TP 13445E

Marine Vessel Exhaust Emissions - Phase II (1998-99)

Prepared for
Transportation Development Centre
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by
Emissions Research and Measurement Division
Environment Canada

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by
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Un sommaire français se trouve avant la table des matières.

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16. Abstract

This report describes the work conducted during the second year of the program to investigate potential after-market control technologies for reducing exhaust emissions from marine vessels, with the focus on Canadian vessels.

A review of technologies used for reducing emissions from both on/off road heavy-duty engines and stationary sources (i.e., boilers and power generation) indicated that SCR (selective catalytic reduction) technologies, water injection, catalysts and fuel additives have the potential for reducing oxides of nitrogen (NOx) and particulate mass from marine vessel propulsion and auxiliary engines. Prior to considering sea trials, laboratory testing was conducted. Of the technologies considered, the continuous water injection system is being installed on a British Columbia ferry for on-board testing. The catalyst approach is being set up for testing on a stationary source engine similar to a marine vessel auxiliary engine.

Laboratory engine testing with the continuous water injection system indicated reductions of up to 30 percent for NOx with large Class 8 truck engines. The diesel oxidation catalyst tests resulted in 30 percent reduction in particulate mass.

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16. Résumé

Ce rapport décrit les travaux effectués durant la deuxième année du programme d'évaluation des technologies destinées au marché secondaire et permettant de réduire les émissions des navires, plus particulièrement celles des navires canadiens.

Un examen des technologies servant à réduire les émissions des moteurs de grosse cylindrée pour applications sur route et hors-route ainsi que les émissions des sources polluantes fixes (chaudières et installations de production d'énergie) a démontré que la réduction catalytique sélective (SCR), l'injection d'eau, les catalyseurs et les additifs pour carburant peuvent réduire la masse de particules et les oxydes d'azote (NO_x) provenant des moteurs de propulsion et des moteurs auxiliaires des navires. Avant d'être soumises à des essais en mer, ces technologies ont été testées en laboratoire. Une de ces technologies, l'injection continue d'eau, sera mise à l'essai sur un traversier de la Colombie-Britannique. Quant à la réduction catalytique, on est à faire les travaux préparatoires pour l'éprouver sur un moteur fixe semblable aux moteurs auxiliaires des navires.

Les essais en laboratoire d'un système à injection continue d'eau ont montré des réductions de NO_x pouvant atteindre 30 p. 100 dans le cas des gros moteurs de classe 8 pour camions. Le catalyseur d'oxydation pour moteur diesel, lors des essais, a diminué la masse de particules de 30 p. 100.

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EXECUTIVE SUMMARY

This phase of the marine vessel emissions program was initiated after extensive testing of exhaust emissions from a number of different forms of marine vessels operating on Canada's east and west coasts and in the St. Lawrence Seaway.

The focus for the exhaust emissions reductions was oxides of nitrogen (NOx) as this is the International Maritime Organization's target for its more stringent guidelines. The secondary emission of importance, due to recent health hazard pronouncements, was particulate mass.

Following a literature search to identify the various technologies that have the potential to reduce NOx from diesel engines, four were selected for consideration: SCR (selective catalytic reduction), water injection, fuel additives and oxidation catalysts. Manufacturers of these technologies were then approached to determine effectiveness and costs with cost being a major factor.

The approach to determine the effectiveness of each technology was based on laboratory optimization and verification testing. With positive results, the technology was to be installed on a vessel and 'sea trials' conducted including durability.

Of the selected technologies for 1998-99, the platinum-based fuel additive did not indicate positive results from the laboratory testing. A continuous water injection system, when laboratory tested on a mechanical fuel injected engine, indicated a 30 percent reduction in NOx without fuel penalty. This technology is being installed on an auxiliary engine on a British Columbia ferry for testing. The third technology, a diesel oxidation catalyst concept, was devised and is to be tested on a 750 hp diesel engine in July 1999.

SOMMAIRE

La présente phase du programme d'évaluation des émissions des navires a été lancée par suite de mesures intensives des émissions gazeuses menées sur divers types de navires opérant dans la Voie maritime du Saint-Laurent et dans les eaux côtières, à l'est et à l'ouest du Canada.

Le programme visait particulièrement à réduire les oxydes d'azote (NO_x), cette substance étant la cible des directives plus sévères de l'Organisation maritime internationale (OMI). Selon de récentes annonces sur les risques pour la santé, la deuxième émission en importance était la masse des particules.

Quatre technologies ont été retenues après une recherche documentaire pour inventorier les diverses technologies ayant le potentiel de réduire les émissions de NO_x par les moteurs diesel : la réduction catalytique sélective (SCR), l'injection continue d'eau, les additifs de carburant et les catalyseurs d'oxydation. Les chercheurs se sont ensuite tournés vers les fabricants de ces technologies pour déterminer leur efficacité et leurs coûts, ce dernier facteur étant un critère majeur.

La méthodologie employée pour mesurer l'efficacité de chaque technologie évaluée reposait sur des essais d'optimisation et de vérification en laboratoire. Celle ayant donné des résultats positifs devait être installée sur un navire pour des essais en mer portant également sur la durabilité.

L'additif à base de platine, une des technologies sélectionnées pour les essais de 1998-1999, n'a pas produit de résultats positifs en laboratoire. Par contre, le système faisant appel à l'injection continue d'eau et essayé en laboratoire sur un moteur à injection mécanique a réduit les NO_x de 30 p. 100, sans entraîner une augmentation de la consommation de carburant. On est à installer, aux fins d'essais, cette technologie sur un moteur auxiliaire d'un traversier de la Colombie-Britannique. Enfin, une troisième technologie, le catalyseur d'oxydation pour moteur diesel, sera mise à l'essai sur un diesel de 750 hp, au mois de juillet 1999.

CONTENTS

1. INTRODUCTION

The Emissions Research and Measurement Division (ERMD) of Environment Canada has been collaborating with the Transportation Development Centre (TDC) of Transport Canada since 1995. Phase I of this work involved the measurement of actual marine vessel exhaust emissions during regular ship activities. The emissions of concern to the International Maritime Organization (IMO), i.e. oxides of nitrogen (NOx), particulate mass (PM) and other compounds related to the combustion of fossil fuels (e.g. total hydrocarbons (THC), carbon monoxide (CO) and carbon dioxide), were measured as they exited from the main and auxiliary engines. Ocean-going tugs, car ferries, lakers, bulk freighters, cruise ships and container vessels were included in the sample of ships that were tested to develop a database of exhaust emissions from marine vessels. In conjunction with exhaust emissions, emissions generated from the loading and unloading of bulk carriers were measured. For vessels carrying petroleum products such as gasoline and kerosene, emissions from crude oil washing, ballasting and hold evaporation were also measured.

Phase II was initiated after the development of the database of emissions from Canadian vessels was designed to investigate cost-effective new technologies that had the potential to reduce exhaust emissions from both the main and auxiliary engines. The focus of the preliminary work was NOx, as IMO was in the process of setting guidelines for this emission. For 1998-99, the proposed work included the following laboratory and field-testing:

- conduct lab evaluation of a Canadian continuous water injection system, and then install the system on a British Columbia (B.C.) ferry;

- purchase fuel additive based on platinum/cerium compounds, which will reduce THC, CO, and PM, for a lab evaluation on its impact on diesel emissions during various modes of operation;

- incorporate a number of catalysts for heavy duty onroad engines into a system in the exhaust system of larger marine vessel main engines;

- use working system of a dual fuel natural gas fumigation system on a 400 hp diesel engine for optimization and testing; this system would be used for the conversion of the auxiliary engine for the Exhaust Gas Recirculation implementation.

The remainder of the report details the work conducted during 1998-99 on this project. As some of the work resulted in specific technical reports, the results are summarized in the body of this report, with reference to the detailed work in the appendices.

2. TECHNOLOGY SELECTION AND LABORATORY TESTING

The five projects that were proposed for 1998-99 were conducted as independent development and test projects. For reporting purposes each project is treated independently.

2.1 Project No. 1 - Fuel Additive

The initial work consisted of the evaluation of a diesel fuel additive developed by Clean Diesel Technologies Inc. The platinum-based additive was developed to improve combustion, thereby reducing exhaust emissions and improving fuel consumption. To evaluate this product, a laboratory test project was initiated on a Detroit Diesel Series 60. The following details the setup and results of the work.

2.1.1 Procedures

The objective of the testing was to determine the impact of the platinum additive on the engine out emissions under two scenarios: continuous use of the fuel additive and dosing the fuel for specific modes of operation.

To simulate the operation of a marine engine, a torque versus engine rpm cycle was created based on the engine operation of a typical BC ferry propulsion engine. The engine was then operated over this cycle using No.2 low sulfur diesel fuel to determine the exhaust emissions of the baseline case. The additive was then added to the diesel fuel as per the specifications of the manufacturer and the testing repeated. The results of the testing did not indicate any significant differences in either exhaust emissions or fuel consumption. Test data in Appendix C summarizes these assessments.

As the continuous application of the additive to the combustion did not alter the exhaust emissions, it was decided to not pursue the dosing aspect of the testing. No additional work was conducted on the additive.

2.2 Project No. 2 - Continuous Water Injection (Electronic Fuel Injection)

MA Turbo/Engine Design provided a prototype continuous water injection (CWI) system for laboratory testing at ERMD on a Caterpillar 3406. The system was set up by representatives from the company for injection of the water in two locations: after the engine's turbocharger, and before and then after the intercooler. The system control for the water pressure and volume to be injected was manual in nature, but the company is planning to produce a microprocessor-controlled model for future marine vessel testing.

With the CWI installed, approximately 50 hours of exhaust emissions and fuel consumption testing was conducted to determine the impact of the CWI in the engine's air inlet. Parameters such as water injection pressure, volume injected and injection location were varied to determine their impact on the exhaust temperature, air inlet temperature, power, exhaust emissions and fuel usage.

The test results did not indicate an increase in horsepower or a decrease in fuel consumption as had been indicated by MA Turbo/Engine Design. It was theorized that the electronic controls on the fuel management system were in some way compensating for the water being introduced into the combustion chamber, thus negating the potential benefits. A detailed technical report on this testing is included in Appendix B.

2.3. Project No. 3 - Continuous Water Injection (Mechanical Fuel Injection)

As a result of the concerns expressed by the manufacturer relating to electronic fuel injection, a second test program was established to conduct the same testing on an engine using mechanical fuel injection.

A second aspect to the testing was included, involving the measurement of combustion pressure by a new technology being developed through another TDC program. To accommodate the installation of the sensor for the device, a new cylinder head was acquired and a hole was machined into the combustion chamber. In addition, accurate speed and position sensors were installed on the engine.

The testing was then repeated as per the test sequence developed for the initial testing on the electronic fuel injection engine. The results indicated reductions in NOx exhaust emissions and potential reductions in fuel consumption. A detailed technical report is included in Appendix A.

Testing for combustion pressure measurement was delayed because the related software required for the system was not available.

2.4 Project No. 4 - Field Evaluation of the Continuous Water Injection System on a BC Ferry

After the positive results from the mechanical fuel injection engine test, an outline was established for installation of the water injection system on a BC ferry. The preliminary plan was to install a unit on one of the main engines of the *Queen of New Westminster*, which was in the process of a refit. Due to a number of delays, the project was modified to install the water injection system on one of the auxiliary engines for initial verification and durability tests. Testing is planned for the summer of 1999-2000.

2.5 Project No. 5 - Diesel Oxidation Catalysts

The second priority emission from marine vessels is particulate mass. Technologies have been developed to remove this emission from other applications where fossil fuels are used for combustion. For stationary sources, such as boilers and power generation, electrostatic precipitators and baghouses are used to collect PM. For other modes of transportation, specifically onroad vehicles and construction/mining equipment, particulate traps and diesel oxidation catalysts have been developed that have the potential to remove from 20 to 90 percent of the particulates from the exhaust streams. However, problems still exist with some of these technologies, primarily the regeneration/durability of particulate traps.

As particulates from diesel engines were recently identified by the California Air Resources Board as a human health hazard no matter the size of the particulate, it was decided to include a project to develop a system to reduce particulates from marine vessel diesel engines. As the cost associated with the design and development of a system specific to a small marine diesel engine, (i.e. 3000 to

5000 hp) was beyond the scope of this project, a concept was designed to incorporate existing technologies.

3. CONCLUSIONS

3.1 Platinum-based Fuel Additive

The testing conducted on the platinum-based fuel additive did not indicate the exhaust emissions reductions that had been suggested by the manufacturer. Two other aspects of the fuel additive that do not support its use are the expense to the operator and the additional burden of platinum emissions to the environment without significant exhaust emissions reductions.

3.2 Diesel Oxidation Catalysts

This technology was extensively tested in the laboratory and in the field. Recent testing conducted by Environment Canada on urban bus applications indicated that the technology continues to be effective in reducing particulate emissions by up 30 percent after 2500 hours of field use. In addition, hydrocarbon and carbon monoxide exhaust emissions are also reduced by as much as 20 percent, depending on the application.

A system design could be developed specifically for a marine engine; however, the cost would be prohibitive and the end product would not be cost-effective for the marine operator. Therefore, the approach of incorporating existing technologies into a design for marine engines would be more cost-effective.

3.3 Continuous Water Injection System

The laboratory testing indicated the potential for NOx reductions of up to 30 percent without a fuel consumption penalty. The potential exists for similar results on a marine diesel engine, provided that an automated control system exists to accurately monitor flow rates and pressures.

4. RECOMMENDATIONS

To proceed with the work to reduce marine vessel exhaust emissions, the following work plans are proposed:

- Conduct field verification testing on the continuous water injection system when it has been installed on a BC ferry marine engine.

- Develop and optimize the diesel oxidation catalyst system for laboratory verification testing and installation on a marine engine for field evaluation.

- Evaluate a diesel fuel emulsion for marine engines to reduce NOx and particulate mass. Conduct preliminary tests on a 750 hp caterpillar engine with an on-board emulsifier. Implement a system on a marine vessel for evaluation.

- Conduct particulate size measurements on the exhaust stream from marine vessel propulsion engines operating on marine diesel oil and bunker C to enhance the knowledge of particulates from this source. This information will support the development of particulate emissions control technologies.

APPENDIX A

Technical Report of Water Injection Testing on a Mechanical Fuel Injected Diesel Engine

1.0 INTRODUCTION

Government environmental agencies in North America have enacted more stringent mobile source emissions standards thus demanding that fleet operators seek out technologies and products that improve diesel exhaust emissions while ensuring no negative effects on fuel consumption.

Turbodyne Systems Incorporated and MA Turbo/Engine Design of Vancouver, British Columbia, supply design and emissions improvement technologies to the diesel engine market. In August 1998, Turbodyne arranged with the Emissions Research and Measurement Division (ERMD) of Environment Canada to conduct a controlled test program on a 1995 Caterpillar 3406E 455 hp engine with the intent of demonstrating the performance of their Continuous Water Injection (CWI) product.

