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Marine Vessel Exhaust Emissions Program:

A Study of the Effects of Multiple Emissions Reduction Technologies on the Exhaust Emissions of Marine Diesel Engines

Prepared for
Transportation Development Centre
Transport Canada

By
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By
Greg Rideout and Norman Meyer
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Un sommaire français se trouve avant la table des matières.

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16. Abstract

The project work described in this report encompassed the following activities:

- A study of a marine vessel in normal operation,
- Laboratory testing of various diesel-water fuel emulsions on an engine operating in marine cycle,
- Laboratory and field-testing of water injection systems on marine engines.

The diesel-water fuel emulsion, at 20% water, achieved 8% reductions in oxides of nitrogen (NOx), 83% reductions in particulate matter (PM), and 30% reductions in carbon monoxide (CO), with a small increase in total hydrocarbon (THC) emissions.

The PM emissions results of the field-testing of a water injection system did not correlate well with the laboratory evaluation. At the highest water injection rate, the laboratory evaluation determined a 28% decrease in NOx emissions, a 3% decrease in CO emissions, no observable change in THC emissions, and a 20% *increase* in PM emissions. The field-testing established NOx reductions ranging from 10 to 22%, no statistical difference in CO emissions, and an average PM *reduction* of 20%. It should be noted that these were quite different diesel engine technologies.

It is evident that water injection and fuel emulsions show promising results toward significantly reducing exhaust emissions from marine vessels. The long-term effect of either system on engine life and maintenance costs is unknown.

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Marine vessel exhaust emissions, oxides of nitrogen, NOx, particulate matter, PM, carbon monoxide, CO, water injection, fuel emulsions

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16. Résumé

Le projet décrit dans le présent rapport comprenait les activités suivantes :

- la mesure des émissions d'un navire dans des conditions normales d'exploitation;
- l'essai en laboratoire de différentes émulsions eau-carburant diesel destinées à un moteur marin;
- l'essai en laboratoire et sur le terrain de systèmes d'injection d'eau installés sur des moteurs de navires.

L'utilisation d'une émulsion eau-carburant diesel, constituée à 20 % d'eau, a permis de réduire de 8 % les oxydes d'azote (NO_x), de 83 % les particules et de 30 % le monoxyde de carbone (CO) rejetés par les moteurs marins. Cependant, cette émulsion de carburant a entraîné une légère augmentation des émissions d'hydrocarbures totaux (HCT).

Les émissions de particules mesurées au cours de l'essai sur le terrain d'un système d'injection d'eau n'étaient pas bien corrélées avec celles résultant des essais en laboratoire. Ces essais, réalisés au taux d'injection d'eau maximal, ont permis de constater une réduction de 28 % des émissions de NO_x et une diminution de 3 % des émissions de CO. Les émissions de HCT sont demeurées stables et les particules émises ont *augmenté* de 20 %. En comparaison, les essais menés sur le terrain ont permis d'observer une diminution de 10 à 22 % des émissions de NO_x, aucune différence statistique en ce qui a trait aux émissions de CO et une *réduction* moyenne de 20 % des particules émises. Il convient toutefois de noter que ces essais mettaient en jeu des moteurs diesel considérablement différents.

Les systèmes d'injection d'eau et les émulsions eau-carburant semblent donc avoir un avenir prometteur et contribueront vraisemblablement à réduire de façon importante les émissions de gaz d'échappement des moteurs de navires. Les effets à long terme de ces systèmes sur la durée de vie des moteurs ou sur les coûts d'entretien de ces derniers sont encore inconnus.

17. Mots clés
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Phase 1- Characterization of Emissions During Normal Operation

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Phase 2- Evaluation of Alternative Technologies

Part 1 - Laboratory testing of water emulsified fuels

ERMD would like to acknowledge the support received from Mr. Ernst Radloff of Transport Canada's Transportation Development Centre, and the Lubrizol Corporation. In addition, the authors would like to thank the ERMD staff who conducted the emissions tests and analysis.

Part 2 - Laboratory testing of a water injection system

ERMD would like to acknowledge the technical and financial support for this work from the program collaborator, Transport Canada's Transportation Development Centre, specifically Mr. Ernst Radloff. In addition, the authors would like to thank the ERMD staff who conducted the emissions tests and analysis.

Part 3 - Field-testing of a water injection system

ERMD would like to acknowledge the support received from Mr. Ernst Radloff of Transport Canada's Transportation Development Centre, Mr. Dave Simpson and Mr. Karl Mohr of the BC Ferry Corporation, and the co-operative effort of the staff and crew aboard the *Queen of New Westminster*. In addition, ERMD would like to acknowledge the support provided by Mr. Ed Witushek of Environment Canada, Pacific and Yukon Region. Finally, the authors would like to thank the ERMD staff who conducted the emissions tests and analysis.

EXECUTIVE SUMMARY

Transport Canada is committed to protect the environment and to achieve a more sustainable transportation system. The Transportation Development Centre (TDC) of Transport Canada, in collaboration with the Emissions Research and Measurement Division (ERMD) of Environment Canada and various other partners have collaborated on a series of projects known as the Marine Vessel Exhaust Emissions Program.

Transport Canada's Marine Safety Directorate and Natural Resources Canada's Program of Energy Research and Development (PERD) funded the emissions program. In addition, Environment Canada has also contributed to the work through a combination of funding and in-kind resources.

Transport Canada initiated an R&D program to reduce airborne emissions in the marine sector. A number of commercially available oxides of nitrogen (NOx) reduction technologies for marine diesel engines were investigated for their applicability in the Canadian context. TDC, with the assistance of ERMD, has established an ongoing program for the development of cost-effective marine emissions control technologies. The program includes measurement of marine exhaust emissions, laboratory demonstrations of emissions control technologies and field trials on operational Canadian vessels.

The program include both laboratory engine tests of water injection systems and various diesel-water fuel emulsions, as well as field trials on a commercial marine vessel to demonstrate the viability of a water injection system to reduce NOx emissions. Emissions of carbon monoxide (CO), carbon dioxide (CO_2), NOx, total hydrocarbons (THC) and total particulate matter (PM) were measured.

The issue of NOx reduction from ships is of prime interest to Marine Safety, the regulatory body of Transport Canada. The international regulations incorporated under International Maritime Organization (IMO) / Marpol 73/78, Annex VI propose to limit airborne emissions, primarily NOx and oxides of sulphur (SOx), from marine vessels. Canada is planning to ratify the 1997 IMO Protocol by December 2002, and enforce the IMO rules through Port-State control under the Canada Shipping Act.

The program work plan was undertaken in two phases: Phase 1 - Conventional Operation and Characterization, and Phase 2- Evaluation of Fuel-Based Technologies. Phase 2 was divided into three parts: Laboratory Testing of Water Emulsified Fuels, Laboratory Testing of a Water Injection System, and Field-testing of a Water Injection System.

Phase 1 - Conventional Operation and Characterization

Phase 1 involved a testing program to measure the exhaust emissions from one of the main engines of a cargo vessel (*MV Cabot*) that operates from Montreal to St. John's on a weekly basis.

The total NOx emissions rate varied between 12.5 to 24.8 g/kW-h under the various operating conditions. The NOx emissions from the vessel were compared to IMO limits. Of the seven separate cruise conditions, the engine exhaust emissions rate exceeded the IMO NOx limit in six out of seven cases. It should be noted that the IMO limit is based on a weighted average over several operating points of speed and load, while the data obtained from this vessel was for single load points.

These results, along with the remainder of the tested species await comparison with the results from a water injection system yet to be installed on the *MV Cabot*.

Phase 2 - Part 1: Laboratory Testing of Water Emulsified Fuels

Phase 2 – Part 1 focused on the effect of two parameters: the quantity of water in the fuel emulsion and the fuel injection timing.

Four diesel-water fuel emulsions of varying percentages of water were evaluated in a high-speed diesel engine operating over four steady states based on the ISO propeller curve. The ISO composite exhaust emissions measurements indicated that of the four water content fuels – 5%, 10%, 15% and 20% – the latter resulted in the largest exhaust emissions reductions of -8% and -83% for NOx and PM, respectively. CO was also reduced by 20% but THC increased by 8%. For the individual modes the reductions varied depending on the fuel and mode.

Modifying the fuel injection timing had the expected NOx-PM trade-off effect of increasing the NOx and reducing the PM when the timing was advanced, and the reverse when the timing was retarded. With the retarded timing and 20% fuel emulsion, NOx was reduced by 58% and PM by 72%.

There was a fuel economy penalty associated with these exhaust emissions reductions. The trend indicated that the penalty was proportional to the amount of water in the fuel, for three of the four modes, if the engine was operated at the same speed and load conditions.

Phase 2 - Part 2: Laboratory Testing of a Water Injection System

Phase 2 - Part 2 involved the investigation of a computer-controlled water injection system intended to reduce NOx from marine vessels. The system was bench tested on a Caterpillar 3406B engine while connected to a power absorption unit that loaded the engine according to the ISO 8178 – E3 propeller curve. Parameters that were varied and investigated included the water injection rate as well as single and multi-point injection of the water.

The results indicated that the maximum reduction for NOx (28%) occurred with multi-point injection at the highest injection rate of 27.0 L/h. This corresponded to a maximum PM increase of ~18%, as well as a 3% reduction in CO and less than 1% increase in THC, CO_2 and fuel consumption. Single-point injection at the 27.0 L/h injection rate resulted in a 23.9% reduction in NOx and a 21.0 % increase in PM emissions.

Phase 2 - Part 3: Field-testing of a Water Injection System

Phase 2 - Part 3 involved a testing program to evaluate the impact of a water injection system on a diesel propulsion engine of the BC Ferry, *Queen of New Westminster*. The program compared the emissions from one of the main engines with and without the water injection system installed.

The use of the continuous water injection system showed a reduction of between 10% and 22% in NOx emission rates (kg/tonne fuel) and an average reduction of PM of 20% without compromising CO and CO_2 emissions.

The manufacturer of the system measured differences in other engine parameters and ambient conditions. An increase of ~1% was measured in engine load and a decrease of ~1% in specific fuel consumption was noted.

In this part of the program, the demonstration of the water injection system focused on quantifying exhaust emissions changes. Further investigation into other conditions related to the use of the water injection system, such as the volume of the water required, cost of the water, associated costs of using the injection system and the long-term effects of using water on the engine components, should be undertaken.

SOMMAIRE

Transports Canada travaille à protéger l'environnement et à créer un réseau de transport durable. Le Centre de développement des transports (CDT) de Transports Canada, de pair avec la Division de la recherche et de la mesure des émissions (ERMD) d'Environnement Canada et plusieurs autres partenaires, a participé à une série de projets mieux connus sous le nom de Programme de mesure des émissions gazeuses des navires.

La Direction générale de la sécurité maritime de Transports Canada, et le Programme de recherche et de développement énergétiques (PRDE) de Ressources naturelles Canada, ont financé le Programme de mesure des émissions gazeuses des navires. De plus, Environnement Canada a contribué aux travaux à la fois financièrement et par l'apport de biens et services.

Transports Canada a lancé un programme de R&D axé sur la réduction des émissions atmosphériques dans le secteur du transport maritime. Les chercheurs ont étudié quelques technologies de réduction des émissions d'oxydes d'azote (NO_x) destinées aux moteurs diesel des navires et offertes sur le marché, en vue de déterminer la possibilité de les appliquer au Canada. Le CDT, avec l'appui de la Division de la recherche et de la mesure des émissions, a mis sur pied un programme continu de développement de technologies rentables de contrôle des émissions gazeuses des navires. Ce programme comprend notamment la mesure des émissions gazeuses des moteurs de navires, la démonstration en laboratoire de technologies de contrôle des émissions et la mise à l'essai de ces technologies à bord de navires canadiens, en conditions réelles d'exploitation.

Le programme englobe l'essai en laboratoire de systèmes d'injection d'eau et de diverses émulsions eau-carburant diesel et des essais à bord d'un navire commercial, dans des conditions réelles d'exploitation, visant à démontrer la capacité des systèmes d'injection d'eau à réduire les émissions de NO_x. Ce programme consiste également à mesurer les émissions de monoxyde de carbone (CO), de gaz carbonique (CO_2), d'oxydes d'azote (NO_x), d'hydrocarbures totaux (HCT) et de particules.

La réduction des émissions de NO_x par les navires est une préoccupation de premier plan pour la Direction générale de la sécurité maritime, l'organisme de réglementation de Transports Canada. Les règlements internationaux énoncés dans l'annexe VI de la convention Marpol 73/78 adoptée par l'Organisation maritime internationale (OMI) visent à limiter les émissions atmosphériques de polluants produites par les navires, principalement les oxydes d'azote (NO_x) et les oxydes de soufre (SO_x). Le Canada entend ratifier l'annexe VI de la convention Marpol de 1997 de l'OMI d'ici décembre 2003 et appliquer les règlements de l'OMI par le contrôle des navires par l'État du port, disposition prévue par la *Loi sur la marine marchande du Canada*.

Le plan de travail du programme se divisait en deux phases : la phase 1 portait sur la mesure des émissions d'un moteur utilisant un carburant conventionnel, et la phase 2, sur l'évaluation de technologies fondées sur l'addition d'eau au carburant. La phase 2 se subdivisait à son tour en trois parties, soit les essais en laboratoire d'émulsions eau-carburant, les essais en laboratoire d'un système d'injection d'eau et, finalement, les essais sur le terrain d'un système d'injection d'eau.

Phase 1 – Mesure des émissions d'un moteur utilisant un carburant conventionnel

La phase 1 des travaux comportait des essais visant à mesurer les émissions gazeuses produites par l'un des moteurs principaux d'un navire de charge (*NM Cabot*) effectuant des trajets hebdomadaires entre Montréal et St. John's.

Le taux d'émission de NO_x observé variait entre 12,5 et 24,8 g/kW-h dans différentes conditions d'exploitation. Ces résultats ont été comparés aux limites prescrites par l'OMI. Les émissions d'oxydes d'azote (NO_x) dépassaient ces limites pour six des sept régimes du moteur du navire. Il convient de noter que les limites prescrites par l'OMI sont fondées sur une moyenne pondérée en fonction de vitesses et de régimes différents, tandis que les données recueillies dans le cas présent correspondaient uniquement à des régimes moteur.

Ces résultats, tout comme les résultats des autres formules de carburant mises à l'essai, seront comparés aux résultats de l'essai du système d'injection d'eau qui sera installé sur le *NM Cabot*.

Phase 2 – 1^{re} partie : Essais en laboratoire de carburants émulsifiés

La première partie de la phase 2 portait sur les effets de deux paramètres, soit la quantité d'eau dans l'émulsion de carburant et le moment de l'injection de carburant dans le moteur.

Les chercheurs ont évalué quatre émulsions de carburant, chacune ayant une teneur en eau différente. Les essais ont été réalisés au moyen d'un moteur diesel à grande vitesse fonctionnant à quatre régimes constants et s'appuyant sur la courbe d'hélice de l'ISO. La mesure composite des émissions gazeuses, effectuée selon la norme de l'ISO, a démontré que des quatre émulsions eau-carburant diesel ayant des teneurs en eau différentes (5 %, 10 %, 15 % et 20 %), celle renfermant 20 % d'eau permettait d'obtenir les meilleurs résultats, soit une réduction de 8 % et de 83 % des émissions de NO_x et de particules, respectivement, ainsi qu'une réduction de 20 % des émissions de CO. Par contre, cette émulsion entraîne une augmentation de 8 % des HCT. Pour chaque mode d'essai, les réductions d'émissions variaient en fonction du type d'émulsion de carburant utilisé et du régime du moteur.

En modifiant le moment de l'injection du carburant dans le moteur, les chercheurs ont réussi à obtenir les compromis escomptés, c'est-à-dire une réduction des émissions de particules et un accroissement des NO_x lorsque le moment d'injection du carburant est devancé et l'inverse, lorsque le moment d'injection est retardé. En retardant le moment de l'injection d'une émulsion de carburant constituée à 20 % d'eau, on a obtenu une réduction de 58 % des NO_x et de 72 % des particules émis.

Toutefois, cette émulsion de carburant entraîne une augmentation de la consommation de carburant. Pour trois des quatre modes d'essai, on a observé une augmentation de la consommation de carburant proportionnelle à la teneur en eau de l'émulsion eau-diesel et ce, à vitesse et régime constants.

Phase 2 – 2^e partie : Essais en laboratoire d'un système d'injection d'eau

La deuxième partie de la phase 2 portait sur l'étude d'un système d'injection d'eau commandé par ordinateur destiné à réduire les émissions de NO_x produites par des navires. Le système, testé au banc d'essai Caterpillar 3406B, était relié à un module d'absorption de puissance qui configurait le régime du moteur conformément à la courbe d'hélice de la norme ISO 8178 – E3. Les divers paramètres étudiés comprenaient notamment le taux d'injection d'eau et l'injection d'eau en un seul point et en des points multiples (injection multipoint).

Les résultats obtenus indiquent qu'on obtient une réduction maximale des émissions de NO_x (28 %) ayant recours à l'injection multipoint, au taux maximal d'injection de 27,0 L/h. Cela correspond à une augmentation maximale d'environ 18 % des émissions de particules, à une réduction de 3 % des émissions de CO et à une augmentation de moins de 1 % des HCT, du CO_2 et de la consommation de carburant. Les essais réalisés au moyen de l'injection d'eau en un seul point, au taux d'injection de 27,0 L/h, ont entraîné une réduction de 23,9 % des émissions de NO_x et une augmentation de 21,0 % des émissions de particules.

Phase 2 – 3^e^ partie : Essais sur le terrain d'un système d'injection d'eau

La troisième partie de la phase 2 a consisté en des essais visant à évaluer l'impact d'un système d'injection d'eau intégré au moteur diesel du traversier *Queen of New Westminster* de la B.C. Ferry. On a comparé, dans le cadre de ce programme, les émissions produites par l'un des moteurs principaux du traversier, avec et sans système d'injection d'eau.

L'utilisation d'un système d'injection continue d'eau a permis d'obtenir une réduction de 10 % à 22 % des NO_x (kg/tonne de carburant) et une réduction moyenne de 20 % des particules et ce, sans augmentation des émissions de CO et de CO_2.

