 - 10
3a	B20 biodiesel (biodiesel + LSD)	05 - 06
3b	B20 biodiesel (biodiesel + ULSD)	07 - 25
4	B100 biodiesel, 0 ppm S	05 - 25
5a	PuriNOx with LSD, 350 ppm S	05 - 06
5b	PuriNOx with ULSD, 10 ppm S	07 - 25
6a	DOC with off-road diesel (563 ppm S)	05 - 06
6b	DOC with ULSD, 10 ppm S	07 - 25
7	Passive DPF with ULSD (10 ppm S)	07 - 25
8	Cleaire "LongView" with ULSD	07 - 25
9	EGR + DPF + ULSD	07 - 25
10a	SCR + LSD (urea added to fuel costs)	05 - 06
10b	SCR + LSD (urea added to fuel costs)	07 - 25
11	NOx Adsorbers	10 - 25

Figure 7.8 - Rest of BC Commercial & Mining

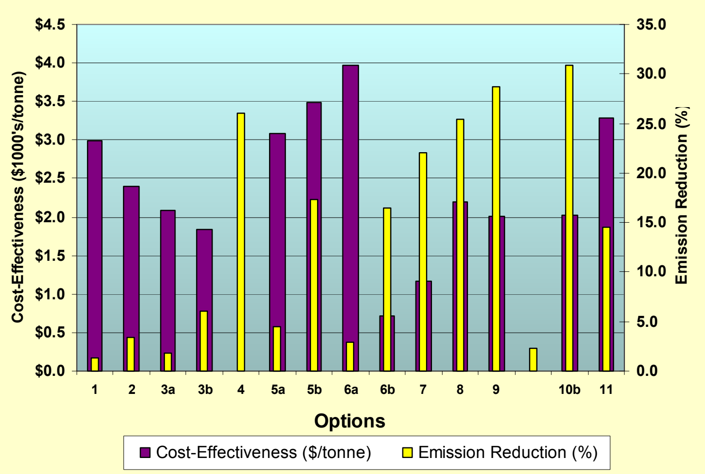
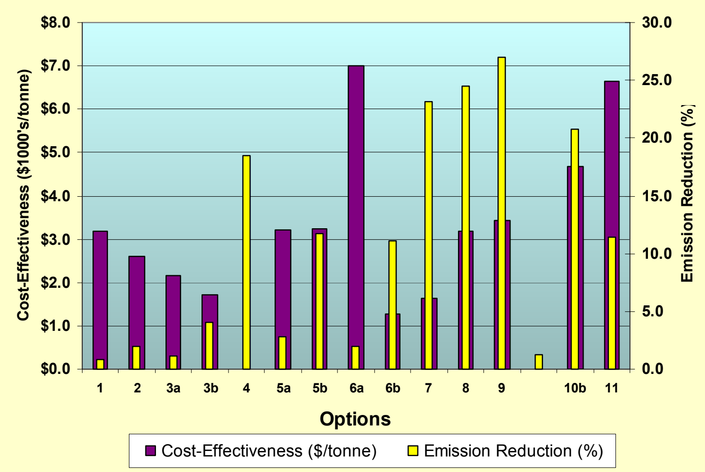


Figure 7.9 - Rest of BC Agricultural Equipment



	Emission Reduction Options	Years
1	Rebranded road diesel, 350 ppm S	05 - 06
2	Ultralow sulphur diesel, 10 ppm S	07 - 10
3a	B20 biodiesel (biodiesel + LSD)	05 - 06
3b	B20 biodiesel (biodiesel + ULSD)	07 - 25
4	B100 biodiesel, 0 ppm S	05 - 25
5a	PuriNOx with LSD, 350 ppm S	05 - 06
5b	PuriNOx with ULSD, 10 ppm S	07 - 25
6a	DOC with off-road diesel (563 ppm S)	05 - 06
6b	DOC with ULSD, 10 ppm S	07 - 25
7	Passive DPF with ULSD (10 ppm S)	07 - 25
8	Cleaire "LongView" with ULSD	07 - 25
9	EGR + DPF + ULSD	07 - 25
10a	SCR + LSD (urea added to fuel costs)	05 - 06
10b	SCR + LSD (urea added to fuel costs)	07 - 25
11	NOx Adsorbers	10 - 25

Figure 7.10 - Rest of BC Logging Equipment

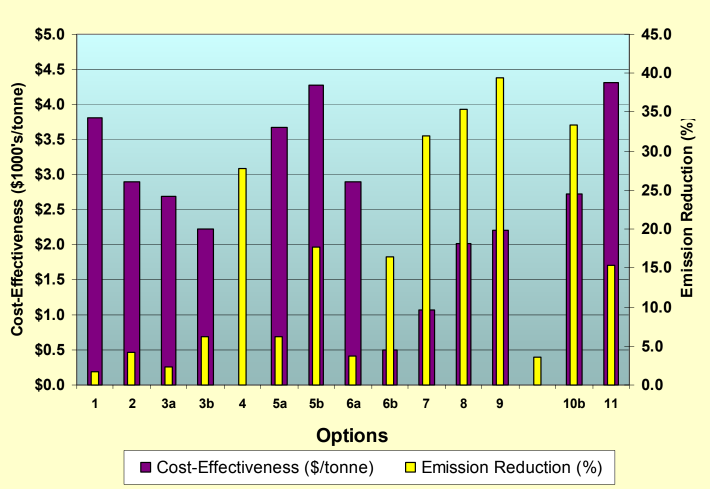
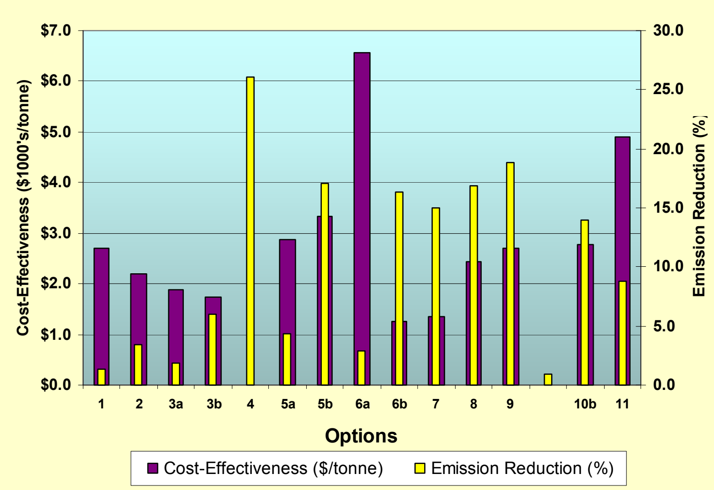


Figure 7.11 - Rest of BC Other Sectors



7.4 Effect of Discount Rate on Cost-Effectiveness

The cost-effectiveness of ERM's that can be implemented over most of the 2005 – 2025 study period are sensitive to the discount rate used in the discounted cash flow analysis. The cost-effectiveness of ERM's that are used only in the immediate future are, on the other hand, relatively insensitive to the choice of discount rate. This can be seen in Tables 7.14 – 7.16 where the cost-benefit ratio for selected HDD fleets are presented for different discount rates (0%, 7% and 14%).

It can be seen from these tables that the relative rankings of the different emission control options does not significantly change with large changes in the discount rate. Generally in investment analysis it is best practice to use a discount rate that reflects the current cost of borrowing plus the expected near-term inflation rate plus some factor that accounts for relative investment risk, although when retrofitting pollution-control devices the latter factor usually is not included. Given the current interest and expected near-term inflation rates a discount rate of 7% is appropriate.

Table 7.14 - Discount Rate Sensitivity (GVRD C & M Fleet)

Control Option	Weighted Reduction (%)	Cost/Benefit (CDN$1000's/tonne) Discount Rate (percent) 0	7	14
Rebranded road diesel, 350 ppm S	1.1	3.51	3.39	3.29
Ultralow sulphur diesel, 10 ppm S	3.1	3.23	2.55	2.06
B20 biodiesel (biodiesel + LSD)	1.6	2.44	2.36	2.29
B20 biodiesel (biodiesel + ULSD)	5.9	3.70	1.81	1.04
B100 biodiesel, 0 ppm S	25.8	27.00	14.19	8.96
PuriNOx with LSD, 350 ppm S	4.4	3.28	3.18	3.08
PuriNOx with ULSD, 10 ppm S	17.9	6.94	3.39	1.95
DOC with off-road diesel (563 ppm S)	2.8	4.24	4.21	4.19
DOC with ULSD, 10 ppm S	16.5	1.54	0.75	0.43
Passive DPF with ULSD (10 ppm S)	21.5	1.91	1.16	0.82
Cleaire "LongView" with ULSD	24.6	3.36	2.20	1.62
EGR + DPF + ULSD	27.8	3.32	2.03	1.42
SCR + LSD (urea added to fuel costs)	2.1	19.40	18.74	18.16
SCR + LSD (urea added to fuel costs)	29.0	3.73	2.07	1.36
NOx Adsorbers	13.9	6.25	3.34	2.00

The last ERM option (NOx Adsorbers) is particularly sensitive to the discount rate as it is assumed to only be applicable after the year 2010, when the technology has matured and is commercially available.

Table 7.15 - Discount Rate Sensitivity (FVRD Agricultural HDD Fleet)				
Control Option	Weighted Reduction (%)	Cost/Benefit (CDN$1000's/tonne)		
		Discount Rate (percent)		
		0	7	14
Rebranded road diesel, 350 ppm S	1.2	2.24	2.16	2.10
Ultralow sulphur diesel, 10 ppm S	3.1	2.08	1.64	1.32
B20 biodiesel (biodiesel + LSD)	1.6	1.51	1.46	1.42
B20 biodiesel (biodiesel + ULSD)	6.2	2.23	1.10	0.63
B100 biodiesel, 0 ppm S	28.0	15.81	8.34	5.29
PuriNOx with LSD, 350 ppm S	4.3	2.21	2.13	2.07
PuriNOx with ULSD, 10 ppm S	18.4	4.28	2.10	1.21
DOC with off-road diesel (563 ppm S)	3.1	8.31	8.27	8.22
DOC with ULSD, 10 ppm S	17.3	3.04	1.49	0.86
Passive DPF with ULSD (10 ppm S)	12.5	2.11	1.29	0.91
Cleaire "LongView" with ULSD	13.4	3.56	2.34	1.73
EGR + DPF + ULSD	14.9	4.73	2.90	2.04
SCR + LSD (urea added to fuel costs)	0.5	33.11	31.99	31.01
SCR + LSD (urea added to fuel costs)	8.4	5.53	3.08	2.03
NOx Adsorbers	6.6	10.07	5.39	3.23

Table 7.16 - Discount Rate Sensitivity (Rest of BC Logging Equipment Fleet)				
Control Option	Weighted Reduction (%)	Cost/Benefit (CDN$1000's/tonne)		
		Discount Rate (percent)		
		0	7	14
Rebranded road diesel, 350 ppm S	1.7	3.93	3.80	3.69
Ultralow sulphur diesel, 10 ppm S	4.2	3.65	2.89	2.34
B20 biodiesel (biodiesel + LSD)	2.3	2.78	2.69	2.61
B20 biodiesel (biodiesel + ULSD)	6.2	4.30	2.23	1.35
B100 biodiesel, 0 ppm S	27.7	31.61	17.86	11.95
PuriNOx with LSD, 350 ppm S	6.4	3.80	3.68	3.57
PuriNOx with ULSD, 10 ppm S	18.3	8.24	4.27	2.58
DOC with off-road diesel (563 ppm S)	3.7	2.90	2.89	2.87
DOC with ULSD, 10 ppm S	16.5	0.97	0.50	0.30
Passive DPF with ULSD (10 ppm S)	31.9	1.66	1.08	0.78
Cleaire "LongView" with ULSD	35.4	2.93	2.02	1.53
EGR + DPF + ULSD	39.4	3.40	2.20	1.60
SCR + LSD (urea added to fuel costs)	3.5	21.32	20.60	19.98
SCR + LSD (urea added to fuel costs)	33.4	4.59	2.73	1.88
NOx Adsorbers	15.4	7.76	4.31	2.65

7.5 Yearly Emission Reductions for Selected Fleets

The Excel/VBA models were modified to enable the estimation of annual HDD fleet emission reductions in 5-year increments – i.e. – for 2005, 2010, 2015, 2020 and 2025. The results for three representative fleets: GVRD Construction & Mining (Table 7.17), FVRD Agriculture (Table 7.18) and the Rest of BC Logging (Table 7.19) are tabulated in the next three pages.

The reduced effectiveness of emission reduction measures with time is obvious in these tables and is due to the reasonable assumption that, as older equipment in the HDD fleets is replaced with new, low-emission equipment, the percent emission reduction afforded by some of these emission reduction measures will decrease because of a nonlinear relation between emission reduction efficiency and emission concentrations. This assumption is accommodated in Table 7.2 in the row labeled "Last Year Reduction".

Also, some short-term ERM's, such as the use of low-sulphur road diesel (Options 1, 3a, 5a and 6a) are only applicable in the first two years until ULSD becomes readily available. This assumption is stipulated in Table 7.2 in the two rows labeled "First Year of Usage" and "Last Year of Usage". Gradual introduction of technology-based ERM's is handled using a percent penetration rate.

Table 7.17 - GVRD Construction & Mining -Emission Reductions (TPY)

Emission Reduction Option:		1	2	3a	3b	4	5a	5b	6a	6b	7	8	9	10a	10b	11
		LSD	ULSD	B20/LSD	B20/ULSD	B100	PNOx/LSD	PNOx/ULSD	DOC/#2	DOC/ULSD	DPF/ULSD	Clearare	EGR/DPF	SCR/LSD	SCR/ULSD	NOx Traps
2005 Reductions (TPY)	**BaseLine**															
NOx	5,563	0.0	0.0	-111.3	0.0	-556.3	1335.1	0.0	0.0	0.0	0.0	0.0	0.0	715.9	0.0	0.0
SOx	184	69.8	0.0	91.8	0.0	183.7	69.8	0.0	0.0	0.0	0.0	0.0	0.0	11.8	0.0	0.0
PM_{10}	417	33.3	0.0	50.0	0.0	195.9	125.0	0.0	62.5	0.0	0.0	0.0	0.0	21.7	0.0	0.0
VOC	520	52.0	0.0	104.1	0.0	348.6	-411.0	0.0	182.1	0.0	0.0	0.0	0.0	48.2	0.0	0.0
CO	2,609	260.9	0.0	287.0	0.0	1252.5	574.0	0.0	913.3	0.0	0.0	0.0	0.0	269.1	0.0	0.0
NH_3	4	0.4	0.0	0.5	0.0	2.0	0.9	0.0	1.5	0.0	0.0	0.0	0.0	-0.7	0.0	0.0
% Reduction (weighted)		6	0	9	0	31	25	0	11	0	0	0	0	8	0	0
2010 Reductions (TPY)	**BaseLine**															
NOx	4,577	0.0	0.0	0.0	-83.9	-400.4	0.0	1006.8	0.0	0.0	0.0	846.1	1353.8	0.0	2765.8	830.8
SOx	6	0.0	5.3	0.0	4.9	4.8	0.0	4.9	0.0	4.9	4.1	4.1	4.1	0.0	3.6	1.1
PM_{10}	351	0.0	45.6	0.0	38.6	144.2	0.0	96.4	0.0	96.4	185.0	174.7	185.0	0.0	68.9	14.0
VOC	403	0.0	60.4	0.0	73.8	236.0	0.0	-291.5	0.0	258.3	178.4	200.8	178.4	0.0	144.8	15.2
CO	2,284	0.0	342.6	0.0	230.3	959.2	0.0	460.6	0.0	1465.4	925.6	1190.0	925.6	0.0	898.2	90.2
NH_3	5	0.0	0.7	0.0	0.5	2.0	0.0	1.0	0.0	3.0	2.5	3.2	2.5	0.0	-3.2	0.2
% Reduction (weighted)		0	9	0	7	25	0	23	0	21	35	40	45	0	34	9
2015 Reductions (TPY)	**BaseLine**															
NOx	2,997	0.0	0.0	0.0	-46.6	-224.8	0.0	559.5	0.0	0.0	0.0	446.1	713.8	0.0	1747.1	1720.7
SOx	5	0.0	0.0	0.0	4.0	3.9	0.0	3.9	0.0	3.9	3.2	3.2	3.2	0.0	3.4	3.4
PM_{10}	228	0.0	0.0	0.0	21.3	80.3	0.0	53.2	0.0	53.2	93.6	88.4	93.6	0.0	39.8	27.9
VOC	311	0.0	0.0	0.0	48.3	156.0	0.0	-190.8	0.0	169.1	122.4	137.7	122.4	0.0	121.3	41.0
CO	1,410	0.0	0.0	0.0	120.6	507.5	0.0	241.2	0.0	767.6	422.6	543.4	422.6	0.0	472.7	161.7
NH_3	5	0.0	0.0	0.0	0.4	1.9	0.0	0.9	0.0	2.9	2.4	3.0	2.4	0.0	-3.5	0.9
% Reduction (weighted)		0	0	0	6	22	0	19	0	18	27	31	35	0	32	27
2020 Reductions (TPY)	**BaseLine**															
NOx	1,814	0.0	0.0	0.0	-23.2	-113.4	0.0	278.1	0.0	0.0	0.0	206.4	330.2	0.0	1047.1	775.3
SOx	5	0.0	0.0	0.0	3.2	3.2	0.0	3.2	0.0	3.2	2.6	2.6	2.6	0.0	3.3	2.7
PM_{10}	114	0.0	0.0	0.0	8.7	33.4	0.0	21.8	0.0	21.8	30.8	29.1	30.8	0.0	17.8	8.9
VOC	253	0.0	0.0	0.0	32.4	106.1	0.0	-127.9	0.0	113.3	87.5	98.4	87.5	0.0	105.8	28.5
CO	770	0.0	0.0	0.0	54.1	231.1	0.0	108.3	0.0	344.5	154.4	198.5	154.4	0.0	219.7	57.5
NH_3	6	0.0	0.0	0.0	0.4	1.7	0.0	0.8	0.0	2.6	2.1	2.7	2.1	0.0	-3.9	0.8
% Reduction (weighted)		0	0	0	5	17	0	14	0	14	18	21	24	0	33	21
2025 Reductions (TPY)	**BaseLine**															
NOx	1,412	0.0	0.0	0.0	-14.1	-70.6	0.0	169.5	0.0	0.0	0.0	124.2	198.7	0.0	826.3	447.0
SOx	5	0.0	0.0	0.0	2.6	2.7	0.0	2.6	0.0	2.6	2.1	2.1	2.1	0.0	3.5	2.1
PM_{10}	66	0.0	0.0	0.0	4.0	15.6	0.0	9.9	0.0	9.9	12.8	12.1	12.8	0.0	9.9	3.6
VOC	233	0.0	0.0	0.0	23.3	78.0	0.0	-92.0	0.0	81.5	68.8	77.4	68.8	0.0	105.7	21.5
CO	513	0.0	0.0	0.0	28.2	123.1	0.0	56.4	0.0	179.5	75.3	96.8	75.3	0.0	135.3	26.9
NH_3	6	0.0	0.0	0.0	0.3	1.5	0.0	0.7	0.0	2.2	1.8	2.3	1.8	0.0	-4.2	0.6
% Reduction (weighted)		0	0	0	4	12	0	10	0	11	12	15	18	0	36	17