The program's anticipated results would allow Turbodyne Systems Incorporated and MA Turbo/Engine Design to establish the ability of their products to benefit the gaseous exhaust of a multi-cylinder diesel engine in operation.

1.1 Emissions Research and Measurement Division

ERMD is a Canadian federal government laboratory. Its mandate is to investigate the pollutant emissions from vehicles and to evaluate industry-related devices that are designed to benefit the environment (e.g. fuel consumption improvements, pollutant reductions.)

The lab participates annually in the joint EPA-AAMA (American Automobile Manufacturer's Association) round-robin emissions cross-correlation study. This is part of ERMD's commitment to emissions measurement quality assurance/quality control within the community of North American mobile source emissions test facilities.

1.2 Background on Diesel Engine Exhaust

The overall chemical reaction of combustion is:

[1]

$$\text{Fuel} + \text{Oxidant} \longrightarrow \text{Products} + \text{Heat Release}$$

For the compression ignition / internal combustion of diesel engines, the fuel used is a hydrocarbon liquid (approx. $C_{14.4}H_{24.9}$) and the oxidant comes from ambient air (approx. 21% oxygen and 79% nitrogen by volume). The heat released from the reaction is converted into usable power by its expansion of the product gases that, in turn, push the engine piston. Ideally, the above reaction [1], which comprises hundreds of intermediate chain reaction steps, becomes:

[2]

$$\begin{aligned}\text{Diesel Fuel}\,(C_{14.4}H_{24.9}) + \text{Air}\,(21\%\ O_2 + 79\%\ N_2) \longrightarrow\ & \text{Carbon Dioxide} + \text{Water Vapour} \\ & + \text{Nitrogen} + \text{Mechanical Energy}\end{aligned}$$

The ideal situation of reaction [2] describes COMPLETE combustion where all of the carbon in the fuel is reacted to form carbon dioxide (CO_2) and all of the hydrogen in the fuel reacted to form water (H_2O). The nitrogen gas (N_2), though resident in the air, is not considered affected in this theoretical scenario.

In reality, combustion in diesel engines is never complete. This shortcoming occurs when the chain reactions of combustion are arrested at some intermediate step. In the region surrounding the flame, reaction interruptions occur due to an insufficient provision of oxygen (rich mixture) or due to excessive heat loss (quenching). The first product of incomplete combustion to appear is usually carbon monoxide (CO) as its reaction to CO_2 is slower than rates of the other reactions in the chain. A worsening of conditions may result in the appearance of various hydrocarbons from the broken reaction chains. In the hottest areas of the combustion chamber where there is an excessive fuel presence (rich zone), solid carbon particles are produced which then enter the exhaust in the form of soot.

Besides the CO and the unburned hydrocarbons of incomplete combustion, oxides of nitrogen (NO and NO_2 - generally referred to as NOx) are a considerable product. They are formed by the reaction between atmospheric N_2 and O_2 at high temperatures and will remain in the products as the exhaust gases cool coming out of the exhaust manifold.

Other gaseous emissions of interest are the oxides of sulphur (generally referred to as SO_X). These are an inevitable by-product of the combustion owing to the trace amounts of sulphur (≤0.05% by mass) resident in commercial diesel fuel.

The overall reaction that best describes the combustion in a compression ignition (CI) of a diesel engine can then be presented as:

$$\begin{aligned}\text{Diesel Fuel} + \text{Air} \xrightarrow{\text{compression}} & \text{Carbon Dioxide} + \text{Carbon Monoxide} + \text{Water} \\ & + \text{Oxygen} + \text{Nitrogen} + \text{Oxides of Nitrogen} \\ & + \text{Hydrocarbons} + \text{Oxides of Sulfur} \\ & + \text{Particulates} + \text{Mechanical Energy}\end{aligned} \quad [3]$$

or in simpler notation:

$$\begin{aligned}Diesel\ Fuel + Air \xrightarrow{\text{compression}} & CO_2 + CO + H_2O + O_2 + N_2 + NO_X + THC \\ & + SO_X + PM + Mechanical\ Energy\end{aligned} \quad [4]$$

With regard to the reactant quantities, diesel fuel is injected at a rate of approximately 1 part fuel to 18 parts air into the combustion chamber. This ratio takes into account that diesel engines operate in a significantly lean regime from stoichiometric (i.e. $\phi \leq 0.8$). Figure A-1 shows the mass balance of a typical diesel engine's operation.

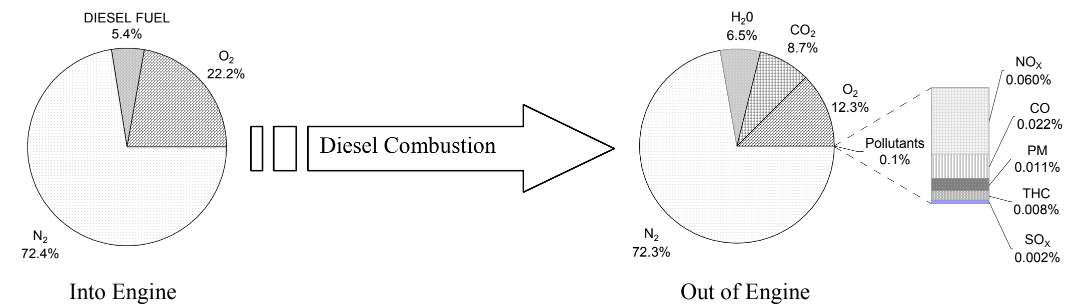


Figure A-1: Typical Diesel Engine Combustion Mass Balance ($\phi \leq 0.8$)

1.3 The Environmental Effects of Diesel Exhaust

Of diesel engine exhaust, it is CO, hydrocarbons (HC), NOx, and soot particulate that are of greatest concern to environmental regulatory bodies. It should be noted that CO_2 is, in fact, a favourable product of combustion. As shown in reaction [2], carbon dioxide's formation indicates the completeness of combustion.

The rationale for reducing the undesirable pollutant emissions from internal combustion engines is appreciated when some of the biological effects are considered.

Carbon Monoxide

CO is the most dangerous pollutant that internal-combustion engines emit. It is poisonous to all forms of life. Inhalation of this gas removes oxygen from the blood and prolonged exposure can be fatal.

Unburned Hydrocarbons

The environmental impact of gaseous varieties of HCs is apparent in the formation of photochemical smog. Specific hydrocarbons, referred to as Volatile Organic Compounds (VOCs), are those compounds known to be reactive. The most hazardous component of this smog is referred to as ground-level ozone.

Human exposure to ozone can diminish lung capacity and cause other respiratory problems. Plant life has also been shown to exhibit retarded growth patterns during prolonged exposure to ozone.

Oxides of Nitrogen

Once dispersed into the atmosphere, NOx will decompose with certain hydrocarbon compounds (VOCs – see above) to form smog, or it will combine with atmospheric moisture and create acid rain. This by-product of combustion is also known to be poisonous to the environment. Concentrations found in exhaust gases will cause immediate irritation in the mucous membranes upon inhalation.

Particulate Matter

The fine, dark coloured soot visible in the exhaust of diesel engines is known as particulate matter (PM). This solid substance is composed mainly of ash or carbon. It is hazardous to all forms of life because of the carcinogenic properties found with the particulate's secondary constituents. (i.e. not the fixed carbon).

2.0 DESCRIPTION OF TEST PROGRAM

2.1 Test Plan

The project outline for the engine testing is contained in Annex A-1. The program was conducted in accordance with the procedures outlined in the Canadian Motor Vehicle Safety Standards (CMVSS) and the USA's EPA Code of Federal Regulations (CFR).

As per the work statement, a series of Marine Test Simulation Protocol emissions dynamometer tests would be performed on a heavy-duty diesel engine in two configurations: the engine operating with and without the CWI in operation.

i) The ***baseline test*** configuration would use conventional #2 low sulphur diesel (LSD #2) as the fuel and SAE 15W40 lubricating oil. This test configuration would be used at the outset and conclusion of the program.

   It should be noted that new filters (fuel and oil), as well as a fresh charge of lubricant had been installed on the test engine at the outset of the previous performance test program. This allowed that the engine's filters and oil for initial baseline configuration testing had already aged to approximately 50 hours of operation.

ii) The ***device-operational test*** configuration would have the CWI installed (per Turbodyne's instructions) as in Figure A-2 and operating at a pre-set injection pressure.

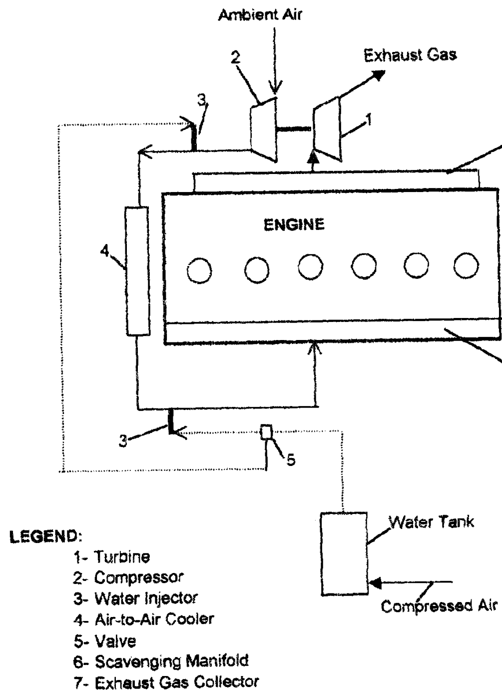


Figure A-2: Schematic of CWI System Installation on the CAT 3406E Engine at ERMD

2.2 Test Engine and Dynamometer Description

The test stand used for this program was a stock Caterpillar 3406E diesel engine and an electronically controlled dynamometer with specifications as listed in Table A-1.

Engine	1995 Caterpillar 3406E (ERMD #97-322) Ser. # 5EK66959, Arr. # 127-5526
Rated Shaft Output	Maximum power = 450 [BHP] @ 1800 [rpm] Maximum torque = 1550 [ft-lb] @ 1200 [rpm]
Size	14.6 litres (inline 6 cylinder)
Operation	4 cycle, turbocharged, air-to-air charge cooling
Fuel	LSD #2
Throttle Control	Electronic Control Module (ECM)
Dynamometer	500 hp electric, regenerative power absorption

Table A-1: ERMD Test Stand Specifications

The engine in the ERMD heavy-duty emissions test cell is shown in Figure A-3.

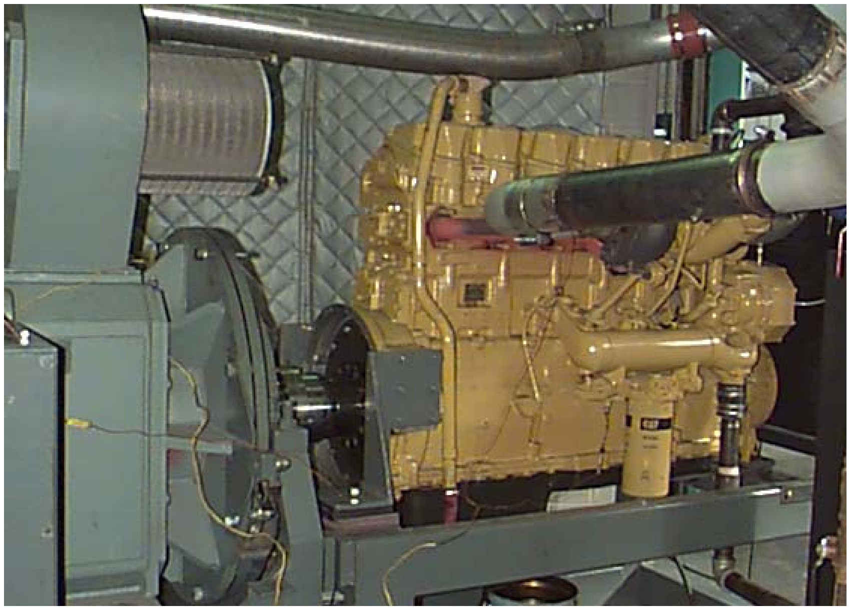
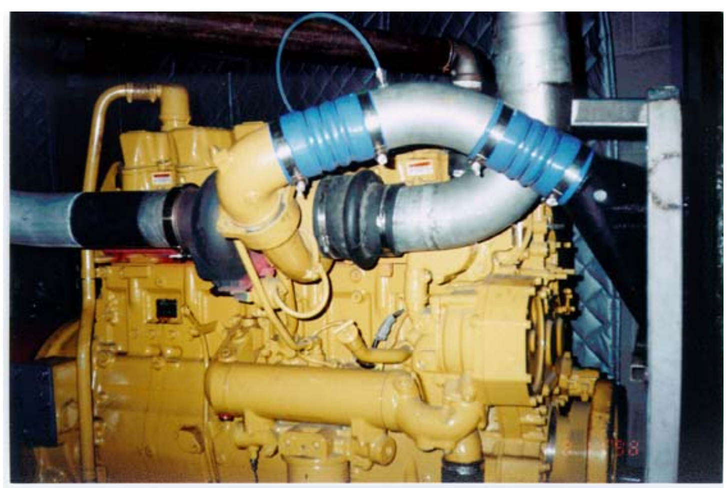


Figure A-3: ERMD Test Engine

2.3 Installation of the CWI system

The demonstrated CWI system consisted of an atomizing nozzle releasing potable water from a pressurized supply tank into the engine's intake air stream. The first test series had the water injection immediately after the compressor, ahead of the air-to-air cooler, and the second test series had the injection after the air-to-air cooler (intercooler), ahead of the intake manifold. Figure A-4a and Figure A-4b show the installation.



FigureA-4a: CWI between Compressor and Air-to-Air Charge Cooler

Figure A-4b: CWI between Air-to-Air Charge Cooler and Intake Manifold

2.4 Fuel Description

The LSD#2 diesel fuel used in the test program was drawn from a single batch with properties as shown in Table A-2.

Specific Gravity	0.8343
Carbon Fraction (by mass)	0.875
Net Heating Value	19753 [BTU/lb.]

Table A-2: Test Diesel Fuel (LSD #2) Analyzed Properties

2.5 Test Cycle

The dynamometer test cycle was the Marine Test Simulation Protocol for stationary heavy-duty diesel engines on an engine dynamometer. The torque and speed values used to generate the test cycle trace come from plots of the engine's performance mapping shown in Table B-3. Using the mapping's output torque versus engine speed values, the Marine Test Simulation Protocol cycle was established. Traces of the speed and torque for the cycle are plotted in Figure A-5.