Le fabricant du système a mesuré les effets sur d'autres paramètres du moteur et conditions ambiantes. Il a observé une augmentation d'environ 1 % de la charge du moteur, ainsi qu'une diminution d'environ 1 % de la consommation spécifique de carburant.

À cette étape du programme, la démonstration du système d'injection d'eau visait principalement à quantifier la réduction des émissions de gaz d'échappement. Il conviendrait de pousser plus avant l'étude d'autres conditions associées à l'utilisation du système d'injection d'eau, comme le volume d'eau requis, le coût de cette ressource, les coûts associés à l'exploitation de ce système d'injection et les effets à long terme de l'utilisation d'eau sur les composants du moteur.

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1.1 Introduction

Canada, as a member of International Maritime Organization (IMO) and a signatory of the Montreal Protocol, has committed to the reduction of gaseous emissions that contribute to global warming and local atmospheric pollution. Ships are responsible for a portion of the man-made air pollution contributing to environmental degradation. It is the particulate matter (PM), oxides of nitrogen (NOx), and carbon dioxide (CO_2) that are of primary concern with regard to health and environmental effects.

The international regulations incorporated under IMO / MARPOL, Annex VI propose to limit airborne emissions from marine vessels. While Annex VI has yet to be ratified, the NOx limits are designed to achieve a worldwide 30% reduction versus 1992 levels. Once ratified, the IMO rules will apply to all new ships (or major retrofits) built after January 1, 2000, with engines rated greater than 130 kW. Canada, as a signatory to IMO, implements and enforces the IMO rules through Port-State control under the Canada Shipping Act. Transport Canada (i.e., the Canadian National Administration) is on record for stating that it will ratify the IMO proposal by early 2003.

Marine vessels contribute to air pollution through the exhaust generated from both their main and auxiliary engines. Though the contribution of this source to the overall pollution burden is relatively small (~7% of the world's total emissions of NOx, according to some estimates), the impact on local air sheds has the potential to be significant. In Vancouver, for example, the port experiences more than 8000 annual marine vessel movements. In an effort to control these emissions, the IMO has negotiated standards for NOx and has initiated discussions on similar controls on PM. Adding to this international effort, IMO participants can apply to have specific locations identified as 'special designated areas' requiring more stringent emission regulations for marine vessels.

The manufacturers of the marine vessel engines and the shipbuilders have responded to the demands to reduce vessel emissions by improving the operation of the engines and by incorporating emissions control technologies in the design of new vessels. Selective Catalytic Reduction (SCR), fuel emulsions, water injection systems and a number of engine modifications are a sample of the technologies being employed.

The Transportation Development Centre (TDC) of Transport Canada, in collaboration with the Emissions Research and Measurement Division (ERMD) of Environment Canada, and various other partners collaborated on a series of projects known as the Marine Vessel Exhaust Emissions Program. Transport Canada's Marine Safety Directorate (MSD) and Natural Resources Canada's Program of Energy Research and Development (PERD) funded the emissions program. In addition, Environment Canada has also contributed to the work through a combination of funding and in-kind resources.

The goal of the program was to determine the exhaust emissions from diesel engines, and evaluate and demonstrate the effect of various technologies on the exhaust emissions. The overall program, consisting of 3 phases, is outlined in the following sections.

Phase 1 - Conventional Operation and Characterization

Phase 1 of the Marine Vessel Exhaust Emissions Program involved the collaboration of Environment Canada's ERMD, Transport Canada's TDC, and Oceanex on a project to measure the exhaust emissions of a cargo vessel (*MV Cabot*) under normal operation. The *MV Cabot*, a cargo vessel that operates from Montreal to St. John's on a weekly basis, was tested under various engine speed and load settings. Measurements to determine the level of NOx, carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2) and PM were completed during each of the sampling periods. These results formed baseline emissions for comparison with future testing of the *MV Cabot* with a water injection system in place. (Testing of the exhaust emissions from the *MV Cabot*, after the installation of a water injection system, is scheduled to be completed in the summer of 2003.)

The description and results of Phase 1 of the program may be found in Section 2 of this report.

Phase 2 - Evaluation of Alternative Technologies

Phase 2 of the Marine Vessel Exhaust Emissions Program focused on the development, demonstration and evaluation of cost-effective technologies for reducing exhaust emissions from marine vessel propulsion and auxiliary engines.

Phase 2 was divided into three parts:

Part 1 - Laboratory testing of water emulsified fuels
Part 2 - Laboratory testing of a water injection system
Part 3 - Field-testing of a water injection system

Phase 2 - Part 1

A laboratory test program was developed to measure the exhaust emissions and engine operating parameters from a heavy-duty diesel engine running at steady-state conditions using fuel emulsions. The Lubrizol Corporation participated in the program by providing the fuel emulsions and the baseline diesel fuel. Using these fuels, a diesel test engine was operated over a marine cycle, defined by the IMO as ISO 8178-4 E3, for no fewer than three different fuel injection timing settings. Measurements to determine the level of NOx, CO, total hydrocarbons (THC), CO_2 and PM were completed during each of these engine trial runs.

Section 3 of this report details the fuel emulsion / marine cycle testing program and results.

Phase 2 - Part 2

A laboratory test program was developed to measure the exhaust emissions and engine operating parameters from a heavy-duty diesel engine running at steady-state conditions using a water injection system. The program involved the development of a bench scale system for laboratory testing, including a non-catalyzed particulate trap, water injection system with single and multi-point water injection and implementation of oxidation catalysts into large diesel engine displacement exhaust streams.

Using a water injection system, a diesel test engine was operated over a marine cycle, defined by the IMO as ISO 8178-4 E3. Various water injection rates as well as multi-point and single point injection were tested. Measurements to determine the level of NOx, CO, THC, CO_2 and PM were completed during each of these engine trial runs.

Section 4 of this report details the water injection / marine cycle testing program and presents the results of the testing program.

Phase 2 - Part 3

A field test program was developed to measure the exhaust emissions and engine operating parameters from a marine diesel engine running at steady-state conditions with and without a water injection system in place.

This work involved the collaboration of ERMD, TDC, and the BC Ferry Corporation on a project to measure the exhaust emissions of the *Queen of New Westminster* with and without the use of a water injection system. The exhaust emissions from the #4 main engine of the *Queen of New Westminster* of the BC Ferry Corporation were tested on two separate occasions, July 1999 and January 2000, while on route from Vancouver to Vancouver Island and on the return runs. This engine had previously been installed with the continuous water injection (CWI) system.

Emissions testing was performed with and without the CWI in operation and emissions of CO, CO_2, NOx and PM were collected. Section 5 of this report details the test plan and procedures, and a comparison of the criteria pollutant emissions with and without the CWI installed.

Section 2 – Engine Exhaust Emissions Evaluation of the *MV Cabot*

2.1 Introduction

ERMC, TDC, and Oceanex collaborated on a project to measure the exhaust emissions from one of the main engines of the *MV Cabot*, a cargo vessel that operates from Montreal to St. John's on a weekly basis.

This work was undertaken as part of a multi-year collaborative R&D project with Transport Canada on marine vessel exhaust emissions. For this first phase of the program, the exhaust emissions from one of the main engines of the *MV Cabot* were measured for the purpose of designing and implementing emissions control technologies.

The exhaust emissions were measured while the vessel was leaving the dock and at low cruise speed up to medium cruise. Due to the restrictions on vessel speeds while in the St. Lawrence River, it was not possible to measure the exhaust emissions while the vessel was operating at high cruise. As this particular vessel uses both marine diesel oil and heavy oil, the emissions were measured with the operating fuel being blends of the two fuels. Figure 2.1 illustrates the *MV Cabot* en route during the emissions testing.

This section discusses the emissions measurements and the results of the analysis from the vessel operating at different speeds and fuel combinations.

Figure 2.1 *MV Cabot* 'En Route' During Exhaust Emissions Testing

2.2 Objective

The objective of the first phase of the program was to determine the exhaust rate and concentration of criteria pollutants for the *MV Cabot* under normal engine speed and load conditions.

2.3 Vessel and Engine Data

Table 2.1 lists the details of the *MV Cabot* and its main engines.

Table 2.1 Vessel and Main Engine Description

Ship Description:	
Length (m)	182
Beam (m)	23
Gross Tonnage	14,000
Main Engine Description:	
Manufacturer	Pielstick
Type	Medium speed diesel
Max. Cont. Rating	7300 hp
Number/Configuration of Cylinders	V-12
Fuel Type	Blends of marine diesel oil (MDO) & bunker C oil

2.4 Test Procedure

A test procedure was developed by ERMD to evaluate the exhaust emissions during typical operation of the vessel. This section describes the test schedule, emissions sampling, and emissions calculation.

2.4.1 Test Matrix

During October 2000, ERMD measured the exhaust emissions from one of the main engines of the *MV Cabot* during typical operation, i.e.:

- Leaving port;
- Low-speed cruise;
- Intermediate speed; and
- Higher speed.

Table 2.2 lists the test conditions during the exhaust emissions sampling.

Table 2.2 Test Conditions During Exhaust Emissions Sampling

Sample	Engine operation	Engine hp*	Engine RPM	Fuel type**
1	Leaving port	1825	388	40%MDO/60% bunker C
2	Low-speed cruise	1825	395	36%MDO/64% bunker C
3	Intermediate speed	3650	450	32%MDC/68% bunker C
4	Intermediate speed	3650	450	100% bunker C
5	Intermediate speed	3650	500	100% bunker C
6	Higher speed	5475	438	100% bunker C
7	Higher speed	5475	500	100% bunker C

Notes * estimated hp based on information provided by engine operator
** information provided by crew

2.4.2 Exhaust Emissions Sampling Methodology and Procedures

The exhaust sampling and analysis system was prepared by ERMD to provide accurate and repeatable data comparable to a more permanent installation of analyzers that would be typical of a standardized test bench configuration. To achieve these criteria, ERMD utilized a portable, commercial, continuous emissions monitor (ECOM-AC) for the measurement of CO, CO_2, NOx, and O_2. Coupled with the emissions analyzer were stainless steel particulate filters holders, a vacuum pump, and a mass flow controller used to collect total particulate mass. PM emission rates were obtained by directing the exhaust through pre-weighed 47 mm Pallflex™ filters, allowing particles to be deposited. Prior to the test, all filters were stored in a desiccator where the conditions were maintained at 40±10% humidity and 24°C. After this stabilization period, the filters were weighed on a Mettler AE240 balance readable to 0.01 mg. The filters were then stored in covered petri dishes for transfer to the test site on board the *MV Cabot*. After the testing, the filters were returned to the petri dishes and sealed for transfer back to the analysis lab. Prior to weighing, the filters were re-stabilized in the desiccator for 12 to 24 hours and then re-weighed to determine the net mass of diesel particulate emissions. This mass, plus the measurement data, was used to calculate the PM emissions rate in kg/tonne fuel.

Table 2.3 outlines the sampling media and analysis methodology as well as the flow rates used during the testing.

Table 2.3 Emissions Sampling and Analysis

Component	Sample/analysis	Flow Rate (L/min)
CO, CO_2, NOx, O_2	Continuous electrochemical sensors	1.5
Total Particulate Mass	47 mm diameter filters/ Gravimetric method	16.5

The sampling system was connected to the exhaust ducting of the ship's propulsion or auxiliary engine by removing the exhaust gas pyrometer from the stack and installing an exhaust sample probe in its place. The probe was a 9.5 mm diameter stainless steel tube with concentric holes drilled along its length. The probe was connected to the inlet of the sampling system with as short a transition as possible. Figure 2.2 illustrates the sampling equipment.

Figure 2.2 ECOM and Particulate Filter Holder Set-Up

Table 2.4 outlines the test procedures that were followed during the engine testing.

Table 2.4 Detailed Test Procedures

1. Boarding	The test equipment was brought aboard the vessel and moved down to the engine room by ERMD.
2. Test Port Selection	The test team and ship engineers selected the access point for the sample probe to the exhaust systems of the main engine. The access location was a valve/thermocouple in the exhaust duct just after the turbocharger.
3. Test Set-up	The thermocouple was removed and the sample probe inserted. The sampling train was assembled and supply voltage was located and connected to the system. The pumps, flow controllers, and continuous emissions monitor were turned on and allowed to warm up for 30 to 45 minutes. After the sampling system was warmed up, the sample flow rates to each of the sample media were calibrated through the use of a bubble meter.
4. Main Engine Test	The sampling lasted for 10 to 15 minutes at each condition. This allowed enough samples to be collected on the filter and provide an indication of the exhaust concentration stability under steady load condition.
5. Test Completion	At the conclusion of the test the sampling system was disassembled and packaged for removal from the vessel.

Figure 2.3 illustrates the top of the engine and the exhaust ducting. Figure 2.4 illustrates the sample probe inserted into the exhaust stream.

Figure 2.3 Exhaust Ducting and the Top View of the Pielstick Engine

Figure 2.4 Sampling Probe Inserted into the Exhaust Port

2.4.3 Emissions Calculations

The mass emissions calculations were based on those outlined in ISO 8178-1.[1] In this method the calculations are based on carbon balance between the fuel and exhaust. It was assumed in the calculation of the results that ambient levels of the pollutants were negligible, and that there was no correction of the NO_X emissions for the relative humidity of the engine intake air. Finally, although O_2 levels were measured in the exhaust, the emissions results presented are not corrected to a standard O_2 concentration. Table 2.5 lists the inputs and outputs of the emissions calculations.

Table 2.5 Emissions Calculations

Inputs	**Outputs**
Fuel density and fuel fraction carbon Exhaust concentration of CO_2 Fuel flow rate	Exhaust flow rate
Exhaust flow rate Exhaust emissions concentration Components density	Mass emissions rate of exhaust
Mass emissions rate & Engine power setting or fuel rate	Power-specific emissions rate g/kW•h (g/hp•h) Fuel-specific emissions rate kg/tonne

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[1] ISO 8178-1:1996(E) Reciprocating internal combustion engines - Exhaust emission measurement. Part 1: Test bed measurement of gaseous and particulate exhaust emissions

2.5 Results and Discussion

Tables 2.6 and 2.7 provide the emissions measurement data that was obtained during the various cruise conditions of the *MV Cabot* on the St. Lawrence in kg/t fuel and g/hp-h respectively.

Table 2.6 Emissions Rates During Cruise Conditions in kg/t fuel

Sample	Engine operation	CO	NO_X	CO_2	PM
1	Leaving port	6.8	94	2982	n/a
2	Low-speed cruise	6.4	82	2932	n/a
3	Intermediate speed	3.6	75	2951	n/a
4	Intermediate speed	7.1	64	2927	5.79
5	Intermediate speed	3.9	59	2918	6.02
6	High speed	4.9	97	2902	11.2
7	High speed	4.9	59	2902	10.5

Table 2.7 Emissions Rates During Cruise Conditions in g/hp-h

Sample	Engine operation	CO	NO_X	CO_2	PM
1	Leaving port	1.3	18.5	2982	n/a
2	Low-speed cruise	1.3	16	2932	n/a
3	Intermediate speed	0.7	15	2951	n/a
4	Intermediate speed	1.4	13	2927	1.14
5	Intermediate speed	0.8	12	2918	1.19
6	High speed	0.8	15	2902	1.77
7	High speed	0.8	9.3	2902	1.66

It should be noted that the calculations used approximations for both the fuel being consumed by the engine and the output horsepower during the measurement periods. The Chief Engineer of the vessel provided the fuel consumption and horsepower data.

To determine how the exhaust emissions results from the *MV Cabot* compare to the IMO Regulations for NOx, the IMO calculation for the applicable engine size was selected. Equation 2-1 applies to the *MV Cabot* as it falls within the criteria of engine speed range of 130 - 2000 rpm.

$$45.0 * n^{(-0.2)} \text{ g/kW-h} \qquad (2\text{-}1)$$

where n = rated engine speed.

Table 2.8 provides the NOx results based on equation 2-1 for each point of measurement.

Table 2.8 Comparison of NOx Measurements with IMO Standards

Sample	Engine RPM	NOx (g/kW-h)	IMO Std. (g/kW-h)
Leaving port	388	24.8	13.7
Low-speed cruise	395	21.5	13.6
Intermediate speed	450	20.1	13.3
Intermediate speed	450	17.4	13.3
Intermediate speed	500	16.1	13.0
Higher speed	438	20.1	13.3
Higher speed	500	12.5	13.0

In addition to the above reported exhaust emission measurements, the analysis determined the nitric oxide (NO) and nitrogen dioxide (NO_2) components of the NOx. Table 2.9 summarizes the measurement of these compounds in the exhaust.

Table 2.9 NO and NO_2 Concentrations in Parts per Million

Sample	Engine RPM	NO (ppm)	NO_2 (ppm)
Leaving port	388	685	66
Low-speed cruise	395	300	20
Intermediate speed	450	392	22
Intermediate speed	450	320	17
Intermediate speed	500	243	9
Higher speed	438	276	13
Higher speed	500	167	7

Typically the combustion of fossil fuels in a conventional internal combustion engine results in a NO_2/NOx ratio in the exhaust stream of approximately 10% or less. The NO_2 results presented in Table 2.9 all account for less than 10% of the total NOx emissions.

2.6 Summary

This project was undertaken to measure the exhaust emissions from the *MV Cabot*, a typical medium-sized cargo vessel operating in Canadian waters. The emissions results, though based on estimates of fuel consumption and engine power, indicated that the NOx exceed the levels regulated by IMO for six of the seven different measurement points during the transit from Montreal to Trois Rivières.

The square data points in Figure 2.5 illustrate the NOx emissions from the main engine of the *MV Cabot* during the various measurement conditions outlined in Table 2.8. It should be noted that the IMO limit is based on a weighted average over several operating points of speed and load, while the data obtained from this vessel is for single load points.