Table 7.18 - FVRD Agricultural Equipment Reductions (TPY)

Emission Reduction Option:	BaseLIne	1 LSD	2 ULSD	3a B20/LSD	3b B20/ULSD	4 B100	5a PNOx/LSD	5b PNOx/ULSD	6a DOC/#2	6b DOC/ULSD	7 DPF/ULSD	8 Clearare	9 EGR/DPF	10a SCR/LSD	10b SCR/ULSD	11 NOx Traps
2005 Reductions (TPY)	**BaseLine**															
NOx	893	0.0	0.0	-17.9	0.0	-89.3	214.4	0.0	0.0	0.0	0.0	0.0	0.0	32.8	0.0	0.0
SOx	29	10.9	0.0	14.3	0.0	28.6	10.9	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0
PM_{10}	111	8.9	0.0	13.4	0.0	52.4	33.4	0.0	16.7	0.0	0.0	0.0	0.0	1.8	0.0	0.0
VOC	118	11.8	0.0	23.6	0.0	79.2	-93.4	0.0	41.4	0.0	0.0	0.0	0.0	3.4	0.0	0.0
CO	621	62.1	0.0	68.3	0.0	298.1	136.6	0.0	217.4	0.0	0.0	0.0	0.0	16.6	0.0	0.0
NH_3	0.7	0.1	0.0	0.1	0.0	0.3	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Reduction (weighted)		7.0	0.0	9.9	0.0	35.9	25.4	0.0	12.3	0.0	0.0	0.0	0.0	2.1	0.0	0.00
2010 Reductions (TPY)	**BaseLine**															
NOx	812	0.0	0.0	0.0	-14.9	-71.0	0.0	178.5	0.0	0.0	0.0	69.1	110.6	0.0	136.6	67.8
SOx	1	0.0	0.8	0.0	0.8	0.7	0.0	0.8	0.0	0.8	0.3	0.3	0.3	0.0	0.1	0.1
PM_{10}	86	0.0	11.2	0.0	9.5	35.6	0.0	23.8	0.0	23.8	21.7	20.5	21.7	0.0	5.4	1.6
VOC	85	0.0	12.7	0.0	15.5	49.7	0.0	-61.3	0.0	54.3	19.8	22.3	19.8	0.0	10.2	1.7
CO	514	0.0	77.1	0.0	51.8	215.7	0.0	103.6	0.0	329.6	86.5	111.2	86.5	0.0	52.8	8.4
NH_3	0.7	0.0	0.1	0.0	0.1	0.3	0.0	0.1	0.0	0.5	0.2	0.2	0.2	0.0	-0.1	0.0
% Reduction (weighted)		0.0	9.8	0.0	7.9	28.7	0.0	23.3	0.0	22.3	18.4	19.8	21.9	0.0	9.2	3.6
2015 Reductions (TPY)	**BaseLine**															
NOx	668	0.0	0.0	0.0	-10.4	-50.1	0.0	124.7	0.0	0.0	0.0	44.4	71.0	0.0	106.6	171.3
SOx	1	0.0	0.0	0.0	0.7	0.6	0.0	0.7	0.0	0.7	0.2	0.2	0.2	0.0	0.1	0.2
PM_{10}	59	0.0	0.0	0.0	5.5	20.7	0.0	13.7	0.0	13.7	13.3	12.6	13.3	0.0	3.8	4.0
VOC	59	0.0	0.0	0.0	9.3	29.9	0.0	-36.6	0.0	32.4	12.6	14.1	12.6	0.0	7.7	4.2
CO	369	0.0	0.0	0.0	31.6	132.9	0.0	63.2	0.0	201.0	51.3	66.0	51.3	0.0	37.9	19.6
NH_3	0.8	0.0	0.0	0.0	0.1	0.3	0.0	0.1	0.0	0.4	0.1	0.2	0.1	0.0	-0.1	0.1
% Reduction (weighted)		0.0	0.0	0.0	6.3	23.0	0.0	19.6	0.0	18.0	15.7	17.0	18.9	0.0	9.6	12.4
2020 Reductions (TPY)	**BaseLine**															
NOx	505	0.0	0.0	0.0	-6.5	-31.6	0.0	77.5	0.0	0.0	0.0	23.9	38.3	0.0	73.7	89.9
SOx	1	0.0	0.0	0.0	0.5	0.5	0.0	0.5	0.0	0.5	0.2	0.2	0.2	0.0	0.1	0.2
PM_{10}	35	0.0	0.0	0.0	2.7	10.4	0.0	6.8	0.0	6.8	7.4	7.0	7.4	0.0	2.6	2.1
VOC	43	0.0	0.0	0.0	5.5	18.1	0.0	-21.9	0.0	19.4	7.9	8.9	7.9	0.0	5.9	2.6
CO	240	0.0	0.0	0.0	16.9	72.0	0.0	33.8	0.0	107.4	28.1	36.1	28.1	0.0	25.6	10.5
NH_3	0.9	0.0	0.0	0.0	0.1	0.3	0.0	0.1	0.0	0.4	0.1	0.2	0.1	0.0	-0.1	0.0
% Reduction (weighted)		0.0	0.0	0.0	4.8	17.6	0.0	15.8	0.0	14.0	13.4	14.5	16.0	0.0	10.1	10.1
2025 Reductions (TPY)	**BaseLine**															
NOx	407	0.0	0.0	0.0	-4.1	-20.4	0.0	48.9	0.0	0.0	0.0	11.5	18.4	0.0	48.6	41.4
SOx	1	0.0	0.0	0.0	0.4	0.4	0.0	0.4	0.0	0.4	0.1	0.1	0.1	0.0	0.1	0.1
PM_{10}	20	0.0	0.0	0.0	1.2	4.7	0.0	3.0	0.0	3.0	3.4	3.2	3.4	0.0	1.6	0.9
VOC	36	0.0	0.0	0.0	3.6	12.2	0.0	-14.4	0.0	12.8	5.3	6.0	5.3	0.0	5.1	1.7
CO	148	0.0	0.0	0.0	8.1	35.4	0.0	16.2	0.0	51.7	13.4	17.2	13.4	0.0	16.6	4.8
NH_3	0.9	0.0	0.0	0.0	0.1	0.2	0.0	0.1	0.0	0.3	0.1	0.1	0.1	0.0	-0.2	0.0
% Reduction (weighted)		0.0	0.0	0.0	3.3	12.0	0.0	11.7	0.0	10.0	9.6	10.4	11.5	0.0	10.1	7.0

Table 7.19 - Rest of BC Logging Equipment Reductions (TPY)																
Emission Reduction Option:	**BaseLIne**	**1**	**2**	**3a**	**3b**	**4**	**5a**	**5b**	**6a**	**6b**	**7**	**8**	**9**	**10a**	**10b**	**11**
		LSD	**ULSD**	**B20/LSD**	**B20/ULSD**	**B100**	**PNOx/LSD**	**PNOx/ULSD**	**DOC/#2**	**DOC/ULSD**	**DPF/ULSD**	**Clearare**	**EGR/DPF**	**SCR/LSD**	**SCR/ULSD**	**NOx Traps**
2005 Reductions (TPY)	**BaseLine**															
NOx	2356.0	0.0	0.0	-47.1	0.0	-235.6	565.4	0.0	0.0	0.0	0.0	0.0	0.0	323.1	0.0	0.0
SOx	122.9	46.7	0.0	61.5	0.0	122.9	46.7	0.0	0.0	0.0	0.0	0.0	0.0	8.5	0.0	0.0
PM_{10}	151.5	12.1	0.0	18.2	0.0	71.2	45.5	0.0	22.7	0.0	0.0	0.0	0.0	10.4	0.0	0.0
VOC	171.3	17.1	0.0	34.3	0.0	114.8	-135.3	0.0	60.0	0.0	0.0	0.0	0.0	22.3	0.0	0.0
CO	794.4	79.4	0.0	87.4	0.0	381.3	174.8	0.0	278.0	0.0	0.0	0.0	0.0	104.9	0.0	0.0
NH_3	2.0	0.2	0.0	0.2	0.0	0.9	0.4	0.0	0.7	0.0	0.0	0.0	0.0	-0.4	0.0	0.0
% Reduction (weighted)		**6.9**	**0.0**	**9.4**	**0.0**	**30.6**	**25.5**	**0.0**	**9.8**	**0.0**	**0.0**	**0.0**	**0.0**	**9.5**	**0.0**	**0.0**
2010 Reductions (TPY)	**BaseLine**															
NOx	1502.6	0.0	0.0	0.0	-27.5	-131.5	0.0	330.6	0.0	0.0	0.0	334.7	535.5	0.0	981.3	328.6
SOx	1.6	0.0	1.6	0.0	1.4	1.4	0.0	1.4	0.0	1.4	1.4	1.4	1.4	0.0	1.1	0.4
PM_{10}	113.1	0.0	14.7	0.0	12.4	46.5	0.0	31.1	0.0	31.1	89.2	84.3	89.2	0.0	29.6	6.8
VOC	111.4	0.0	16.7	0.0	20.4	65.3	0.0	-80.7	0.0	71.5	78.9	88.8	78.9	0.0	58.1	6.7
CO	633.8	0.0	95.1	0.0	63.9	266.2	0.0	127.8	0.0	406.7	381.6	490.7	381.6	0.0	331.2	37.2
NH_3	1.9	0.0	0.3	0.0	0.2	0.8	0.0	0.4	0.0	1.2	1.2	1.5	1.2	0.0	-1.4	0.1
% Reduction (weighted)		**0.0**	**8.9**	**0.0**	**7.0**	**25.1**	**0.0**	**23.1**	**0.0**	**20.1**	**52.2**	**57.4**	**64.0**	**0.0**	**40.3**	**11.3**
2015 Reductions (TPY)	**BaseLine**															
NOx	685.9	0.0	0.0	0.0	-10.7	-51.4	0.0	128.0	0.0	0.0	0.0	129.5	207.2	0.0	446.3	499.5
SOx	1.3	0.0	0.0	0.0	1.0	0.9	0.0	0.9	0.0	0.9	0.9	0.9	0.9	0.0	0.9	1.0
PM_{10}	49.5	0.0	0.0	0.0	4.6	17.4	0.0	11.5	0.0	11.5	32.9	31.1	32.9	0.0	11.7	9.8
VOC	68.7	0.0	0.0	0.0	10.7	34.5	0.0	-42.2	0.0	37.4	41.6	46.9	41.6	0.0	36.9	13.9
CO	270.8	0.0	0.0	0.0	23.2	97.5	0.0	46.3	0.0	147.4	137.2	176.4	137.2	0.0	134.2	52.5
NH_3	1.8	0.0	0.0	0.0	0.2	0.6	0.0	0.3	0.0	1.0	0.9	1.2	0.9	0.0	-1.3	0.4
% Reduction (weighted)		**0.0**	**0.0**	**0.0**	**6.0**	**21.4**	**0.0**	**18.9**	**0.0**	**17.2**	**43.6**	**48.2**	**53.8**	**0.0**	**39.3**	**37.8**
2020 Reductions (TPY)	**BaseLine**															
NOx	203.6	0.0	0.0	0.0	-2.6	-12.7	0.0	31.2	0.0	0.0	0.0	31.7	50.7	0.0	138.9	119.1
SOx	1.1	0.0	0.0	0.0	0.7	0.7	0.0	0.7	0.0	0.7	0.6	0.6	0.6	0.0	0.8	0.7
PM_{10}	9.4	0.0	0.0	0.0	0.7	2.8	0.0	1.8	0.0	1.8	5.2	4.9	5.2	0.0	2.5	1.5
VOC	55.6	0.0	0.0	0.0	7.1	23.3	0.0	-28.0	0.0	24.8	27.7	31.2	27.7	0.0	30.5	9.0
CO	81.7	0.0	0.0	0.0	5.7	24.5	0.0	11.5	0.0	36.5	34.3	44.1	34.3	0.0	43.1	12.8
NH_3	1.7	0.0	0.0	0.0	0.1	0.5	0.0	0.2	0.0	0.8	0.7	1.0	0.7	0.0	-1.2	0.3
% Reduction (weighted)		**0.0**	**0.0**	**0.0**	**5.0**	**16.7**	**0.0**	**10.2**	**0.0**	**15.1**	**32.3**	**38.1**	**42.3**	**0.0**	**47.5**	**33.4**
2025 Reductions (TPY)	**BaseLine**															
NOx	113.5	0.0	0.0	0.0	-1.1	-5.7	0.0	13.6	0.0	0.0	0.0	13.8	22.1	0.0	76.5	49.7
SOx	1.0	0.0	0.0	0.0	0.5	0.5	0.0	0.5	0.0	0.5	0.5	0.5	0.5	0.0	0.7	0.5
PM_{10}	4.3	0.0	0.0	0.0	0.3	1.0	0.0	0.6	0.0	0.6	1.9	1.8	1.9	0.0	1.3	0.5
VOC	51.8	0.0	0.0	0.0	5.2	17.4	0.0	-20.5	0.0	18.1	20.3	22.8	20.3	0.0	28.5	6.3
CO	54.5	0.0	0.0	0.0	3.0	13.1	0.0	6.0	0.0	19.1	17.9	23.0	17.9	0.0	28.7	6.4
NH_3	1.6	0.0	0.0	0.0	0.1	0.4	0.0	0.2	0.0	0.6	0.6	0.7	0.6	0.0	-1.2	0.2
% Reduction (weighted)		**0.0**	**0.0**	**0.0**	**4.4**	**14.2**	**0.0**	**4.1**	**0.0**	**13.5**	**25.2**	**30.3**	**33.0**	**0.0**	**50.7**	**25.2**

8.0 LOCOMOTIVE EMISSION REDUCTION OPTIONS

(Photo courtesy of CN)

The purpose of this section is to explore cost-effective emission reduction measures that may be taken to reduce locomotive emissions in the GVRD, FVRD1 and the rest of BC. It should be noted here that locomotive emissions are within the federal government jurisdiction and, since there is presently a *Memorandum of Understanding* between the Railway Association of Canada and Environment Canada to cap railway locomotive NOx emissions within Canada, any further emission reductions would require some sort of amendment to this agreement. Significant emission reductions are already occurring within the Canadian locomotive fleet, as older engines are replaced with newer engines which are more fuel-efficient and which reduce specific emissions (grams emissions per kilowatt-hour). This was apparent in Table 4.1, where the projected emissions of certain pollutants are seen to remain approximately the same or even decrease over the period of 2005 – 2025, despite an increase in total locomotive fleet power.

Despite these improvements in locomotive emissions the railway industry may, in some circumstances, wish to pursue further emission reductions. It is hoped that this analysis will provide guidance to those emission reduction measures that are most cost-effective.

There are seven different companies operating within the Lower Fraser Valley (LFV) as shown in Table 8.1 below. Most rail activity is from the large national lines – CN and CPR. BC Rail was recently acquired by CN, while the Washington Group acquired the Southern Railway.

Table 8.1 – 2000 Canadian LFV Rail Fuel Consumption (Litres)		
Company	**Line**	**Yard**
Canadian National	22,097,226	1,298,461
Canadian Pacific	43,668,215	2,081,617
BC Rail	1,159,302	125,101
BNSF	1,101,839	118,900
Southern Railway of BC	240,626	25,966
VIA Rail	902,933	2,717
West Coast Express	960,331	2,890
Total	**70,130,473**	**3,655,652**

Table 8.1 (Table from Ref. 175) shows the fuel consumption during the year 2000 for these fleets and provides an indication of their relative activity and emission levels. (The fuel consumption data was not used in the following analysis.)