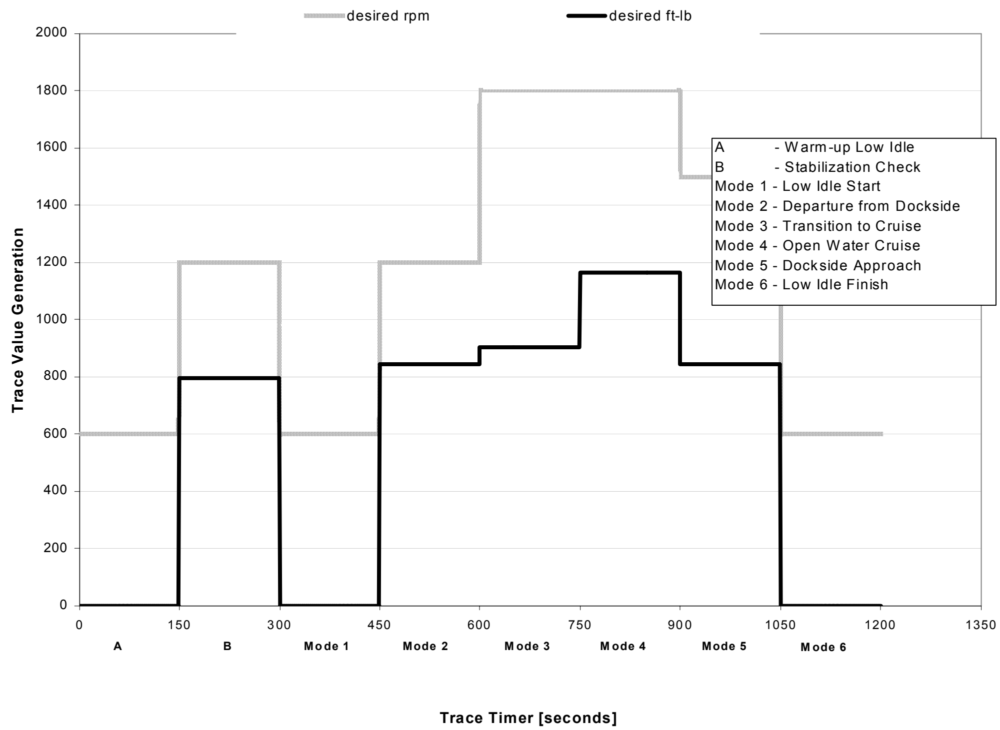


Figure A-5: Plots of Speed and Torque for the Marine Simulation Test Protocol

2.6 Emissions Analysis Apparatus

The emissions collection apparatus made use of a constant volume sampling (CVS) system that dilutes the engine exhaust during a test with ambient air from the test cell. A schematic of the test cell is shown in Figure A-6. This allows measurement of the true mass of the gaseous and particulate emissions from the engine's operation.

During the test, a continuously proportioned dilute exhaust sample is drawn from the CVS. Temperature and pressure sensors in the region of the venturi and sampling zone allow correction of volumetric flow rate to standard conditions. The exhaust sampling is finally measured by detector response (in real time) for gaseous emissions concentrations and by filter weight gain for the PM emissions. Fuel consumption was measured with an electronic gravimetric fuel meter. The following list details the equipment used:

- Oxides of Carbon (CO and CO_2) – Horiba AIA-23 infrared detectors
- Total hydrocarbons (THC) – Pierburg FID 2000 heated flame ionization detector
- Oxides of Nitrogen (NOx) – Pierburg CLD 2000 heated chemiluminesence detector
- Particulate Matter (PM) – double dilution gravimetric analysis
- Fuel Consumption – AVL 733S gravimetric fuel meter

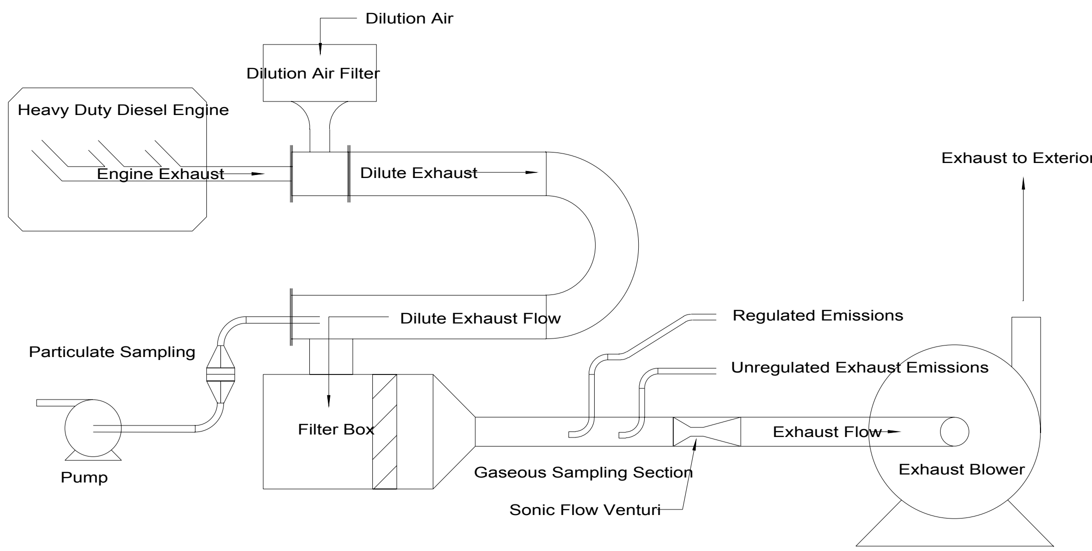


Figure A-6: Heavy-Duty Engine Test Cell Exhaust Emissions Sampling System

3.0 RESULTS

The tabulated values for the Marine Test Simulation Protocol runs are shown in Tables A-4, A-5 and A-6 for the test dates August 19 and August 20, 1998. The engine runs were conducted as follows in Table A-3.

Date	Water Injection Location On Engine	Details	Water Injection (on modes 3-5 only)
8/19/98		Baseline initial	None
8/19/98	Between the turbocharger and intercooler	Injection at 50 psig	0.256 [litres/min.]
8/19/98		Injection at 70 psig	0.358 [litres/min.]
8/19/98		Injection at 80 psig	0.390 [litres/min.]
8/19/98		Injection at 90 psig	0.430 [litres/min.]
8/19/98		Injection at 80 psig	0.385 [litres/min.]
8/19/98		Baseline final	None
8/20/98		Baseline initial	None
8/20/98		Constant flow (~50 psig)	0.333 [litres/min.]
8/20/98		Injection at 70 psig	0.358 [litres/min.]
8/20/98		Injection at 80 psig	0.403 [litres/min.]
8/20/98		Injection at 85 psig	0.435 [litres/min.]
8/20/98		Baseline final	None

Table A-3: Caterpillar 3406E/CWI Configuration on Marine Test Simulation Protocol Runs

Test data was collected and is presented in the format consistent the testing outline presented in Annex A-2 with use of EPA protocol for exhaust emissions calculations (CFR Title 50 Part 86.1342-90) where applicable.

The results are summarized for modes 3 (transition to cruise), 4 (open water cruise), and 5 (dockside approach) in Tables A-4, A-5, and A-6, respectively.

Date	Water Injection [Litres/min]	CO_2 $\left[\frac{g}{bhp \cdot hr}\right]$	CO $\left[\frac{g}{bhp \cdot hr}\right]$	NOx $\left[\frac{g}{bhp \cdot hr}\right]$	BSFC $\left[\frac{g}{bhp \cdot hr}\right]$	Temp. After [deg.C]	Temp. Exhaust [deg.C]	Turbo out [psia]	Engine Power [bhp]
8/19/98	Baseline	458.69	0.21	1.29	141.23	71.07	371.97	27.12	311.20
8/19/98	0.256	454.46	0.16	1.00	140.65	40.00	354.14	27.30	311.41
8/19/98	0.358	458.64	0.20	0.92	140.62	39.12	350.05	27.14	311.26
8/19/98	0.376	461.95	0.16	0.89	140.69	39.85	349.97	27.30	311.39
8/19/98	0.430	VOID	VOID	VOID	VOID	VOID	VOID	VOID	VOID
8/19/98	0.385	454.17	0.13	0.87	139.97	40.00	348.68	27.51	312.57
8/19/98	Baseline	457.92	0.17	1.24	141.16	70.65	373.34	26.95	311.56
8/20/98	Baseline	453.70	0.35	1.17	140.69	67.22	366.92	26.84	311.31
8/20/98	0.333	456.73	0.28	0.90	144.07	35.03	356.68	27.26	311.93
8/20/98	0.358	469.65	0.29	1.05	141.73	44.04	382.28	27.61	310.88
8/20/98	0.403	466.11	0.30	0.88	142.28	35.99	355.86	27.14	310.94
8/20/98	0.435	468.21	0.28	0.89	142.11	36.64	357.14	27.13	311.38
8/20/98	Baseline	458.48	0.29	1.24	142.71	72.98	376.06	26.96	311.18

Table A-4: Emission Results from Mode 3 (Transition to Cruise) of Marine Simulation Engine Operating Schedule

Date	Water Injection [Litres/min.]	CO_2 $\left[\frac{g}{bhp \cdot hr}\right]$	CO $\left[\frac{g}{bhp \cdot hr}\right]$	NOx $\left[\frac{g}{bhp \cdot hr}\right]$	BSFC $\left[\frac{g}{bhp \cdot hr}\right]$	Temp. After [deg.C]	Temp. Exhaust [deg.C]	Turbo out [psia]	Engine Power [bhp]
8/19/98	Baseline	456.10	0.16	1.08	141.00	91.94	429.65	31.65	400.27
8/19/98	0.256	451.01	0.12	0.88	140.79	78.26	409.97	31.67	400.60
8/19/98	0.358	457.54	0.16	0.81	141.12	73.87	406.87	31.66	399.31
8/19/98	0.376	462.78	0.12	0.78	140.85	71.20	403.97	31.55	399.00
8/19/98	0.430	VOID	0.11	VOID	VOID	VOID	VOID	VOID	VOID
8/19/98	0.385	457.47	0.11	0.75	141.35	68.39	402.84	31.70	399.37
8/19/98	Baseline	456.21	0.14	1.05	141.55	91.94	429.92	31.51	400.15
8/20/98	Baseline	455.81	0.28	0.91	141.27	90.00	426.95	31.54	399.95
8/20/98	0.333	455.42	0.20	0.76	142.58	42.84	413.33	31.41	400.48
8/20/98	0.358	469.24	0.23	0.92	142.59	52.37	450.39	32.15	399.32
8/20/98	0.403	466.20	0.22	0.76	142.61	44.08	412.89	31.53	398.79
8/20/98	0.435	469.55	0.21	0.77	142.00	43.95	414.93	31.42	399.78
8/20/98	Baseline	458.91	0.23	1.05	142.00	95.47	433.77	31.41	399.93

Table A-5: Emission Results from Mode 4 (Open Water Cruise) of Marine Simulation Engine Operating Schedule

Date	Water Injection [Litres/min.]	CO_2 $\left[\frac{g}{bhp \cdot hr}\right]$	CO $\left[\frac{g}{bhp \cdot hr}\right]$	NOx $\left[\frac{g}{bhp \cdot hr}\right]$	BSFC $\left[\frac{g}{bhp \cdot hr}\right]$	Temp. After Intercooler [deg.C]	Temp. Exhaust [deg.C]	Turbo out [psia]	Engine Power [bhp]
8/19/98	Baseline	455.48	0.32	0.94	140.88	44.83	452.64	19.38	193.78
8/19/98	0.256	449.04	0.27	0.64	139.80	26.60	428.75	19.59	194.50
8/19/98	0.358	450.21	0.34	0.60	140.06	26.78	425.46	19.71	194.06
8/19/98	0.376	458.96	0.31	0.59	140.29	27.16	424.48	19.70	194.23
8/19/98	0.430	VOID	VOID	VOID	VOID	VOID	VOID	VOID	VOID
8/19/98	0.385	453.70	0.32	0.57	140.48	27.16	422.77	19.71	193.90
8/19/98	Baseline	451.97	0.26	0.92	140.60	45.38	455.42	19.33	194.02
8/20/98	Baseline	452.58	0.60	0.85	140.11	42.49	451.85	19.34	194.13
8/20/98	0.333	454.92	0.58	0.64	142.25	24.17	430.27	19.51	193.82
8/20/98	0.358	470.64	0.62	0.68	148.29	34.65	474.15	19.88	193.74
8/20/98	0.403	465.22	0.73	0.62	142.79	25.21	425.97	19.57	193.71
8/20/98	0.435	467.94	0.82	0.63	143.03	25.18	427.45	19.62	193.32
8/20/98	Baseline	458.27	0.48	0.92	142.93	45.96	457.47	19.38	193.46

Table A-6: Emission Results from Mode 5 (Dockside Approach) of Marine Simulation Engine Operating Schedule

A weighted-average calculation based on the factors (W) of Table A-1-1 of Annex A-1 allows comparison of integrated test values representative of the entire 6-mode marine simulation. The calculation is of the following form:

[5]

$$\text{Weighted Measurement} = \sum_{i=1}^{6}\left[W_i \times (\text{measurement value})_i\right]$$

where W refers to a weighting factor and subscript *i* refers to the mode of the schedule.

The summarized results for the weighted-average tabulation are shown in Table A-7.

Date	Water Injection [*Litres/min.*]	CO_2 $\left[\frac{g}{bhp \cdot hr}\right]$	CO $\left[\frac{g}{bhp \cdot hr}\right]$	NOx $\left[\frac{g}{bhp \cdot hr}\right]$	PM* $\left[\frac{g}{bhp \cdot hr}\right]$	BSFC $\left[\frac{g}{bhp \cdot hr}\right]$	Temp. After Intercooler [*deg.C*]	Temp. Exhaust [*deg.C*]	Turbo out [*psia*]	Engine Power [*bhp*]
8/19	Baseline init.	456.36	0.22	1.06	0.033	141.2	71.2	424.7	26.6	314.7
8/19	0.256	451.10	0.18	0.81	0.032	140.5	54.1	404.8	26.8	315.1
8/19	0.358	455.46	0.23	0.76	0.031	140.7	51.9	401.6	26.8	314.3
8/19	0.376	461.69	0.20	0.73	0.030	140.7	50.8	400.0	26.7	314.2
8/19	0.430	VOID	0.23	VOID	VOID	VOID	VOID	VOID	VOID	VOID
8/19	0.385	455.84	0.19	0.70	0.032	140.8	49.4	398.5	26.8	314.5
8/19	Baseline fin.	455.41	0.19	1.03	0.025	141.1	71.4	426.2	26.5	314.7
8/20	Baseline init.	453.99	0.40	0.93	0.033	140.8	68.9	422.6	26.5	314.6
8/20	0.333	455.89	0.35	0.74	0.034	142.6	34.7	407.7	26.6	314.9
8/20	0.358	469.27	0.38	0.85	0.036	143.8	44.2	442.5	27.1	314.2
8/20	0.403	465.81	0.42	0.73	0.041	142.5	35.9	405.5	26.7	313.9
8/20	0.435	469.12	0.43	0.74	0.042	142.3	35.9	407.1	26.6	314.3
8/20	Baseline fin.	458.04	0.32	1.03	0.021	142.2	73.8	429.1	26.5	314.4

Table A-7: Weighted Emissions Results from 1995 Caterpillar 3406E on Marine Test Simulation Protocol Runs

4.0 REVIEW OF DEMONSTRATION RESULTS

4.1 Comparative Analysis

The data from the weighted-average tabulation in Table A-7 is a compendium of the modal data that came from specific operating conditions (i.e. water injection pressure or injection location as detailed in Table A-3). For this reason, a statistical study could not be undertaken, but a direct comparison can be presented. This comparison is simply the percent relative difference on each single test point to the corresponding value of the initial baseline for each test day.