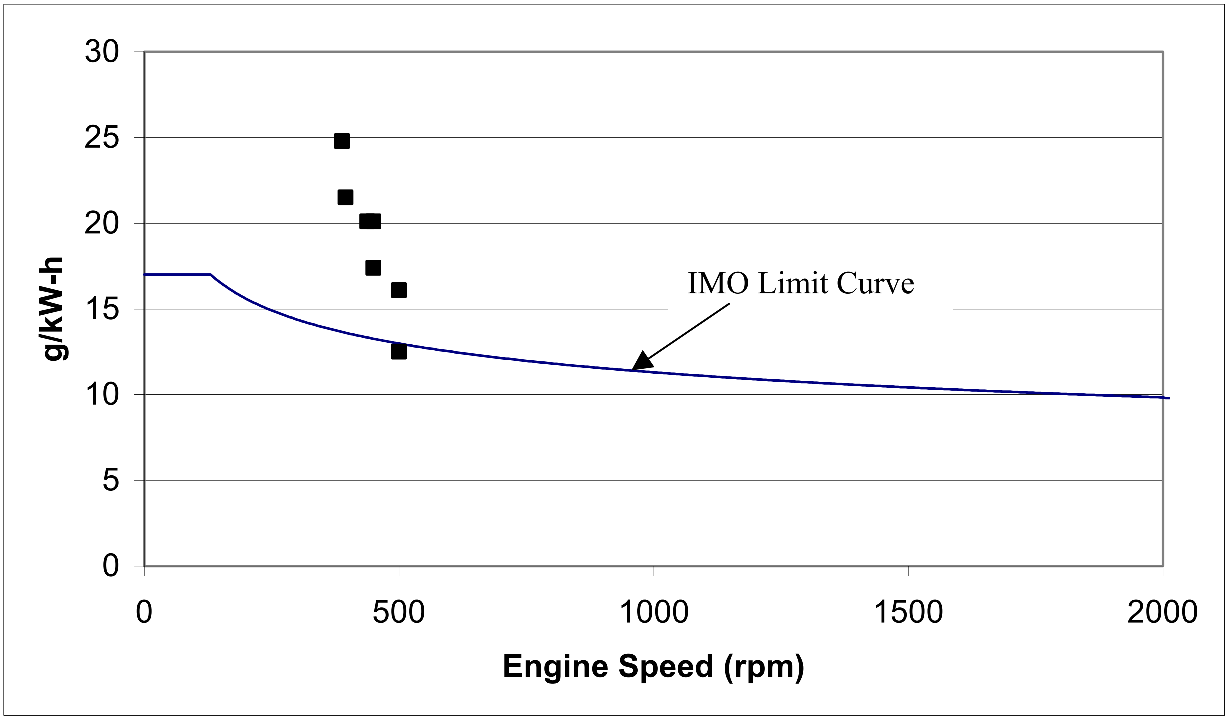

Figure 2.5 NOx Emissions Rates versus IMO Limits

Section 3 – Evaluation of Fuel Emulsions for Medium-Speed Marine Diesel Engine NOx Reduction

3.1 Introduction

New marine diesel engines have been designed for lower exhaust emissions, but as the result of the long life of existing engines, their impact on the reduction of exhaust emissions has been limited, if not negligible. Under the auspices of the joint TDC-ERMD program, work has been undertaken to investigate cost-effective emissions control technologies for in use vessel engines under the Marine Vessel Exhaust Emissions Program. The information contained in this section pertains to Phase 2 – Part 1 of the investigation and studies the effect of fuel emulsions on marine exhaust emissions.

Phase 2 – Part 1 of the program involved the study of diesel-water fuel emulsions, a technology that has been demonstrated by Lubrizol Corporation on highway and construction vehicles, and that may have potential for reducing marine vessel exhaust emissions. A manufacturer of marine engines, MAN B&W, has developed a fuel emulsions option for new engines as a means of lowering NOx emissions. The product is based on the blending of 50% water/diesel fuel, either Intermediate Fuel Oil (IFO) or Heavy Fuel Oil (HFO) (resulting in 33% water in the total emulsion). This emulsion, unlike the Lubrizol system, 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 the volumetric flow rate.[2]

The impact of this fuel on marine engines (medium and heavy-duty) is a reduction of NOx, PM, THC and CO_2 in the exhaust stream of the main engines. According to a study by Polar Design Associates, NOx emissions may be reduced by 1% for each 1% water in the HFO (i.e., 50% water and 50% HFO gives a reduction of 50% NOx), fine particulate can be reduced up to 80%, THC can be reduced 30% to 50% and CO 20% to 50%. These benefits came at the expense of a 1.5% increase in specific fuel consumption.

Lubrizol, a lubricant manufacturer, has developed a fuel emulsion for the in-use market of heavy-duty engines, with the present focus being high- and medium-speed engines. This product consists of a blend of 20% water, 80% low sulphur diesel and a surfactant to maintain the water droplets in suspension. No engine modifications are required for the use of this product. Exhaust emissions testing on both on-road and off-road heavy-duty diesel engines has been conducted by ERMD. The results indicated an average reduction of 30% in NOx and PM, with some increases in THC and CO.

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[2] Marine Atmospheric Pollution in Canadian Waters, Polar Design Associates Inc., March 1996.

This technology[3] has indicated the potential to reduce exhaust emissions of NOx and PM, in a relatively cost-effective manner (i.e., no engine modifications, low capital cost, and minimal infrastructure modifications) with the exception of an increase in operational costs due to a decrease in fuel economy in order to maintain equivalent power. To investigate the potential of optimizing the reduction in emissions with a minimal loss in fuel economy (or horsepower), a proposal was developed to evaluate both of these parameters with fuel emulsions containing less water. The remainder of this section details the laboratory testing that was undertaken for this investigation.

3.2 Objective

The work conducted during the first part of the second phase of the program focused on the measurement of the exhaust emissions and fuel consumption of a heavy-duty highway engine operating on four fuel emulsions ranging from 5% to 20% water, emulsified with low-sulphur diesel. By varying the water content and the fuel injection timing, the project was designed to investigate the potential for optimized exhaust emissions reduction with minimal power loss.

3.3 Program Description

3.3.1 Overview

A laboratory test program was developed to measure the exhaust emissions and engine operating parameters from a heavy-duty diesel engine running at steady-state conditions using fuel emulsions. The Lubrizol Corporation participated in the program by providing the fuel emulsions and the baseline diesel fuel. Using these fuels, a diesel test engine was operated over a marine cycle, defined by the IMO as ISO 8178-4 E3, with no fewer than three different fuel injection timing settings. Measurements to determine the level of NOx, CO, THC, CO_2 and PM were completed during each of these engine trial runs.

3.3.2 Test Fuels

The Lubrizol Corporation provided 20 gal. of a baseline low-sulphur fuel at 5%, 10%, 15% and 20% fuel and water emulsions. The specifications for the base fuel are found in Table 3.1.

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[3] Cost/Benefit Study of Marine Engine NOx Emission Control Systems – A Case Study on the Oceanex Vessel, MV Cabot, ERMD, January 2001.

Table 3.1 Baseline Fuel Specifications

Specific Gravity	0.8343 (typical)
Carbon Fraction (by mass)	0.875 (typical)
Net Heating Value	19,753 [BTU/lb.] (typical)

3.3.3 Test Engine

The test engine used for this project was a Caterpillar 3306, in-line six-cylinder, mechanically controlled fuel injection engine.

3.3.4 Test Instrumentation

Engine Dynamometer – The engine was connected to a 750 hp Clayton waterbrake, which served as the power absorption unit. The waterbrake operation was controlled by a computer, which activated valves to load and unload the water turbine based on feedback on the engine speed and torque.

3.3.5 Exhaust Emissions Sampling and Analysis System

The engine exhaust pipe was connected via a flexible stainless steel hose to a 25.4 cm diameter dilution tunnel and Constant Volume Sampling System (CVS). The tunnel had a constant flow rate of 56.6 m^3/min, controlled by a critical flow venturi. A continuous dilute sample of the exhaust was drawn from the tunnel and directed through a heated line to the analyzer bench. The sample was directed to: a Heated Chemiluminesence instrument for the measurement of NOx, a Heated Flame Ionization detector for THC and two Non-Dispersive Infrared analyzers for CO and CO_2. A heated filter was used to gravimetrically determine total particulate mass.

3.3.6 Engine Test Cycle

The test program followed the ISO standard marine four-mode steady-state cycle detailed in the ISO 8178-4 E3 cycle. The test cycle consisted of the engine operation as detailed in Table 3.2.

Table 3.2 ISO 8178-4 E3 Cycle Specifications

Operating Mode	% engine speed	% power – at speed	Weighting factor	Stabilize/measurement timing (seconds)
1	100	100	0.2	90 / 60
2	91	75	0.5	90 / 60
3	80	50	0.15	90 / 60
4	63	25	0.15	90 / 60

The ISO E3 cycle is based on the marine application propeller law where, in a typical propeller operation, the shaft power varies as a cube of the shaft rotational speed. Equation 3-1 describes the relationship:

$$(N_B / N_A) = (P_B / P_A)^3 \qquad (3\text{-}1)$$

where N is the propeller rotational speed,

P is the power, and

A and B refer to two different operating points along the propeller curve.

A plot of a propeller curve and the ISO E3 cycle operating points are shown in Figure 3.1.

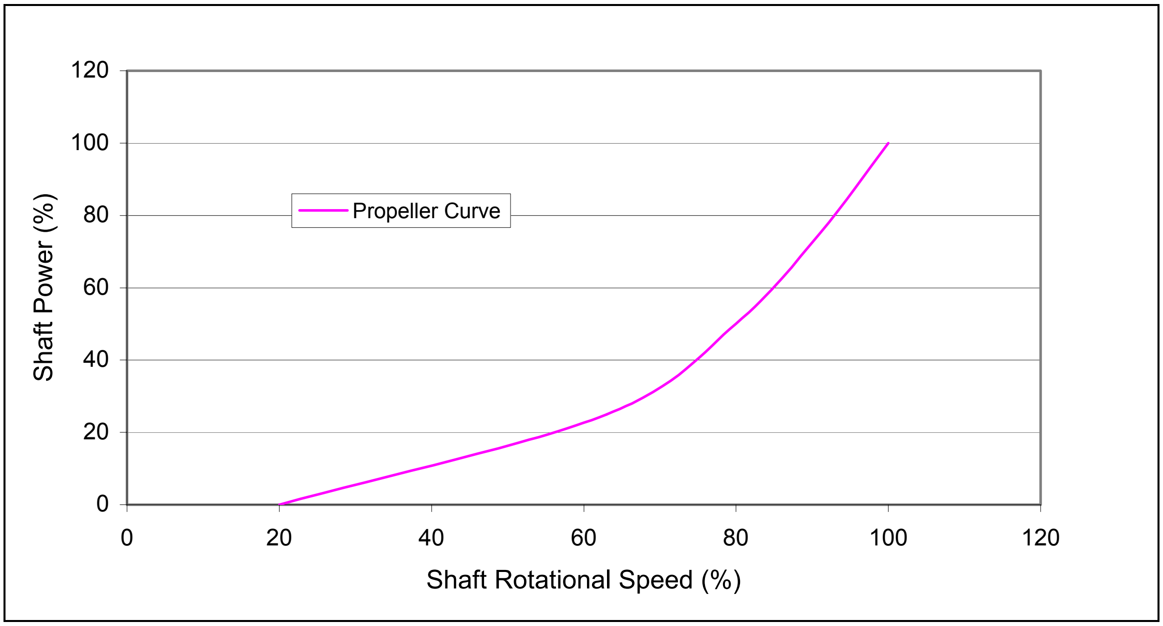

Figure 3.1 ISO 8178-4 E3 Propeller Curve

3.3.7 Test Procedures

The engine dynamometer exhaust emissions testing was conducted according to the protocols as outlined in the US EPA Federal Register CFR 40 Part 86 for exhaust emissions testing of Heavy Duty Diesel engines.

3.3.8 Methodology

The testing was conducted in three phases, based on the fuel injection timing. The initial testing was conducted at the original equipment manufacturer specifications of 26 degrees BTDC (before top dead centre). The measurements were then repeated with the timing advanced to 30 degrees and then retarded to 17 degrees BTDC. For each of these conditions, the engine was operated on all five fuels with a minimum of three repeats of the E3 cycle.

Prior to initiating the sampling, the engine was brought up to normal operating temperature. The four test modes of the E3 cycles were then run for a minimum of 10 minutes at each mode, with the final 90 seconds used for sampling. For each steady state, dilute exhaust emissions samples were analyzed for THC, CO, NOx, CO_2 and PM.

3.4. Results and Discussion

A summary of the test results for the three fuel injection points and the five fuels is found in Table 3.3.

Table 3.3 Summary of the ISO Composite Emissions Results for the Propeller Curve

Testing of LUBRIZOL diesel fuel blends for Marine Duty performed on the Caterpillar 3406B test platform										
						Heavy-Duty Transient Emissions Test Results				
Injection Timing	**Test Config.**	**Power [hp]**	**Oil Sump [°C]**	**Coolant [°C]**	**Turbo Out [°C]**	**CO [g/hp-h]**	**CO_2 [g/hp-h]**	**NOx [g/hp-h]**	**THC [g/hp-h]**	**PM [g/hp-h]**
	ISO Marine cycle E3									
orig (26.0^{O}BTC)	Baseline	249.0	103.6	86.9	552.4	1.36	522.23	5.94	0.12	0.46
orig (26.0^{O}BTC)	5% emulsion	250.1	103.7	86.3	548.3	1.20	520.78	6.18	0.12	0.27
orig (26.0^{O}BTC)	10% emulsion	250.2	102.9	85.3	541.5	1.08	515.44	5.86	0.12	0.16
orig (26.0^{O}BTC)	15% emulsion	247.0	103.5	86.0	536.5	0.99	514.87	5.85	0.12	0.09
orig (26.0^{O}BTC)	20% emulsion	242.8	102.1	83.8	525.7	0.94	518.86	5.48	0.13	0.08

For purposes of analyzing the data, the discussion will focus on the impact of the various levels of water in the emulsion and then the effect of the fuel injection timing.

3.4.1 ISO Cycle Composite Results

Table 3.3 illustrates the ISO composite results, calculated by weighting the emissions results using the factors provided in Table 3.2. The second mode represents 50% of the ISO composite based on a 0.5 weighting factor. This mode sets the engine speed at 91% of the rated speed and the horsepower at 75%, at the rated speed.

The results indicate that with the increase in water in the emulsion, CO, NOx and PM were reduced by 31%, 8% and 83%, respectively (based on the difference between the baseline emissions and those with the 20% fuel emulsion). The power output from the cycle was also reduced by approximately 3% as a result of the addition of 20% water to the fuel. As the dynamometer was set to maintain specific horsepower levels, the 3% overall loss in power must have been a result of the fuel system not having the capacity to provide the volume of fuel required for the horsepower set point.

To determine the effect of the various fuel emulsions on the exhaust emissions, the measurements have been plotted for the various modes. Mode 1 represents the engine operating at rated speed and full power. Mode 2 at 91% rated speed and 75% power is defined as high-speed cruise. Mode 3 reflects a medium-speed cruise at 80% speed and 50% power, and Mode 4 defines a low-speed cruise. Table 3.4 and Figures 3.2 and 3.3 present the exhaust emissions data for the four modes with all of the fuels.

Table 3.4 Summary Exhaust Emissions Results for E3 Cycle Using all Test Fuels

Testing of LUBRIZOL diesel fuel blends for Marine Duty performed on the Caterpillar 3406B test platform											
							Heav- Duty Transient Emissions Test Results				
Injection Timing	**Test Config.**	**Mode**	**Power [hp]**	**Oil Sump [ºC]**	**Coolant [ºC]**	**Turbo Out [ºC]**	**CO [g/hp-h]**	**CO$_2$ [g/hp-h]**	**NOx [g/hp-h]**	**THC [g/hp-h]**	**PM [g/hp-h]**
	ISO Marine cycle E3										
orig (26.0^{O}BTC)	Baseline	1	369.8	98.7	78.6	597.7	1.50	530.2	5.01	0.11	0.55
orig (26.0^{O}BTC)	5% emulsion	1	376.4	99.1	79.4	598.2	1.33	527.4	5.21	0.12	0.29
orig (26.0^{O}BTC)	10% emulsion	1	374.5	98.0	75.8	586.1	1.18	518.2	4.87	0.11	0.21
orig (26.0^{O}BTC)	15% emulsion	1	358.1	99.4	80.9	581.7	1.02	518.3	4.95	0.11	0.14
orig (26.0^{O}BTC)	20% emulsion	1	338.2	98.3	75.9	561.3	0.92	525.2	4.78	0.11	0.11
orig (26.0^{O}BTC)	Baseline	2	275.4	105.2	92.2	590.7	1.30	515.3	6.11	0.10	0.43
orig (26.0^{O}BTC)	5% emulsion	2	275.0	105.4	91.5	584.4	1.16	515.0	6.32	0.11	0.27
orig (26.0^{O}BTC)	10% emulsion	2	276.0	104.6	90.6	579.1	1.05	511.0	5.99	0.10	0.16

Testing of LUBRIZOL diesel fuel blends for Marine Duty performed on the Caterpillar 3406B test platform

							Heav- Duty Transient Emissions Test Results				
Injection Timing	**Test Config.**	**Mode**	**Power [hp]**	**Oil Sump [°C]**	**Coolant [°C]**	**Turbo Out [°C]**	**CO [g/hp-h]**	**CO$_2$ [g/hp-h]**	**NOx [g/hp-h]**	**THC [g/hp-h]**	**PM [g/hp-h]**
orig (26.0^{O}BTC)	15% emulsion	2	276.1	105.2	90.4	574.5	0.99	510.1	5.97	0.10	0.08
orig (26.0^{O}BTC)	20% emulsion	2	275.8	103.3	88.3	563.6	0.93	513.4	5.58	0.10	0.08
orig (26.0^{O}BTC)	Baseline	3	172.3	106.6	89.7	523.4	1.17	517.9	7.15	0.14	0.42
orig (26.0^{O}BTC)	5% emulsion	3	172.8	105.8	87.1	515.2	1.02	515.1	7.60	0.14	0.20
orig (26.0^{O}BTC)	10% emulsion	3	171.9	105.6	88.3	511.0	0.87	511.0	7.33	0.13	0.07
orig (26.0^{O}BTC)	15% emulsion	3	172.2	105.9	87.6	506.4	0.78	509.9	7.10	0.13	0.01
orig (26.0^{O}BTC)	20% emulsion	3	171.7	104.8	87.5	500.8	0.72	512.1	6.27	0.14	0.01
orig (26.0^{O}BTC)	Baseline	4	76.5	101.9	77.4	393.4	1.49	564.4	7.14	0.29	0.34
orig (26.0^{O}BTC)	5% emulsion	4	76.1	102.2	77.1	395.0	1.27	560.6	7.73	0.31	0.21
orig (26.0^{O}BTC)	10% emulsion	4	76.9	101.4	77.2	387.6	1.28	560.7	7.46	0.33	0.05
orig (26.0^{O}BTC)	15% emulsion	4	76.4	101.2	76.4	379.8	1.36	561.6	7.21	0.42	0.01
orig (26.0^{O}BTC)	20% emulsion	4	76.9	100.7	75.6	376.6	1.63	562.4	6.60	0.62	0.01