8.1 Methodology

Cost-effectiveness is estimated using a discounted cash-flow approach wherein all future costs were discounted to their equivalent present values to arrive at a total net present value (NPV). This total NPV cost was then divided by the total reduction in emissions (tonnes) over the same time period to arrive at a cost/benefit ratio (dollars per tonne of pollution avoidance). A low value for a cost/benefit ratio would indicate that pollution emissions could be reduced at a low cost to the operator.

Two methods are used to determine total emissions and emission reductions:

1. Weighted: the total reduction in emissions is calculated by first multiplying the reduction in each species by a weighting factor, which is roughly proportional to the environmental impact of the pollutant species, and then summing up these weighted values to arrive at the total emission reduction. In this way relatively hazardous species such as diesel particulate are attributed a much higher weighting then are less hazardous species such as CO. (The weightings used in this analysis are shown at the bottom of Table 8.2.)

2. Non-weighted: Here no weightings are assigned to species that contribute to smog and atmospheric haze (NOx, SOx, VOC, $PM_{2.5}$ and NH_3); they are simply summed to arrive at total emissions or emission reductions.

The projected estimates of locomotive emissions and fuel consumption for the period 2005 – 2020 were first curve-fitted so that values between the data years could be estimated. Next, computer programs were written in VBA (*Visual Basic for Applications*) to estimate total emission reductions (2005 – 2025) and total NPV costs (2005 – 2025), given the assumptions listed in Table 8.2. Finally, the cost-effectiveness for each emission reduction measure (ERM) was calculated as described above.

The following sections discuss some of the assumptions that were used in this study. Further assumptions are provided in Table 8.2 for the different emission reduction measures and will be described in more detail below.

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] In Canada line-haul locomotives spend approximately 60% of their operational time idling, whereas the yard locomotives may spend approximately 81% of their operational time idling. [177] The large fraction of time spent idling is due to the cold weather in Canada; if the engines were shut off they would be extremely difficult to restart. The size of add-on pollution reduction equipment (next section) 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]

Average locomotive fuel consumption during idling is that derived during a study of the BNSF fleet [179]: 4 gph for line haul and 3 gph for switch engines. Idling emission factors were derived from measurements taken by the Southwest Research Institute (Report No. 08-5374-024, Aug.1995). [177] They are applied by multiplying the average emissions factors, as used by GVRD to estimate annual locomotive emission inventories, by the following factors: NOx (0.89), CO (1.73), HC/VOC (2.7) and PM (1.85). As expected, NOx decreases during idling while other emissions increase.

Description of assumptions in Table 8.2

1. Fuel Consumption Factor: allows for differences in gph fuel usage as compared with baseline consumption.
2. Fuel costs: commodity fuel cost in the Pacific Northwest, taxes not included. (These values were used, as they are readily available, whereas local GVRD or BC data is difficult or impossible to obtain).
3. Fuel taxes: colored nonroad fuel taxes (federal excise tax + BC tax).
4. Fuel sulphur: Baseline fuel sulphur for the LFV and the rest of the BC is 400 ppm to 2011, 15 ppm thereafter.
5. Installed cost: based upon literature values for the ERM in $USA
6. Rebuild cost: It is assumed that an ERM has a useful life identical to its amortization period, after that it is replaced or rebuilt at a cost that is some percentage of the original installed cost.
7. Application: what percent of the fleet is the ERM applicable to. (For line engine rebuilds this is taken to be the SD-75 and Dash 9 engines as included in Table 4.1)
8. Years of usage: the period over which the NPV analysis was performed.
9. Penetration rate: the rate of introduction of an ERM per year.

Table 8.2 - Assumptions Used In Estimating Cost-Effectiveness of Emission Reduction Options

Line Haul Locomotives

Emission Reduction Option:		1	2	3	4	5	6	7	8
	BaseLIne	ULSD	Tier 0 Rebuild	Tier 1 Rebuild	Water Inj.	MEC System	DOC	SCR	Idle Control
Fuel Factors									
Fuel consumption factor	1	1	1	0.99	1	1	1	1	0.973
Locomotive Code	1	1	1	1	1	1	1	1	1
Fuel cost (US$/gallon)	1.57	1.63	1.57	1.57	1.58	1.58	1.57	1.67	1.57
Baseline fuel cost (US$/gal)	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57
Fuel Taxes (CAD $/L)	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Fuel Sulphur (PPM)		10							
Installed Cost: $USA		0	30,000	200,000	55,000	90,000	10,000	170,000	70,000
Rebuild Cost (% Original)			100	30	50	50	100	50	50
Maintenance (% installed capital)		0	0	2.5	5	5	5	5	5
Amortization (Years)		10	10	10	15	15	10	10	15
Application (Fraction of Fleet)		100	20	20	100	100	100	100	100
Percent Idling Time		0	0	0	0	0	0	0	60
First Year of Usage		2007	2005	2005	2005	2005	2005	2005	2005
Last Year of Usage		2011	2025	2025	2025	2025	2025	2025	2025
Penetration Rate (%)		100	25	25	50	50	50	25	25
Last Year Reduction (% Initial)		100	0	0	0	10	10	25	90
Initial Emission Reductions (%)									
(Negative indicates increase)									
NOx		0	23	97	25	22	0	80	4.84
CO		0	0	85	0	27	70	75	5.03
PM		25	0	54	30	50	30	40	4.63
VOC		0	0	65	0	27	70	75	9.71
NH_3		0	0	65	0	27	70	-100	15.11

Yard Locomotives

Emission Reduction Option:		1	2	3	4	5	6	7
	BaseLIne	ULSD	Tier 1 Rebuild	Water Injection	DOC	Idle Control	Hybrid	Smart Start
Fuel Factors								
Fuel consumption factor	1	1	0.99	1.01	1	0.82	0.55	0.256
Locomotive Code	0	0	0	0	0	0	0	0
Fuel cost (US$/gallon)	1.57	1.63	1.57	1.58	1.57	1.57	1.57	1.57
Baseline fuel cost (US$/gal)	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57
Fuel Taxes (CAD $/L)	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Fuel Sulphur (PPM)		10						
Installed Cost: $USA		0	190,000	55,000	10,000	70,000	700,000	20,000
Rebuild Cost (% Original)			30	50	100	50	20	50
Maintenance (% installed capital)		0	2.5	5	5	5	0	10
Amortization (Years)		10	10	10	10	15	10	15
Application (Fraction of Fleet)		100	25	100	100	100	100	100
Percent Idling Time						81		81
First Year of Usage		2007	2005	2005	2005	2005	2005	2005
Last Year of Usage		2011	2015	2025	2025	2025	2025	2025
Penetration Rate (%)		100	25	50	50	25	15	25
Last Year Reduction (% Initial)		100	50	0	0	90	50	90
Initial Emission Reductions (%)								
(Negative indicates increase)								
NOx		0	91	25	0	47.7	85	68.9
CO		0	84	0	70	0.0	85	95
PM		25	72	30	30	17.7	85	90
VOC		0	73	0	70	37.6	85	90
NH_3		0	73	0	70	29.8	85	90

Other Assumptions	
Discount Rate %	7
Exchange ($CAD/$USA)	1.25
Impact-related weightings	
NOx	1
CO	0.14
PM2.5	25
VOC	1
NH_3	0
SOx	3

10. Last year reduction: takes into account the reduced effectiveness of an ERM over its period of usage due to a general reduction in fleet emissions as old engines are replaced with new engines. Expressed as a percentage of the initial emission reduction.
11. Initial emission reductions: typical literature values for the percent reduction in emissions to be expected for a particular ERM. For idle control technologies the initial reductions in locomotive emissions were estimated via a utility program that allowed for different fuel consumption rates and different specific emission factors (g/L).

8.2 Emission Reduction Options

Emission reduction options that are explored in this chapter include using ultra-low sulphur diesel (ULSD), rebuilding engines to EPA's Tier 0 or to Tier 1 emission standards, using continuous water injection (CWI), using MEC System's water-emulsification system, using diesel oxidation catalysts (DOC), using compact selective catalytic reduction (SCR) of NOx and using idle-control technologies. Diesel particulate filters were not included because of the concern that they may plug up during the prolonged periods of idling experience by locomotives in Canada. This concern will be further discussed near the end of this section.

The following section estimates the total emission reductions over the period 2005 - 2025 and NPV costs associated with each of the options mentioned above during the same period. Cost-effectiveness is estimated by dividing the total NPV cost by the total emission reduction. The results are summarized in Table 8.3 (GVRD), Table 8.4 (FVRD1) and Table 8.5 (Rest of BC), which show the estimated cost-effectiveness ($/tonne of pollution reduction). Where the cost-effectiveness is negative due to an actual cost saving, the entry is shown in red. Percent emission reductions are for the total period 2005 – 2025. For the base case it is assumed that the locomotive fleet generally used rebranded road diesel with sulphur content and fuel cost as described above.

1. Using Ultra-Low Sulphur Diesel – Total Fleet

The early use of ULSD (average of 10 ppm sulphur) would reduce SOx emissions by 98%, but at a cost increase of about US$0.06/gallon diesel. It is also assumed that PM emissions are reduced by 25%. Overall unweighted emissions are reduced by 0.5% for line haul locomotives and by 0.6% for switch locomotives.

It is assumed that this ERM takes effect in 2007, when ULSD becomes readily available, and continues until 2011, after which federal law mandates time the use of ULSD and hence this ERM would not provide any net reduction in emissions.

Tables 8.3 – 8.5 show both the weighted-total cost-effectiveness and the un-weighted cost-effectiveness, expressed as $/tonne avoided emissions, for the three regions and two different types of locomotives. On a weighted-total basis line haul emissions are reduced by about 3%, over the time span 2005 – 2025, at a cost of approximately $2,800/tonne, while yard engine emissions are reduced by 4% at a cost of about $1,700/tonne.

2. Rebuild to Tier 0 – Line Haul Locomotives

Locomotive engines are regularly rebuilt. Assume that the older 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 fleet emissions, in which case the existing GVRD emission factors [175] are used. Further assume that the capital is amortized over 10 years and that there is no significant change in maintenance costs or in fuel costs. After 10 years the rebuild costs are assumed to be 100% of the initial rebuild cost of $30,000 per locomotive. Other assumptions used in the modeling are listed in Table 8.2.

Using the above qualifications, only freight locomotives (line haul) benefit from a Tier 0 rebuild. They would experience a 23% reduction in NOx; all other emissions would remain the same as the baseline emissions. It is assumed that this option is applicable to 20% of the fleet.

The change in costs and emissions are shown in Tables 8.3 – 8.5. Weighted total emissions are reduced by about 1.6 % at a cost of about $550/tonne of emissions.

Table 8.3 - GVRD Estimated Cost-Effectiveness of Emission Reduction Options

Line Haul Locomotives

Emission Reduction Option:	BaseLIne Emissions	1 ULSD	2 Tier 0 Rebuild	3 Tier 1 Rebuild	4 Water Inj.	5 MEC System	6 DOC	7 SCR	8 Idle Control
Total Reductions (2005 - 2025), tonnes									
NOx	30,246	0	698	2,944	4,383	4,107	0	14,396	1,226
CO	5,132	0	0	438	0	855	2,218	2,290	216
$PM_{2.5}$	461	38	0	25	80	142	85	110	18
VOC	719	0	0	47	0	120	310	321	58
NH_3	2	0	0	0	0	0	1	-1	0
SOx	203	128	0	2	0	0	0	0	5
NPV Cost (Thousands $CAD)		$3,718	$384	$2,314	$4,796	$6,651	$629	$31,840	($2,473)
Weighted Cost-Effectiveness ($/tonne)		**$2,770**	**$551**	**$628**	**$751**	**$842**	**$228**	**$1,791**	**($1,391)**
Un-weighted Cost-Effectiveness ($/tonne)		$22,396	$551	$767	$1,075	$1,522	$1,587	$2,148	($1,891)
Weighted Percent Reduction		**3.1**	**1.6**	**8.4**	**14.6**	**18.0**	**6.3**	**40.6**	**4.1**
Un-weighted Percent Reduction		0.5	2.2	9.5	14.1	13.8	1.3	46.9	4.1

Yard Locomotives

Emission Reduction Option:	BaseLIne Emissions	1 ULSD	2 Tier 1 Rebuild	3 Water Injection	4 DOC	5 Idle Control	6 Hybrid	7 Smart Start
Total Reductions (2005 - 2025), tonnes								
NOx	1,594.38	0.00	154.29	231.24	0.00	637.00	806.22	919.35
CO	293.55	0.00	26.22	0.00	119.22	0.00	148.43	233.38
$PM_{2.5}$	42.73	3.56	3.27	7.43	7.43	6.33	21.61	32.19
VOC	99.98	0.00	7.75	0.00	40.57	31.49	50.57	75.32
NH_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOx	10.35	6.45	0.10	-0.10	0.00	1.86	4.66	7.70
NPV Cost (Thousands $CAD)		$187.77	$1,469	$2,127	$385	$889	$22,750	($9,324)
Weighted Cost-Effectiveness ($/tonne)		**$1,734**	**$5,931**	**$5,105**	**$1,584**	**$1,068**	**$15,889**	**($5,026)**
Un-weighted Cost-Effectiveness ($/tonne)		$18,768	$8,882	$8,918	$8,018	$1,314	$25,763	($9,013)
Weighted Percent Reduction		**3.8**	**8.7**	**14.7**	**8.6**	**29.4**	**50.5**	**65.4**
Un-weighted Percent Reduction		0.6	9.5	13.7	2.7	38.7	50.5	59.2

Table 8.4 - FVRD Estimated Cost-Effectiveness of Emission Reduction Options

Line Haul Locomotives

Emission Reduction Option:		1	2	3	4	5	6	7	8
	BaseLIne	ULSD	Tier 0 Rebuild	Tier 1 Rebuild	Water Inj.	MEC System	DOC	SCR	Idle Control
Total Reductions (2005 - 2025), tonnes									
NOx	14,078	0	325	1,370	2,040	1,912	0	6,701	570
CO	2,388	0	0	204	0	398	1,032	1,065	101
$PM_{2.5}$	214	18	0	12	37	66	39	51	8
VOC	333	0	0	22	0	56	144	149	27
NH_3	1	0	0	0	0	0	0	-1	0
SOx	94	59	0	0	0	0	0	0	0
NPV Cost (Thousands $CAD)		1,730.8	178.9	1,077.0	2,232.6	3,096.1	292.8	14,820.5	-1,150.8
Weighted Cost-Effectiveness ($/tonne)		**$2,793**	**$551**	**$630**	**$753**	**$845**	**$230**	**$1,792**	**($1,405)**
Un-weighted Cost-Effectiveness ($/tonne)		$22,456	$551	$767	$1,075	$1,523	$1,592	$2,148	($1,899)
Weighted Percent Reduction		**3.0**	**1.6**	**8.4**	**14.6**	**18.0**	**6.3**	**40.6**	**4.0**
Un-weighted Percent Reduction		0.5	2.2	9.5	14.1	13.8	1.2	46.9	4.1

Yard Locomotives

Emission Reduction Option:		1	2	3	4	5	6	7
	BaseLIne	ULSD	Tier 1 Rebuild	Water Injection	DOC	Idle Control	Hybrid	Smart Start
Total Reductions (2005 - 2025), tonnes								
NOx	739	0.00	71.46	107.13	0.00	295.45	373.93	426.40
CO	136	0.00	12.15	0.00	55.26	0.00	68.89	108.32
$PM_{2.5}$	20	1.65	1.52	3.44	3.44	2.91	9.93	14.79
VOC	46	0.00	3.60	0.00	18.81	14.61	23.45	34.94
NH_3	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOx	5	2.98	0.05	-0.05	0.00	0.86	2.16	3.56
NPV Cost (Thousands $CAD)		86.94	679	984	178	409	10,526	($4,326)
Weighted Cost-Effectiveness ($/tonne)		**$1,729**	**$5,918**	**$5,101**	**$1,582**	**$1,061**	**$15,906**	**($5,048)**
Un-weighted Cost-Effectiveness ($/tonne)		18,745	8,867	8,908	8,004	1,303	25,706	($9,018)
Weighted Percent Reduction		**3.8**	**8.8**	**14.7**	**8.6**	**29.4**	**50.5**	**65.4**
Un-weighted Percent Reduction		0.6	9.5	13.6	2.7	38.7	50.5	59.2

Table 8.5 - Rest of BC Estimated Cost-Effectiveness of Emission Reduction Options

Line Haul Locomotives

Emission Reduction Option:		1	2	3	4	5	6	7	8
	BaseLIne	**ULSD**	**Tier 0 Rebuild**	**Tier 1 Rebuild**	**Water Inj.**	**MEC System**	**DOC**	**SCR**	**Idle Control**
Total Reductions (2005 - 2025), tonnes									
NOx	245,825	0	5,734	24,183	36,150	33,791	0	117,511	9,907
CO	37,744	0	0	3,227	0	6,307	16,351	16,857	1,588
$PM_{2.5}$	4,310	347	0	230	734	1,308	785	1,019	168
VOC	10,412	0	0	675	0	1,724	4,470	4,635	849
NH_3	31	0	0	2	0	5	13	-19	4
SOx	2354	1,503	0	24	0	0	0	0	64
NPV Cost (Thousands $CAD)		30,883	3,200	19,566	39,817	55,471	5,273	261,438	($18,198)
Weighted Cost-Effectiveness ($/tonne)		**$2,342**	**$558**	**$628**	**$731**	**$803**	**$200**	**$1,743**	**($1,184)**
Un-weighted Cost-Effectiveness ($/tonne)		$16,690	$558	$779	$1,079	$1,506	$1,001	$2,123	($1,656)
Weighted Percent Reduction		**3.5**	**1.5**	**8.3**	**14.5**	**18.4**	**7.0**	**39.9**	**4.1**
Un-weighted Percent Reduction		0.7	2.2	9.6	14.0	14.0	2.0	46.8	4.2

Yard Locomotives

Emission Reduction Option:		1	2	3	4	5	6
	BaseLIne	**ULSD**	**Tier 1 Rebuild**	**Water Injection**	**DOC**	**Idle Control**	**Hybrid**
Total Reductions (2005 - 2025), tonnes							
NOx	12,395	0.00	1,194.09	1,791.50	0.00	4,958.39	6,275.58
CO	3,512	0.00	311.94	0.00	1,419.98	0.00	1,778.65
$PM_{2.5}$	405	33.47	30.79	70.13	70.13	60.18	205.45
VOC	1,183	0.00	90.81	0.00	476.30	373.80	600.22
NH_3	4	0.00	0.27	0.00	1.43	0.89	1.80
SOx	111	70.66	1.09	-1.11	0.00	20.03	50.07
NPV Cost (Thousands $CAD)		1,451.6	11,293	16,407	2,969	6,690	175,331
Weighted Cost-Effectiveness ($/tonne)		**$1,384**	**$5,373**	**$4,633**	**$1,223**	**$970**	**$14,127**
Un-weighted Cost-Effectiveness ($/tonne)		$13,940	$8,574	$8,819	$5,420	$1,236	$24,580
Weighted Percent Reduction		**4.3**	**8.6**	**14.4**	**9.9**	**28.1**	**50.6**
Un-weighted Percent Reduction		0.7	9.3	13.2	3.9	38.4	50.6

3. Rebuild to Tier 1

Here it is assumed that engines can meet Tier 1 if converted using new pistons, injectors, and electronic engine control at a cost of $190,000/engine. [122, 127] We 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. Rebuild costs after the amortization period is assumed to be 30% of the initial Tier 1 rebuild cost. This option is further assumed to apply to 20% of the road fleet and to 100% of the yard fleet. Other assumptions used in the modeling are listed in Table 8.2.