* the particulate emission is a time average not weighted-average number for comparison

[6]

$$\text{Measurement \% Relative Difference} = \frac{\text{measurement value} - \text{inital baseline value}}{\text{inital baseline value}} \times 100\%$$

In Table A-8, the CWI data relevant to the study is compared by way of the percent relative difference to the initial baseline results, except for the exhaust temperature, which is simply a degree Celsius difference from the initial baseline value.

Date	Water Injection [*Litres/min.*]	NOx [*mass*]	PM* [*mass*]	BSFC [*mass*]	Exhaust Temperature [*deg.C*]	Turbo out Pressure	Engine Power
8/19/98	Baseline init.	datum	Datum	datum	datum	datum	Datum
8/19/98	0.256	-23.3%	-2.1%	-0.5%	-19.9	+0.4%	+0.1%
8/19/98	0.358	-28.7%	-5.6%	-0.3%	-23.0	+0.5%	-0.1%
8/19/98	0.390	-31.0%	-8.4%	-0.4%	-24.6	+0.3%	-0.2%
8/19/98	0.430	VOID	VOID	VOID	VOID	VOID	VOID
8/19/98	0.385	-33.5%	-2.9%	-0.2%	-26.2	+0.7%	-0.1%
8/20/98	Baseline init.	datum	Datum	datum	datum	datum	Datum
8/20/98	0.333	-20.4%	+3.7%	+1.3%	-14.8	+0.3%	+0.1%
8/20/98	0.358	-7.9%	+10.3%	+2.1%	+19.9	+2.3%	-0.1%
8/20/98	0.403	-21.0%	+24.4%	+1.2%	-17.1	+0.5%	-0.2%
8/20/98	0.435	-20.3%	+27.3%	+1.1%	-15.5	+0.3%	-0.1%

Table A-8: Relative Difference of the Weighted Data Points to the Weighted Initial Baseline Values

4.2 Observations and Discussion

The general trend given by Table A-5 is that the operation of the CWI device impacts the NOx and PM emissions and the temperature of the exhaust out of the turbocharger.

The test runs done when the CWI operated between the compressor and air-to-air cooler (Aug. 19) show that the mass emission of NOx was reduced from 23.3 to 33.5 percent. This improvement is observed when the water injection is increased from 0.26 up to 0.39 [litres/min.] and the mass is compared to the initial baseline test data of that day. Particulate mass also reduced from 2 to 8.4 percent for these same test runs. Exhaust temperatures are reduced by roughly 20°C to as much as 26°C for the same test runs. The fuel consumption record shows a reduction of as much as 0.5 percent with water injection 0.26 [litres/min.] though this impact was found to lessen as the water injection rate increased. The energy expended to provide the water injection could not be quantified, but it is understood that this assessment would reduce whatever benefits are apparent in the measure of the brake specific fuel consumption.

* The particulate emission is a time average not weighted-average number for comparison

The test runs done when the CWI operated between the air-to-air cooler and the intake manifold (Aug. 20) show less influence on NOx with the volume of water injected, but generally it is observed that the mass emission of NOx to be reduced by 20 percent. This is in comparison to the initial baseline test data of that day. Particulate mass is conversely increased by 4 percent to as much as 27 percent for the same test runs. Exhaust temperatures are reduced by approximately 15°C, though there is no clear trend as water injection volume is increased. Unlike the previous test series' data, the fuel consumption on this series of test runs show increases by as much as 2 percent.

4.3 Conclusions and Recommendation

A general conclusion that can be made on this CWI demonstration study is that the best results, in terms of emissions benefit to the NOx and particulate matter, can be found with the water injection between the compressor and air-to-air charge cooler. An additional point of interest is that this configuration provided no negative effects to the other test data (i.e. fuel consumption, boost pressure, shaft power) from the Caterpillar 3406E engine's operation.

One strong recommendation is that a thorough laboratory study be undertaken to provide some measure of statistical significance to the cursory data presented here. This would provide more conclusive evidence to support the CWI product's beneficial impact on diesel engine pollutant emissions. It is recognized that the present study provided a valid demonstration of the CWI but did not allow for repetitive study of the various test configuration and injection pressures.

The demonstration of this product was done under 'ideal conditions' in a certified laboratory on a secure, well-tuned engine over a short time frame. The observations obtained are particular to the test engine and should not be taken out of the demonstration program's context.

ANNEX A-1 PROJECT OUTLINE

Marine Test Simulation Protocol at ERMD August 1998

INTRODUCTION

This protocol was derived in large part by the standards set out by the MAPTEST (Manufacturer's Protocol for Exhaust Systems Testing) as issued by Natural Resources Canada (document #MMSL 97-064, September 1997) and the ISO/DIS 8178-4 Reciprocating Internal Combustion Engine – Exhaust Emission Measurement specifications.

OPERATION TEST CONDITIONS FOR EACH ENGINE CONFIGURATION

Both the 'baseline test' and the 'CWI test' engine configurations will be conducted under a series of steady-state load conditions that relate to a typical marine duty cycle: more specifically, for the operation of a ferry from dockside departure, to cruise transition, to cruise, and finally to dock approach speed transition. The steady state operation points are based on ERMD field test experience with marine vessels, as well as review of the Final Report of Marine Emissions Quantification in the GVRD for the BC Ferry Corp. (97/EE/7002 issued September 1997).
The conditions of the 6-mode test are as shown in Table A-1-1.

MODE	DESCRIPTION OF SIMULATION	SPEED[a] (values of CAT3406E)	LOAD[b]	WEIGHING FACTOR[c]
1	Low idle	(600 rpm)	0%	0
2	Departure from dockside	Intermediate (1200 rpm)	10%	10
3	Transition to cruise	Rated (1800 rpm)	70%	15
4	Open water cruise	Rated (1800 rpm)	90%	50
5	Dockside approach	Intermediate (1200 rpm)	50%	25
6	Low idle	0	0%	0

Table A-1-1: Marine Simulation Engine Operating Schedule

[a] Rated and Intermediate are the engine speeds of max. power and torque, respectively, as obtained by the engine mapping.

[b] Percent load is the fraction of the maximum available torque (obtained by the engine mapping) at the given engine speed.

[c] Weighing factors are used to calculate the integrated measurement values.

The engine will follow the following routine to generate test results:

- The engine will be started at low idle speed and operated for 2.5 minutes.
- The engine will then be operated at 50 percent of full load at the intermediate speed for 2.5 minutes to confirm the stabilization of the measurement signals.
- The engine will then be operated in each of the test modes for 2.5 minutes where measurement recording will occur for the final minute of each mode.
- At the conclusion of the sixth mode, the engine will be shut off for a period of 20 minutes to allow a temperature restabilization before conducting any subsequent 6-mode test schedules.

It is suggested that completing **five** such 6-mode test schedules would suffice to provide statistical significance to the final analysis of test results.

The engine test bed is operating within the manufacturer's recommended specifications with the exhaust backpressure adjusted to the maximum allowable at the engine's full rated operation.

RECORDED MEASUREMENTS DURING EACH STEADY STATE POINT

For each steady state operating point shown in Table A-1-1, a number of relevant measurements will be recorded by the data acquisition system. The recorded values are taken in real time (approx. 4 Hz) and are integrated over the steady state time period. These measurements are shown in Table A-1-2.

MEASUREMENT	VALUE	DETAILS
CO, CO_2	ppm grams/bhp-hr	IR detection (Horiba analyzers)
NOx	ppm grams/bhp-hr	CL detection (Pierburg analyzer)
THC	ppm grams/bhp-hr	FI detection (Pierburg analyzer)
Particulate Matter	grams/bhp-hr	Gravimetric analysis
Engine / Dynamometer Operation (shaft speed, torque, power)	rpm ft-lb bhp	Tachogenerator Electronic Load Cell Transducer Dynamometer Trace Reference Values
Fuel Consumption	kg / hr	AVL Fuel Meter
Temperature Probes (engine air inlet, exhaust manifold, oil sump, fuel inlet, coolant, dilution tunnel)	deg. C	K , J-type thermocouples

Pressure Probes (barometric, tunnel flow, inlet air, exhaust manifold)	kPa inch H_2O gauge	Electronic transducer Water manometer
Ambient Humidity	% RH	Electronic transducer

Table A-1-2: Recorded Test Measurements

PRESENTATION OF RECORDED MEASUREMENTS

The recorded values will be presented in tabular format with comparisons made between the various configurations on a mode by mode basis. A student T-test would be adopted to provide a measure of confidence in the significance of the comparison.

A weighted average based on the factors (W) of Table A-1-1 would allow comparison of integrated test values representative of the entire 6-mode marine simulation. In effect, an overall understanding of the consequences of a CWI test configuration. The calculation of the integrated value is as follows:

$$\text{Weighted Measurement} = \sum_{i=1}^{6}\left[\mathrm{W_i} \times \left(\text{measurement value}\right)_i\right]$$

where subscript *i* refers to the mode of the schedule.

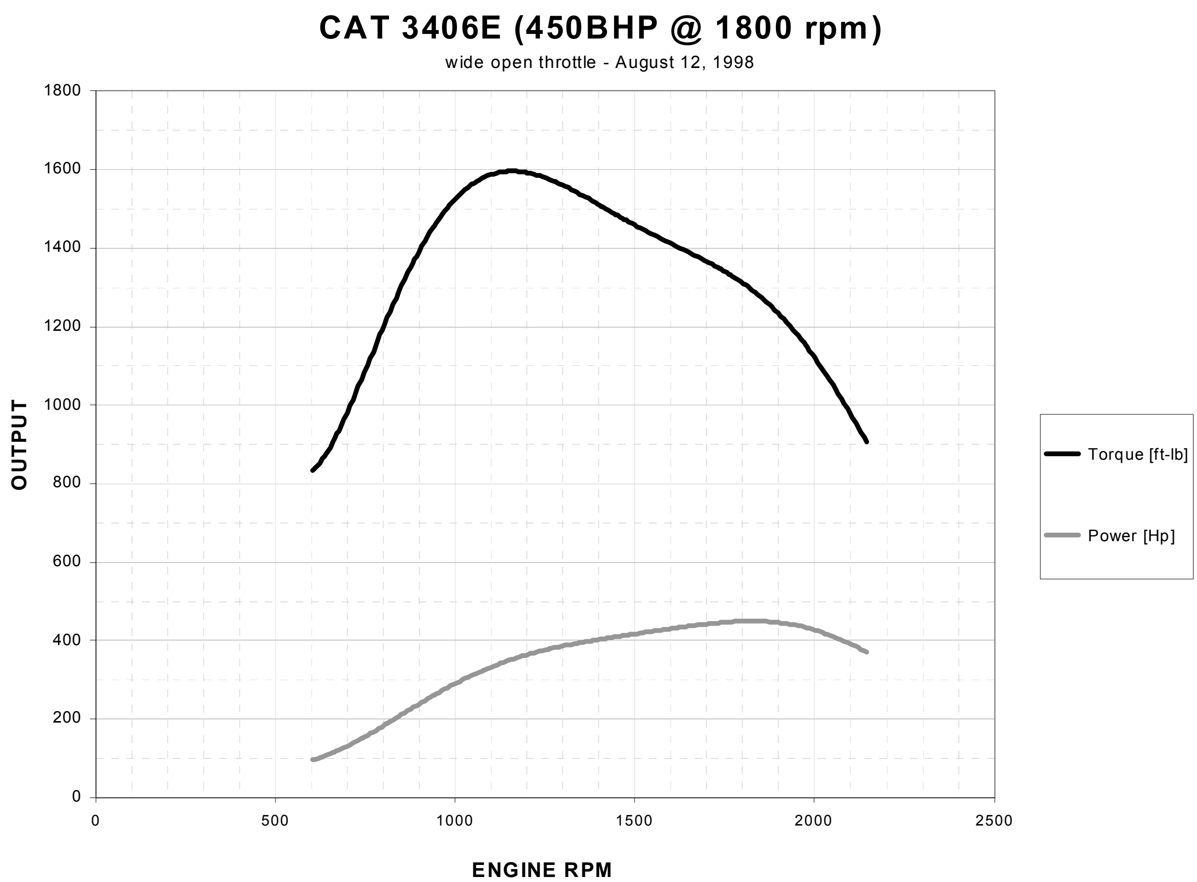


Figure A-1-1: Test Engine Performance Map

APPENDIX B

Technical Report of Water Injection Testing on an Electronic Fuel Injection Diesel Engine

1.0 INTRODUCTION

MA Turbo/Engine Design of Vancouver, British Columbia, supplies technologies to the diesel engine market for design and exhaust emissions improvement. In August of 1998, MA Turbo/Engine Design arranged with the Emissions Research and Measurement Division (ERMD) of Environment Canada to conduct a controlled test program on a 1995 Caterpillar 3406E 455 hp engine with the intent of demonstrating the performance of their Continuous Water Injection (CWI) product.

Results from this previous dynamometer-based program showed a favourable impact of the CWI in reducing the emissions of the oxides of nitrogen (NOx) in the order of 23 to 34 percent by mass and the particulate mass by 2 to 8 percent. These reductions were determined by comparing the exhaust emissions from the test engine when operated on a regenerative-electric engine dynamometer using ERMD's Marine Test Simulation Protocol. An additional observation during this previous testing was that the CWI did not negatively affect other measured engine operations (i.e. fuel consumption, boost pressure, shaft power).

The main recommendation from the report of the August 1998 program was that a subsequent program be pursued. The further study would have the intent of permitting repetitive engine dynamometer emissions testing and thus allow a numerical analysis of the test results for statistical significance.

This report presents the results of emissions testing conducted on a Cummins 'Big Cam' NTC-350 engine in response to the aforementioned recommendation from the report of the previous test program.