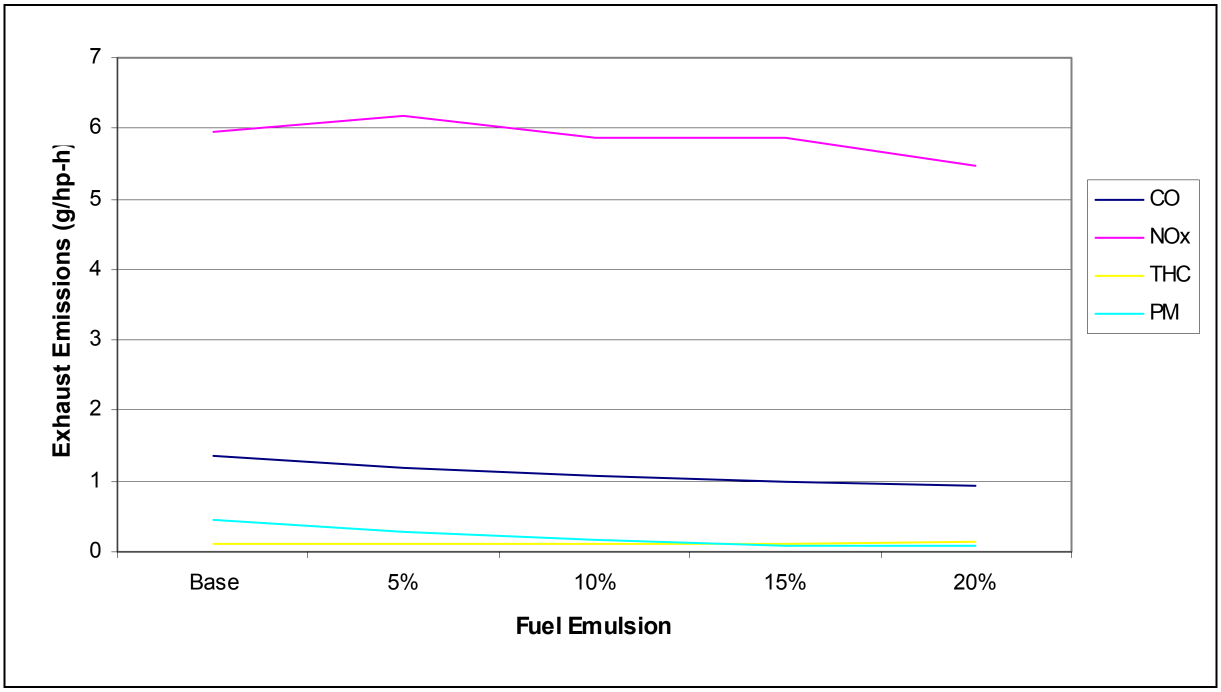

Figure 3.2 ISO Composite Regulated Emissions

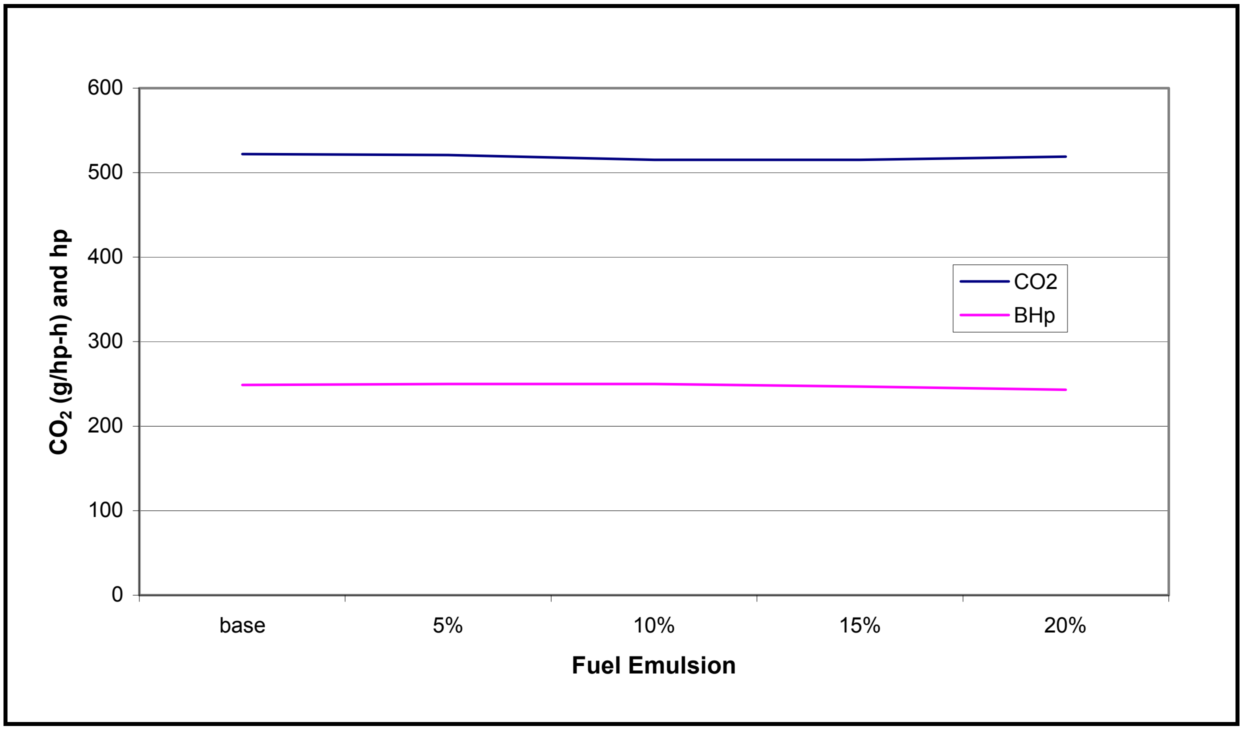

Figure 3.3 ISO Composite Emissions for CO_2 and hp

For the ISO Composite cycle, the general trend indicates that the greater the increase in the percentage of water in the fuel emulsion, the larger the reduction for CO, NOx and PM. The exception is for the low-speed cruise mode (Mode 4), where both the CO and THC increase for the 15% and 20% blends. Both CO_2 and THC emissions are essentially percentage water insensitive except for Mode 4 THC. Table 3.5 indicates the changes in exhaust emissions resulting from the fuel emulsions over the E3 cycle.

Table 3.5 Percent Change in ISO Composite Exhaust Emissions with Fuel Emulsions

Fuel	CO	CO_2	NOx	THC	PM
5%	-12	-0.2	4	0	-41
10%	-21	-1.3	-1	0	-65
15%	-27	-1.3	-1	0	-80
20%	-31	-0.6	-8	8	-83

3.4.2 Mode Effects

Evaluating the effects of the fuel emulsions on the individual modes, as summarized in Table 3.6, indicates that the potential benefits of emissions reductions occur when the engine is operating under simulated medium to high cruise conditions. Lower speed and load conditions, where diesel engines do not inherently operate efficiently, do not show the same overall emissions benefits, with the exception being PM with a reduction of 97%.

Table 3.6 Comparison of Exhaust Emissions Between Baseline Fuel and 20% Emulsion

Mode	**% Difference**				
	CO	**CO_2**	**NOx**	**THC**	**PM**
1	-39	-8.6	-4.6	0	-80
2	-28	-2	-8.7	0	-81
3	-38	-2	-12	0	-97
4	9	0	-7.6	114	-97

The addition of the water into the combustion chamber results in a reduction in combustion temperature and, correspondingly, a decrease in the NOx emissions. The exhaust temperature at the outlet of the turbo reflects this decrease, as this value decreases with the increase in water content in the fuel. The trend for each mode is similar, with a drop of from 4% to 6% from the baseline to the 20% fuel emulsion.

Figures 3.4 to 3.9 illustrate the impact on the emissions per mode for the various fuel emulsions.