The change in costs and emissions are shown in Tables 8.3 – 8.5. Weighted total emissions are reduced by about 8 % at a cost of $630/tonne of emissions for line haul locomotives, and by about 8.7 % at a cost of around $5,900/tonne of emissions for yard locomotives. Clearly this is an expensive method of control for yard engines, which spend much of their time idling or operating at a low duty cycle.

4. Use Continuous Water Injection (CWI) - Total Fleet

Continuous water injection (CWI) is a relatively low cost method to reduce NOx and PM emissions by approximately 25% - 30%, and fuel consumption by about 1%. Up to 50% by weight water is used to effect this NOx reduction. A special water tank would be required to carry the necessary extra water and hence more detailed engineering studies are required to identify which locomotives could benefit from this technology.

Assume an installed cost of $15,000 for the CWI system and $40,000 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. No credit is taken for reduced fuel consumption as this technology has yet to be demonstrated on a locomotive engine.

The change in costs and emissions are shown in Tables 8.3 – 8.5. Weighted total emissions are reduced by about 14.6 % at a cost of $750/tonne of emissions for line haul locomotives, and by about 14.7 % at a cost of around $5,100 per tonne of emissions for yard locomotives.

5. Use MEC Micro-emulsification Technology – Line Haul Locomotives

The MEC system combines the diesel fuel and water together as a micro-emulsification immediately before injection. Therefore expensive emulsifying agents, such as those produced by Lubrizol, are not required.[164] (This technology was described in detail in

Section 6 of this report.) Fuel consumption has been demonstrated, on a large marine vessel engine, to be reduced by 2%.

Assume an installed cost of $70,000 for the MEC system and $20,000 for the water tankage, both being amortized at 7% over a 15-year period. Assume that water costs $2/tonne (extra labour costs) and that the extra maintenance is 5% of installed capital.

Further assume that NOx is reduced by 22%, PM by 50%, VOC and CO by 27%, CO_2 by 6% (better combustion, as per the results of testing on the cruise ship *Veendam*[164)]. No credit is taken here for reduced fuel consumption as this technology has yet to be demonstrated on a locomotive engine.

The resulting change in costs and emissions are shown in Tables 8.3 – 8.5. Weighted total emissions are reduced by about 18 % at a cost of about $840/tonne of emissions for line haul locomotives.

There appears to be a slight advantage in emission reduction potential of the MEC NOx reduction system over that of the CWI system, but at a slightly higher cost. However, if testing on locomotives actually demonstrates that the CWI system provides a 1% reduction in fuel consumption and that the MEC provides a 2% reduction in fuel consumption as claimed, then the weighted-total cost-effectiveness of the MEC system would be such that it will actually save money for the railroad industry.

6. Use Diesel Oxidation Catalysts – Total Fleet

Diesel oxidation catalysts (DOC) are a relatively low cost method to reduce the emissions of the soluble organic fraction (SOF) of diesel particulate and to reduce CO and VOC emissions. They can easily be retrofitted as a replacement "muffler". However, they may be prone to plugging and testing is required to ascertain their suitability to specific applications.

Assume that the installed cost of a DOC is $10,000, maintenance is 5% of this and that amortization is 7% over 10 years. Further assume that CO and VOC are reduced by 70% and particulate matter by 30%.

The change in costs and emissions are shown in Tables 8.3 – 8.5. Total weighted emissions are reduced by about 6% at a cost of about $230/tonne of emissions for line haul locomotives, and by about 8.6 % at a cost of around $1,600/tonne of emissions for yard locomotives.

7. Using Selective Catalytic Reduction (SCR) – Line Haul

Compact SCR units are becoming available for marine applications as well as for freight trucks. The volume of urea solution required is much less than the amount of water required in the water-addition systems, therefore the extra tankage will be less of a problem. On the other hand, SCR may be too bulky to be retrofitable to all line haul locomotives. In this study we arbitrarily assume that SCR can be adapted to all line haul locomotives and estimate the resulting cost-effectiveness that, of course, would be applicable to a single engine with similar operating parameters.

The installed cost for a SCR system is estimated to be $170,000, using the derived relationship: Cost = $24,000 + $40*(horse-power). The cost of urea is estimated to increase the effective fuel cost by 6.4% ($0.10/L). Maintenance is taken as 5% of installed equipment costs and amortization is assumed to be 7% over 10 years.

Emission reductions are assumed to be 80% for NOx, 40% for PM and 75% for VOC and CO. NH_3 emissions are assumed to increase 100% due to ammonia "slip".

The resulting change in costs and emissions are shown in Tables 8.3 – 8.5. Total weighted emissions are reduced by about 41 % at a cost of around $1,800/tonne of emissions for the line haul locomotives.

8. Use Idle Control (Hotshot-Smart Start) – Total Fleet

An effective way to reduce idling emissions and fuel consumption is to use a system similar to the *Hotshot-Smart Start* package that was discussed in Section 6. The *Hotshot* system uses a small, 40 hp, EPA Tier 2 diesel to warm and circulate the locomotive's fluids, 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. The *Hotshot* system is somewhat bulky and may not be amenable to retrofitting on all locomotives, especially some of the smaller yard engines.

The bare-bones price of this package is approximately $35,000. It is assumed that the total installed cost is twice this, or $70,000. Further assume that the 40 hp diesel operates at 70% full load and has a SFOC of 250 g/kWh, whereas a line haul locomotive engine burns 4 gph while idling and a yard locomotive engine burns 3 gph while idling.

The change in costs and total emissions are shown in Tables 8.3 – 8.5. Total emissions are reduced by about 4% at a cost of around (-$1,400)/tonne of emissions for line haul locomotives, and by about 29 % at a cost of about $1,100 per tonne of emissions for yard locomotives. In other words, the use of the *Hotshot-Smart Start* package on line haul locomotives **saves** money for every tonne of smog that is reduced, due to decreased fuel consumption. However, for yard engines the fuel savings are not enough to offset the high initial cost of the retrofit package. (The difference in fuel consumption for the average yard locomotives is assumed to be only 0.7 gph as compared with about 1.7 gph for line haul locomotives.)

The use of the *Smart Start* package, without the *Hotshot* auxiliary engine, for yard engines is discussed in a further section

9. Re-Power with Hybrid Power System – Yard Locomotives

A hybrid diesel-battery system takes advantage of the fact that yard locomotives spend most of their operational time (81%) in the idle mode of operation. As discussed in Section 6, *RailPower Technologies Ltd.* 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.

Emissions of NOx, PM and VOC are estimated to be reduced by 85%, while fuel and lube-oil costs are reduced by 45%. [119] However, the reduced operating costs are not enough to offset the high capital cost of this option as a retrofit. The weighted total emissions are reduced by 50% at a cost of $16,000 per tonne.

If the cost of a hybrid rebuild ($700,000) is compared to the cost of a new yard engine (approx. $1.2 million)), or to the cost of remanufacturing an existing engine (approx. $500,000), then this option looks much more favorable.

10 SmartStart Idle Reduction – Yard Locomotives

Electronic idle-reduction (e.g. *SmartStart*) is being installed in locomotives in California and may have application in the warmer regions of British Columbia. This study looks at the cost-effectiveness of this technology assuming that it can be utilized in the Lower Mainland year around. The installed cost is taken as $20,000. Other assumptions are listed in Table 8.2.

Total weighted emissions are reduced by about 65% at a cost of -$5,000/tonne. Thus there is a cost savings of about $5,000/tonne of emission reduction. In practice there will probably be cold spells during the winter when the yard engines must be kept running, hence the cost savings will be less than this figure. Further studies, looking at specific applications, are required to identify the potential of this technology in B.C.

11 Other Potential Emission Reduction Options

Other potential emission reduction options for locomotives are diesel particulate filters (DPF) or exhaust gas recirculation (EGR) used in combination with DPF. Due to the large amount of time that Canadian locomotives spend idling it was felt that particulate filters would plug up due to an inadequate operating temperature for particulate filter regeneration. Perhaps clever engineering would allow the filter to be bypassed during idling operation, but this would then allow the idling emissions to be uncontrolled. These devices (EGR and DPF) could also be used in conjunction with the *Hotshot-Smart Start* package, although the over-all system would become more complex and expensive. Further studies are required to explore the full potential of idling control technologies used in conjunction with other technologies, such as those mentioned above.

8.3 Comparison of Emission Reduction Options

The cost-effectiveness of the different locomotive emission-reduction options that were investigated is summarized in Table 8.6 below. The most cost-effective solutions are highlighted in blue. Also shown is the effect of different discount rates, from 0% to 15%.

An obvious strategy for line haul locomotives is to save fuel and reduce emissions by installing the Hotshot/SmartStart idle-control system (Option #8). For yard engines the SmartStart idle-control system (Option #6) can rapidly pay for itself in fuel savings in those regions where its use is applicable. The major rail companies are already studying these options and starting to install them on some engines.

The diesel oxidation catalyst retrofit looks to be cost-effective for both the road locomotives and the yard engines. Its use is still exploratory and some applications with excessive engine idling may experience plugging problems. Another option for yard engines is the use of ULSD when it becomes available. However, this is a short-term emission reduction measure applicable to the period of 2007 – 2011. (It is assumed that Canada mandates the use of ULSD in 2012, hence this fuel then becomes the baseline fuel in 2012.)

Table 8.6 - Comparison of Emission Reduction Options For Locomotives

Emission Reduction Option	Weighted Percent Reduction	Cost/Benefit (CDN$/tonne) Discount Rate		
		0%	7%	15%
Line Haul Control Option				
1. Ultra-low sulphur diesel	3.1	$3,621	**$2,770**	$2,104
2. Tier 0 Rebuild	1.6	$814	**$551**	$417
3. Tier 1 Rebuild	8.4	$904	**$628**	$492
4. Water Injection (CWI)	14.6	$1,235	**$751**	$541
5. MEC Micro-Emulsion	18.0	$1,346	**$842**	$626
6. Diesel Oxidation Catalyst	6.3	$343	**$228**	$173
7. Selective catalytic reduction (SCR)	40.6	$3,232	**$1,791**	$1,136
8. Idle (Hotshot/Smartstart)	4.1	-$3,373	**-$1,391**	-$358
Yard Engine Control Option				
1. Ultra-low sulphur diesel	3.8	$2,262	**$1,734**	$1,319
2. Tier 1 Rebuild	8.7	$6,636	**$5,931**	$5,361
3. Water Injection (CWI)	14.7	$7,414	**$5,105**	$4,018
4. Diesel Oxidation Catalyst	8.6	$2,345	**$1,584**	$1,219
5. Idle (Hotshot/Smartstart)	29.4	$1,119	**$1,068**	$1,203
6. Idle (Smartstart only)	65.4	-$9,544	**-$5,026**	-$2,889
7. Hybrid Diesel/Battery	50.5	$23,320	**$15,889**	$11,991

The Tier 0 rebuild is applicable in the USA for engines manufactured during 1973 – 2001, while the Tier 1 rebuild is necessary for engines made during 2002 through 2004, but may also be carried out for certain older engines. Canadian Rail companies are not obligated to comply with the USA regulations but may do so on a voluntary basis.

8.4 Effect of Discount Rate on Cost-Effectiveness

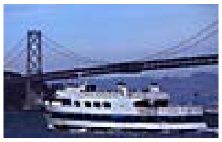
The cost-effectiveness of capital-intensive retrofits is somewhat sensitive to the discount rate used in the discounted cash flow analysis. This can be seen in Table 8.6 where the cost-benefit ratio for different emission reduction options is presented for different discount rates (0%, 7% and 15%).

For line haul locomotives the ranking of the different options does not change with these large variations in discount rate – i.e. – Options 2-6 and Option 8 are still the most cost-effective.

For yard engines the ranking of the different options also does not change with these large variations in discount rate, with idling reduction Options 5 and 6 remaining the most cost-effective ERM's.

Generally in investment analysis it is best practice to use a discount rate that reflects the current cost of borrowing plus the expected near-term inflation rate plus some factor that accounts for relative investment risk, although when retrofitting pollution-control devices the latter factor usually is not included. Given the current interest and expected near-term inflation rates a discount rate of 7% is appropriate.

9.0 MARINE ALTERNATIVES TO ROAD TRANSPORTATION



Expanded passenger ferry services are the subject of continued interest in Greater Vancouver, given the potential of such services to decongest traffic bottlenecks, reduce travel times, improve reliability and attract new transit-system ridership. However, a 2003 study of an expanded passenger ferry system in the San Francisco Bay Area showed that emissions of NOx would increase significantly unless advanced technologies were used to reduce these emissions. It was concluded that by using advanced technologies it should be feasible to design and implement an enhanced ferry service to conform to both regional transportation goals and to air quality goals.[170]

TransLink has recently concluded the *Vancouver Harbour Passenger Marine Study,* a study to explore the feasibility of this increased passenger service in Vancouver Harbour. Although TransLink has no plans to implement passenger ferry service at this time, this present study has reviewed potential emissions from four passenger-ferry routes, traveled by a representative ferry fleet that was considered in the TransLink study, and has compared the forecasted ferry emissions with the avoided road-commute emissions.

9.1 Methodology

Four conceptual routes, all of which were identified as potential service options in TransLink's *Vancouver Harbour Passenger Marine* study, were studied:

1. Snug Cove – Ambleside – Vancouver Waterfront.
2. Lonsdale – Ambleside – Jericho (with direct bus service from Jericho to UBC).
3. Deep Cove – Maplewood - Vancouver Waterfront.
4. Ioco – Maplewood – Lonsdale

Table 9.1 shows the worksheet used to compare emissions between a ferry and the displaced single-occupancy vehicles (SOV's), as well as to estimate the cost-effectiveness of different emission-reduction options for the ferry engines. Inputs are highlighted in yellow or brown, calculated values are highlighted in green.

For the waterside (left side of worksheet), waterside distances, vessel characteristics, average load (% capacity), engine emissions factors and emission reductions through the use of alternative fuels or add-on control devices, must be input. The emission factors are assumed to be 90% of EPA Tier 2 marine engines operating on ultra-low sulphur diesel (ULSD).