1.1 Emissions Research and Measurement Division

ERMD is a Canadian federal government laboratory. Its mandate is to investigate the pollutant emissions from vehicles and to evaluate industry-related devices that are designed to benefit the environment (e.g. fuel consumption improvements, pollutant reductions)

The lab participates annually in the joint EPA-AAMA (American Automobile Manufacturer's Association) round-robin emissions cross-correlation study. This is part of ERMD's commitment to emissions measurement quality assurance/quality control within the community of North American mobile source emissions test facilities.

2.0 DESCRIPTION OF TEST PROGRAM

2.1 Test Plan

The project outline for the engine testing is contained in Annex B-1. The program was conducted in accordance with the procedures outlined in the Canadian Motor Vehicle Safety Standards (CMVSS), the USA's EPA Code of Federal Regulations (CFR), and the International Organization for Standardization (ISO).

The evaluation would consist of a series of 5-mode dynamometer emissions tests performed on a heavy-duty diesel engine in two configurations: the engine running with and without the CWI in operation.

i) The ***baseline test*** configuration would use conventional #2 low sulphur diesel (LSD #2) as the fuel and SAE 40 lubricating oil. This test configuration would be used at the outset and conclusion of the program.

New filters (fuel and oil), as well as a fresh charge of lubricant were installed on the test engine at the outset of the test program.

ii) The ***device-operational test*** configuration would have the CWI installed as shown in the schematic of Figure B-1. The water used for the injection was drawn from a water tank that was manually filled between test runs from the laboratory potable water supply to the test cell. Water consumption measurements were made by recording change in the water level from a graduated scale up the side of the water tank.

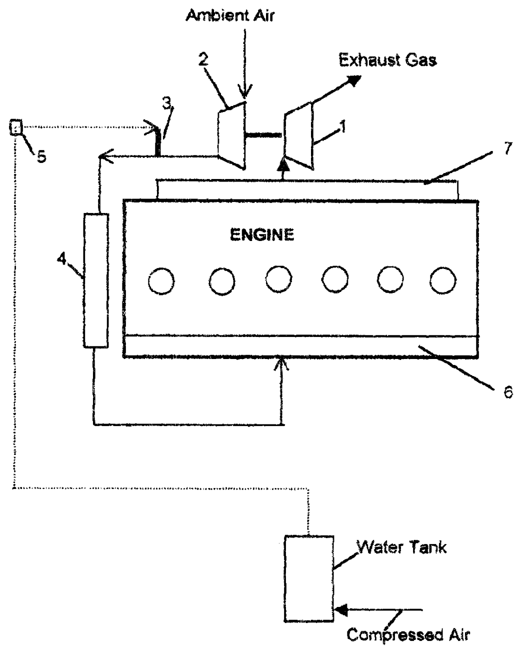
Operation of the CWI system during the engine's duty cycle is as follows:

- The operator sets the water injection pressure (e.g. 55 to 85 psig) by adjusting a compressed air regulator at the top of the water tank. The air is supplied by the laboratory compressed air system to the test cell.

- The water injection valve automatically opens when air charge temperature (read from an RTD probe installed after the compressor and before the water injector) reaches a pre-selected value (e.g. 45°C).

- With the water injection valve opened, water flows through a pair of parallel atomizing nozzles and thus is sprayed into the air charge. The rate of injection is determined by the pressure difference between the injection pressure and the boost pressure of the air charge.

- When air charge temperature drops below the pre-selected value then the valve closes and the water injection ceases.



Legend:
1. Turbine
2. Compressor
3. Water Injector
4. Water-Air Charge Aftercooler
5. Valve (operated by temp. signal from 2)
6. Inlet Manifold
7. Exhaust Gas Manifold

Figure B-1: Schematic of CWI System Installation on the Test Diesel Engine at ERMD

2.2 Test Engine and Dynamometer Description

The test stand used for this program was a stock Cummins 'Big Cam' diesel engine with a manual throttle and a water-brake dynamometer with specifications as listed in Table B-1.

Engine	Cummins NTC-350 (ERMD #97-302) Ser. # 11146538, CPL 0450
Rated Shaft Output	Maximum power = 350 [BHP] @ 2100 [rpm] Maximum torque = 1120 [ft-lb] @ 1300 [rpm]
Size	14.0 litres (inline 6 cylinder)
Operation	4 cycle, turbocharged, water-to-air charge aftercooling
Fuel	LSD #2
Engine Throttle Control	Remote controlled by Jordan 1200 Servo Module
Dynamometer	Clayton Industries 17-700-CE water-brake

Table B-1: ERMD Test Stand Specifications

The engine in the ERMD heavy-duty emissions test cell is shown in Figure B-2.

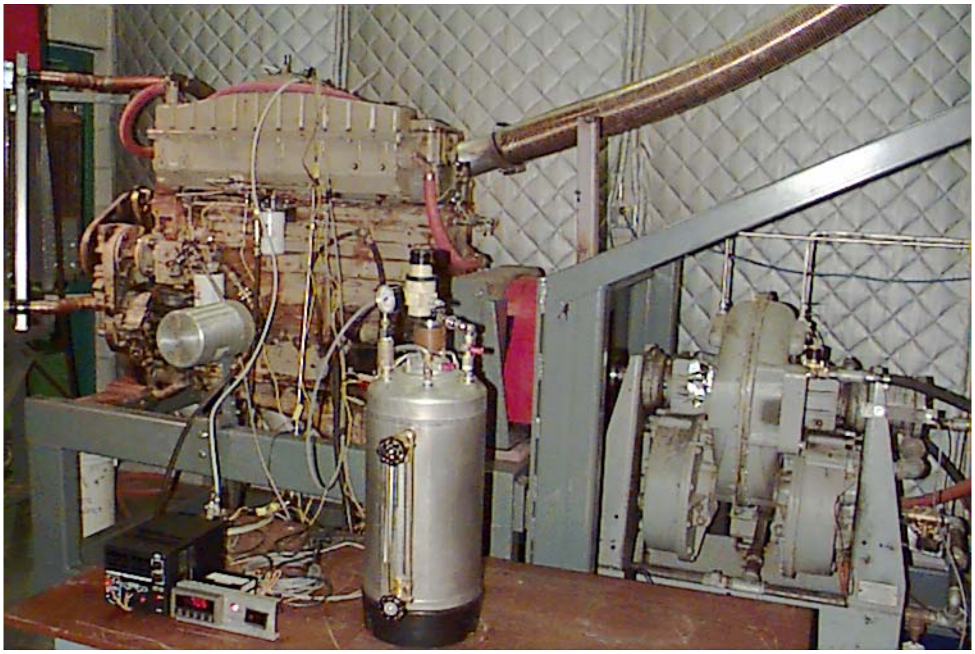


Figure B-2: ERMD Test Engine

2.3 Installation of the CWI System

The CWI system consisted of two atomizing nozzles spraying potable water from the pressurized supply tank into the engine's intake air stream. The water was injected immediately after the compressor, ahead of the water-to-air charge aftercooler. Figure B-3 shows the installation.

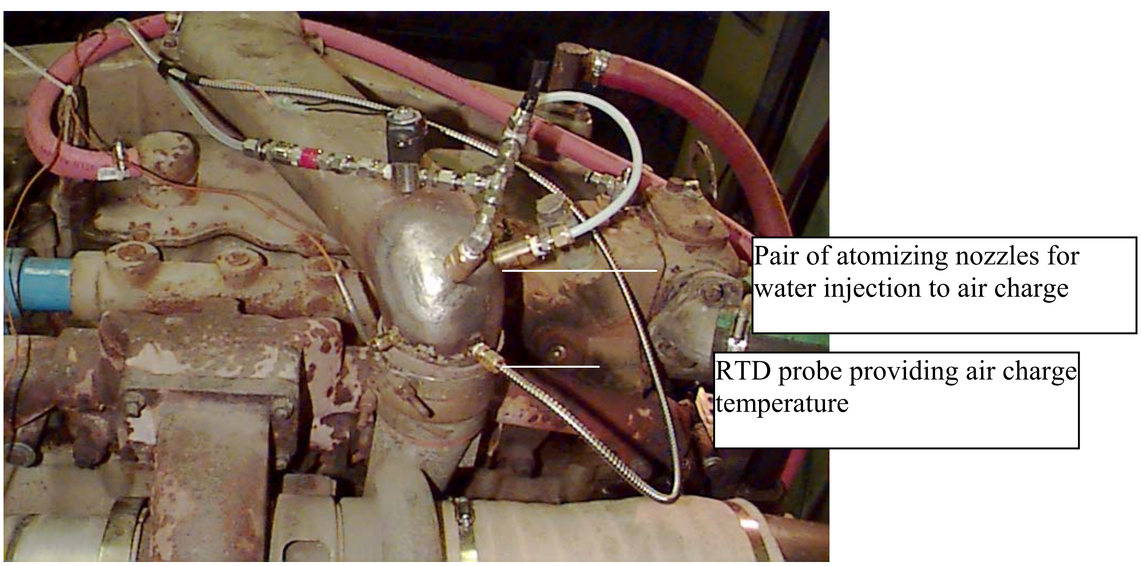


Figure B-3: CWI between Compressor and Water-to-Air Charge Aftercooler

2.4 Fuel Description

The LSD#2 diesel fuel used in the test program was drawn from a single batch with properties as shown in Table B-2.

Specific Gravity	0.8343
Carbon Fraction (by mass)	0.875
Net Heating Value	19753 [BTU/lb.]

Table B-2: Test Diesel Fuel (LSD #2) Analysed Properties

2.5 Test Cycle

The torque and speed values used to generate the test cycle engine operating points come from plots of the engine's rated performance. Using the engine manufacturer's rating, the Engine Operating Schedule was established. Actual target engine speed and torque values are shown in Table B-3.

MODE	DESCRIPTION OF SIMULATION	SPEED *[rpm]*	TORQUE *[ft-lb]*	POWER *[bhp]*
1	**Low idle**	**675**	**-**	**-**
2	**50% Engine Rating**	**2100**	**437.7**	**175.0**
3	**75% Engine Rating**	**2100**	**656.5**	**262.5**
4	**100% Engine Rating**	**2100**	**875.4**	**350.0**
5	**Low idle**	**675**	**-**	**-**

Table B-3: Values of Speed and Torque for the 5-mode Engine Operating Schedule

2.6 Emissions Analysis Apparatus

The emissions collection apparatus made use of a constant volume sampling (CVS) system that dilutes the engine exhaust during a test with ambient air from the test cell. A schematic of the test cell is shown in Figure B-4. This allows measurement of the true mass of the gaseous and particulate emissions from the engine's operation.

During the test, a continuously proportioned dilute exhaust sample is drawn from the CVS. Temperature and pressure sensors in the region of the venturi and sampling zone allow correction of volumetric flow rate to standard conditions. The exhaust sampling is finally measured by detector response (in real time) for gaseous emissions concentrations and by filter weight gain for the PM emission. Fuel consumption was measured using the EPA standard method of carbon balance on the dilute exhaust analysis. The following list details the equipment used:

- Oxides of Carbon (CO and CO_2) – Horiba AIA-23 infrared detectors
- Total hydrocarbons (THC) – Pierburg FID 2000 heated flame ionization detector
- Oxides of Nitrogen (NOx) – Pierburg CLD 2000 heated chemiluminesence detector
- Particulate Matter (P.M.) – double dilution gravimetric analysis

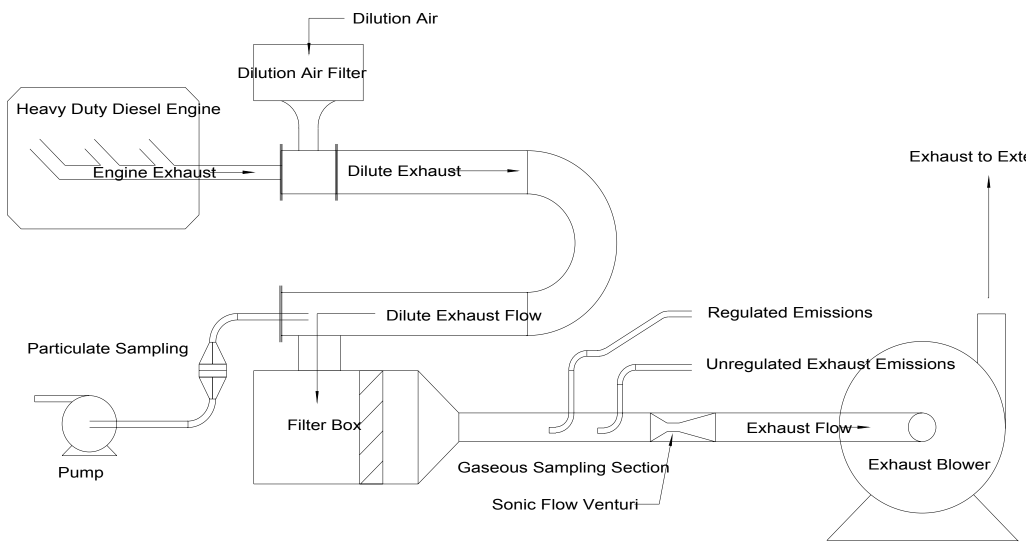


Figure B-4: Heavy-Duty Engine Test Cell Exhaust Emissions Sampling System

3.0 Results

The tabulated values for the 5-mode Engine Operating Schedule runs are shown in Annex B-2 for the test dates January 20 and 21, 1999. The engine runs were conducted as follows in Table B-4.

Date	Number of Emissions Tests	Configuration Details
Jan. 20	3	Baseline
	3	CWI at 75 psig
	3	CWI at 85 psig
	3	CWI at 65 psig
	3	Baseline
Jan. 21	2	Baseline
	3	CWI at 55 psig
	2	Baseline

Table B-4: Cummins NTC-350/CWI Configuration on 5-mode Engine Operating Schedule Runs

Test data was collected and is presented in the format consistent the testing outline presented in Annex B-1 with use of the EPA protocol for exhaust emissions calculations (CFR Title 50 Part 86.1342-90) where applicable. The brake-specific fuel consumption (BSFC) was obtained using a carbon balance method of calculation per the EPA protocol of CFR Title 50.

The results are summarized in Table B-5 for modes 2 (50% load), 3 (75% load), and 4 (100% load) in Tables B-2-1, B-2-2, and B-2-3, respectively. In addition, time-averaged values for each test run are tabulated and shown in Table B-2-4 of Annex B-2.

A weighted calculation based on the factors (W) of Table B-1-1 of Annex B-1 allows comparison of composite test values representative of the 5-mode Engine Operating Schedule. The calculation is of the following form:

$$\text{Weighted Measurement} = \sum_{i=1}^{6} \left[W_i \times \left(\text{measurement value} \right)_i \right] \qquad [1]$$

where W refers to a weighting factor and subscript *i* refers to the mode of the schedule. The summarized results for the weighted-average tabulation are shown in Table B-5.