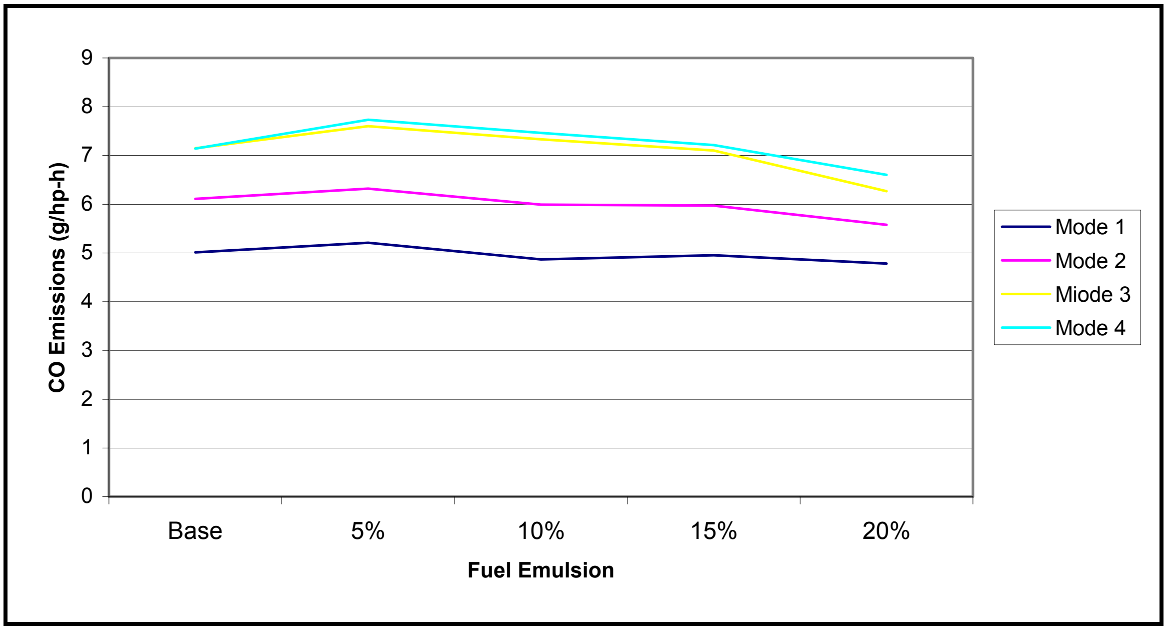

Figure 3.4 CO per Mode at Standard Fuel Injection Timing

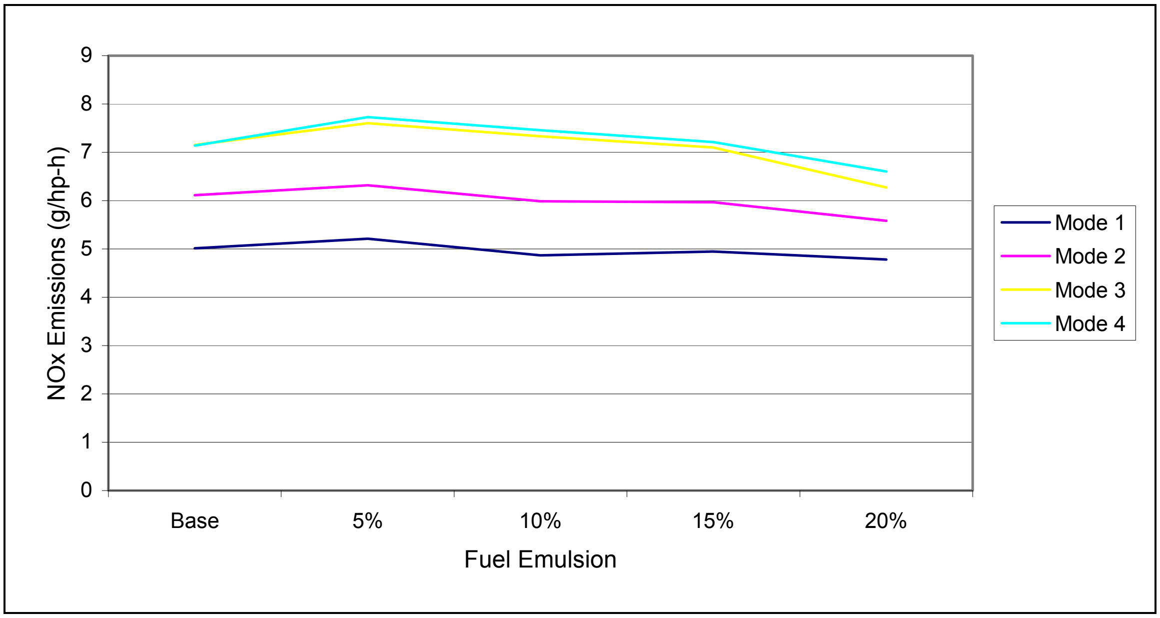

Figure 3.5 NOx per Mode at Standard Fuel Injection Timing

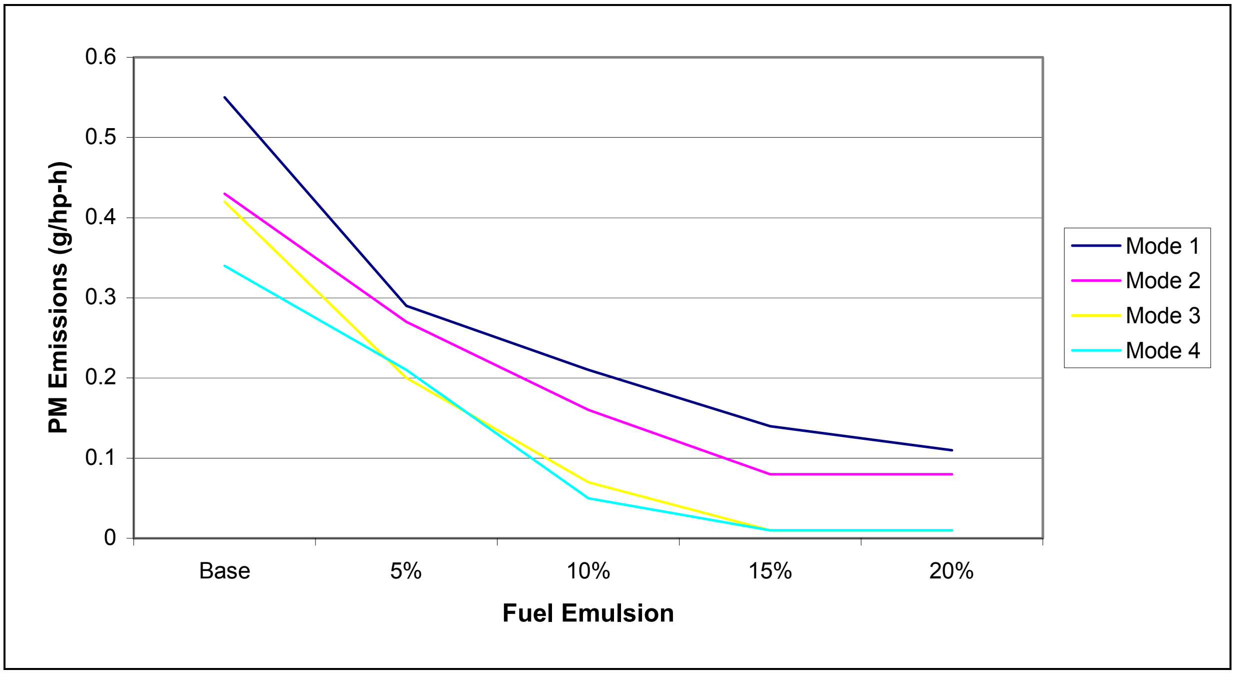

Figure 3.6 PM per Mode at Standard Fuel Injection Timing

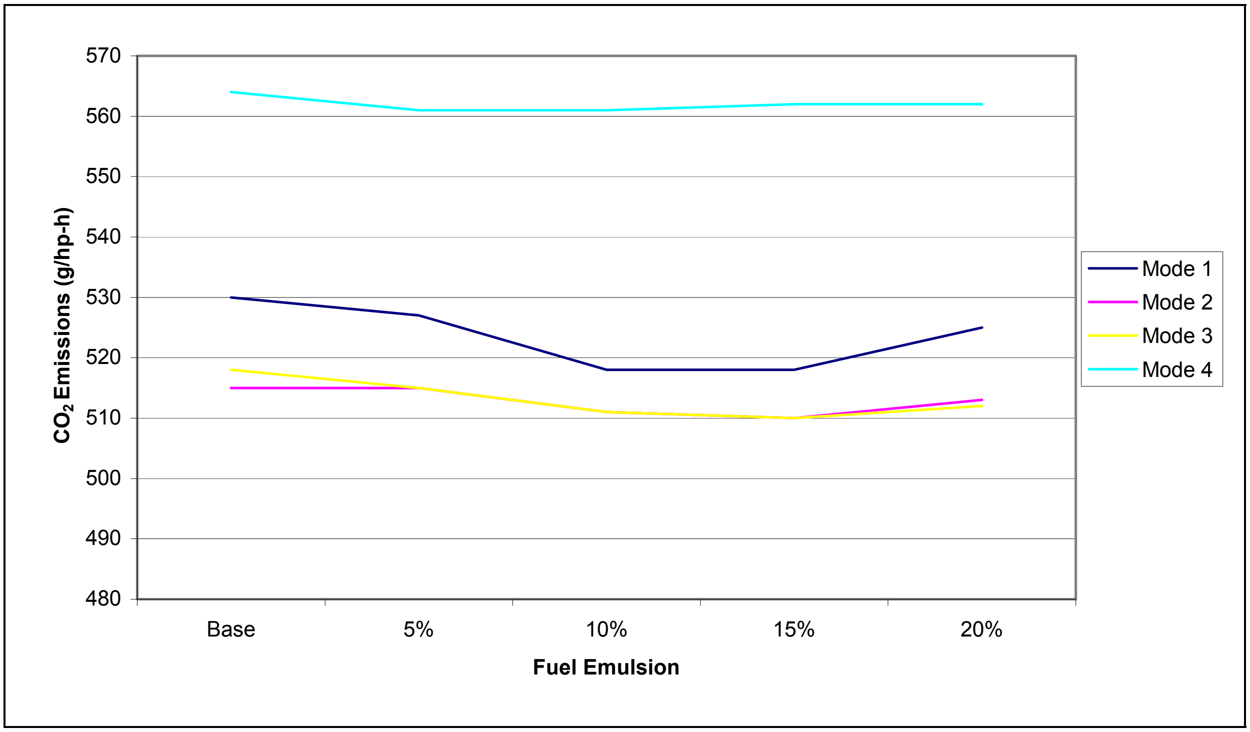

Figure 3.7 CO_2 per Mode at Standard Fuel Injection Timing

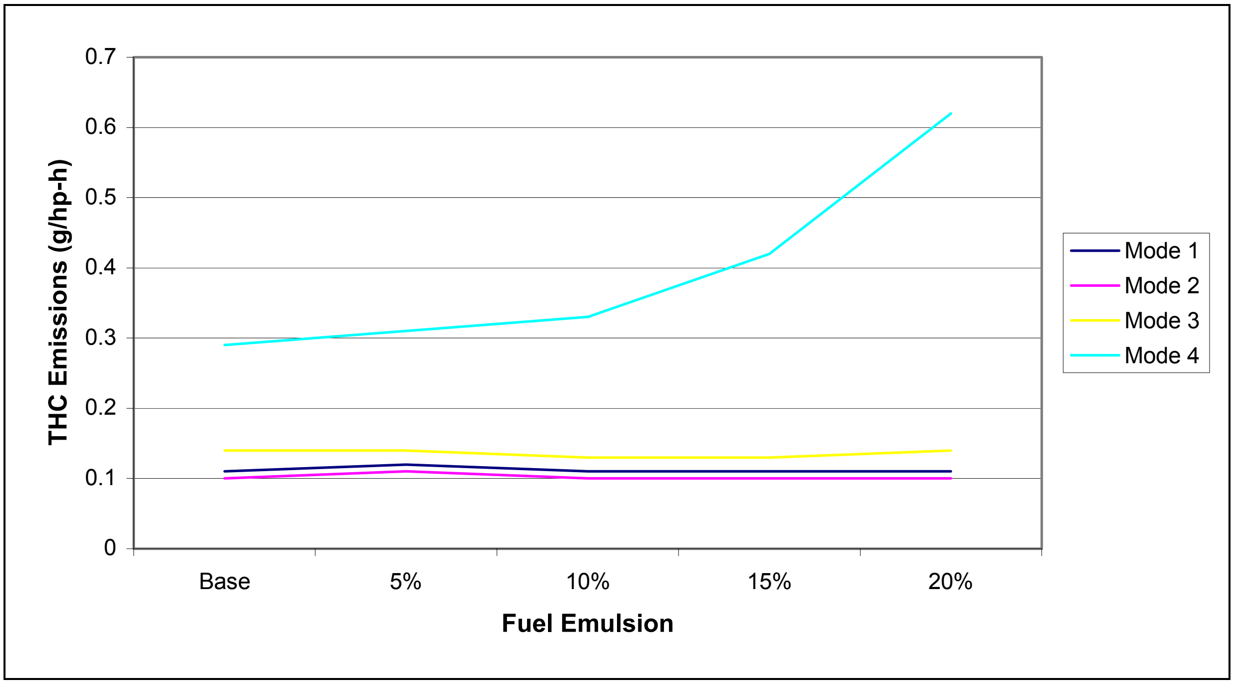

Figure 3.8 THC per Mode at Standard Fuel Injection Timing

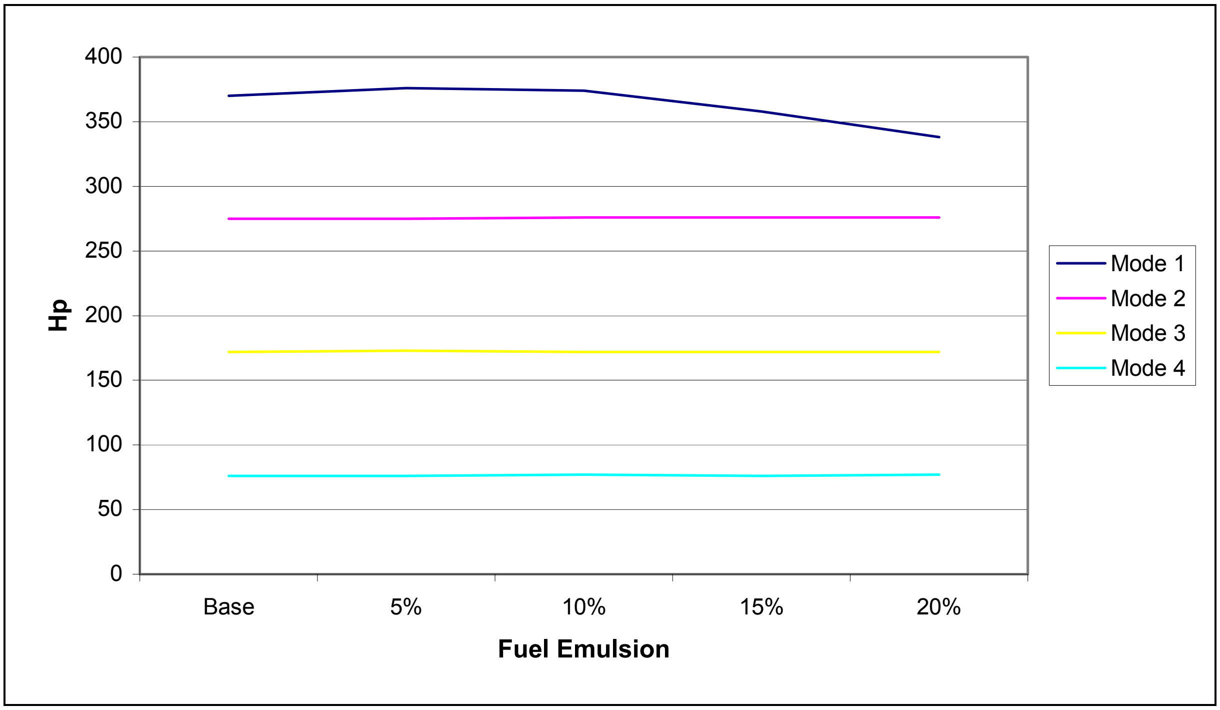

Figure 3.9 Power per Mode at Standard Fuel Injection Timing

As mentioned above, the test data indicates that the engine power decreases with respect to the baseline with the increase in fuel water content. The 100% speed and load cruise (Mode 1) represents the greatest decrease in power of 8.6%. As the engine is set up to provide the same power regardless of the fuel, it is assumed that the fuel system cannot provide the volume of fuel necessary. Therefore, there is a decrease in fuel economy when using the fuel emulsion that decreases as the water content increases. Table 3.7 summarizes the fuel economy for the various modes.

Table 3.7 Fuel Consumption per Mode (US gal/h)

Fuel	**Mode**			
	1	**2**	**3**	**4**
baseline	16.84	12.18	7.66	4.38
5%	17.94	12.80	8.04	3.86
10%	18.50	13.44	8.37	4.12
15%	18.73	14.21	8.85	4.34
20%	19.04	15.18	9.42	4.66

The data shows that the fuel economy decreases as the content of the water in the fuel emulsion increases. This is consistent for each mode. Table 3.8 summarizes this decrease for each of the modes.

Table 3.8 Percent Difference in Fuel Economy by Mode

Fuel	**Mode**			
	1	**2**	**3**	**4**
baseline	6.5	4.8	5	11.9*
5%	9.9	10.3	9.3	5.9*
10%	11.2	16.7	15.5	0.9*
15%	13.1	24.6	23	6.4
20%	6.5	4.8	5	11.9*

* indicates an increase in the fuel economy

For modes 1, 2 and 3 the observed decreases in fuel economy reflect the same level of decreases in the energy content per unit volume of 5%, 10%, 15% and 20%. Figure 3.10 illustrates the increase in the volume of fuel required to meet the same load demands when operating with the fuel emulsions.

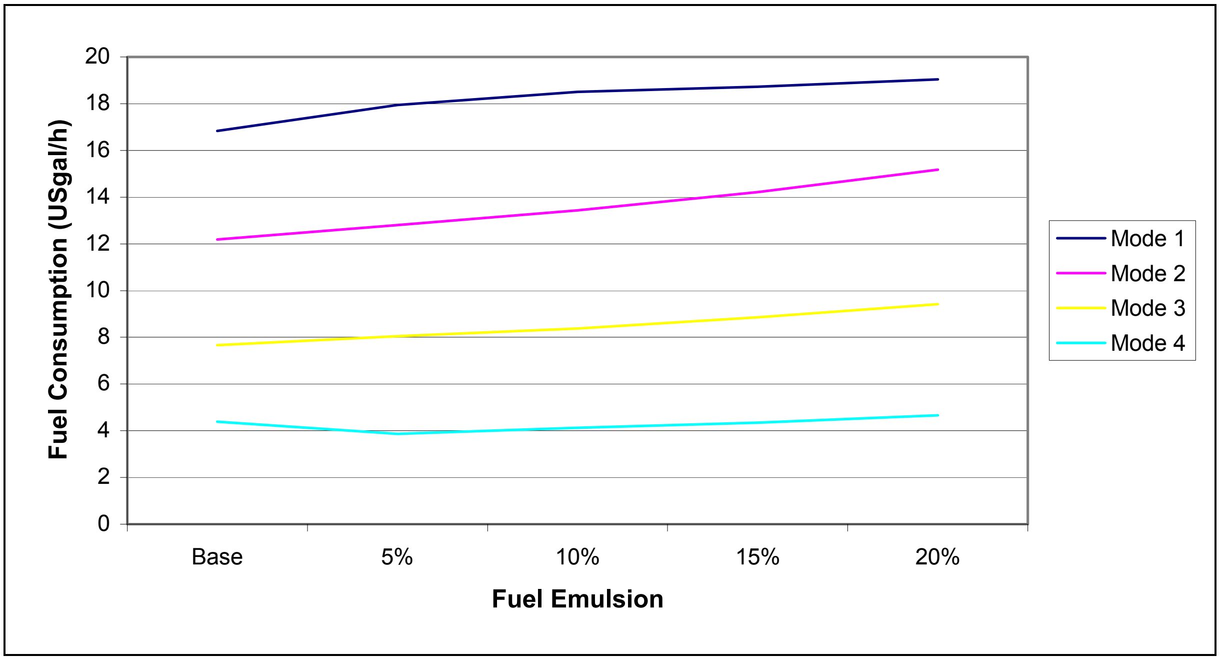

Figure 3.10 Fuel Consumption per Mode for the Various Fuels

For the NOx, the increase in water into the combustion chamber does not necessarily result in a proportional decrease in the NOx emissions. Table 3.9 represents the decrease in NOx as a function of the fuel emulsion water content.

Table 3.9 Comparison of NOx Reduction and % Water Content in the Fuel Emulsions

% Water Content	Mode 1	Mode 2	Mode 3	Mode 4
5	4.0	3.4	6.3	8.3
10	-2.8	-2.0	2.5	4.5
15	-1.2	-2.3	-0.7	1.0
20	-4.6	-8.7	-12	-8.2

For the 100% speed and power condition (Mode 1), an increase in NOx occurs with the use of 5% water. This increase is consistent for all modes, with an 8.3% increase occurring at the slow speed cruise (Mode 4). Increasing the water content to 10% results in a 2% to 3% decrease in NOx for Modes 1 and 2. The additional water also decreases the NOx for Modes 3 and 4 relative to the 5% fuel emulsion; however, the results are still greater than those with the baseline diesel. The 15% fuel emulsion decreases the NOx values for Mode 1, 2 and 3, with Mode 4 still indicating an increase of 1%. For Mode 1 the NOx emissions actually increase relative to the values measured for the 10% fuel. Increasing the water content to 12% results in NOx reductions for all modes, with a maximum of 12% for Mode 3.

Figure 3.6 illustrates significant reductions in PM as the water content increases in the fuel emulsions. The reductions range from 80% at high-speed cruise (Mode 2) to 97% at low-speed cruise (Mode 4). Even with the 5% water emulsion, the PM reductions range from 37% to 48% for the different modes.

3.4.3 Fuel Injection Timing

The final portion of Phase 2 – Part 1 of the program was to investigate whether benefits could be realized with the fuel emulsion fuels through the introduction of fuel injection timing changes. To accomplish this, the complete data sets were repeated with the fuel injection timing advanced an additional 4 degrees to 30 degrees, and then retarded by 9 degrees to a final value of 17 degrees BTDC. The finalized data sets are found in Table 3.10.

Table 3.10 Injection Timing Data Table

Testing of LUBRIZOL diesel fuel blends for Marine Duty performed on the Caterpillar 3406B test platform

Injection Timing	**Test Config.**	**Calc**	**Power [hp]**	**Oil Sump [ºC]**	**Coolant [ºC]**	**Turbo Out [ºC]**	**CO [g/hp-h]**	**CO$_2$ [g/hp-h]**	**NOx [g/hp-h]**	**THC [g/hp-h]**
	ISO Marine cycle E3									
orig (26.0^{O}BTC)	Baseline	ISO Composite	249.0	103.6	86.9	552.4	1.36	522.23	5.94	0.12
orig (26.0^{O}BTC)	5% emulsion	ISO Composite	250.1	103.7	86.3	548.3	1.20	520.78	6.18	0.12
orig (26.0^{O}BTC)	10% emulsion	ISO Composite	250.2	102.9	85.3	541.5	1.08	515.44	5.86	0.12
orig (26.0^{O}BTC)	15% emulsion	ISO Composite	247.0	103.5	86.0	536.5	0.99	514.87	5.85	0.12
orig (26.0^{O}BTC)	20% emulsion	ISO Composite	242.8	102.1	83.8	525.7	0.94	518.86	5.48	0.13
adv (30.0^{O}BTC)	Baseline	ISO Composite	249.7	102.2	83.7	547.0	1.67	520.53	8.00	0.10
adv (30.0^{O}BTC)	5% emulsion	ISO Composite	250.5	102.7	83.0	539.5	1.38	514.68	8.12	0.16
adv (30.0^{O}BTC)	10% emulsion	ISO Composite	247.9	102.6	82.7	533.6	1.30	512.94	8.06	0.13
adv (30.0^{O}BTC)	15% emulsion	ISO Composite	245.6	104.1	85.3	532.9	1.25	514.34	7.84	0.14
adv (30.0^{O}BTC)	20% emulsion	ISO Composite	240.2	102.1	78.6	517.2	1.20	518.04	7.89	0.17
ret (17.0^{O}BTC)	Baseline	ISO Composite	242.6	105.4	89.8	600.8	2.06	568.2	3.09	0.08
ret (17.0^{O}BTC)	5% emulsion	ISO Composite	241.9	109.3	93.3	602.0	1.73	569.7	3.15	0.07
ret (17.0^{O}BTC)	10% emulsion	ISO Composite	239.8	106.8	92.7	589.9	1.52	563.4	2.94	0.07
ret (17.0^{O}BTC)	15% emulsion	ISO Composite	239.3	103.7	87.7	573.8	1.38	564.3	1.81	0.05
ret (17.0^{O}BTC)	20% emulsion	ISO Composite	232.1	104.2	89.3	564.3	1.22	563.0	2.50	0.09

Modifying the fuel injection timing has an impact on the exhaust emissions and performance of internal combustion engines. For diesel engines, there is a NOx-PM relationship, which in basic terms means changes to combustion conditions to lower NOx emissions result in PM increases; the inverse also holds true. If the fuel injection timing is advanced, the combustion temperature increases, therefore NOx increases and PM decreases. For the other emissions and performance, it would generally be expected that CO, THC, and CO_2 would decrease, and an increase in power would be observed. If the timing were retarded from 26 to 17 degrees BTDC, increases in PM, CO, CO_2 and THC would be expected. NOx and horsepower would be decreased. Table 3.11 presents a comparison of the exhaust emissions and power using the baseline fuel for the three fuel injection timing conditions. The data verifies the general trends for all but two points, CO at 30 degrees and THC at 17 degrees.

Table 3.11 Effect of Fuel Injection Timing Changes on Emissions and Performance

Baseline Fuel						
Timing	CO (g/hp-h)	CO_2 (g/hp-h)	NOx (g/hp-h)	THC (g/hp-h)	PM (g/hp-h)	Power hp
17	2.06	568	3.09	0.08	0.62	243
26	1.36	522	5.94	0.12	0.46	249
30	1.67	521	8.00	0.10	0.29	250

Figures 3.11 to 3.14 illustrate the effect on exhaust emissions while operating the engine on the various fuel emulsions for the three injection timing conditions. The graphs are based on the ISO Composite values.