Table 9.1 Comparison of Ferry Emissions With Vehicle Emissions - Template

Route: Sea Route Name

Water Side Inputs		Emission Weightings		Land Side Inputs	
Distance (km)	23.3			Distance (km)	18
Ave. Speed (km/hr)	46.3	SOx	3	Mode switch (%)	60
Power (kW)	800	NOx	1		
Ave. MCR	0.9	VOC	1	Displaced SOV's/trip	11.25
Fuel Consumption (LPH)	150	$PM_{2.5}$	25		
Passenger Capacity	75	NH_3	0		
Ave Load (% capacity)	25	CO	0.14		
Base Fuel Costs ($/L)	0.631				

	Base Emission Factors (g/kWh)	Baseline Emissions (g/trip)	Emission Reduction (%)	Reduction (g/trip)		Emission Factors (g/vkt)	Emissions (g/trip)
SOx	0.00412	1.49	0	0.00	SOx	0.035	7.0875
NOx	5.83	2,112.40	20	422.48	NOx	1.248	252.72
VOC	0.648	234.79	-10	-23.48	VOC	1.401	283.7025
$PM_{2.5}$	0.174	63.05	30	18.91	$PM_{2.5}$	0.011	2.2275
NH_3	0.0025	0.91	-10	-0.09	NH_3	0.056	11.34
CO	4.5	1,630.50	-10	-163.05	CO	14.931	3023.5275
Weighted Total		**4,156.09**		**849.02**	**Weighted Total**		**1,036.67**
Unweighted Total		2,412.64		417.82	**Unweighted Total**		557.0775
Weighted tonnes/year		**24.78**		**5.06**	**Weighted tonnes/year**		**6.18**
Unweighted tonnes/year		14.38		2.49	**Unweighted tonnes/year**		3.32
Percent of Landside Weighted Emissions			**319**				
Percent of Landside Unweighted Emissions			358				

Economic Analysis of Emission Reduction Options

(Costs are the **added** costs of the emission reduction measure - assumed to be factored into any lease price for ferry service)

Inputs		Calculated Values	
Annual hours of Operation	3000	Trips/year	5,961
Discount Rate (%/100)	0.07	Baseline "Avoided" Unweighted Emissions (tpy)	-11.06
Amortization Period (Yrs)	10	"Controls" Unweighted Emissions (tpy)	0.00
Capital Cost(CDN$)	$0	Annualized Capital Cost (CDN$)	$0
Maintenance (% Capital)	0	Maintenance Costs ($)	$0
Fuel Costs ($/L)	0.7	Other Costs ($/year)	$0
Other costs ($/year)	0	Extra Fuel Costs ($/year)	$31,050
Fuel Consumption Factor	1	Total Annual Costs ($)	$31,050
CRF=	0.1424	**Cost/Benefit ($/weighted tonne)**	**$6,134.77**
		Cost/Benefit ($/un-weighted tonne)	$12,465.85

The landside inputs (right side of worksheet) include the average additional distance that a SOV would be driven if the drivers were not using the passenger ferry, the percent of ferry passengers who switched from driving a SOV (mode switch, %) and the LDV emission factors (GVRD's emission factors for LDGVs operating in the LFV during 2000).

Between the waterside inputs and the landside inputs is a tabulation of emission weightings. These are used to weight the individual pollutant emissions and emission reductions prior to summing them to arrive at an impact-weighted total. The un-weighted totals, on the other hand, are simply calculated by summing up the values (SOx + NOx + VOC + $PM_{2.5}$ + NH_3).

The economic analysis is based upon a discounted cash flow method using a "capital recovery factor", which converts capital costs into equal annual payments over the life of the investment. To these payments are added other additional annual expenses (maintenance, extra fuel costs, etc.) in order to arrive at a total annual cost. This total annual cost is then divided by the expected annual reduction in total vessel emissions (weighted or un-weighted) to arrive at cost-effectiveness expressed as a cost/benefit ratio.

Note that the economic analyses are based upon the incremental costs that can be attributed to reducing emission from the ferries. If the ferries are leased or operated by a private contractor then it is to be expected that these incremental costs will be reflected in an increased lease rate or service contract price.

Table 9.2 summarizes the assumptions that were made for the different ferry routes. Distances were approximated using 1:50,000 topographic maps. The SOV modal shifts are similar to those surveyed in a San Francisco Bay area study.[170] It was assumed that each route used the same 75 passenger ferries which operated for about 3000 hours per year at an average speed of 25 knots and which burn 150 litres/hour of ULSD in Tier 2 engine (2 x 400kW engines per vessel).

Table 9.2 - Assumptions In Marine Passenger Transportation Study

Parameter	Ferry Route			
	SAW	LAJ	DMW	IML
Water Distance (km)	23.3	13	17	16
Ave. Land Distance (km)	18	23	14	26
SOV Mode Shift (%)	60	60	70	60
Annual Hours Operation	3000	3000	3000	3000
Passenger Capacity	75	75	75	75
Installed Power (kW)	800	800	800	800
Percent MCR	90%	90%	90%	90%
Engine Type (EPA)	Tier 2	Tier 2	Tier 2	Tier 2
Ave. Speed (knots)	25	25	25	25
Fuel (L/hr)	150	150	150	150
Fuel Type	ULSD	ULSD	ULSD	ULSD

Routes
SAW: Snug Cove - Ambleside - Waterfront
LAJ: (Lonsdale - Ambleside - Jericho)
DMW: Deep Cove - Maplewood - Waterfront
IML: Ioco - Maplewood - Lonsdale

The assumed ULSD (ultra-low sulphur fuel; S < 15 ppm) will be readily available in the Lower Mainland region by 2007, as it is a federally mandated fuel for highway vehicles that burn diesel fuel.

Emission reduction measures that were explored, and the assumptions that were made are listed below:

1. ***PuriNOx*** water/diesel emulsion at a US$0.20/gal premium (CDN$0.069/litre). NOx reduced 20% and $PM_{2.5}$ by 30%.

2. **Continuous Water Injection** (CWI). Installed cost CDN$39,000 for 2 engines. NOx reduced 25%, $PM_{2.5}$ by 30% and fuel consumption reduced 1%. 15-year life; discounted at 7%.

3. **Diesel Oxidation Catalyst**. Installed cost is CDN$13,000 for 2 engines. NOx reduced 0%, $PM_{2.5}$ by 35%, VOC, CO and NH3 by 90%. 10-year life; discounted at 7%.

4. **Exhaust Gas Recirculation + Diesel Particulate Filter**. Installed cost is CDN$80,760 for 2 engines. NOx reduced 45%, $PM_{2.5}$ by 35% and VOC by 80%. Fuel consumption increased 2%. 10-year life; discounted at 7%.

5. **Selective Catalytic Reduction** (SCR). Installed cost is CDN$166,000 for 2 engines. NOx reduced 90%, $PM_{2.5}$ by 35% and VOC by 80%. 10-year life; discounted at 7%. Urea cost equivalent to US$0.015/gal.

6. **Cleaire "*Longview*"**. Installed cost is CDN$169,000 for 2 engines. NOx reduced 25%, $PM_{2.5}$ by 85% and VOC by 90%. 10-year life; discounted at 7%. Fuel consumption increased 3%.

7. **Natural gas** (LNG, gas at US$9/MMBtu) to reduce all emissions. It is assumed that new, ultra-low emission natural gas engines are used with a cost 40% greater than Tier 2 engines and that the additional cost of the LNG cryogenic storage tanks and gas safety equipment is 30% of the cost of the gas engines .The total extra capital cost is estimated to be CDN$390,000 per vessel and that by using natural gas maintenance costs (lube oil, rebuilds, etc.) are reduced by CDN$24,400 per year per vessel. It is assumed that LNG costs 1.55 times the natural gas commodity price (e.g. a commodity price of US$9/MMBtu gives an LNG price of US$13.95/MMBtu, which is equivalent to US$1.81/gallon diesel equivalent, or CDN$0.598/litre diesel equivalent). It is also assumed that there are no taxes on the use of natural gas fuel. The comparison cost for ULSD, with taxes, is taken as CDN$0.631/litre. The emission factors for the gas engines are those used in the San Francisco Bay area study.[170] Resulting emission reductions are NOx 80%, PM 90% and VOC 53%.

9.2 Cost-Effectiveness and Emission Comparisons

The top section of Table 9.3 compares the amount of year 2005 emission reductions (tonnes per year of weighted emissions) and weighted cost-effectiveness for the 7 different options that were studied. This table is followed by Table 9.4, which compares the amount of year 2005 un-weighted emissions reductions and un-weighted cost-effectiveness, for the 7 different options that were studied. (In these tables the "Displaced Land Emissions" are emission reductions due to decreased vehicle usage.)

Table 9.3 - Weighted-Emissions Marine Passenger Transportation Analysis

Run	Emission Reduction Option						
	1	2	3	4	5	6	7
All runs	**Year 2005 emissions**						
Ferry, no controls (tpy)	24.8	24.8	24.8	24.8	24.8	24.8	24.8
Ferry Emission reduction (tpy)	5.1	6	5.8	16.6	16.8	13.6	20.9
Cost-Effectiveness ($/tonne)	$6,135	$793	$433	$1,278	$2,048	$2,764	$809
Snug Cove - Ambleside - Waterfront	**Ferry Emissions - Percent Of Displaced Vehicle Emissions**						
25% occupancy	319	304	307	132	129	181	76
50% occupancy	160	152	154	66	64	90	38
75% occupancy	106	101	102	44	43	60	25
Lonsdale-Ambleside-Jericho	**Ferry Emissions - Percent Of Displaced Vehicle Emissions**						
25% occupancy	139	133	134	58	56	79	33
50% occupancy	70	66	67	29	28	39	17
75% occupancy	46	44	45	19	19	26	11
Deep Cove-Maplewood-Waterfront	**Ferry Emissions - Percent Of Displaced Vehicle Emissions**						
25% occupancy	257	245	247	106	103	145	61
50% occupancy	128	122	124	53	52	73	30
75% occupancy	86	82	82	35	34	48	20
Ioco-Maplewood-Lonsdale	**Ferry Emissions - Percent Of Displaced Vehicle Emissions**						
25% occupancy	158	150	152	65	64	89	37
50% occupancy	79	75	76	33	32	45	19
75% occupancy	53	50	51	22	21	30	12

Ferry Emission Reduction Options
1. PuriNOx water/diesel emulsion
2. Continuous Water Injection (CWI)
3. Diesel Oxidation Catalyst
4. Exhaust Gas Recirculation + Diesel Particulate Filter
5. Selective Catalytic Reduction (SCR)
6. Cleaire "Longview"
7. Natural gas (LNG, gas at US$9/MMBtu commodity price)

It can be seen from Table 9.3 that the weighted-emissions cost/benefit ratio ranges from $433/tonne (Option 3 – *Diesel Oxidation Catalyst*) to $6,135/tonne (Option 1 – *PuriNOx water-diesel emulsion*). Significant emission reductions are achieved using Options 4 – 7, at a cost of from $809/tonne to $2,764/tonne. The use of LNG, at $809/tonne and providing an 84% emission reduction, seems to give a lot of "bang for the buck".

On an un-weighted basis (Table 9.4) the cost/benefit ratio ranges from $1450/tonne (Option 2 – *Continuous Water Injection*) to $12,465/tonne (Option 1 – *PuriNOx water-*

diesel emulsion). Significant emission reductions are achieved using Options 4,5 and 7, at a cost of from $1,456/tonne to $7,956/tonne. The use of LNG, at $1,456/tonne provides a 77% reduction in smog-forming emissions.

The lower sections of the two tables compares the ferry emissions with the displaced land emissions (second column) for the four different routes and for three different ferry occupancy levels (25%, 50% and 75%). The comparison shows the passenger ferry

Table 9.4 - Unweighted Emissions Marine Passenger Transportation Analysis

Run	Emission Reduction Option						
	1	2	3	4	5	6	7
All runs	**Year 2005 emissions**						
Ferry, no controls (tpy)	14.4	14.4	14.4	14.4	14.4	14.4	14.4
Emission reduction (tpy)	2.5	3.3	1.4	7.3	12.6	4.7	11.1
Cost-Effectiveness ($/tonne)	$12,465	$1,450	$1,791	$2,918	$2,738	$7,956	$1,456
Snug Cove - Ambleside - Waterfront	**Ferry Emissions - Percent Of Displaced Vehicle Emissions**						
25% occupancy	358	335	391	214	54	291	97
50% occupancy	179	167	196	107	27	145	49
75% occupancy	119	112	130	71	18	97	32
Lonsdale-Ambleside-Jericho	**Ferry Emissions - Percent Of Displaced Vehicle Emissions**						
25% occupancy	156	146	171	94	24	127	42
50% occupancy	78	73	85	47	12	63	21
75% occupancy	52	49	57	31	8	42	14
Deep Cove-Maplewood-Waterfront	**Ferry Emissions - Percent Of Displaced Vehicle Emissions**						
25% occupancy	288	269	314	172	43	234	78
50% occupancy	144	135	157	86	22	117	39
75% occupancy	96	90	105	57	14	78	26
Ioco-Maplewood-Lonsdale	**Ferry Emissions - Percent Of Displaced Vehicle Emissions**						
25% occupancy	177	166	193	106	27	144	48
50% occupancy	89	83	97	53	13	72	24
75% occupancy	59	55	64	35	9	48	16

Ferry Emission Reduction Options

1. PuriNOx water/diesel emulsion
2. Continuous Water Injection (CWI)
3. Diesel Oxidation Catalyst
4. Exhaust Gas Recirculation + Particulate Filter
5. Selective Catalytic Reduction (SCR)
6. Cleaire "Longview"
7. Natural gas (LNG, gas at US$9/MMBtu commodity price)

emissions as a percent of displaced vehicle emissions (assumes a vehicle fleet similar to the year 2000 LFV LDGV fleet). Scenarios wherein ferry emissions are less than, or do not significantly exceed the displaced vehicle emissions, are highlighted in blue.

On a weighted-emissions basis Option 7 (LNG) and Options 4 – 6 reduce emissions for most ferry occupancy levels in all four runs that were studied. These options would therefore support TransLink's sustainable transportation objectives, whereas the other options would place an increased burden upon air quality within the GVRD.

On an un-weighted basis, Option 5 (SCR) and Option 7 (LNG) reduce emissions at most ferry occupancy levels on all four runs.

This "first-pass" study illustrates that it is possible to reduce road and bridge congestion through the use of fast passenger ferries, while at the same time reducing atmospheric pollution within the GVRD region. Further engineering studies and economic analyses are needed to firm up the optimal emission reduction strategies and resultant impact upon air quality within the GVRD region.

10.0 DISCUSSION AND CONCLUSIONS

10.1 Nonroad HDD Equipment

The BC nonroad heavy-duty diesel (HDD) equipment fleet presently (2005) consists of approximately 101,000 pieces of equipment, with 34% of these located within the GVRD and 11% within the FVRD1. The GVRD nonroad fleet is dominated by construction equipment (backhoes, front-end loaders, excavators, etc.) while the fleet within the FVRD1 and the rest of BC is mainly agricultural equipment (farm tractors, combines, etc.).

In the following discussion two different methods are referred to in the context of a total, or aggregate, emission or emission reduction:

1. Weighted: the emissions of each species first are multiplied by a weight and then the resulting products are summed. The weights used are NOx = 1, SOx = 3, PM_{10} = 25, VOC = 1 and CO = 1/7)
2. Non-weighted: the emissions of each species are simply added up (NOx = 1, SOx = 1, $PM_{2.5}$ = 1, VOC = 1, NH_3 =1 and CO = 0). CO is normally excluded from this total because it does not contribute directly to smog and haze and because its morbidity effects are thought to occur only in high-density, vehicular traffic locations.

The emissions were aggregated in this manner in order to be consistent with previous GVRD studies. The weights are reflective of what is felt to be the relative environmental impacts of the associated species, with diesel particulate matter (PM_{10}) receiving the highest weight because of its suspected strong impact on human morbidity. However, the weighting used in this and other studies are open to controversy. It is difficult to separate out the contribution of individual pollutants when conducting epidemiological studies into the effects of air pollution on human morbidity/mortality. The non-weighted aggregates (second method) are somewhat reflective of the smog-forming potential of the total emissions, although again this is open to debate.

The total (unweighted) emissions from this sector during the year 2005 are projected to be 35,700 tonnes in BC, including 11,800 tonnes from the Lower Fraser Valley. In GVRD these emissions represent 14% of the total mobile-source emissions and 8.5% of the total emissions from all sources. Projected total emissions (2005 – 2025) from the nonroad HDD equipment sector are 422,000 tonnes in BC, including 146,600 tonnes from the LFV.

It can be appreciated that these emissions form a significant portion of the total emissions within the different regions. This section will discuss ways to reduce these emissions in a cost-effective manner over the period 2005 – 2025 and will provide estimates of total emission reductions, both impact-weighted and un-weighted, that would result if the different emission reduction measures were implemented.

Four different fleets were investigated for the **GVRD** study area:

1. Construction and Mining Equipment
2. Agricultural Equipment
3. Industrial and Commercial Equipment
4. Other Equipment

For the **FVRD1** the major fleets are:

1. Construction and Mining Equipment
2. Agricultural Equipment
3. Other Equipment

For the **Rest of BC** the fleets investigated are:

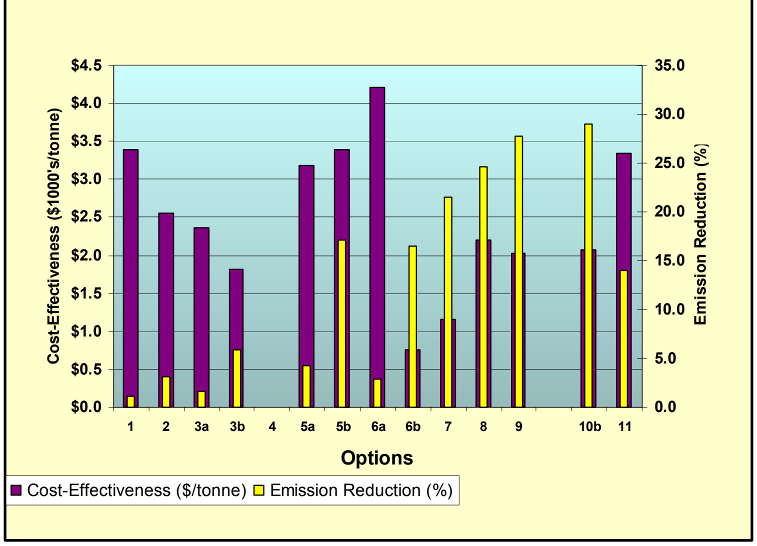
1. Construction and Mining Equipment
2. Agricultural Equipment
3. Logging Equipment
4. Other Equipment

The cost-effectiveness (based upon weighted aggregate emissions reductions) of the 11 different ERMs was evaluated in Section 7 for the major nonroad fleets within each of the three study areas and the results for all fleets are summarized in Table 10.1 below and are compared for selected fleets in Figures 10.1 – 10.6. Emission reductions are given as a percent of the total projected emissions over the 20-year period 2005 – 2025, while the cost-effectiveness is the *net present value* cost-effectiveness (NPV of total 20-year costs divided by the weighted aggregate emissions reductions). Differences between fleets and regions are due to differences in fleet compositions and associated emissions, as estimated using the NONROAD 2004 model. Differences between ERMs are due to different assumptions about the ERM efficacy, cost, and years of applicability. These assumptions were summarized in Table 7.2 and the resulting annual emission reductions, for the years 2005, 2010, 2015, 2020 and 2025, were tabulated in Tables 7.17 – 7.19.