Test Configuration Details	Water Inject [L/hr.]	CO_2 $\left[\frac{g}{bhp \cdot hr}\right]$	CO $\left[\frac{g}{bhp \cdot hr}\right]$	NOx $\left[\frac{g}{bhp \cdot hr}\right]$	THC $\left[\frac{g}{bhp \cdot hr}\right]$	BSFC $\left[\frac{g}{bhp \cdot hr}\right]$	Temp. Exhaust [deg.C]	Temp. Intake [deg.C]	Press. Intake [psig]	Engine Power [bhp]
Baseline 1	0.0	532.0	0.82	9.76	0.06	168.2	421.6	88.3	14.5	275.1
Baseline 1	0.0	533.1	0.81	8.91	0.05	168.5	422.2	87.4	14.5	274.8
Baseline 1	0.0	528.8	0.81	9.16	0.05	167.2	418.0	87.9	14.5	279.5
CWI @75 psig	29.7	507.1	0.95	5.76	0.05	160.4	399.1	77.8	14.3	283.7
CWI @75 psig	28.5	537.0	1.01	6.08	0.09	169.9	398.9	77.3	14.5	269.7
CWI @75 psig	29.2	512.2	0.94	5.76	0.05	162.0	397.7	78.7	14.2	274.4
CWI @85 psig 1	31.9	564.2	1.12	6.78	0.06	178.5	401.5	77.1	15.5	264.8
CWI @85 psig 2	32.3	528.3	0.98	6.23	0.06	167.1	400.2	78.2	15.7	285.5
CWI @85 psig 3	31.9	494.0	0.98	5.35	0.06	156.3	400.6	77.0	14.9	286.0
CWI @65 psig 1	25.9	514.3	0.94	6.46	0.06	162.7	401.8	78.9	15.2	282.4
CWI @65 psig 3	26.5	528.7	1.00	6.27	0.05	167.2	398.9	78.9	14.2	264.3
CWI @65 psig 4	28.7	527.8	0.96	5.96	0.05	166.9	403.2	79.5	14.9	273.3
Baseline 2	0.0	540.5	0.78	8.29	0.05	170.8	414.8	87.5	14.2	264.0
Baseline 2	0.0	536.6	0.78	8.10	0.05	169.6	415.8	86.9	14.1	265.9
Baseline 2	0.0	524.2	0.76	8.50	0.05	165.7	413.2	86.6	14.1	268.5
Baseline 3	0.0	538.9	0.86	8.80	0.06	170.4	415.8	86.7	14.7	273.3
Baseline 3	0.0	518.3	0.82	8.42	0.05	163.8	419.6	87.3	14.5	280.3
CWI @55 psig 1	23.2	538.6	0.93	5.90	0.05	170.3	404.6	79.6	14.3	263.1
CWI @55 psig 2	25.7	532.1	0.92	6.47	0.05	168.3	404.1	80.2	14.9	277.2
CWI @55 psig 3	23.1	538.1	1.01	6.34	0.05	170.2	405.7	80.7	14.9	273.4
Baseline 4	0.0	526.4	0.86	8.66	0.05	166.4	422.5	87.3	14.3	276.0
Baseline 4	0.0	528.1	0.86	8.28	0.05	166.9	419.4	87.9	13.9	272.6

Table B-5: Weighted Results from 5-mode Engine Operating Schedule Run

4.0 REVIEW OF TEST RESULTS

4.1 Statistical Analysis

A statistical study was undertaken on the weighted test data to compare the engine's exhaust emissions from its "baseline" to each of the CWI injection pressure configurations. This would reveal any trends in the behaviour of each of the measurements as the test configuration was altered through the extent of the program.

The means of comparison was the 'Student t-distribution' analysis, which best suits those studies looking for significance among small sample sizes, as is the case with this test program. The tabulation of this analysis is shown in Annex B-3.

By use of all the "baseline" series of tests as the basis of comparison, it was possible to statistically gauge the effect of the CWI on the operation of the test engine in this emissions study. The confidence level of statistical significance appropriate for this field of scientific study is considered to be the 95% boundary.[1]

The statistical analysis of the results with the CWI in operation reveals a statistically significant impact on the NOx emission. The CWI injecting water at 55, 65, 75, and 85 psig produced NOx emissions reductions of 28.2, 28.3, 32.5, and 29.5 percent, respectively, from the baseline weighted values.

The effect of the CWI on the test engine's CO_2 emission, fuel consumption (BSFC), and shaft output power is not found to be statistically significant.

Exhaust gas temperatures (measured immediately after the turbine) are found to decrease with the CWI operation. The CWI injecting water at 55, 65, 75, and 85 psig served to cooled the exhaust gas 13.5, 17.0, 19.7, and 17.5 °C, respectively, from the baseline average value of 418.3°C.

4.2 Observations and Discussion

The general trend given by statistical analysis is that the CWI operation significantly impacts the NOx at all of the water injection pressures of 55, 65, 75, and 85 psig. This effect is undoubtedly related to the observation of the cooler exhaust gas temperature suggesting cooler combustion. Decreased combustion temperatures in a diesel engine are understood to curb the oxidation of nitrogen.

With regard to the optimal rate of water injection for the decrease of the NOx emission, it can be seen in Table B-3-1 that at a CWI pressure of 75 psig the formation of NOx is reduced by 32.5 percent. This operating point corresponds to a CWI pressure of a factor of 5.2 over the boost pressure (14.3 psig from Table B-5). The brake-specific water consumption for this optimal situation is shown as 0.105 [litres/bhp-hr] in Table B-3-1.

The statistical confirmation that the CWI did not significantly influence the CO_2 emission, fuel consumption (BSFC), and shaft output power supports the repeatability dynamometer test bed over the course of the program. Any deviation in the ability of the engine to follow the dynamometer loading would result in a variation within the throttle control feedback loop. The net effect from any such variation would be a relative change between the brake-specific CO_2 emission and shaft output power. It is also understood that any change in the brake-specific CO_2 emission would directly affect the BSFC because of the carbon balance calculation described in Section 3.1

Problems in the interpretation of the time-averaged particulate (PM) results have prevented any discussion on this specific emission. It is supposed, from the results of the previous study, that the impact of the CWI on this measurement should be minimal.

4.3 Conclusions and Recommendation

This follow-up laboratory test program on the CWI concludes that the best results, in terms of emissions benefit to the NOx, can be found with the CWI injecting water at a factor of 5.2 over the

[1] Environment Canada analytical standard

boost pressure with a brake-specific flow rate of 0.105 [litres/bhp-hr]. This was achieved with a pair of water injectors located immediately after the compressor, but before the charge air cooler.

An additional point of interest was that this CWI configuration statistically provided no negative effects to other important test data (i.e. CO_2, fuel consumption, and shaft power). This supports the question of quality control and repeatability of the instrumentation and engine operation over the course of the test program.

The main recommendation from this study for any future CWI commercial application is that an effort be made to ensure that the operating parameters be in accord with those demonstrated for optimal NOx reduction. Location, injection pressure, and brake-specific flow rates for the water injection should attempt to duplicate those cited above to maximize the impact on the decrease of NOx formation in diesel engine combustion.

The demonstration of this product was done under 'ideal conditions' in a certified laboratory on a secure, well-tuned engine over a short time frame. The measured observations obtained are particular to the test bed and should not necessarily be taken out of the test program's context.

ANNEX B-1 PROJECT OUTLINE

MA Turbo/Engine Design CWI Test Protocol at ERMD January 1999

OPERATION TEST CONDITIONS FOR EACH ENGINE CONFIGURATION

Both the 'baseline test' and the 'CWI test' engine configurations will be conducted under a series of steady-state load conditions that represent the full range of operation of a heavy duty diesel engine. The 5-mode steady state operation points were those specified by MA Turbo/Engine Design.
The conditions of the 5-mode test are as shown in Table B-1-1 and will follow the following routine to generate test results:

- The engine will be started at low idle speed and operated for 0.5 minutes.
- The engine will then be operated in each of the test modes for 2.5 minutes where measurement recording will occur for the final minute of each mode.
- At the conclusion of mode 5, the engine will be shut off for a period of 20 minutes to allow a temperature restabilization before conducting any subsequent 5-mode test schedules.

It is suggested that completing **three** such 5-mode test schedules would provide statistical significance to the final analysis of test results.

The test bed is operating according to the manufacturer's specifications with the exhaust backpressure checked so that it is within manufacturer's recommended range for engine rated operation.

MODE	DESCRIPTION OF SIMULATION	SPEED[a] (values of Cummins NTC-350)	LOAD[b]	WEIGHING FACTOR[c]
1	**Low idle**	**(600 rpm)**	**0%**	**0**
2	**50% Engine Power Rating**	**Rated (2100 rpm)**	**50%**	**0.25**
3	**75% Engine Power Rating**	**Rated (2100 rpm)**	**75%**	**0.30**
4	**100% Engine Power Rating**	**Rated (2100 rpm)**	**100%**	**0.45**
5	**Low idle**	**0**	**0%**	**0**

Table B-1-1: MA Turbo/Engine Design 5-mode Engine Operating Schedule

[a] Rated and Intermediate are the engine speeds of max. power and torque, respectively, as obtained by the engine mapping.

[b] Percent load is the fraction of the maximum available torque (obtained by the engine mapping) at the given engine speed.

[c] Weighing factors are used to calculate the integrated measurement values.

RECORDED MEASUREMENTS DURING EACH STEADY STATE POINT

For each steady state operating point shown in Table B-1-1, a number of relevant measurements will be recorded by the data acquisition system. The recorded values are taken in real time (approx. 4 Hz) and are integrated over the steady state time period. These measurements are shown in Table B-1-2.

MEASUREMENT	VALUE	DETAILS
CO, CO_2	Ppm grams/bhp-hr	IR detection (Horiba analyzers)
Nox	Ppm grams/bhp-hr	CL detection (Pierburg analyzer)
THC	Ppm grams/bhp-hr	FI detection (Pierburg analyzer)
Particulate Matter	grams/bhp-hr	Gravimetric analysis
Engine / Dynamometer Opera (shaft speed, torque, power)	Rpm ft-lb bhp	Tachogenerator Electronic Load Cell Transducer Dynamometer Trace Reference Values
Temperature (engine air inlet, exhaust manifold, oil sump, coolant, dilution tunnels)	deg. C	K type thermocouples, RTD probes
Pressure (barometric, tunnel flow, inlet air, exhaust manifold)	Kpa p.s.i. guage	Electronic Transducer
Ambient Humidity	% RH	Electronic transducer

Table B-1-2: Recorded Test Measurement

PRESENTATION OF RECORDED MEASUREMENTS

The recorded values will be presented in tabular format with comparisons made between the various configurations on a mode by mode basis. A student T-test would be adopted to provide a measure of confidence in the significance of the comparison.

A weighted average based on the factors (W) of Table B-1-1 would allow comparison of integrated test values representative of the entire 5-mode marine simulation. In effect an overall understanding of the consequences of a CWI test configuration. The calculation of the integrated value is as follows:

$$\text{Weighted Measurement} = \sum_{i=1}^{5} \left[\mathrm{W_i} \times (\text{measurement value})_i \right]$$

where subscript *i* refers to the mode of the schedule.

ANNEX B-2 RECORDED RESULTS

Configuration Details	Water Inject [L/hr]	CO_2 $\left[\frac{g}{bhp \cdot hr}\right]$	CO $\left[\frac{g}{bhp \cdot hr}\right]$	NOx $\left[\frac{g}{bhp \cdot hr}\right]$	THC $\left[\frac{g}{bhp \cdot hr}\right]$	BSFC $\left[\frac{g}{bhp \cdot hr}\right]$	Temp. Exhaust [deg.C]	Temp. Intake [deg.C]	Press. Intake [psig]	Engine Power [bhp]
Baseline 1	0.0	551.6	0.81	6.13	0.06	174.3	365.3	76.3	8.9	183.8
Baseline 1	0.0	554.1	0.75	5.24	0.06	175.1	359.8	76.1	8.2	177.5
Baseline 1	0.0	583.0	0.84	5.90	0.05	184.3	362.7	75.5	8.8	173.7
CWI @75 psig	28.0	571.3	1.03	3.45	0.06	180.7	346.6	67.0	9.6	179.8
CWI @75 psig	25.0	584.0	1.07	3.27	0.10	184.7	342.9	65.7	9.0	176.2
CWI @75 psig	29.0	540.8	1.00	3.04	0.05	171.0	345.2	66.6	9.0	184.2
CWI @85 psig 1	29.0	591.0	1.14	3.57	0.06	186.9	345.0	65.7	9.8	178.6
CWI @85 psig 2	30.0	540.7	1.01	3.18	0.06	171.0	344.9	66.3	9.7	187.4
CWI @85 psig 3	29.0	553.4	0.99	2.72	0.06	175.0	342.9	64.6	9.6	181.1
CWI @65 psig 1	16.0	569.7	0.96	3.57	0.06	180.1	348.8	67.3	9.6	184.3
CWI @65 psig 3	23.0	576.6	0.97	3.58	0.05	182.3	348.4	67.7	9.6	176.8
CWI @65 psig 4	24.0	587.4	1.05	3.21	0.05	185.8	351.1	68.5	9.7	175.9
Baseline 2	0.0									
Baseline 2	0.0	571.8	0.81	5.28	0.05	180.7	360.1	76.9	8.9	172.6
Baseline 2	0.0	561.2	0.79	5.21	0.05	177.4	362.4	75.7	9.4	178.9
Baseline 2	0.0	539.3	0.77	5.49	0.05	170.4	360.5	74.4	8.7	173.5
Baseline 3	0.0	576.4	0.81	5.25	0.06	182.2	360.4	75.8	9.3	177.2
Baseline 3	0.0	563.1	0.80	4.88	0.05	178.0	361.1	76.2	8.4	173.6
CWI @55 psig 1	20.0	571.5	1.05	3.63	0.06	180.8	348.9	67.8	9.0	177.5
CWI @55 psig 2	21.0	575.5	0.93	3.72	0.05	182.0	346.9	67.8	9.6	178.0
CWI @55 psig 3	21.0	582.1	1.20	3.68	0.06	184.2	351.5	68.7	9.3	174.3
Baseline 4	0.0	555.2	0.82	5.18	0.05	175.5	365.0	74.9	8.9	184.3
Baseline 4	0.0	572.8	0.81	4.90	0.05	181.0	357.0	75.1	8.1	165.6

Table B-2-1: Emission Results from Mode 2 (50% load) of 5-mode Engine Operating Schedule