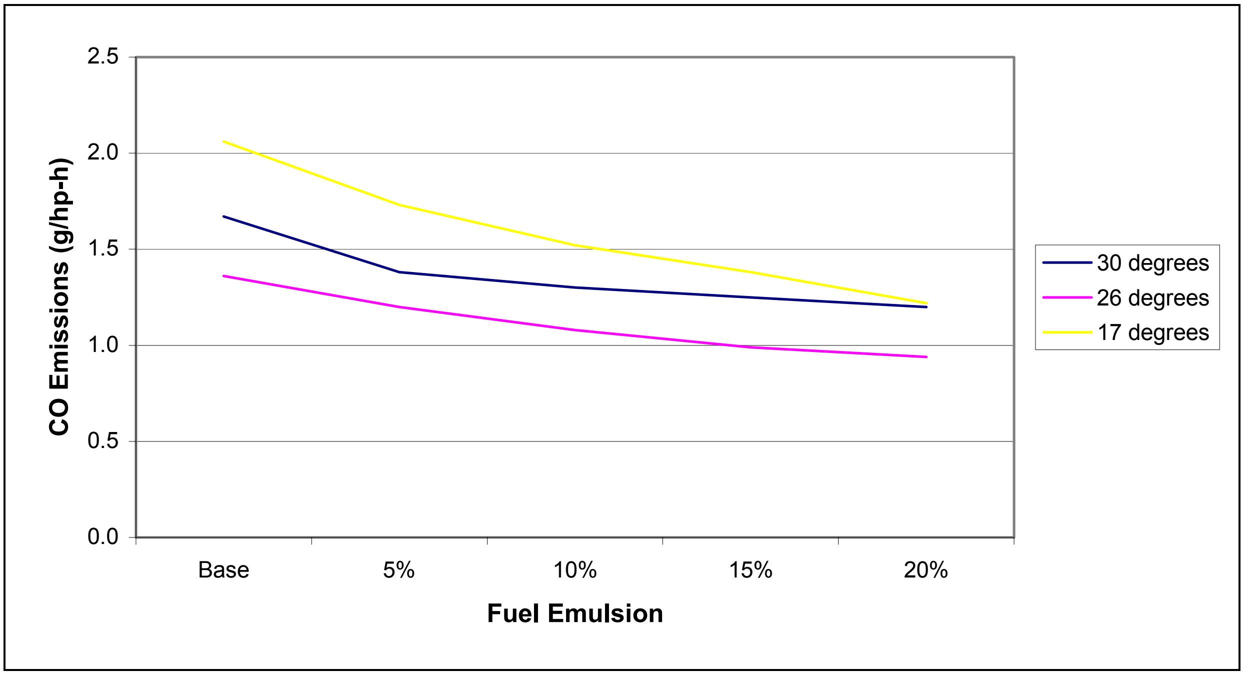

Figure 3.11 ISO Composite CO Emissions versus Injection Timing

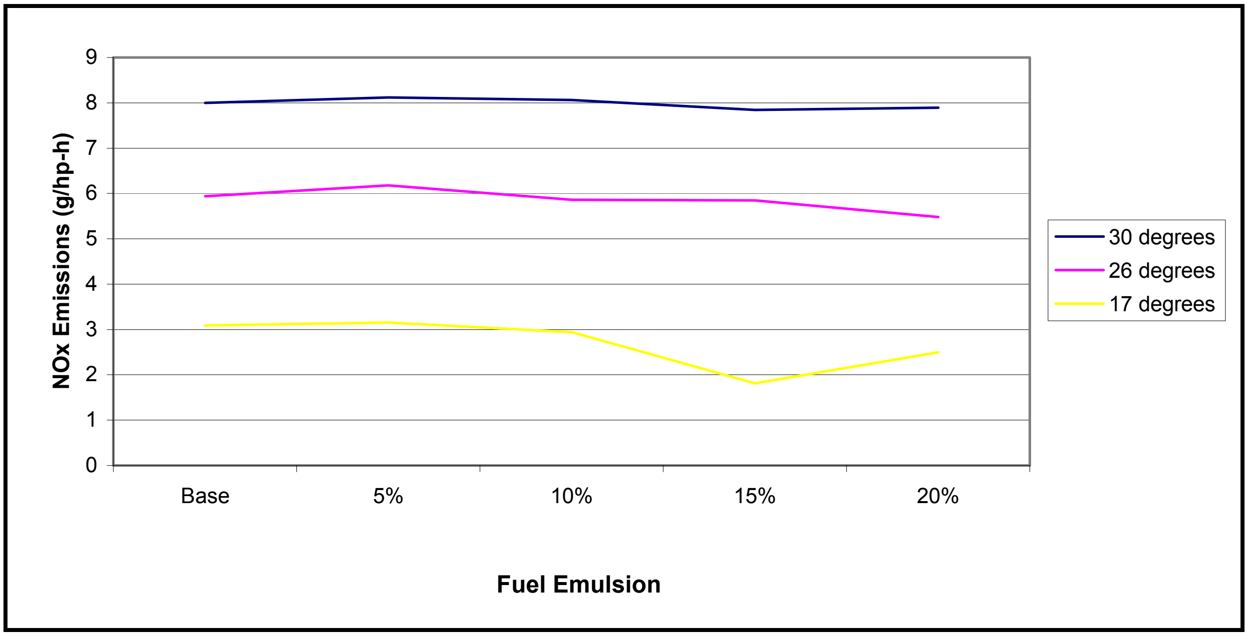

Figure 3.12 ISO Composite NOx Emissions versus Injection Timing

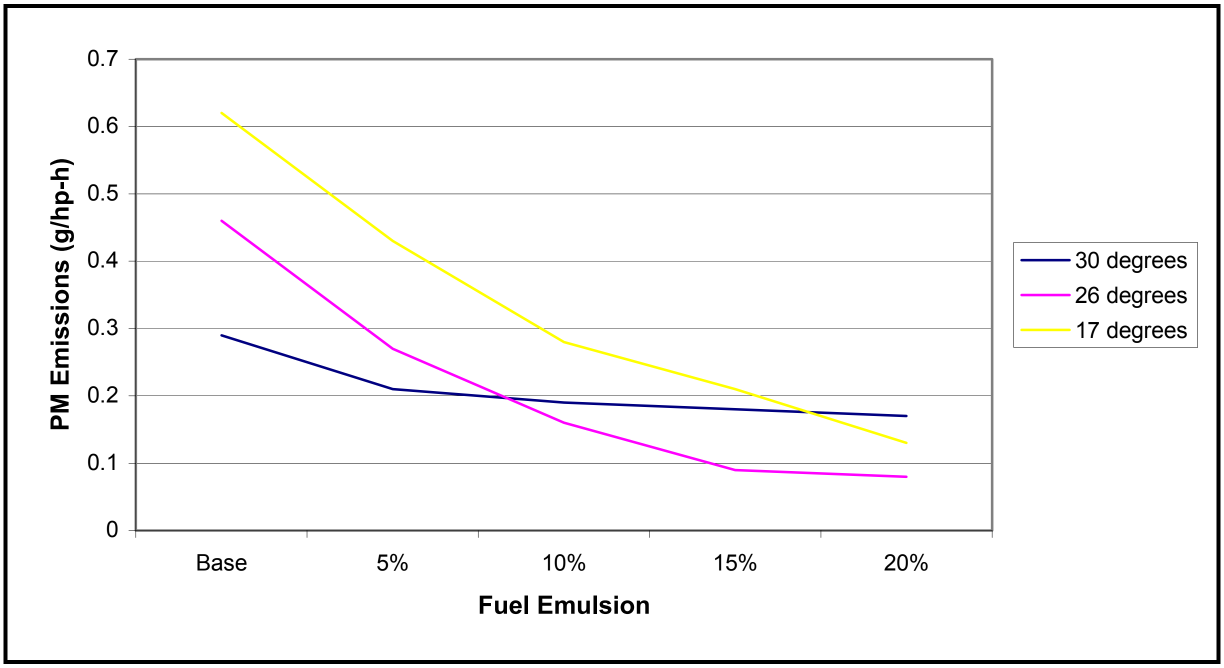

Figure 3.13 ISO Composite PM Emissions versus Injection Timing

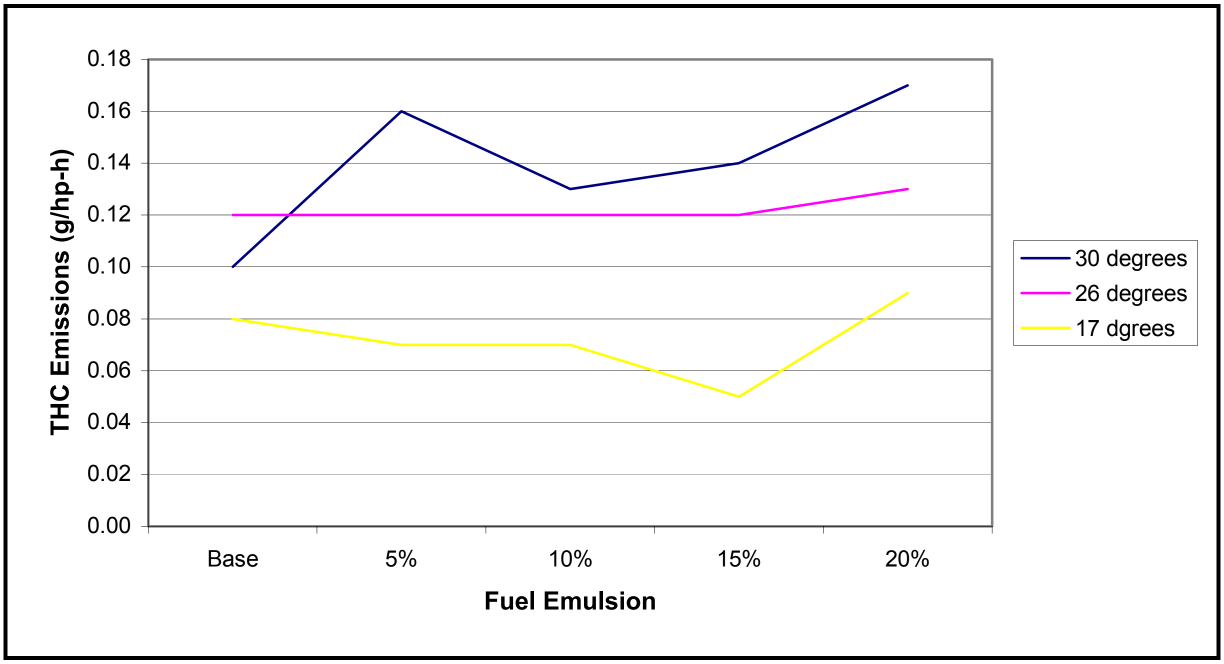

Figure 3.14 ISO Composite THC Emissions versus Injection Timing

The rationale for investigating the changes in fuel injection timing was to determine whether the introduction of the fuel emulsion could control the NOx emissions increase that would normally be associated with the advance in fuel injection timing. The net result would be an increase in combustion efficiency (i.e., a reduction in fuel consumed and CO_2 emissions) and a significant reduction in PM emissions with a small decrease in NOx.

The data in Table 3.12 and the associated Figures 3.15 to 3.18 do not support this postulation. The CO_2 values are essentially the same, with a result of 518 .9 and 518.0 g/hp-h with the 20% fuel emulsion for the 26 and 30 degrees injection timing. The power is increased by 1%. The NOx values resulting from advancing the timing are higher for all of the fuel emulsions than the baseline fuel value at 26 degrees timing. The net result would be a 44% increase in NOx with the 20% fuel emulsion. The baseline fuel PM emissions rates are decreased by 37%; however, with the 20% fuel emulsion the rate at 30 degrees is almost twice that of the 26 degrees setting.

With the retarded fuel injection timing of 17 degrees, the baseline fuel NOx emissions rate was decreased by 48% compared to the base fuel at 26 degrees. An additional reduction occurred with the introduction of the fuel emulsions down to 58% with the 20% fuel. A summary of the emissions and performance of the engine at 17 degrees fuel injection timing operating on the 20% emulsion compared to the 26-degree timing with base fuel is found in Table 3.12.

Table 3.12 Comparison of Baseline Operation to Retarded Timing with a 20% Emulsion

Timing	Fuel	CO (g/hp-h)	CO_2 (g/hp-h)	NOx (g/hp-h)	THC (g/hp-h)	PM (g/hp-h)	Power hp
26	base	1.36	522	5.94	0.12	0.46	249
17	20%	1.22	563	2.5	0.09	0.13	232
% diff		**-10.3**	**7.9**	**-58**	**-25**	**-72**	**-7**

For the other regulated emissions, CO was decreased by 10%, THC by 25% and PM by 72%. These reductions came at a cost of a loss in power of 7% and an increase in CO_2/fuel efficiency of approximately 8% (based on the assumption that CO_2 is a prime indicator of fuel consumption).

For fuel consumption Figures 3.15 to 3.18 indicate the impact of the timing and fuels on the amount of fuel consumed. As the engine is set to run at conditions that are less efficient – i.e., low-speed cruise – the impact of both the injection timing and fuels is reduced to the point where the curve of fuel economy versus type of fuel is almost equivalent for Mode 4.