Table 10.1 - Summary of the Cost-Effectiveness of NonRoad HDD Equipment Emission Reduction Options

Emission Reduction Option:	1	2	3a	3b	4	5a	5b	6a	6b	7	8	9	10a	10b	11
	LSD	ULSD	B20 LSD	B20 ULSD	B100	PNOx LSD	PNOx ULSD	DOC #2D	DOC ULSD	DPF ULSD	Clear-aire	EGR DPF	SCR LSD	SCR ULSD	NOx Traps
Application start year/end year	2005 2006	2007 2010	2005 2006	2007 2025	2005 2025	2005 2006	2007 2025	2005 2006	2007 2025	2007 2025	2007 2025	2007 2025	2005 2006	2007 2025	2010 2025
Region & Fleet	Percent Emission Reductions (weighted)														
GVRD															
Construction & Mining	1.1	3.1	1.6	5.9	25.8	4.4	17.9	2.8	16.5	21.5	24.6	27.8	2.1	29.0	13.9
Agriculture	1.2	3.1	1.6	6.2	28.0	4.2	18.4	3.1	17.3	12.6	13.6	15.1	0.5	8.6	6.6
Industrial & Commercial	1.0	2.9	1.4	6.0	26.3	3.8	17.7	2.7	16.9	8.8	9.7	10.8	0.4	7.1	5.1
Others	0.6	1.6	0.8	3.4	14.6	2.3	10.1	1.5	9.4	12.0	13.4	15.1	0.8	12.4	7.3
FVRD															
Construction & Mining	1.1	3.2	1.6	6.2	27.2	4.3	18.0	2.9	17.3	19.6	22.0	24.7	1.6	22.2	11.5
Agriculture	1.2	3.1	1.6	6.2	28.0	4.3	18.4	3.1	17.3	12.5	13.4	14.9	0.5	8.4	6.6
Others	1.0	2.7	1.4	5.6	24.5	3.6	16.4	2.5	15.7	9.3	10.3	11.5	0.5	7.7	5.4
Rest of BC															
Construction & Mining	1.3	3.4	1.8	6.1	26.1	4.7	18.0	2.9	16.5	22.0	25.4	28.7	2.3	30.9	14.6
Agriculture	0.8	2.0	1.1	4.1	18.5	2.9	12.1	2.0	11.1	23.1	24.5	27.0	1.3	20.8	11.4
Logging	1.7	4.2	2.3	6.2	27.7	6.4	18.3	3.7	16.5	31.9	35.4	39.4	3.5	33.4	15.4
Others	1.3	3.4	1.8	6.0	26.1	4.5	17.7	2.9	16.4	15.0	16.8	18.8	1.0	13.9	8.8
	Cost Effectiveness ($1000's/Tonne Avoided Emissions)														
GVRD															
Construction & Mining	3.4	2.6	2.4	1.8	14.2	3.1	3.3	4.2	0.8	1.2	2.2	2.0	18.7	2.1	3.3
Agriculture	2.1	1.3	1.4	0.6	5.3	2.0	1.2	8.2	0.9	0.9	1.7	2.0	31.0	2.0	3.2
Industrial & Commercial	2.7	2.0	1.8	1.3	10.2	2.6	2.4	12.0	2.1	1.6	2.8	3.3	40.8	3.7	5.9
Others	2.8	2.1	1.9	1.4	10.7	2.6	2.6	10.9	1.9	1.5	2.7	3.1	34.6	3.4	5.6
FVRD															
Construction & Mining	3.1	2.3	2.2	1.6	12.5	2.9	3.0	4.9	0.8	1.3	2.4	2.4	23.7	2.7	4.3
Agriculture	2.2	1.6	1.5	1.1	8.3	2.1	2.1	8.3	1.5	1.3	2.3	2.9	32.0	3.1	5.4
Others	2.8	2.1	1.9	1.4	10.7	2.7	2.7	10.9	1.9	1.5	2.7	3.1	34.6	3.4	5.6
Rest of BC															
Construction & Mining	3.0	2.4	2.1	1.8	14.5	3.0	3.4	4.0	0.7	1.2	2.2	2.0	17.8	2.0	3.3
Agriculture	3.2	2.7	2.2	1.8	13.4	3.1	3.3	7.0	1.4	1.7	3.2	3.5	50.0	4.7	6.8
Logging	3.8	2.9	2.7	2.2	17.9	3.6	4.1	2.9	0.5	1.1	2.0	2.2	20.6	2.7	4.3
Others	2.7	2.2	1.9	1.7	13.6	2.8	3.2	6.6	1.2	1.4	2.4	2.7	24.0	2.8	4.9

Figure 10.1 - GVRD Construction & Mining Equipment



In the figures the yellow bars represent the emission reductions, expressed as a percent of the weighted aggregate nonroad HDD emissions for the different options that were discussed in Section 7, while the purple bars represent the cost-effectiveness, expressed as a cost/benefit ratio. The greatest efficiencies will be provided by those options that provide a significant emission reduction at a low cost/benefit ratio (high yellow bar, low purple bar).

	Emission Reduction Options	Years
1	Rebranded road diesel, 350 ppm S	05 - 06
2	Ultralow sulphur diesel, 10 ppm S	07 - 10
3a	B20 biodiesel (biodiesel + LSD)	05 - 06
3b	B20 biodiesel (biodiesel + ULSD)	07 - 25
4	B100 biodiesel, 0 ppm S	05 - 25
5a	PuriNOx with LSD, 350 ppm S	05 - 06
5b	PuriNOx with ULSD, 10 ppm S	07 - 25
6a	DOC with off-road diesel (563 ppm S)	05 - 06
6b	DOC with ULSD, 10 ppm S	07 - 25
7	Passive DPF with ULSD (10 ppm S)	07 - 25
8	Cleaire "LongView" with ULSD	07 - 25
9	EGR + DPF + ULSD	07 - 25
10a	SCR + LSD (urea added to fuel costs)	05 - 06
10b	SCR + LSD (urea added to fuel costs)	07 - 25
11	NOx Adsorbers	10 - 25

Emission reductions for the ERM's are presented as a percentage of the total emissions over the period of 2005 – 2025. Hence ERM options that are applicable over only a small portion of this time span will have a relatively small emission reduction (right vertical axis of the charts).

Two of the ERM options (#4 - 100% Biodiesel and #10a – SCR & LSD) are not shown in the figures because their costs are far in excess of the other options and hence their inclusion would distort the vertical axis of the charts. (For the GVRD Construction and Mining sector the use of B100 is estimated to reduce total contaminant-weighted emissions by 20% but at a cost of over $18,000/tonne of avoided emissions. The expense of the SCR & LSD option is not viable because of the assumed short-term applicability of this ERM; it is replaced by the use of SCR & ULSD in 2007 (Option 10b).

Figure 10.2 - Rest of BC Construction & Mining

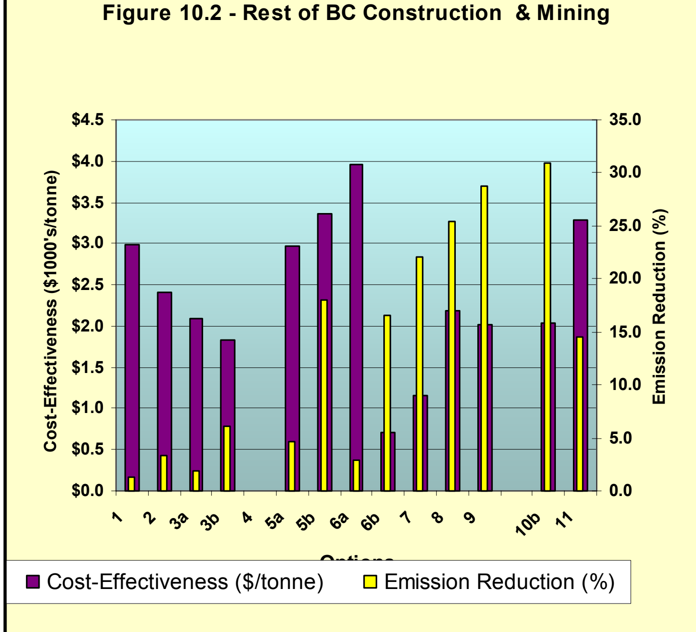
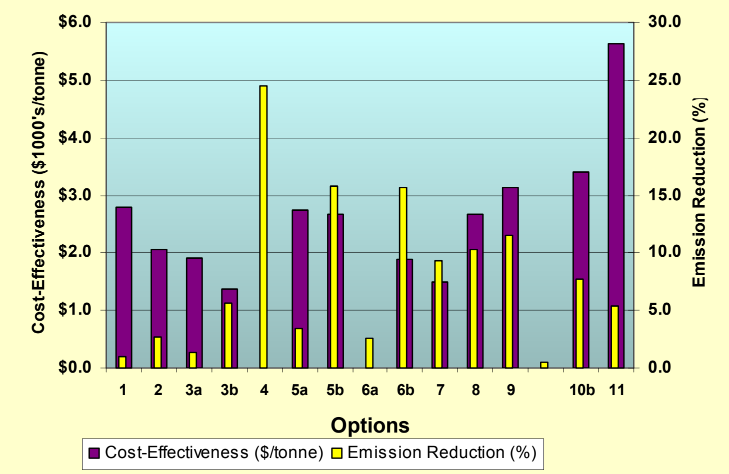


Figure 10.3 - FVRD Agricultural Equipment



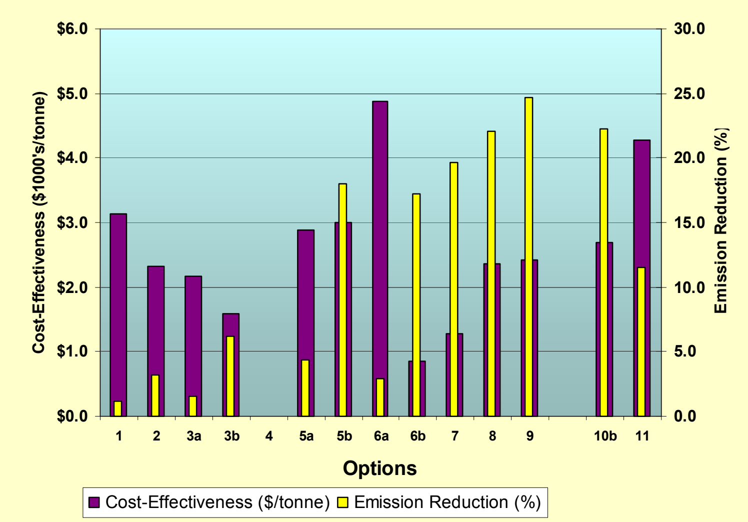
The most cost-effective ERM's, at less than $2000 per tonne of weighted, avoided emission reductions are seen to be a biodiesel blend (B20), a diesel oxidation catalyst (DOC) or a diesel particulate filter (DPF), all in combination with the upcoming ULSD road diesel. If the existing taxes on colored B20 are reduced from 5.6 ¢/L down to 4.5 ¢/L then the cost of using B20 becomes cost-neutral to fleet operators and they will start using this alternative fuel, which not only reduces overall emissions by about 6% but also reduces the emission of greenhouse gases (CO_2).

	Emission Reduction Options	Years
1	Rebranded road diesel, 350 ppm S	05 - 06
2	Ultralow sulphur diesel, 10 ppm S	07 - 10
3a	B20 biodiesel (biodiesel + LSD)	05 - 06
3b	B20 biodiesel (biodiesel + ULSD)	07 - 25
4	B100 biodiesel, 0 ppm S	05 - 25
5a	PuriNOx with LSD, 350 ppm S	05 - 06
5b	PuriNOx with ULSD, 10 ppm S	07 - 25
6a	DOC with off-road diesel (563 ppm S)	05 - 06
6b	DOC with ULSD, 10 ppm S	07 - 25
7	Passive DPF with ULSD (10 ppm S)	07 - 25
8	Cleaire "LongView" with ULSD	07 - 25
9	EGR + DPF + ULSD	07 - 25
10a	SCR + LSD (urea added to fuel costs)	05 - 06
10b	SCR + LSD (urea added to fuel costs)	07 - 25
11	NOx Adsorbers	10 - 25

NOx adsorbers (Option 11) are not expected to become commercially available until 2010, which reduces their effectiveness in reducing contaminant-weighted emissions over the 2005 – 2025 timeframe.

This study shows that for a given ERM option there is not a large amount of difference in its cost-effectiveness when compared between the three different operating areas and the different nonroad HDD fleets. This can be observed in Figures 10.1 and 10.2 above where the Construction and Mining fleets for GVRD and the Rest of BC are compared.

Figure 10.4 - FVRD1 Construction & Mining Equipment



Figures 10.3 and 10.4 compare the Agricultural and the Construction and Mining fleets for FVRD1. Again, it can be observed that the costs of the different ERM options are

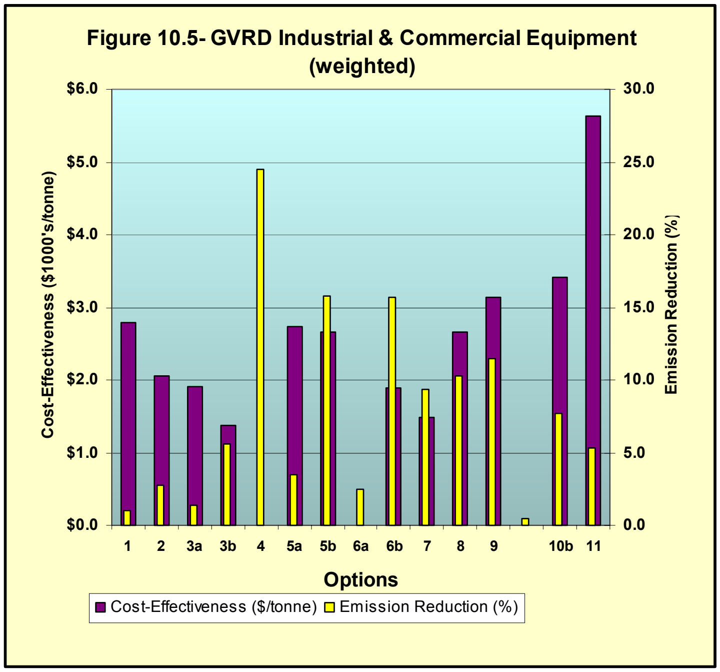


Figure 10.5- GVRD Industrial & Commercial Equipment (weighted)

quite similar.

Figures 10.5 and 10.6 compare the ERM costs and emission reductions when calculated using weighted totals and when calculated using un-weighted totals. It can be seen that there are significant differences in the results of these two methods, with the weighted aggregate method generally resulting in lower costs per tonne of avoided emissions.

ERM options that result in significant $PM_{2.5}$ reduction will be favored by the weighted aggregate method whereas options that provide a strong reduction in NOx (a major component of diesel exhaust) will be favored by non-weighted approach to book-keeping.