Configuration Details	Water Inject [L/hr]	CO_2 $\left[\frac{g}{bhp \cdot hr}\right]$	CO $\left[\frac{g}{bhp \cdot hr}\right]$	NOx $\left[\frac{g}{bhp \cdot hr}\right]$	THC $\left[\frac{g}{bhp \cdot hr}\right]$	BSFC $\left[\frac{g}{bhp \cdot hr}\right]$	Temp. Exhaust [deg.C]	Temp. Intake [deg.C]	Press. Intake [psig]	Engine Power [bhp]
Baseline 1	0.0	531.4	0.68	7.78	0.05	167.9	417.5	84.9	13.9	263.4
Baseline 1	0.0	525.3	0.68	6.99	0.04	166.0	420.7	83.8	14.0	267.8
Baseline 1	0.0	507.3	0.63	6.74	0.04	160.3	409.5	84.6	13.2	271.0
CWI @75 psig	32.0	517.2	0.87	4.63	0.04	163.5	390.1	75.9	13.4	267.4
CWI @75 psig	32.0	565.6	0.92	5.01	0.08	178.8	392.4	75.3	14.3	247.5
CWI @75 psig	28.0	504.2	0.88	4.42	0.04	159.4	392.7	75.9	12.8	259.7
CWI @85 psig 1	34.0	595.0	1.10	5.58	0.05	188.2	397.8	74.7	15.1	240.0
CWI @85 psig 2	33.0	518.4	0.85	4.65	0.05	163.9	394.9	75.9	14.7	270.9
CWI @85 psig 3	34.0	550.8	0.91	4.96	0.05	174.1	394.1	75.6	14.8	264.2
CWI @65 psig 1	34.0	475.8	0.87	4.59	0.04	150.5	397.9	75.1	13.8	264.5
CWI @65 psig 3	27.0	517.2	0.89	4.67	0.04	163.5	392.2	75.7	12.5	245.3
CWI @65 psig 4	38.0	528.5	0.86	4.59	0.04	167.1	393.7	76.8	13.7	257.1
Baseline 2	0.0	522.6	0.66	6.82	0.04	165.1	410.2	83.2	14.5	266.3
Baseline 2	0.0	521.7	0.67	6.59	0.04	164.8	414.2	83.9	13.7	265.4
Baseline 2	0.0	530.4	0.66	6.88	0.04	167.6	410.1	83.2	13.5	258.9
Baseline 3	0.0	533.7	0.70	6.40	0.05	168.6	410.5	82.5	13.5	252.0
Baseline 3	0.0	524.8	0.69	6.52	0.04	165.8	415.4	84.2	13.9	263.4
CWI @55 psig 1	26.0	529.4	0.85	5.09	0.05	167.3	401.6	76.3	14.6	263.6
CWI @55 psig 2	35.0	534.1	0.81	5.05	0.05	168.8	399.3	77.3	14.0	260.7
CWI @55 psig 3	25.0	537.0	0.85	4.97	0.05	169.8	404.5	77.7	14.3	261.3
Baseline 4	0.0	527.9	0.73	6.40	0.04	166.8	420.5	82.6	12.8	250.9
Baseline 4	0.0	525.6	0.69	6.21	0.04	166.1	414.9	83.1	13.2	254.7

Table B-2-2: Emission Results from Mode 3 (75% load) of 5-mode Engine Operating Schedule

Configuration Details	Water Inject [L/hr]	CO_2 $\left[\frac{g}{bhp \cdot hr}\right]$	CO $\left[\frac{g}{bhp \cdot hr}\right]$	NOx $\left[\frac{g}{bhp \cdot hr}\right]$	THC $\left[\frac{g}{bhp \cdot hr}\right]$	BSFC $\left[\frac{g}{bhp \cdot hr}\right]$	Temp. Exhaust [deg.C]	Temp. Intake [deg.C]	Press. Intake [psig]	Engine Power [bhp]
Baseline 1	0.0	521.6	0.92	13.10	0.06	165.0	455.6	97.3	18.0	333.7
Baseline 1	0.0	526.6	0.92	12.23	0.06	166.5	457.9	96.1	18.3	333.5
Baseline 1	0.0	513.0	0.92	12.57	0.06	162.3	454.3	97.0	18.5	343.9
CWI @75 psig	29.0	464.7	0.96	7.79	0.05	147.0	434.4	85.0	17.6	352.4
CWI @75 psig	28.0	491.9	1.05	8.36	0.09	155.7	434.4	85.0	17.6	336.4
CWI @75 psig	30.0	501.6	0.95	8.16	0.06	158.7	430.1	87.2	17.9	334.3
CWI @85 psig 1	32.0	528.8	1.12	9.37	0.06	167.3	435.3	85.1	18.8	329.2
CWI @85 psig 2	33.0	527.9	1.05	8.99	0.06	167.0	434.5	86.3	19.6	349.7
CWI @85 psig 3	32.0	423.2	1.02	7.08	0.06	134.0	436.9	84.9	17.9	358.7
CWI @65 psig 1	26.0	509.2	0.97	9.32	0.06	161.1	434.0	87.9	19.1	348.7
CWI @65 psig 3	28.0	509.7	1.08	8.82	0.06	161.3	431.4	87.2	17.8	325.5
CWI @65 psig 4	25.0	494.1	0.97	8.40	0.05	156.3	438.5	87.3	18.6	338.2
Baseline 2	0.0	535.0	0.84	10.95	0.06	169.1	448.3	96.2	17.0	313.2
Baseline 2	0.0	532.9	0.85	10.72	0.06	168.5	446.6	95.1	16.9	314.6
Baseline 2	0.0	511.7	0.82	11.25	0.06	161.8	444.5	95.7	17.6	327.6
Baseline 3	0.0	521.5	0.98	12.36	0.06	164.9	450.2	95.4	18.5	340.9
Baseline 3	0.0	489.0	0.91	11.65	0.05	154.7	455.0	95.4	18.2	350.8
CWI @55 psig 1	23.0	526.6	0.93	7.70	0.05	166.5	437.6	88.5	17.0	310.3
CWI @55 psig 2	22.0	506.6	0.99	8.94	0.06	160.3	439.2	89.1	18.5	343.2
CWI @55 psig 3	23.0	514.4	1.01	8.74	0.06	162.7	436.7	89.2	18.5	336.4
Baseline 4	0.0	509.3	0.98	12.10	0.06	161.1	455.8	97.2	18.2	343.7
Baseline 4	0.0	504.9	1.00	11.53	0.06	159.7	456.9	98.1	17.6	343.9

Table B-2-3: Emission Results from Mode 4 (100% load) of 5-mode Engine Operating Schedule

Configuration Details	Water Inject [L/hr]	CO_2 $\left[\frac{g}{bhp \cdot hr}\right]$	CO $\left[\frac{g}{bhp \cdot hr}\right]$	NOx $\left[\frac{g}{bhp \cdot hr}\right]$	THC $\left[\frac{g}{bhp \cdot hr}\right]$	BSFC $\left[\frac{g}{bhp \cdot hr}\right]$	PM $\left[\frac{g}{bhp \cdot hr}\right]$	Temp. Exhaust [deg.C]	Temp. Intake [deg.C]	Press. Intake [psig]	Engine Power [bhp]
Baseline 1	0.0	534.9	0.80	9.00	0.06	169.1	0.17	81.9	8.3	156.7	325.5
Baseline 1	0.0	535.4	0.79	8.15	0.05	169.2	0.18	81.2	8.2	156.5	325.9
Baseline 1	0.0	534.4	0.80	8.40	0.05	168.9	0.18	81.8	8.2	158.7	322.2
CWI @75 psig	20.8	517.7	0.96	5.29	0.05	163.7	0.24	71.0	8.3	160.8	308.5
CWI @75 psig	19.6	547.2	1.01	5.55	0.09	173.1	0.39	71.8	8.3	152.9	307.3
CWI @75 psig	20.2	515.5	0.94	5.21	0.05	163.0	0.25	72.6	8.1	156.4	307.9
CWI @85 psig 1	22.0	571.6	1.12	6.17	0.05	180.8	0.26	71.5	8.9	150.5	310.1
CWI @85 psig 2	21.8	529.0	0.97	5.60	0.06	167.3	0.24	72.2	8.9	162.4	308.3
CWI @85 psig 3	21.8	509.2	0.97	4.92	0.05	161.0	0.32	71.4	8.5	161.3	310.6
CWI @65 psig 1	18.0	518.2	0.93	5.82	0.05	163.9	0.23	72.3	8.7	160.3	309.6
CWI @65 psig 3	18.6	534.5	0.98	5.69	0.05	169.0	0.24	71.6	8.1	150.3	309.1
CWI @65 psig 4	20.2	536.7	0.96	5.40	0.05	169.7	0.23	73.2	8.5	155.0	310.9
Baseline 2	0.0	543.1	0.77	7.68	0.05	171.7	0.18	81.6	8.2	151.0	321.7
Baseline 2	0.0	538.6	0.77	7.51	0.05	170.2	0.18	80.7	8.1	152.4	320.3
Baseline 2	0.0	527.1	0.75	7.87	0.05	166.6	0.18	80.7	8.1	152.7	320.1
Baseline 3	0.0	543.8	0.83	8.01	0.06	171.9	0.19	79.8	8.5	154.5	321.4
Baseline 3	0.0	525.6	0.80	7.68	0.05	166.2	0.18	81.4	8.2	158.4	323.5
CWI @55 psig 1	16.0	542.5	0.94	5.47	0.05	171.5	0.23	72.5	8.2	151.0	311.2
CWI @55 psig 2	18.6	538.8	0.91	5.90	0.05	170.3	0.22	72.9	8.7	157.2	310.2
CWI @55 psig 3	16.6	544.5	1.02	5.80	0.05	172.2	0.23	73.1	8.6	154.9	312.0
Baseline 4	0.0	530.8	0.84	7.89	0.05	167.8	0.18	80.4	8.1	156.8	324.7
Baseline 4	0.0	534.4	0.84	7.55	0.05	168.9	0.19	81.6	7.9	153.8	321.6

Table B-2-4: Time-Averaged Emission Results from 5-mode Engine Operating Schedule Run

ANNEX B-3 STATISTICAL ANALYSIS

TEST CONFIGURATION	CWI RATE $\left[\frac{litres}{bhp-hr}\right]$	CO_2 $\left[\frac{g}{bhp-hr}\right]$	NOx $\left[\frac{g}{bhp-hr}\right]$	BSFC $\left[\frac{g}{bhp-hr}\right]$	PM† $\left[\frac{g}{bhp-hr}\right]$	Exhaust Temp. [deg.C]	Power [BHP]
	5-MODE OPERATING SCHEDULE WEIGHTED RESULTS						
BASELINE	0.0	532.0	9.76	168.19	0.17	421.6	275.1
	0.0	533.1	8.91	168.51	0.18	422.2	274.8
	0.0	528.8	9.16	167.16	0.18	418.0	279.5
	0.0	540.5	8.29	170.82	0.18	414.8	264.0
	0.0	536.6	8.10	169.60	0.18	415.8	265.9
	0.0	524.2	8.50	165.69	0.18	413.2	268.5
	0.0	538.9	8.80	170.35	0.19	415.8	273.3
	0.0	518.3	8.42	163.84	0.18	419.6	280.3
	0.0	526.4	8.66	166.41	0.18	422.5	276.0
	0.0	528.1	8.28	166.94	0.19	419.4	272.6
Average	0.0	530.7	8.69	167.75	0.18	418.3	273.0
Standard Deviation		6.917	0.495	2.180	0.006	3.289	5.417
CWI @55 PSIG	0.088	538.6	5.90	170.32	0.24	404.6	263.1
	0.093	532.1	6.47	168.25	0.39	404.1	277.2
	0.085	538.1	6.34	170.20	0.25	405.7	273.4
Average	0.088	536.3	6.24	169.59	0.29	404.8	271.2
Standard Deviation		3.637	0.298	1.160	0.080	0.812	7.270
Difference		1.06%	-28.21%	1.10%	63.03%	-13.5 deg.C	-0.66%
Variance of comparison, ?[2]		41.551	0.217	4.135	0.001		33.618
t Distribution (?=11)		-1.322	8.000	-1.373	-5.000		0.470
Statistically significant (95% confidence)?		No	Yes	No	Yes		No
CWI @65 PSIG	0.092	514.3	6.46	162.65	0.26	401.8	282.4
	0.100	528.7	6.27	167.21	0.24	398.9	264.3
	0.105	527.8	5.96	166.90	0.32	403.2	273.3
Average	0.099	523.6	6.23	165.59	0.27	401.3	273.3
Standard Deviation		8.051	0.254	2.547	0.039	2.205	9.049
Difference		-1.34%	-28.31%	-1.29%	51.75%	-17.0 deg.C	0.11%
Variance of comparison, ?[2]		50.931	0.212	5.070	0.000		38.897
t Distribution (?=11)		1.510	8.111	1.460	-8.024		-0.073
Statistically significant (95% confidence)?		No	Yes	No	Yes		No

† The particulate emission is a time average not weighted-average number for comparison

CWI @75 PSIG	0.104	507.1	5.76	160.38	0.23	399.1	283.7
	0.105	537.0	6.08	169.88	0.24	398.9	269.7
	0.106	512.2	5.76	161.98	0.23	397.7	274.4
Average	0.105	518.8	5.87	164.08	0.24	398.6	275.9
Standard Deviation		16.014	0.189	5.087	0.008	0.796	7.154
Difference		-2.25%	-32.48%	-2.19%	30.44%	-19.7 deg.C	1.08%
Variance of comparison, $?^2$		85.773	0.207	8.595	0.000		33.312
t Distribution (?=11)		1.956	9.424	1.903	-12.669		-0.773
Statistically significant (95% confidence)?		No	Yes	No	Yes		No
CWI @85 PSIG	0.120	564.2	6.78	178.47	0.23	401.5	264.8
	0.113	528.3	6.23	167.08	0.22	400.2	285.5
	0.111	494.0	5.35	156.28	0.23	400.6	286.0
Average	0.115	528.8	6.12	167.28	0.23	400.8	278.7
Standard Deviation		35.071	0.720	11.092	0.006	0.646	12.081
Difference		-0.35%	-29.52%	-0.28%	26.00%	-17.5 deg.C	2.10%
Variance of comparison, $?^2$		262.773	0.295	26.258	0.000		50.545
t Distribution (?=11)		0.173	7.177	0.141	-11.333		-1.226
Statistically significant (95% confidence)?		No	Yes	No	Yes		No

Table B-3-1: Statistical Comparison of Weighted Test Data of CWI to the Baseline

APPENDIX C

Results from Platinum-based Fuel Additive

EMISSIONS RESEARCH AND MEASUREMENT DIVISION
3439 RIVER ROAD
GLOUCESTER, ONTARIO K1A 0H3
CANADA
PHONE (613) 998-9590
FAX: (613) 952-1006

Friday, December 18, 1998

T. J. Tarabulski
Clean Diesel Technologies, Inc.
300 Atlantic Street, Suite 702
Stamford, CT 06901-3522
USA

Cc: Fred Hendren, Chief-ERMD, Environment Canada

RE: November emissions testing of the additive mixed at concentration 1:750

Dear Mr. Tarabulski:

I attach statistical summaries of the additive emission testing on your product at concentration 1:750 (additive: fuel by volume). The pages show results of engine runs using the HD transient, ISO 8 mode, and ERMD 6-mode marine engine dynamometer traces.