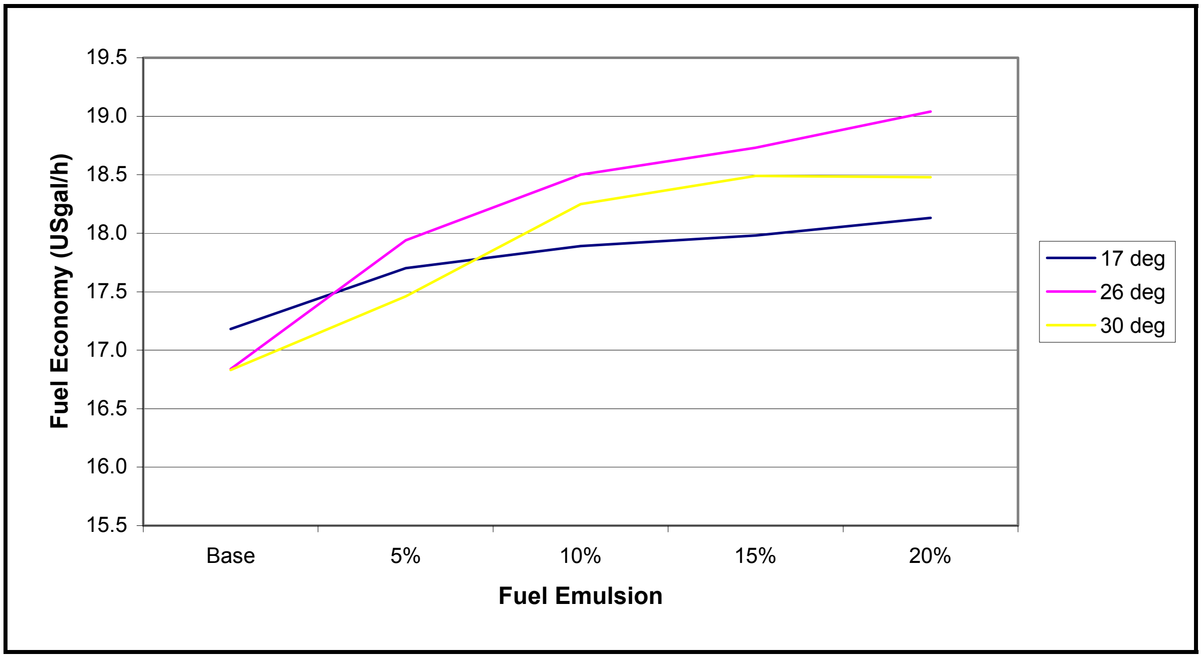

Figure 3.15 Mode 1 Fuel Economy versus Fuel Injection Timing

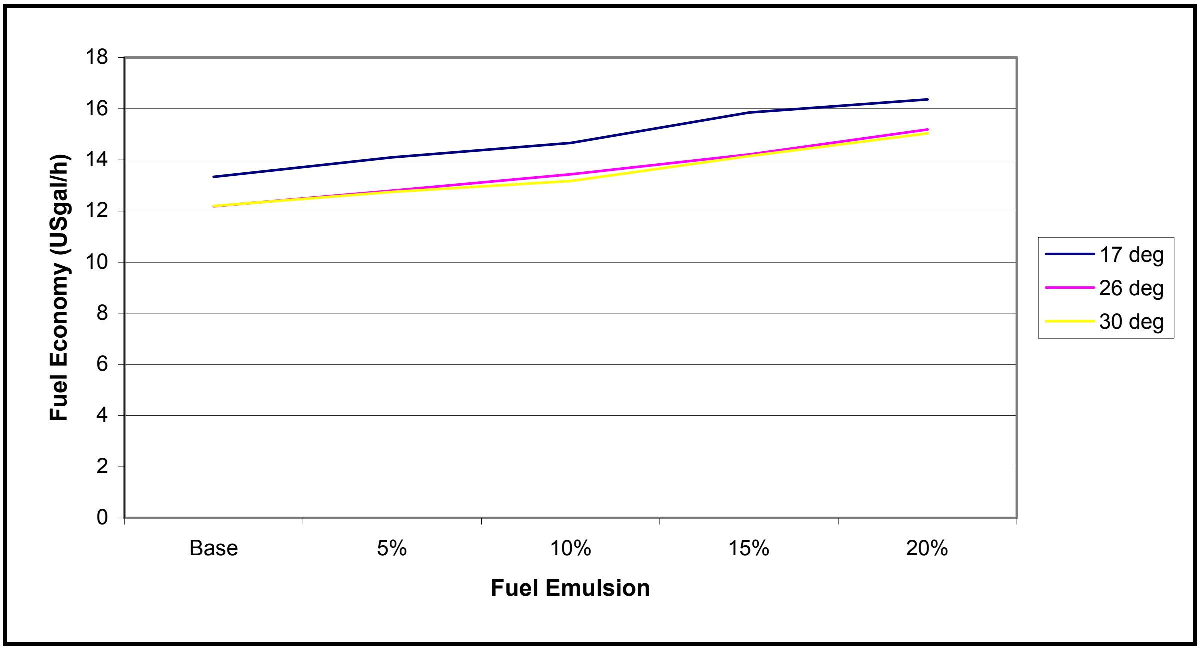

Figure 3.16 Mode 2 Fuel Economy versus Fuel Injection Timing

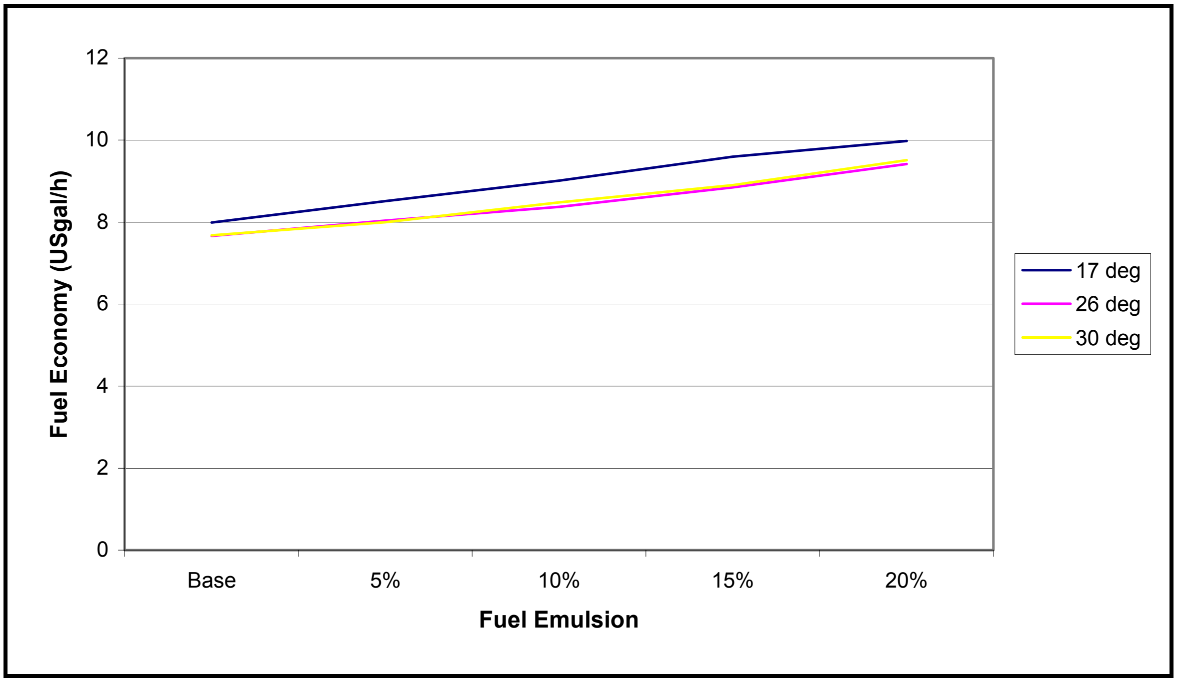

Figure 3.17 Mode 3 Fuel Economy versus Fuel Injection Timing

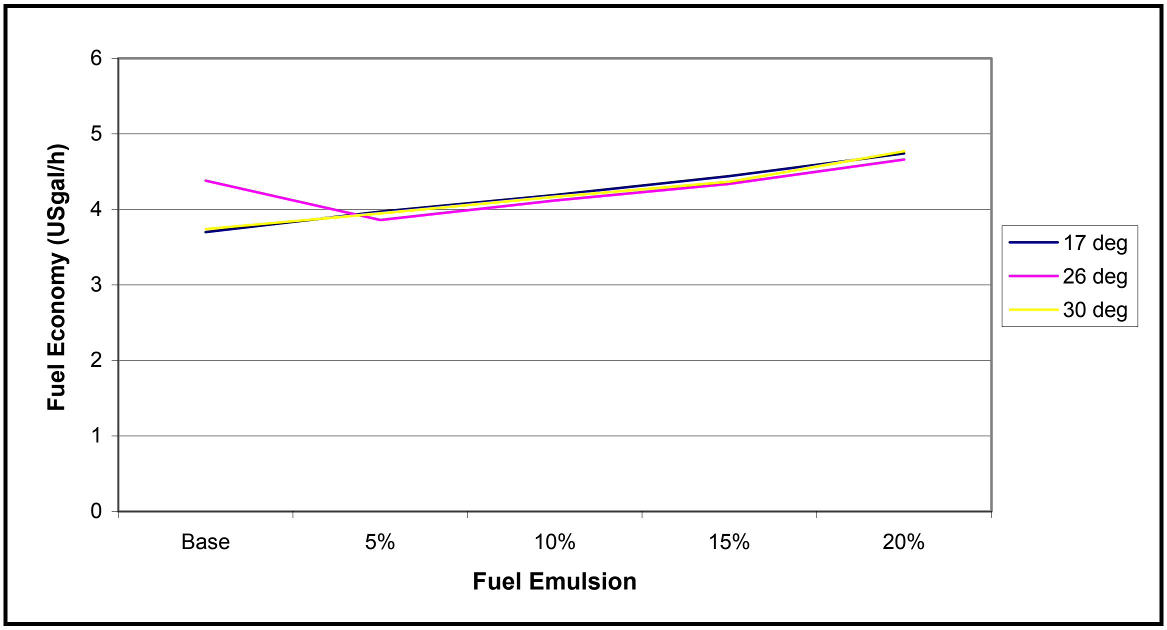

Figure 3.18 Mode 4 Fuel Economy versus Fuel Injection Timing

3.5 Conclusions

1. With the engine operating using the standard fuel injection timing, the 20% fuel emulsion results indicate the greatest exhaust emissions reductions for all four modes. The only exceptions are the THC and CO measurements during Mode 4.

2. The amount of fuel consumed increases with the amount of water emulsified into the base diesel fuel. These increases correspond to the loss in energy content resulting from the addition of the water to the fuel.

3. Advancing the timing resulted in the expected increases in efficiency and NOx. The addition of the fuel emulsion did not, however, provide enough of a reduction in the combustion temperature to reduce the NOx emissions below the base fuel base timing conditions.

4. 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%. Operating the engine on fuel emulsions decreased the emissions that had increased due to the timing change. Table 3.13 summarizes the effects of the fuel emulsions.

Table 3.13 Exhaust Emissions with Retarded Fuel Injection Timing

Timing	Fuel	CO (g/hp-h)	CO_2 (g/hp-h)	NOx (g/hp-h)	THC (g/hp-h)	PM (g/hp-h)	Power hp
26	base	1.36	522	5.94	0.12	0.46	249
17	5%	1.73	570	3.15	0.07	0.43	242
17	10%	1.52	563	2.94	0.07	0.08	240
17	15%	1.38	564	1.81	0.05	0.21	239
17	20%	1.22	563	2.50	0.09	0.13	232

It is assumed that the effects on the exhaust emissions of retarding the timing and operating on fuel emulsion is very engine specific. Therefore, it would be difficult to directly translate these results to other engines; however, it is evident that a combination of the two will result in significant emissions reductions. For this particular engine, retarding the timing by less than 9 degrees may result in an acceptable loss of power and efficiency while maintaining the significant gains in emissions reductions.

Section 4 – Laboratory Evaluation of Water Injection as an Emissions Control

4.1 Introduction

Section 3 described the evaluation of the potential emissions reduction of fuel consisting of diesel-water emulsified fuels as either a stand-alone technology or used in conjunction with a modification to the timing of the fuel injection. An alternative to using emulsified fuels is to inject water into the combustion chamber. This avoids the technical challenge of keeping the fuel and water in solution and enables the system operator to control the timing of the introduction of water as well as the volume. Under this approach, water can be added by injecting it into the air that is being drawn into the engine for combustion or by humidifying the air being drawn into the engine for combustion.

In the second part of this phase of the project, a work plan was established with the objective to develop a computer-controlled system that would inject water into the engine air inlet during non-idle conditions and result in a minimum of 20% NOx reduction with minimal fuel consumption penalty. To achieve equivalent water distribution at all of the cylinders, a multi-point injector system was designed. The prototype was set up on a Caterpillar 3406B engine and exhaust emissions testing was conducted to determine the impact on the emissions and engine performance. After the preliminary tests, a single injection point technology was set up and tested for comparison to the multi-point approach. The single point would reduce the hardware, installation and maintenance costs for a full-size vessel installation.

This section describes the bench scale system designs and bench scale exhaust emissions testing.

4.2 Objective

The objective was to develop and evaluate a bench scale water injection system for a heavy-duty diesel engine that would reduce NOx by a minimum of 20% at all loaded operating conditions. The system was also to be cost-effective for the operator to install, operate and maintain, and have little or no impact on the engine's fuel consumption.

4.3 System Design

The purpose of adding water to the combustion process is to reduce the temperature of the combustion. This in turn reduces the formation of NOx that occurs in the high temperature regions within the cylinder. The two major criteria for effective emissions reduction through water injection are to have small water droplets and to ensure that these are evenly dispersed in the engine air flow. The smaller water droplets result in a larger temperature decrease as they evaporate more rapidly, absorbing the heat of combustion. Evaporation consumes more heat than just raising the temperature of a liquid, which consumes more heat due to the latent heat of evaporation. Evenly distributed moisture throughout the combustion chamber would reduce the potential for hot spots in the flame zone, thus reducing NOx.

However, the addition of excessive amounts of water, while reducing NOx, will adversely effect the formation of other emissions in the combustion process. For example:

- as the combustion temperature decreases, the oxidation process becomes less efficient, resulting in increases in THC, CO and PM.
- excess water can also result in cooling of the cylinder walls, which would result in locations where fuel does not become combusted, resulting in increased hydrocarbon emissions and particulates.
- increased water vapour can also effect the propagation of the flame front after ignition, again resulting in reduced efficiency and higher emissions.

4.3.1 Multi-point Injection

The initial design concept was based on the principle of multi-point port injection with the injectors connected to a single injector body for water flow control using a microprocessor. The bench scale unit was adapted from a commercially available system as described in section 4.3.2.

4.3.2 Injectors

An injection system was required that would provide water injection at a location as close as possible to the intake valve for each cylinder. A multi-port gasoline fuel injection system was obtained (manufacturer's product for a six-cylinder 4.3 L engine) for use with the water system.

The AC Delco fuel system consists of a body, which contains the electrical connections for the individual injectors, a minimum injection pressure control and a connection for the fuel (water) input. The injectors do not open until a minimum pressure of approximately 55 psi is applied. A pressurized tank and gauge were added to the system to stabilize the building water pressure used in this work.

The multi-port systems work on the principle of injecting fluid when the intake valve opens for each specific cylinder. This is accomplished by sending a signal to the solenoid valve at the injector for it to open. With a constant pressure on the fluid in the injector line, the volume of fluid injected into the cylinder is controlled by the amount of time the solenoid valve is open, or the length of the pulse sent to the valve. The control computer varies the opening and closing of the injectors to obtain the desired volume of fluid that is to be injected.

The reference for the injection timing was based on the timing mark (Top Dead Centre) for the No. 1 cylinder on the harmonic balancer. A Hall Effect sensor was used to record each revolution of the crankshaft.

4.3.3 Engine Installation

To mount the individual injectors on the engine, a Swagelok™ connector was adapted for each. A ridge in the centre of the bored hole was used to clip the injector in place. Appropriately sized holes were then machined into the intake manifold and threaded for installation of the Swagelok™ connectors.

The manufacturer's injector lines were extended to reach each cylinder using stainless steel tubing with clamps at both ends. Electrical connections were then made between the injector body and computer. This set up was used for the laboratory bench testing. For a marine vessel application, Swagelok™ fittings and stainless steel lines would be incorporated in the design.

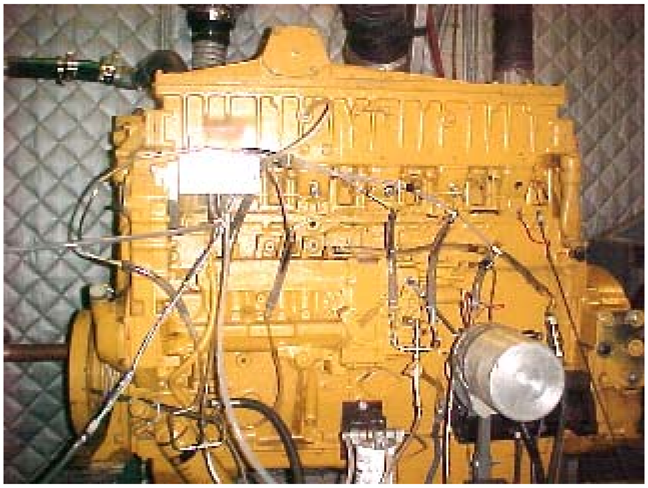

Figure 4.1 Cat 3406B with Multi-point Water Injection System

Figure 4.2 Injector Connection to Engine

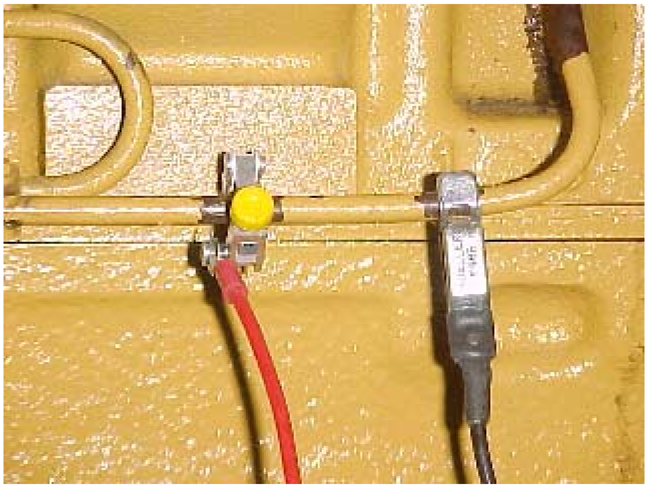

Figure 4.3 Measurement of Fuel Pulses

The software control was designed to inject water into the intake manifold as the intake valve for each cylinder is opened. The initiation of the water injection was the fuel pulse to the specific injectors. Figure 4.3 illustrates the connections for this measurement. The volume of water to be injected was based on engine speed and was to be determined by experimental testing. For the purposes of minimizing the potential for engine corrosion from water, the control software was designed to shut off the flow of water when the engine was operating at idle.

The technology of water injection has been used in the past on diesel engines for reducing NOx and continues today. However, these applications use single point injection or an apparatus that humidifies the engine intake air (similar to steam generators for air handling systems in buildings). These systems are known to provide NOx reduction of 20% with a minimal or negligible impact on the fuel consumption based on an average injection of water equivalent to 30% of the volume of fuel being combusted.

To verify the effectiveness of the multi-point (MP) system, similar testing was conducted on both forms of water injection. To facilitate this process, the multi-point system was reconfigured to simulate a single point by having the six injectors mounted at one point in a 2 in. diameter circle. The injection point was located after the turbocharger where the air enters the intake manifold. The rest of the injection system remained the same.

Figure 4.4 Single Point (SP) Injector

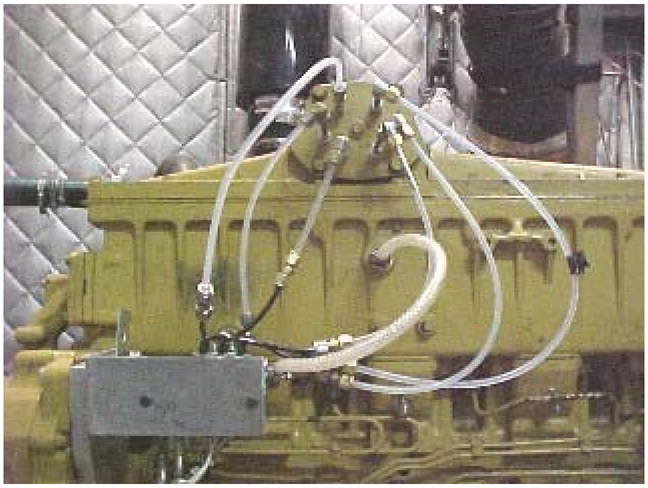

Figure 4.5 Single Point (SP) Injection System

4.4 Test Description

4.4.1 Overview

A test plan was established to measure and optimize the effectiveness of the system for exhaust emissions reduction. To optimize the technology, a series of test sequences was conducted at various engine load conditions while the volume of water being injected was varied. An optimized water volume was then selected for each engine load condition. With these points the software for the control system was developed to vary the water injection rate based on the engine load conditions, with engine idle being the only operation when water was not being injected.

4.4.2 Test Engine

The test engine used for this project was a Caterpillar 3406, six-cylinder, mechanically controlled engine.

4.4.3 Test Instrumentation

Engine Dynamometer – The engine was connected to a 750 hp Clayton waterbrake, which served as the power absorption unit. The waterbrake operation was controlled by a computer, which activated the valves to load and unload the water turbine based on feedback on the engine speed and torque.

4.4.4 Exhaust Emissions Sampling and Analysis System

The engine exhaust pipe was connected via a flexible stainless steel hose to a 25.4 cm diameter dilution tunnel and Constant Volume Sampling System (CVS). The tunnel had a constant flow rate of 56.6 m^3/min, controlled by a critical flow venturi. A continuous dilute sample of the exhaust was drawn from the tunnel and directed through a heated line to the analyzer bench. The sample was directed to: a Heated Chemiluminesence instrument for the measurement of NOx, a Heated Flame Ionization detector for THC and two Non-Dispersive Infrared analyzers for CO and CO_2. A heated filter was used to gravimetrically determine total PM.

4.4.5 Engine Test Cycle

The test program followed the ISO standard marine four-mode steady-state cycle detailed in the ISO 8178-4 E3 cycle. The test cycle consisted of the engine operation as detailed in Table 4.1.

Table 4.1 ISO 8178-4 E3 Cycle Specifications

Operating Mode	% engine speed	% power – at speed	Weighting factor	Stabilize/measurement timing (seconds)
1	100	100	0.2	90 / 60
2	91	75	0.5	90 / 60
3	80	50	0.15	90 / 60
4	63	25	0.15	90 / 60

The ISO E3 cycle is based on the marine application propeller law where, in a typical propeller operation, the shaft power varies as a cube of the shaft rotational speed. Equation 4-1 describes the relationship:

$$(N_B / N_A) = (P_B / P_A)^3 \qquad (4\text{-}1)$$

where N is the propeller rotational speed,

P is the power, and

A and B refer to two different operating points along the propeller curve.

A plot of a propeller curve and the ISO E3 cycle operating points are shown in Figure 4.6.

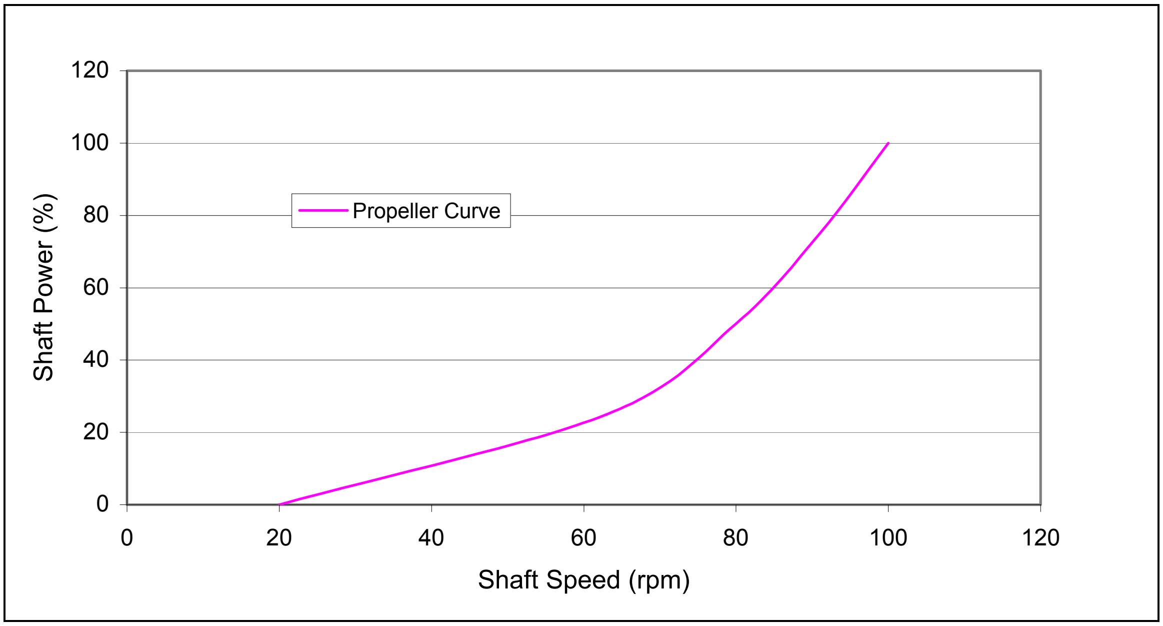

Figure 4.6 ISO 8178-4 E3 Propeller Curve

4.4.6 Test Procedures

The engine dynamometer exhaust emissions testing was conducted according to the protocols as outlined in the US EPA Federal Register CFR 40 Part 86 for exhaust emissions testing of Heavy Duty Diesel engines.