	Emission Reduction Options	Years
1	Rebranded road diesel, 350 ppm S	05 - 06
2	Ultralow sulphur diesel, 10 ppm S	07 - 10
3a	B20 biodiesel (biodiesel + LSD)	05 - 06
3b	B20 biodiesel (biodiesel + ULSD)	07 - 25
4	B100 biodiesel, 0 ppm S	05 - 25
5a	PuriNOx with LSD, 350 ppm S	05 - 06
5b	PuriNOx with ULSD, 10 ppm S	07 - 25
6a	DOC with off-road diesel (563 ppm S)	05 - 06
6b	DOC with ULSD, 10 ppm S	07 - 25
7	Passive DPF with ULSD (10 ppm S)	07 - 25
8	Cleaire "LongView" with ULSD	07 - 25
9	EGR + DPF + ULSD	07 - 25
10a	SCR + LSD (urea added to fuel costs)	05 - 06
10b	SCR + LSD (urea added to fuel costs)	07 - 25
11	NOx Adsorbers	10 - 25

The proposed Canadian nonroad diesel engine regulations are expected to become final and to apply to 2006 and later engines. They will mirror the EPA Tier 2, 3 and 4 regulations. A previous study showed that if all the existing nonroad diesel equipment fleets in BC could be immediately re-engined with Tier 2 engines the smog-forming emissions, from this source, would be reduced by approximately 40 – 50%. Similarly, if the existing nonroad diesel equipment fleets in BC could be immediately re-engined with Tier 3 engines these emissions would be reduced by approximately 60 – 70%. These options were not explored in this study because they are not practical. Generally, the engines built for new Tier 2 or Tier 3 compliant nonroad HDD equipment are not retrofitable to old equipment due to changes and improvements in equipment chassis design. Hence any sort of Tier 2 or Tier 3 compliant retrofit would entail buying all

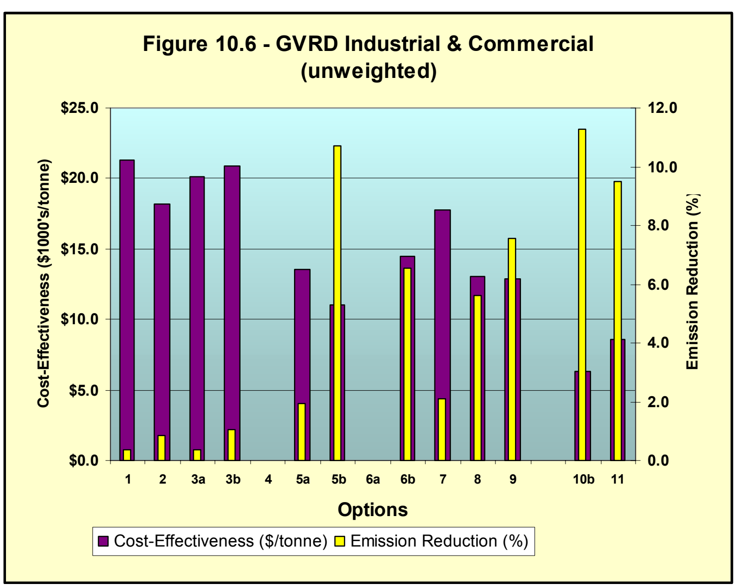


Figure 10.6 - GVRD Industrial & Commercial (unweighted)

new equipment. This is not cost-effective unless an old machine needs to be completely rebuilt or replaced.

Emission reductions through engine and technology retrofits are being accomplished in California through a government subsidized "Carl Moyer" program, wherein the state will pay for the incremental cost of replacing an engine with a Tier 2 or better engine. The incremental cost is the total cost of the retrofit (engine purchase plus any special engineering to enable the new engine to be retrofitted) less the cost of simply rebuilding the existing engine. This successful program reduces NOx at a cost of about US$4,000 - $5,000/ton. (There is a cap of US$12,000/ton to prevent the program from subsidizing improvements that are not cost-effective.) The Carl Moyer program also applies to locomotives, marine vessels and other heavy-duty diesel engines.

However, in the nonroad HDD equipment sector the Carl Moyer program has mainly been applied to diesel engine powered agricultural pumps or to emission-reduction retrofits, such as diesel oxidation catalysts and diesel particulate filters. As stated above, it is usually not possible to install a new, low-emission engine into an old piece of equipment.

This study has shown that weighted aggregate emissions reductions of in the order of 20% can be achieved at a cost of around $2,000/tonne or less in the nonroad HDD equipment sector. The most cost-effective ERM's are those that can benefit from fuel tax reductions, such as B20 biodiesel, in which case the cost to the operator can be made neutral or even negative. With appropriate tax reductions clean-fuel ERM's can be combined with low-cost technology ERM's such as retrofit diesel oxidation catalysts to achieve in excess of a 25% emission reduction at a neutral cost to the operator.

On a non-weighted basis the emission reductions are generally lower and the costs higher than when treated on a weighted basis. One of the most cost-effective options using this method of aggregation is the use of selective catalytic reduction (SCR). Emissions can be reduced by 29% at a fleet cost-effectiveness generally under $6,000 per avoided tonne. SCR is being successfully applied to HDD engines in Europe.

10.2 Locomotives

CN photo

The locomotive fleet operating part-time or full time within BC consists of approximately 480 locomotives (line haul and yard), with 10% of these located within the GVRD and 5% within the FVRD1. The line haul locomotives have an average power of about 3580 hp, are operational approximately 7500 hours/year and on average spend around 60% of this time idling. Yard locomotives are operational approximately 7000 hours/year and on average spend around 81% of this time idling. The line haul locomotives exhaust a large majority of the total emissions coming from the railroad sector.

The total emissions in the Lower Fraser Valley from the locomotive equipment fleet during the year 2005 are estimated to be 4,272 tonnes. These emissions represent 2.3% of the total emissions in the Lower Fraser Valley from all sources. Hence these emissions are a small but not insignificant portion of the total emissions.

It should be noted here that a *Memorandum of Understanding* between the Railway Association of Canada and Environment Canada caps railway locomotive NOx emissions in Canada. Further emission reductions would require some sort of amendment to this agreement. This MOU is presently under review by the two stakeholder parties.

Line Haul Locomotives

Possible options for the line haul locomotives include:

1. Use of ultra-low sulphur diesel (ULSD).
2. Rebuilding the engines to EPA Tier 0 emission requirements.
3. Rebuilding the engines to EPA Tier 1 emission requirements.
4. Using water injection (CWI) to reduce NOx and other emissions.
5. Using the MEC system to produce a micro-emulsion of diesel and water.
6. Replacing the muffler with a diesel oxidation catalyst (DOC).
7. Using selective catalytic reduction (SCR) to reduce NOx and other emissions.
8. Using an idle reduction system (*Hotshot/Smart-Start*) to largely eliminate locomotive idling, which is normally used to keep the engine and engine fluids hot.

Yard Engines

Options for switch engines include:

1. Use of ultra-low sulphur diesel (ULSD).
2. Rebuilding the engines to EPA Tier 1 emission requirements.
3. Using water injection (CWI) to reduce NOx and other emissions.
4. Diesel oxidation catalyst (DOC) muffler replacement.
5. Idle control (*Hotshot/Smart-Start*)
6. Hybrid rebuilds (*RailPower Technologies Ltd*. diesel/battery).
7. Idle control (*Smart-Start* only)

Table 10.2 and Figures 10.7 – 10.10 provide a summary of the cost-effectiveness of the different ERM options as applied to the different locomotive fleets in the LFV. (The charts for the rest of BC are almost identical to those for the LFV and hence are not included here.) Emission reductions are given as a percent of the total projected emissions over the 20-year period 2005 – 2025, while the cost-effectiveness in the net present value cost-effectiveness (NPV of total 20-year costs divided by the total, weighted emissions).

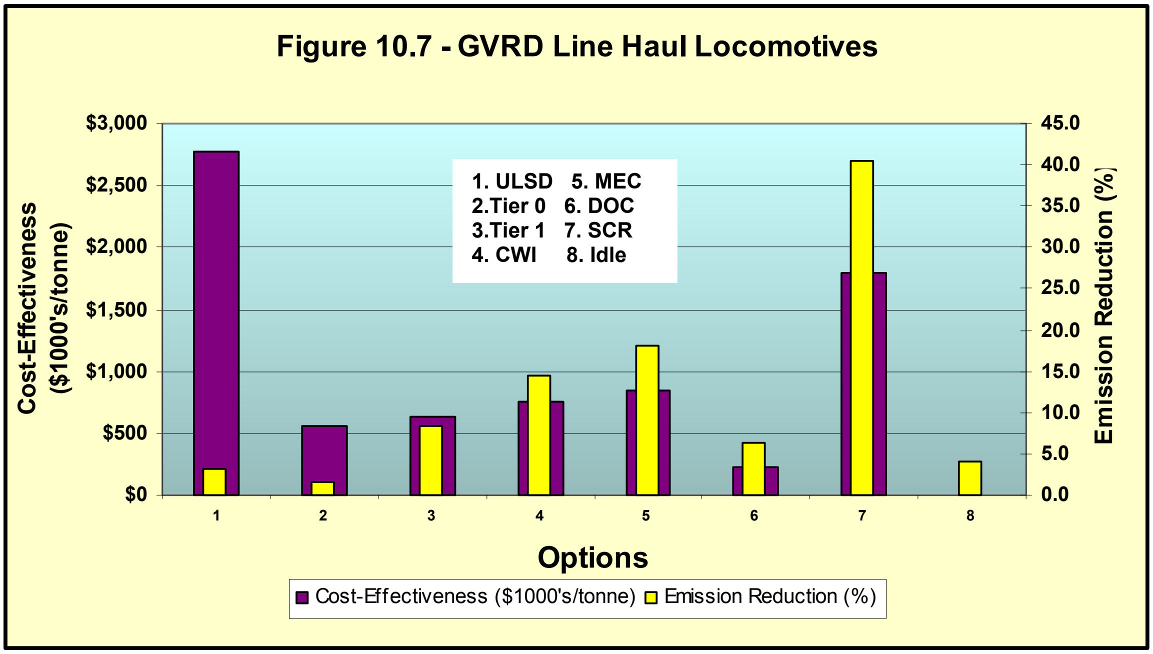
Table 10.2 - Summary of Weighted Cost-Effectiveness

Line Haul Locomotives

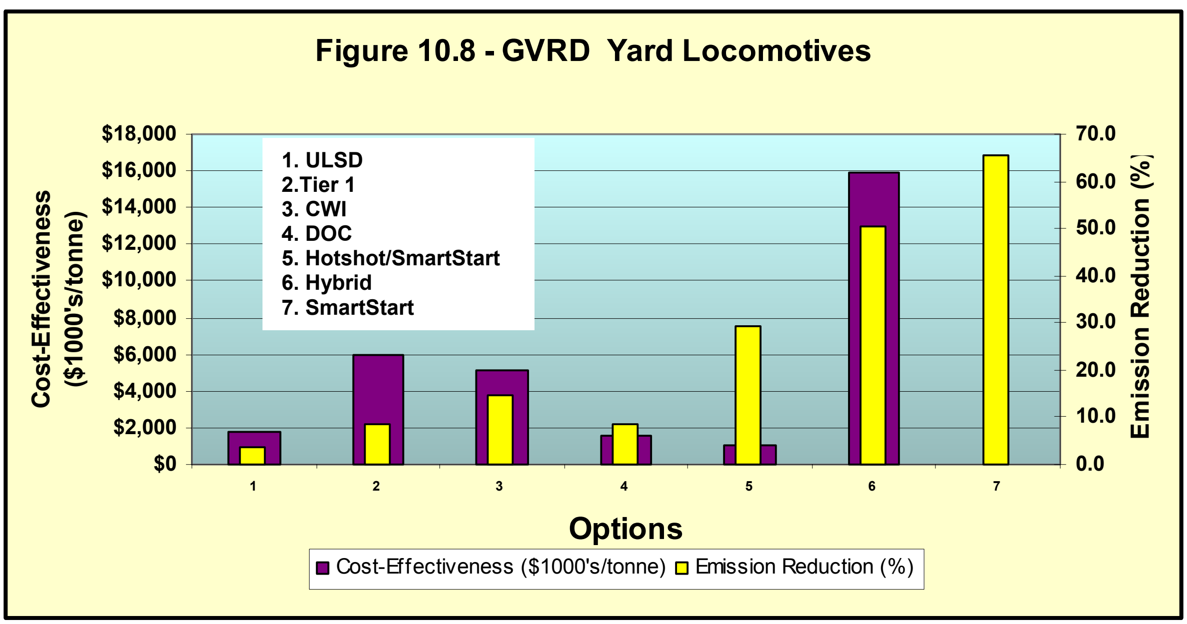
Region	1 ULSD	2 Tier 0 Rebuild	3 Tier 1 Rebuild	4 Water Inj.	5 MEC System	6 DOC	7 SCR	8 Hot Shot SmartStart
Percent Emission Reduction (2005 - 2025)								
GVRD	3.1	1.6	8.4	14.6	18.0	6.3	40.6	4.1
FVRD	3.0	1.6	8.4	14.6	18.0	6.3	40.6	4.0
Rest of BC	3.5	1.5	8.3	14.5	18.4	7.0	39.9	4.1
Cost-Effectiveness ($/tonne Avoided Emissions)								
GVRD	$2,770	$551	$628	$751	$842	$228	$1,791	($1,391)
FVRD	$2,793	$551	$630	$753	$845	$230	$1,792	($1,405)
Rest of BC	$2,342	$558	$628	$731	$803	$200	$1,743	($1,184)

Yard Locomotives

Region	1 ULSD	2 Tier 1 Rebuild	3 Water Injection	4 DOC	5 Hot Shot SmartStart	6 Hybrid	7 Smart Start
Percent Emission Reduction (2005 - 2025)							
GVRD	3.8	8.7	14.7	8.6	29.4	50.5	65.4
FVRD	3.8	8.8	14.7	8.6	29.4	50.5	65.4
Rest of BC	4.3	8.6	14.4	9.9	28.1	50.6	-
Cost-Effectiveness ($/tonne Avoided Emissions)							
GVRD	$1,734	$5,931	$5,105	$1,584	$1,068	$15,889	($5,026)
FVRD	$1,729	$5,918	$5,101	$1,582	$1,061	$15,906	($5,048)
Rest of BC	$1,384	$5,373	$4,633	$1,223	$970	$14,127	-

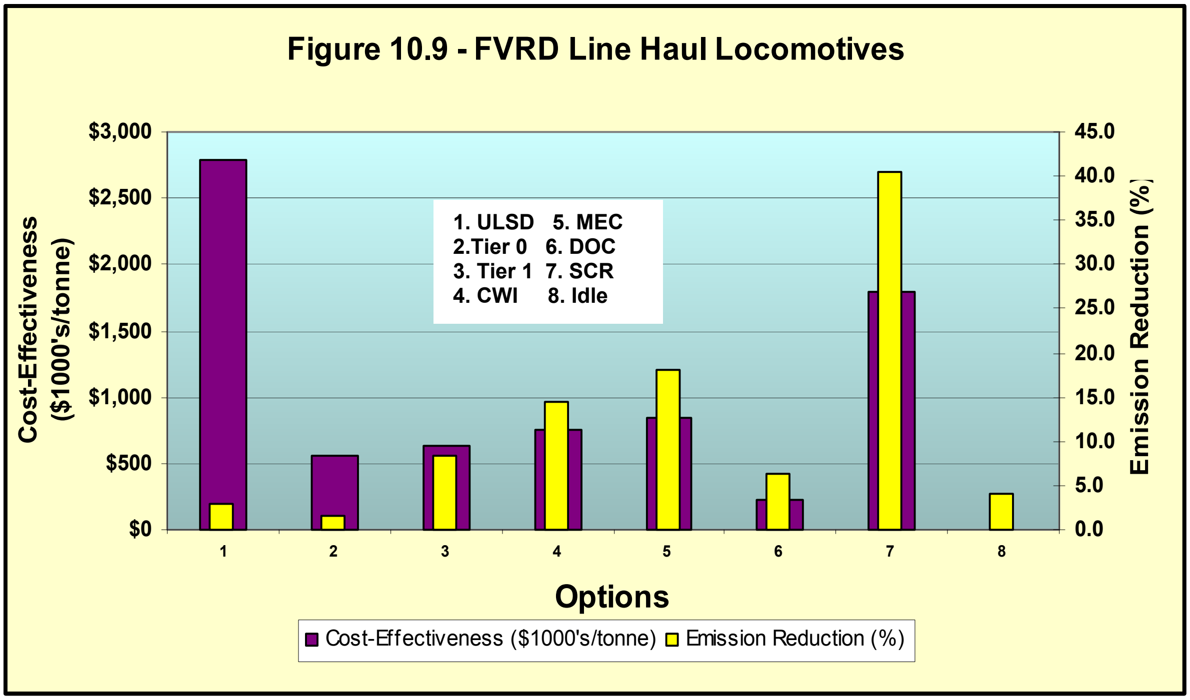


It can be observed that, for a given type of locomotive (line or yard), the emission reductions and costs are quite similar for the two regions. However, the costs for reducing emissions from yard engines are generally higher than for line haul engines.



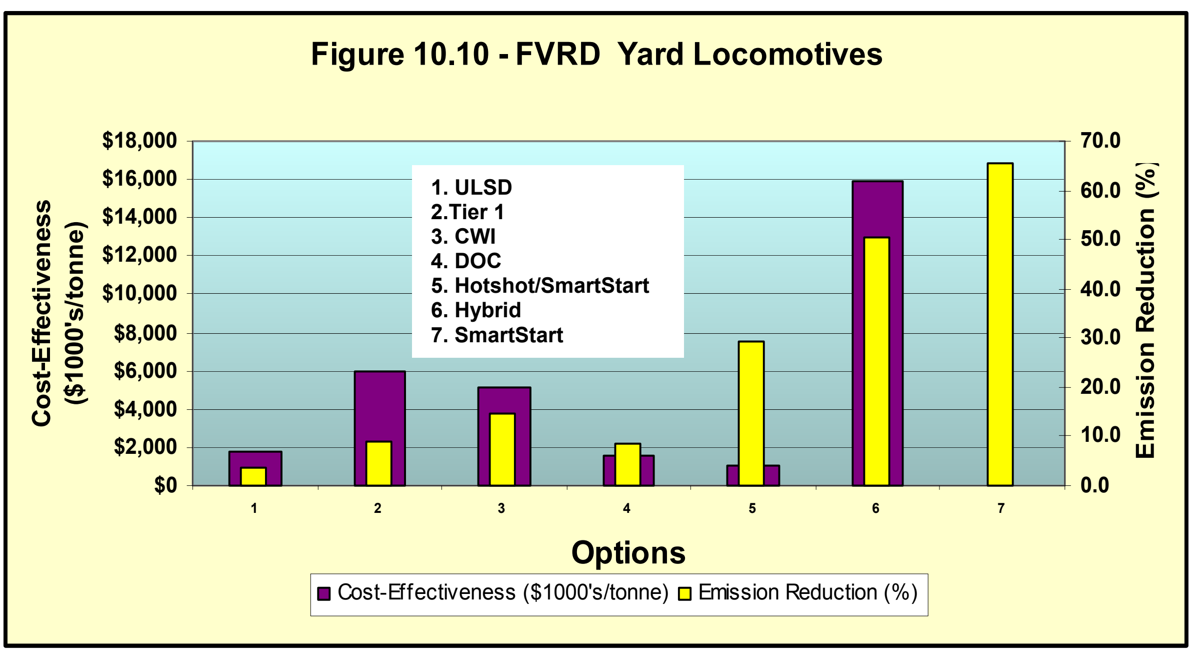
For line haul engines Option 8 (idling control using a combination of *HotShot* and *SmartStart* systems) actually saves money for the railway industry. It has a negative cost/benefit ratio as shown in Table 10.2. (The emission reduction is relatively small, 4%, so that when the cost-savings from reduced fuel expenditures are divided by the emission reductions, a large negative cost/benefit ratio results.)