The test data on the effect of your product is inconclusive. This is owing to the degree of variation in results within each test configuration. It is not necessarily a reflection of your product.

Please review this summary, but be aware that the results (in general) do not show any statistical significance (95 percentile-industry standard) on the effect of the product.

Please call me to discuss at your earliest convenience.

Sincerely,

Angus Craig
Project Engineer
Heavy Duty Engine Testing

EPA Heavy-Duty Transient

- comparison of engine emissions data with PRODUCT-INSTALLED to the INITIAL BASELINE testing

#97-320 Detroit Diesel Series 60		*Heavy Duty Transient Emission Test Results*							
test configuration		power [bhp]	CO [g/bhp-hr]	CO2 [g/bhp-hr]	NOx [g/bhp-hr]	THC [g/bhp-hr]	P.O.M. [g/bhp-hr]	FUEL CONS. [g/bhp-hr]	FUEL CONS [lb/bhp-hr]
baseline -initial		84.5	1.14	416.7	7.57	0.22	0.104	39.32	0.087
baseline -initial		88.9	0.93	436.0	8.10	0.18	0.086	43.26	0.095
baseline -initial		88.5	0.76	434.0	8.15	0.18	0.091	42.94	0.095
BASELINE AVERAGE	3 tests	87.3	0.94	428.9	7.94	0.19	0.094	41.84	0.092
Baseline Standard Deviation		2.469	0.192	10.642	0.319	0.020	0.009	2.189	0.005
fuel additive pre-accumulation		87.9	0.99	427.0	8.14	0.23	0.085	42.50	0.094
fuel additive pre-accumulation		87.0	0.98	432.1	8.27	0.22	0.089	43.03	0.095
fuel additive pre-accumulation		88.8	0.90	436.8	8.09	0.21	0.089	43.22	0.095
FUEL ADDITIVE PRE-ACCUM. AVG.	3 tests	87.9	0.96	432.0	8.17	0.22	0.088	42.92	0.095
Fuel Additive Pre-Accum. Stan. Dev.		0.893	0.046	4.903	0.090	0.011	0.002	0.376	0.001
% Difference		0.71%	1.61%	0.71%	2.85%	13.13%	-6.59%	2.57%	2.57%
# degrees of freedom for statistics, ν =	4								
variance of comparison, σ^2		3.447	0.019	68.649	0.055	0.000	0.000	2.467	0.000
'T' Distribution		-0.406	-0.133	-0.452	-1.182	-1.915	1.138	-0.840	-0.840
statistically significant (95% confidence)?		No	No	No	No	No	No	No	No
fuel additive post-accumulation		88.7	0.96	440.0	8.26	0.22	0.102	43.24	0.095
fuel additive post-accumulation		89.9	0.99	440.3	8.33	0.20	0.099	43.48	0.096
fuel additive post-accumulation		87.8	1.06	444.0	8.30	0.24	0.101	43.92	0.097
FUEL ADDITIVE POST-ACCUM. AVG.	3 tests	88.8	1.00	441.4	8.30	0.22	0.100	43.55	0.096
Fuel Additive Post-Accum. Stan. Dev.		1.055	0.048	2.224	0.037	0.020	0.002	0.348	0.001
% Difference		1.68%	6.29%	2.93%	4.47%	15.70%	7.08%	4.08%	4.08%
# degrees of freedom for statistics, ν =	4								
variance of comparison, σ^2		3.606	0.020	59.100	0.052	0.000	0.000	2.456	0.000
'T' Distribution		-0.944	-0.519	-1.999	-1.914	-1.838	-1.231	-1.333	-1.333
statistically significant (95% confidence)?		No	No	No	No	No	No	No	No

8 Mode Steady State

- comparison of engine emissions data with PRODUCT-INSTALLED to the INITIAL BASELINE testing

#97-320 Detroit Diesel Series 60		*8 Mode Weighted Emission Test Results*							
test configuration		power [bhp]	CO [g/bhp-hr]	CO2 [g/bhp-hr]	NOx [g/bhp-hr]	THC [g/bhp-hr]	P.O.M. [g/bhp-hr]	FUEL CONS. [g/bhp-hr]	FUEL CONS [lb/bhp-hr]
baseline -initial		179.2	1.28	473.3	14.25	0.32	0.102	150.15	0.331
baseline -initial		181.2	1.29	475.8	14.73	0.40	0.108	151.04	0.333
baseline -initial		178.8	0.87	465.2	8.98	0.43	0.114	147.50	0.325
BASELINE AVERAGE	3 tests	179.7	1.15	471.4	12.65	0.38	0.108	149.56	0.330
Baseline Standard Deviation		1.269	0.236	5.566	3.192	0.057	0.006	1.839	0.004
fuel additive pre-accumulation		182.0	1.13	464.7	8.40	0.30	0.121	147.34	0.325
fuel additive pre-accumulation		181.9	1.05	446.5	8.02	0.37	0.110	141.65	0.312
fuel additive pre-accumulation		184.8	0.95	448.8	8.21	0.28	0.105	142.25	0.314
FUEL ADDITIVE PRE-ACCUM. AVG.	3 tests	182.9	1.04	453.3	8.21	0.32	0.112	143.75	0.317
Fuel Additive Pre-Accum. Stan. Dev.		1.662	0.091	9.886	0.191	0.049	0.008	3.127	0.007
% Difference		1.76%	-8.99%	-3.84%	-35.12%	-16.85%	4.00%	-3.89%	-3.89%
# degrees of freedom for statistics, ν =	4								
variance of comparison, σ^2		2.185	0.032	64.355	5.113	0.003	0.000	6.582	0.000
'T' Distribution		-2.615	0.706	2.762	2.407	1.484	-0.731	2.778	2.778
statistically significant (95% confidence)?		No	No	No	No	No	No	No	No
fuel additive post-accumulation		189.0	0.87	465.0	8.54	0.22	0.138	147.25	0.325
fuel additive post-accumulation		186.2	0.78	462.8	9.03	0.23	0.124	146.51	0.323
fuel additive post-accumulation		186.4	0.90	465.6	9.07	0.21	0.141	147.45	0.325
FUEL ADDITIVE POST-ACCUM. AVG.	3 tests	187.2	0.85	464.5	8.88	0.22	0.134	147.07	0.324
Fuel Additive Post-Accum. Stan. Dev.		1.561	0.061	1.490	0.296	0.006	0.009	0.494	0.001
% Difference		4.18%	-25.78%	-1.47%	-29.82%	-42.32%	24.49%	-1.67%	-1.67%
# degrees of freedom for statistics, ν =	4								
variance of comparison, σ^2		2.023	0.030	16.598	5.139	0.002	0.000	1.814	0.000
'T' Distribution		-6.468	2.100	2.084	2.039	4.885	-4.168	2.270	2.270
statistically significant (95% confidence)?		Yes	No	No	No	Yes	Yes	No	No

ERMD 6 Mode Marine Steady State

- comparison of engine emissions data with PRODUCT-INSTALLED to the INITIAL BASELINE testing

#97-320 Detroit Diesel Series 60		*6 Mode Weighted Emission Test Results*							
		power	CO	CO2	NOx	THC	P.O.M	FUEL CONS.	FUEL CONS.
test configuration		[bhp]	[g/bhp-hr]	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	[g/bhp-hr]	[lb/bhp-hr]
baseline -initial		260.5	0.83	445.6	7.72	0.16	0.083	141.04	0.311
baseline -initial		257.5	0.81	438.0	8.21	0.11	0.086	138.59	0.306
baseline -initial		262.0	0.83	447.9	8.13	0.15	0.083	141.76	0.313
BASELINE AVERAGE	3 tests	260.0	0.82	443.8	8.02	0.14	0.084	140.46	0.310
Baseline Standard Deviation		2.330	0.011	5.181	0.263	0.024	0.002	1.662	0.004
fuel additive post-accumulation		251.1	0.97	452.7	8.06	0.13	0.090	143.34	0.316
fuel additive post-accumulation		256.5	0.95	446.2	8.06	0.13	0.082	141.26	0.311
fuel additive post-accumulation		255.4	0.85	445.0	8.16	0.13	0.078	140.82	0.310
OIL ADDITIVE AVERAGE	3 tests	254.3	0.92	448.0	8.09	0.13	0.083	141.81	0.313
Oil Additive Standard Deviation		2.876	0.062	4.179	0.056	0.004	0.006	1.342	0.003
% Difference		-2.19%	12.71%	0.93%	0.95%	-7.98%	-0.71%	0.96%	0.96%
# degrees of freedom for statistics, n =	4								
variance of comparison, σ^2		6.851	0.002	22.153	0.036	0.000	0.000	2.283	0.000
'T' Distribution		2.666	-2.887	-1.077	-0.490	0.793	0.168	-1.091	-1.091
statistically significant (95% confidence)?		No	Yes	No	No	No	No	No	No

#97-320 Detroit Diesel Series 60 — Heavy Duty Marine Steady-StateTest Results

test configuration		date	time		power	CO	CO2	NOx	THC	P.O.M.	FUEL CONS.
					[bhp]	[g/bhp-hr]	[g/bhp-hr]	[g/bhp-hr]	[g/bhp-hr]	[g/bhp-hr]	[g/bhp-hr]
marine SS –3											
	AVG	17-Nov	14:27	124.53	0.67	431.1	8.20	0.15	0.083	136.37	
	MODE A			5.47	5.07	634.8	15.03	2.58		205.26	
	MODE B			160.12	0.54	436.6	7.54	0.10		137.99	
	MODE 1			11.61	2.55	461.2	10.81	0.91		147.59	
	MODE 2			35.26	4.51	502.7	10.12	0.84		161.55	
	MODE 3			258.80	0.44	447.7	7.66	0.09		141.45	
	MODE 4			356.69	0.36	457.6	7.44	0.06		144.50	
	MODE 5			159.42	0.52	397.4	7.35	0.11		125.66	
	MODE 6			14.60	1.99	262.6	5.84	0.80		84.59	
	Weighted			260.55	0.83	445.6	7.72	0.16	0.083	141.04	
marine SS –4											
	AVG	17-Nov	15:40	122.60	0.63	404.6	8.49	0.10	0.086	127.97	
	MODE A			4.01	5.70	211.0	24.08	2.11		71.49	
	MODE B			160.28	0.49	425.6	7.96	0.06		134.48	
	MODE 1			11.36	1.85	236.9	11.61	0.19		75.78	
	MODE 2			34.02	4.50	446.7	11.03	0.63		143.70	
	MODE 3			253.21	0.41	452.3	8.24	0.07		142.87	
	MODE 4			352.82	0.36	458.4	7.88	0.05		144.75	
	MODE 5			158.73	0.47	385.0	7.72	0.06		121.66	
	MODE 6			18.50	1.06	66.3	4.82	0.18		21.62	
	Weighted			257.48	0.81	438.0	8.21	0.11	0.086	138.59	
marine SS –5											
	AVG	17-Nov	16:20	122.53	0.65	418.0	8.37	0.14	0.083	132.24	
	MODE A			5.56	4.89	562.6	15.69	3.02		182.85	
	MODE B			157.84	0.54	443.8	8.02	0.10		140.29	
	MODE 1			11.30	2.42	474.2	11.62	0.80		151.51	
	MODE 2			33.15	4.49	535.5	11.27	0.85		171.89	
	MODE 3			255.64	0.43	454.9	8.13	0.09		143.70	
	MODE 4			362.86	0.37	449.0	7.63	0.06		141.78	

	MODE 5			155.83	0.51	406.5	7.86	0.10		128.51	
	MODE 6			9.92	2.06	386.8	8.99	1.03		124.02	
	Weighted			262.05	0.83	447.9	8.13	0.15	0.083	141.76	
marine SS –2											
	AVG	27-Nov	10:55	124.15	0.75	430.1	8.48	0.18	0.090	136.16	
	MODE A			5.76	5.11	636.3	2.81	2.49		205.65	
	MODE B			156.00	0.56	440.9	7.85	0.08		139.35	
	MODE 1			10.52	3.16	442.5	12.10	0.54		141.61	
	MODE 2			34.41	5.72	492.9	10.52	0.72		158.95	
	MODE 3			257.13	0.48	446.4	7.83	0.08		141.04	
	MODE 4			338.19	0.39	478.0	7.96	0.06		150.94	
	MODE 5			159.83	0.52	389.9	7.43	0.08		123.26	
	MODE 6			10.81	4.29	292.6	8.01	0.64		95.02	
	Weighted			251.07	0.97	452.7	8.06	0.13	0.090	143.34	
marine SS –4											
	AVG	27-Nov	12:15	124.48	0.70	414.5	8.46	0.16	0.082	131.18	
	MODE A			6.41	5.40	623.4	2.99	1.91		201.15	
	MODE B			155.34	0.57	444.3	8.00	0.08		140.43	
	MODE 1			10.97	3.19	424.7	11.76	0.49		135.95	
	MODE 2			33.49	5.89	507.4	10.97	0.73		163.60	
	MODE 3			253.21	0.44	453.8	8.06	0.08		143.35	
	MODE 4			350.95	0.34	459.4	7.74	0.05		145.03	
	MODE 5			158.81	0.50	390.8	7.54	0.08		123.52	
	MODE 6			17.65	1.70	178.9	4.95	0.37		57.61	
	Weighted			256.51	0.95	446.2	8.06	0.13	0.082	141.26	
marine SS -5		AVERAGE	27-Nov-98	12:55	126.16	0.61	427.7	8.82	0.16	0.078	135.31
	MODE A			10.11	2.27	551.5	2.66	1.18		176.19	
	MODE B			156.62	0.50	439.1	8.04	0.08		138.75	
	MODE 1			12.14	1.91	382.7	10.77	0.44		122.04	
	MODE 2			36.65	5.06	461.7	10.14	0.66		148.73	
	MODE 3			250.05	0.44	459.4	8.29	0.08		145.12	
	MODE 4			351.47	0.34	457.8	7.84	0.05		144.55	
	MODE 5			153.97	0.44	403.9	7.92	0.08		127.64	
	MODE 6			17.08	1.17	184.8	5.20	0.38		59.23	
	Weighted			255.40	0.85	445.0	8.16	0.13	0.078	140.82	