Similarly, for yard engines Option 7 (idling control using the *SmartStart* system) also saves money in those applications where it can be used. It has a large negative cost/benefit ratio as shown in Table 10.2.



The two lowest cost options for line haul locomotives are to retrofit the *HotShot*/*SmartStart* idle-control system and to retrofit diesel oxidation catalysts. Some operators are presently pursuing the former option, while latter would require incentives, perhaps similar to those of the Carl Moyer program.

The two options that provide the greatest emission reductions for line haul locomotives are the MEC water emulsifying system (Option 5) and the use of Selective Catalytic Reduction of NOx (Option 7), providing 18% and 41% emission reductions, respectively.



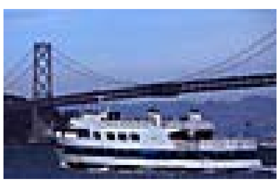
However, neither of these options has yet been tested in locomotive applications.

It is apparent from Table 10.2 and the figures that it cost significantly more per tonne to reduce emissions from yard engines than it does from line engines. This is because although the installed cost of retrofit equipment is similar, the resultant emission reductions from yard engines are much less than those from the line haul engines.

The two lowest cost options for yard locomotives are those using idle control technology (Options 5 & 7). If the *SmartStart* idle control technology could be used year around it would provide a very significant (65%) emission reduction while at the same time reducing operational costs.

A more in-depth study is required to properly evaluate the applicability of idle control technology in different regions of the Province – what fraction of the year can the *SmartStart* idle control technology be used alone and what fraction of the year would the *HotShot* system also be required to keep the engine fluids warm. The study could also investigate the emission reductions attainable and the corresponding cost-effectiveness of other retrofit technologies used in conjunction with idle control technologies, such as the use of diesel oxidation catalysts and diesel particulate filters.

10.3 Marine Alternatives to Road Transportation



Expanded passenger ferry services are the subject of continued interest in Greater Vancouver, given the potential of such services to bypass traffic bottlenecks, reduce travel times, improve reliability and attract new transit-system ridership. A 2003 study of an expanded passenger ferry system in the San Francisco Bay Area showed that emissions of NOx would increase significantly unless advanced technologies were used to reduce these emissions. It was concluded that it should be feasible to design and implement an enhanced ferry service to conform to regional transportation and air quality goals.

TransLink has recently concluded the *Vancouver Harbour Passenger Marine Study*; a study intended to explore the feasibility of this increased passenger ferry service in Vancouver Harbour. Although TransLink has no plans to implement passenger ferry service at this time, this present study has reviewed potential emissions from four passenger-ferry routes, traveled by a representative ferry fleet that was considered in the TransLink study, and has compared the forecasted ferry emissions with the avoided road-commute emissions. Four conceptual routes, all of which were identified as potential service options in TransLink's *Vancouver Harbour Passenger Marine* study, were studied.

Table 10.13 summarizes the estimated increase in emissions into the GVRD airshed for the four different routes that were studied, expressed as a percent of the displaced vehicle emissions. Seven different emission reduction options were then studied. For sustainable transportation alternatives the emissions into the airshed should not substantially increase. Those options that do not increase emissions, or actually reduce them, are highlighted in blue. It can be seen that rider-occupancy is an important parameter in determining whether an emission reduction option qualifies for sustainability or not.

Table 10.13 - Weighted-Emissions Marine Passenger Transportation Analysis

Run	Emission Reduction Option						
	1	2	3	4	5	6	7
All runs	**Year 2005 emissions**						
Ferry, no controls (tpy)	24.8	24.8	24.8	24.8	24.8	24.8	24.8
Ferry Emission reduction (tpy)	5.1	6	5.8	16.6	16.8	13.6	20.9
Cost-Effectiveness ($/tonne)	$6,135	$793	$433	$1,278	$2,048	$2,764	$809
Snug Cove - Ambleside - Waterfront	**Ferry Emissions - Percent Of Displaced Vehicle Emissions**						
25% occupancy	319	304	307	132	129	181	76
50% occupancy	160	152	154	66	64	90	38
75% occupancy	106	101	102	44	43	60	25
Lonsdale-Ambleside-Jericho	**Ferry Emissions - Percent Of Displaced Vehicle Emissions**						
25% occupancy	139	133	134	58	56	79	33
50% occupancy	70	66	67	29	28	39	17
75% occupancy	46	44	45	19	19	26	11
Deep Cove-Maplewood-Waterfront	**Ferry Emissions - Percent Of Displaced Vehicle Emissions**						
25% occupancy	257	245	247	106	103	145	61
50% occupancy	128	122	124	53	52	73	30
75% occupancy	86	82	82	35	34	48	20
Ioco-Maplewood-Lonsdale	**Ferry Emissions - Percent Of Displaced Vehicle Emissions**						
25% occupancy	158	150	152	65	64	89	37
50% occupancy	79	75	76	33	32	45	19
75% occupancy	53	50	51	22	21	30	12

Ferry Emission Reduction Options

1. PuriNOx water/diesel emulsion
2. Continuous Water Injection (CWI)
3. Diesel Oxidation Catalyst
4. Exhaust Gas Recirculation + Diesel Particulate Filter
5. Selective Catalytic Reduction (SCR)
6. Cleaire "Longview"
7. Natural gas (LNG, gas at US$9/MMBtu commodity price)

If the passenger occupancy level is 50% or greater, Options 4 – 7 qualify in three out of the four runs. LNG looks especially attractive, even at a commodity price of US$9/MMBtu. (It is assumed that ultra-low emission natural-gas engines, such as those under development by Cummings-Westport, are used to power the ferries in this option).

Of the four options that qualify for sustainability, SCR is widely used on ferries in Europe to reduce NOx emissions, while LNG is used on a number of vessels there, including one car ferry.

10.4 Conclusions and Recommendations

Conclusions:

- Nonroad heavy-duty diesel equipment contributes substantially to the emission inventory in BC. In 2005 this source is expected to contribute 35,700 tonnes. Within the GVRD the 2005 nonroad HDD equipment emissions would represent 14% of the mobile source emissions. Emission reductions (weighted) in the order of 20% can be achieved at a cost of approximately $2,000/tonne or less. The most cost-effective ERM's are the retrofit of a diesel oxidation catalyst, a diesel particulate filter or the use of B20 (all in conjunction with ULSD). If the taxes on coloured (off-road) B20 are reduced by 2 cents per litre (cpl), from the existing 5.6 cpl, then this fuel becomes highly attractive for fleet operators to use. Not only are the emissions of exhaust contaminants reduced through the use of B20 but also there results a significant reduction in the emissions of greenhouse gases, thereby helping Canada to meet its Kyoto commitments.

- During 2005 railway locomotive emissions are expected to represent 2.3% of the total emissions in the Lower Fraser Valley. Hence these emissions are a small but not insignificant portion of the total emissions. On line-haul locomotives these emissions can be substantially reduced, at a cost of $1,000/tonne or less, using various retrofit technologies. Idle-reduction technologies for line locomotives, that are based upon using a small auxiliary diesel engine to keep the locomotive engine fluids warm when the engine is shut down, would provide a modest 4 % reduction in emissions while at the same time actually save money for the railways through reduced fuel consumption. For yard locomotives idle control, in the form of an electronic system to shut down the engine during idling, would provide a large (65%) reduction in emissions while also significantly reducing operational costs through reduced fuel consumption.

- Possible future TransLink fast passenger ferry systems would increase emissions into the GVRD airshed if the ferries were powered with modern Tier 2 diesel engines. However, technologies are now available to reduce these potential emissions down below those of the displaced land-based transportation, at a cost of $2,000/tonne or less, thereby both improving air quality and decongesting roadways.

Recommendations:

This present study explored ways to reduce emissions from nonroad HDD equipment and from locomotives, as well as from a possible expanded TransLink passenger ferry system, and showed that there are clean-fuel and technology options available to significantly reduce these emissions at a cost of $2,000/tonne or less.

1. Tax and other incentives should be readily available for nonroad HDD operators to use clean-fuel and technology options to reduce their emissions. Emission reduction options should be screened for cost-effectiveness, with an upper limit placed on the cost/tonne, similar to that used in California's successful Carl Moyer program.

2. A follow-up study to the present "broad-brush" study is needed to provide operators with detailed information on sources and prices of the most cost-effective emission reduction technology, as well as their performance history under similar operating conditions.

3. A more in-depth study is required to properly evaluate the applicability of idle control technology in different regions of the Province – what fraction of the year can the *SmartStart* idle control technology be used alone and what fraction of the year would the *HotShot* system also be required to keep the engine fluids warm. The study should also investigate the emission reductions attainable and the corresponding cost-effectiveness of other retrofit technologies used in conjunction with idle control technologies, such as the use of diesel oxidation catalysts and diesel particulate filters.

4. A study is required to identify economic instruments, as well as regulatory methods, for implementing the early introduction of clean fuels and emission reduction technologies into the three regions that were studied (GVRD, FVRD1 and BC). In this study consideration should be given to the differences between government-managed fleets and private fleets as the economic consequences and competitive impacts will differ.

5. Stakeholder concerns about the effect of certain emission reduction technologies upon equipment performance need to be addressed. It is recommended that pilot projects, with multi-party stakeholder funding, be initiated to demonstrate these emission reduction technologies under a wide range of actual operating conditions. These pilot projects need to be coordinated with those planned or underway in other jurisdictions and countries. (One forum for such coordination would be the *West Coast Diesel Emission Reduction Collaborative*.)

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APPENDIX A *- Rationale for Using the Health-Related Weighting Factor Scheme*

Emission reduction measures for diesel engines reduce emissions of multiple pollutants simultaneously, but to varying degrees. In some cases, an emission reduction measure can cause an increase in emissions of one or more pollutants. This range of effects on individual pollutant emissions creates a dilemma when calculating cost effectiveness ($/tonne reduced), as the simple sum of all emission changes may not reflect the changes in estimated health impacts or air quality priorities ascribed to individual pollutants, and cost effectiveness can not be determined if there is an overall increase in emissions. Preferably, the changes in emissions of individual criteria pollutants achieved by implementing an emission reduction measure could be weighted to determine an impact-weighted cost effectiveness. This approach enables the cost effectiveness calculation to reflect different priorities assigned to individual pollutants for each of the emission reductions measures for heavy-duty vehicles. Comparisons could be made with emission reductions measures applied to other sources if the same cost effectiveness methodology was applied. In this study, an impact-weighted change in emissions was calculated for each emission reduction measure as the change in $VOC+NOx+CO/7+3SOx+25PM_{10}$ emissions and then used to determine an impact-weighted cost effectiveness. This is an evolving area of policy development for determining and comparing the cost effectiveness of emission reduction measures that has had limited application in past air quality studies for the Lower Fraser Valley (Shaffer, 2001; Taylor, et.al., 2002). This weighting system for emission changes gives the highest priority to reductions in particulate matter (PM_{10}) emissions because of the large body of recent epidemiological data on the adverse health effects of PM_{10}. The weighting of NOx and VOC is 1/1, while the weighting of CO is 1/7 based on the nominal contribution of these precursor gases to ground-level ozone formation in smog-prone areas of California.

Some believe that the current scientific evidence on the effects of combinations of pollutants is presently inadequate to support a certain weighting system for individual pollutants. The weighting system used in this study was chosen because of its development and use in previous similar studies in the LFV, and the ability of this approach to differentiate the effectiveness of emission reduction measures based on a prioritization of pollutant impacts. . In 2005, the California Air Resources Board adopted a weighting system for calculating the cost effectiveness of emission reduction measures. Its approach is conceptually similar to that used in this study with the highest priority given to changes in combustion PM_{10} emissions. This system calculates the change in emissions as NOx + 10(combustion PM_{10})+ noncombustion PM_{10} + Reactive organic gases. The use of this methodology is not widespread at this time and the weighting factors that are used differ. Additional study, on a standardized basis, of the relative health damage costs of individual air pollutants would be beneficial to develop a stronger scientific foundation for the impact weighting system most appropriate for the LFV.

APPENDIX B - CPPI Position on the Application of Health Weighting Factors in Cost-Effectiveness Calculations

The Canadian Petroleum Products Institute (CPPI) is the funding partner of the BC Clean Air Research Fund and is a funding participant of this study "Reduction of Nonroad Diesel Emissions in the Lower Fraser Valley and the Rest of BC". The study's consultant was asked during the development of the report to change the methodology used to assess the cost effectiveness of the various HDDV emission reduction measures. The conventional approach of using a simple additive methodology to assess the cost effectiveness of the reduction measures for the different pollutants was replaced by a relatively new methodology that applies weighting factors for various pollutants based on the expected human health impacts of the individual pollutants. This methodology is embodied in the equation: Impact Weighted Emissions = $25*PM_{10}$ + NOx + VOC + CO/7 + 3*SOx. The results for both methodologies are included in the report but the assessment and recommendations of the report are based on the new methodology.

While the majority of the study participants agreed to the change in study scope, CPPI did not agree and does not support this change in methodology. Although CPPI has concerns about the methodologies used, we wanted to maintain funding support of the study.

CPPI has concerns about the methodology that applies health based emission weighting factors designed to place a higher priority on some pollutants versus others because we do not believe the methodology had been adequately documented nor is it adequately supported by the available science and epidemiological data.

The CPPI disagreement with the application of health weighting factors in cost effectiveness calculations is based on our understanding and interpretation of the literature on air pollution and health effects. We do not disagree with regulators seeking to further improve air quality in the region, and are willing to play our part in meeting the challenge; however, we are very concerned that the weighting scheme has no basis in fact and therefore is a poor and misleading input to discussions about preferred future policies.

The CPPI contracted with an internationally recognized scientist, Dr. Suresh Moolgavkar, to review the proposed cost effectiveness calculation. His report, Review of the Proposed Weighting Scheme for Air Pollutants in the Greater Vancouver Regional District, can be accessed on the CPPI website (www.cppi.ca under Documents), and a peer-reviewed paper by him on the same subject was recently published[1]. The CPPI fully supports Moolgavkar's conclusions; a summary of our position follows:

1. Interpretation of the results of epidemiological studies is problematic due to the small risks associated with exposure to air pollution, and the large number of

[1] Moolgavkar, S. H. A Review and Critique of the EPA's Rationale for a Fine Particulate Standard. Reg. Tox. & Pharmacol., 42 (2005) 123-144

confounders that must be controlled.

2. It is difficult, if not impossible, to single out any specific pollutant as being the principal bad actor. The investigator's choice of model to use and how to control the confounders (e.g. fine particle vs. respirable particle vs. ozone vs. nitrogen oxides vs. carbon monoxide) largely determines which specific pollutant(s) becomes the focus of the investigation. This in turn can create false expectations about which pollutant(s) need to be controlled.

3. Unlike gaseous air pollutants, Particulate Matter (PM) is not a single substance. Some PM is directly emitted from various sources (e.g. combustion processes), but its composition will vary widely according to the fuels used. Most PM is "secondary" in origin and forms when various chemical reactions take place in the air between the major gaseous pollutants like nitrogen oxides, sulphur oxides and ammonia. Given this variation, it is naïve and misleading to assume PM is a single and unchanging pollutant, when in reality it is a complex and changing chemical mixture.

4. Concentration-response relationships cannot be reliably estimated. There are very large uncertainties associated with any attempt at estimating such relationships. Thus, the current epidemiological literature cannot be used to support the proposed, or any, weighting scheme to estimate the benefits that might accrue from a reduction of air pollution levels.

5. Taken together, the epidemiology studies indicate there are associations of air pollution with adverse effects on human health. But detailed analyses, such as those carried out by Moolgavkar, confirm that our current methodology is unable to make meaningful statements regarding the individual components of the mix.

It is CPPI's position that individual pollutants are best regarded as indices of the pollution mix. Therefore actions to improve air quality should not be based on decisions using calculations of relative potency, but at a more holistic level, by looking broadly at the full suite of major gaseous and particulate contributors to air pollution. For instance, because most fine particles are "secondary" in origin, reductions in the precursor gases may be superior to other reduction techniques. We simply do not know the details to make more discriminating decisions, and therefore any reduction policy that is too focused on a presumed "highest priority" pollutant runs the serious risk of being later shown to have been a poor and costly "solution".

Policy makers need to be provided information that encourages "no-regrets" solutions and tools. CPPI believes that, given the current state of the available science, the application of health weighting factors to cost effectiveness calculations will not provide the basis for such policy. CPPI urges regulators to focus their efforts on identifying broad strategies that would deal simultaneously with both the gaseous and particulate air pollutant