4.4.7 Methodology

The emissions testing was conducted by the following procedure:

- The pressurized tank used to provide the water for injection was filled and pressurized with air to a minimum of 55 psi. This was the specified operating pressure for the injectors.
- The engine was started and brought up to operating temperature without the water system being operational.
- The engine load and rpm were set as per the 2nd mode of the propeller curve (75% load and 90% rated speed) and the water injection system was turned on for MP injection at the lowest setting for the injector pulse width or volume flow.
- When the speed and load were stabilized, exhaust emissions measurements were conducted for a period of three minutes, then the water injection rate (WIR) was increased to the next level and the emissions sampling repeated.
- A total of seven different volume flow rates plus a baseline, or no water, condition were evaluated for exhaust emissions.

- The engine speed and load were changed to the 3rd mode (50% load and 80% rated speed) and the testing as noted above was repeated. This process was repeated for the 4th and last mode (25% load and 63% rated speed).

It should be noted that the spray patterns resulting from the injector operation had previously been evaluated. At slightly above 55 psi, the pattern was in the shape of a cone with fine droplets. As the water pressure increased, the droplet sized increased and the spray changed to a single jet of water from the centre of the injector. The water flow rates were determined by removing the injector from the connector on the engine block, placing the injector in a calibrated container, and initiating the operation of the injection system as per the normal engine operational sequence. The flow rates for all six of the injectors were measured in this manner. NOTE – An assumption was made that the flow rates would not deviate from the measured values when injecting into the intake manifold during engine operation.

Table 4.2 indicates the flow rates for the injectors at the various pulse width settings.

Table 4.2 Measured Injector Water Flow Rates (L/h)

Pulse Width	3	4	5	6	7	8	9
Water Injection Rate (L/h)	11.2	14.1	16.7	19.4	21.6	24.1	27.0

The exhaust emissions samples were collected from a dilution tunnel that combined all of the engine's raw exhaust with dilution air, which varied depending on the exhaust volume flow rate entering the fixed volume flow rate of the tunnel. Continuous dilute exhaust samples were then directed to a bench of analyzers for analysis. These included a heated flame ionization detector for THC, non-dispersive infrared detectors for CO and CO_2 and a chemiluminescent analyzer for NOx. Particulate mass was determined gravimetrically using 47 mm filters.

At the conclusion of the testing, the single point (SP) injection system was fabricated and installed on the same engine. The flow rates were then verified for all of the injectors, and the emissions testing initiated. The testing consisted of an identical sequence as for the MP set-up in order to perform a comparative analysis of the two injection systems.

4.5 Results and Discussion

The preliminary testing with the MP system indicated excessive PM emissions when the injection system was functioning and the engine operational. Though the NOx reductions were above the design criteria for the 2nd propeller curve mode, the increase in PM emissions outweighed these benefits. To determine the cause of these significant increases in PM, a technical expert from Caterpillar was asked to investigate the performance of the engine. The technician found that the turbo charger was leaking oil into the inlet air stream and the injection timing was retarded. In addition to the repair of these two items, all of the fuel injectors were replaced as preventive maintenance.

The testing was then repeated. The data from the pre-maintenance is not included in this report.

Table 4.3 indicates the exhaust emissions results from operating the MP water injection system over a range of pulse width settings.

Table 4.3 Exhaust Emissions at Various Water Injection Rates

WIR	THC (g/hp-h)	CO (g/hp-h)	NOx (g/hp-h)	PM (g/hp-h)	CO_2 (g/hp-h)	FC (g/hp-h)	Exhaust Temp (°C)*
Baseline	0.163	0.696	4.89	0.352	510.5	160.88	519
3	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-
5	0.195	0.720	4.59	0.413	513.0	162.12	516
6	0.173	0.708	4.06	0.423	511.6	161.66	510
7	0.168	0.689	4.00	0.408	512.6	161.96	508
8	0.164	0.670	3.58	0.425	512.7	161.99	509
9	0.163	0.672	3.52	0.415	512.6	161.95	506

* Exhaust temperature for cylinder No. 6.

The testing was conducted by initiating the water injection system after the engine was in a steady-state condition at the specified horsepower and speed rating These parameters were continually adjusted during the testing to ensure that the mode conditions were precisely maintained. The average horsepower for this testing was 274.85 (+/- 0.32) at 1638 rpm. By maintaining these conditions, the impact of the water on the performance of the engine would be indicated through the emissions and the fuel consumed.

The testing for the multi-point system as summarized in Table 4.3 indicated that the introduction of the water results in a maximum reduction of 28% for NOx, at the pulse width of 9 or 27 L/h. The corresponding maximum PM increase is approximately 18%. For fuel consumption the data indicates a 0.7% increase at the maximum water injection rate.

For the maximum NOx reduction, the water consumed as a percentage of the total liquid injected into the combustion chamber is approximately 34% or 5.95 gal. of water compared to 11.5 gal. of fuel. For the THC and CO exhaust emissions, the introduction of water at a rate of 16.7 L/h resulted in an increase in both emissions by 20% and 3%, respectively. However, these emissions decreased as the volume of water injected into the engine increased. At the maximum pulse width that resulted in 27 L/h of water being injected, there was no difference in THC and a reduction of 3% for CO. Though the cause for these results was not investigated, it is assumed that as they are all a function of incomplete combustion, the oxidation of the fuel in the combustion chamber becomes less efficient as the water content increases. This process continues until there is not enough fuel to sustain combustion. Prior to this end point, unburned fuel is being emitted into the exhaust, as there would be areas within the combustion chamber where no oxidation is occurring.

Because an SP injection system would be more cost-effective for an operator to install and to maintain, a system of this form was set up for comparison with the MP arrangement. If the SP system resulted in similar emissions benefits, then the cost factor would determine the system configuration to be selected for in use applications (i.e., marine vessels.)

The test sequence for the SP was identical to that for the MP; however, only three water injection points were evaluated: 21.6, 24.1, and 27.0 L/h. A summary of the data is found in Table 4.4.

Table 4.4 Exhaust Emissions and Engine Performance with SP Technology

WIR (L/h)	Pulse Width	THC (g/hp-h)	CO (g/hp-h)	NOx (g/hp-h)	PM (g/hp-h)	CO_2 (g/hp-h)	FC (g/hp-h)	Exhaust Temp (°C)
Baseline		0.167	0.642	4.86	0333	509	160.7	515
21.6	7	0.181	0.668	3.97	0.395	510	161.0	510
24.1	8	0.173	0.699	3.78	0.415	510	161.3	501
27.0	9	0.170	0.687	3.70	0.403	510	161.3	499

To compare the emissions based on the use of the two different injection forms, a percentage difference was calculated from the baseline diesel fuel emissions for each of the separate test runs. The data from this comparison, seen in Table 4.5, indicates that for NOx emissions, above pulse width 7, the MP reductions are approximately 4% greater for points 8 and 9, for a maximum of 28% at pulse width 9. For PM each measurement point indicated that the SP arrangement experienced greater emissions for all three pulse widths than the MP system. The range was from 3% to 4% greater. For this engine, assuming that it was operated for 50% of the time on an annual basis, the MP system would result in an additional reduction of approximately 1/4 tonne of NOx emissions.

Table 4.5 Comparison of Emissions for Multi-point and Single Point Injection

WIR (L/h)	NOx Emissions (% difference vs. conventional)		PM emissions (% difference vs. conventional)	
	MP	**SP**	**MP**	**SP**
21.6	-18.2	-18.3	15.9	18.6
24.1	-26.8	-22.2	20.7	24.6
27.0	-28.0	-23.9	17.9	21.0

Figures 4.7 and 4.8 provide a graphical illustration of the differences in exhaust emissions between the two technologies.

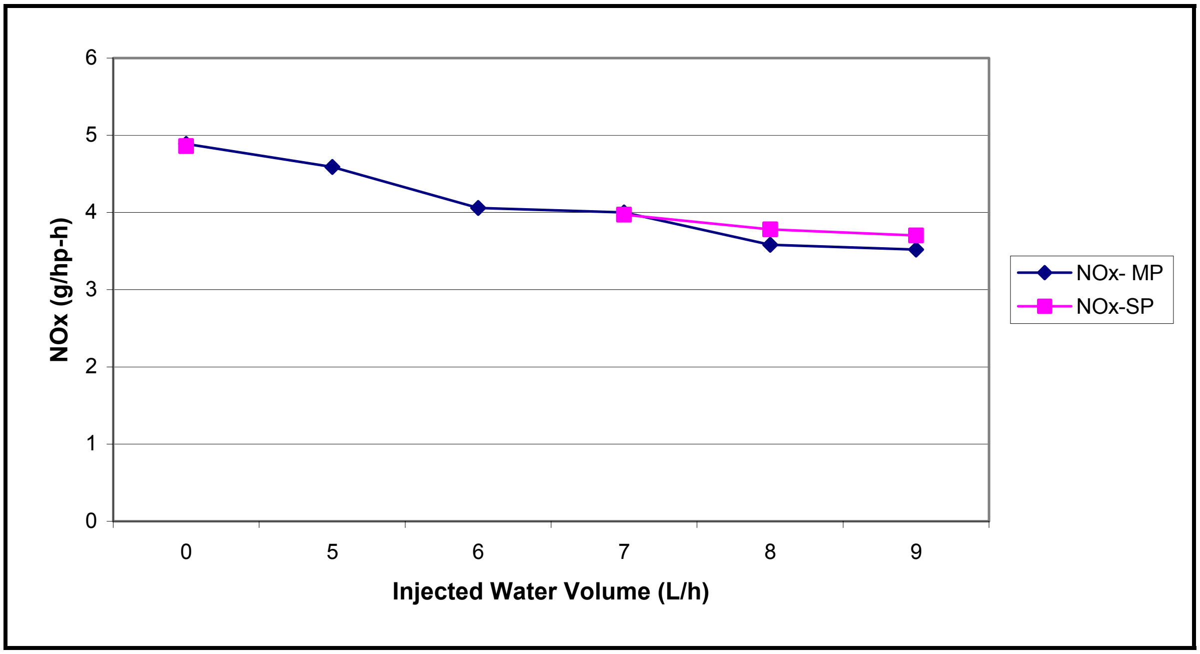

Figure 4.7 Comparison of NOx Emissions Between the MP and SP Injection Systems

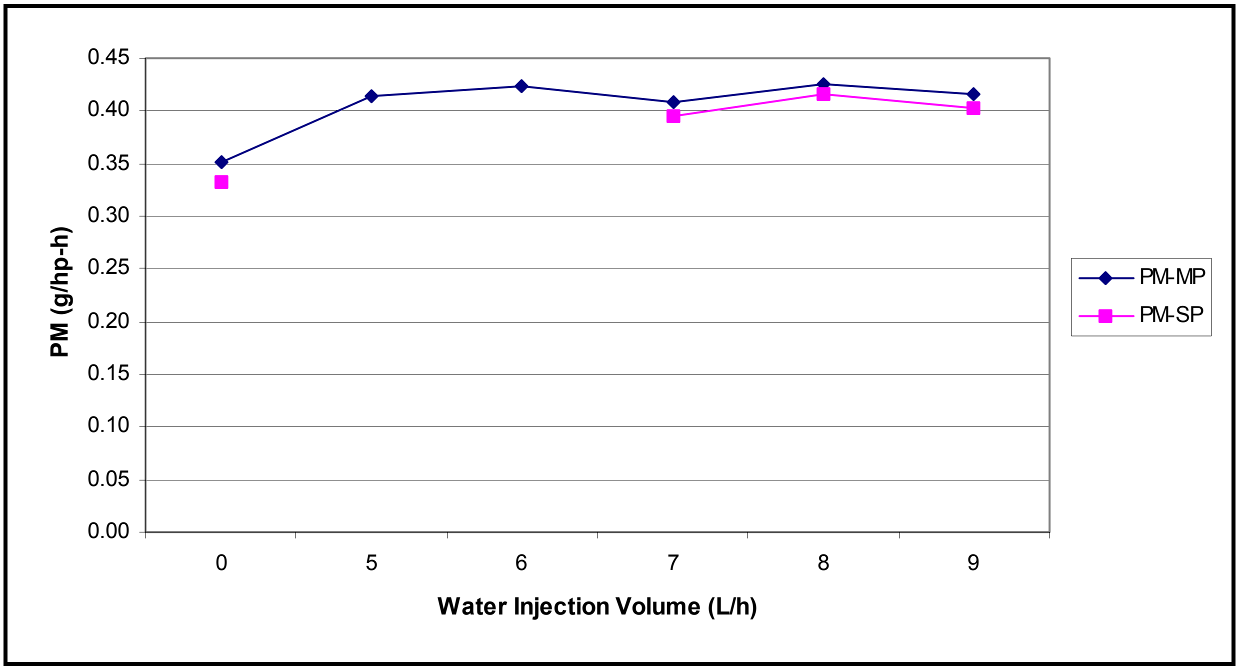

Figure 4.8 Comparison of PM Emissions for the Two Injection Systems

To evaluate the emissions reductions at different engine operating conditions, testing was conducted with the SP system at three of the four modes described by the propeller curve. The first mode, which is 100% speed and load, was difficult to maintain on the laboratory test system due to water temperature for the water brake, so this mode was not included in the testing. The tests at modes 2, 3 and 4 while injecting water at pulse widths of 3, 5, 7, and 9 are summarized in Tables 4.6 to 4.8.

Table 4.6 CO and THC Exhaust Emissions for SP versus Flow Rate

	Propeller Curve					
	Mode 4	**Mode 3**	**Mode 2**	**Mode 4**	**Mode 3**	**Mode2**
WIR (L/h)	**CO (g/hp-h)**	**CO (g/hp-h)**	**CO (g/hp-h)**	**THC (g/hp-h)**	**THC (g/hp-h)**	**THC (g/hp-h)**
baseline	1.27	0.636	0.61	0.320	0.136	0.150
11.2	1.31	0.660	0.63	0.356	0.142	0.151
16.7	1.43	0.732	0.65	0.361	0.148	0.151
21.6	1.63	0.732	0.65	0.369	0.132	0.146
24.0	1.77	0.746	0.67	0.401	0.147	0.151

Table 4.7 PM and NOx Exhaust Emissions for SP versus Flow Rate

	Propeller Curve					
	Mode 4	**Mode 3**	**Mode 2**	**Mode 4**	**Mode 3**	**Mode2**
WIR (L/h)	**PM (g/hp-h)**	**PM (g/hp-h)**	**PM (g/hp-h)**	**NOx (g/hp-h)**	**NOx (g/hp-h)**	**NOx (g/hp-h)**
baseline	0.122	0.125	0.118	7.07	5.32	4.89
11.2	0.150	0.138	0.125	5.75	4.52	4.35
16.7	0.157	0.162	0.127	5.16	4.12	4.14
21.6	0.189	0.177	0.136	4.8	3.8	3.92
24.0	0.256	0.179	0.144	4.4	3.46	3.69

Table 4.8 CO_2 Exhaust Emissions and Fuel Consumed for SP versus Flow Rate

	Propeller Curve					
	Mode 4	**Mode 3**	**Mode 2**	**Mode 4**	**Mode 3**	**Mode2**
WIR (L/h)	**CO_2 (g/hp-h)**	**CO_2 (g/hp-h)**	**CO_2 (g/hp-h)**	**FC (g/hp-h)**	**FC (g/hp-h)**	**FC (g/hp-h)**
baseline	564.6	509.7	506.9	177.7	160.6	159.7
11.2	564.1	510.4	509.2	178.4	161.0	160.6
16.7	564.1	511.5	508.5	178.5	161.4	160.4
21.6	566.3	511.4	509.1	179.3	161.3	160.6
24.0	568.4	512.7	509.6	180.1	161.8	160.8

Note: Mode 4 > 25% load at 63% maximum rated speed
Mode 3 > 50% load at 80% maximum rated speed
Mode 2 > 75% load at 90% maximum rated speed

The NOx emissions were decreased by a maximum 24.5% at the maximum water injection rate for mode 2, 35% at mode 3, and 38% at mode 4. For the maximum water injection rate at mode 2, the PM and CO were increased by 21% and 10%, respectively, while the THC was essentially unchanged. The fuel consumption calculations indicated an increase of 0.7 percent. Table 4.9 summarizes the percentage changes for all of the exhaust emissions for the three modes at the four water injection rates that were used in the testing: i.e. 11.2, 16.7, 21.6 and 27.0 L/h.

Table 4.9 Comparison of Emissions and Fuel Consumption versus Water Injection Rates

WIR (L/h)	Mode	% change NOx	% change PM	% change THC	% change CO	% change FC
27.0	4	-38	110	25	39	1.3
27.0	3	-35	43	8	17	0.7
27.0	2	-25	21	0.7	9	0.7
21.6	4	-32	55	28	15	0.9
21.6	3	-29	42	15	-3	0.5
21.6	2	-20	15	7	-3	0.6
16.7	4	-27	29	13	13	0.5
16.7	3	-23	30	15	9	0.5
16.7	2	-15	8	7	0.7	0.5
11.2	4	-19	23	3	11	0.4
11.2	3	-15	10	4	4	0.3
11.2	2	-11	6	3	0.7	0.6

The measured data for the three modes using the SP and the four different injection rates are graphically presented in Figures 4.9 to 4.12.

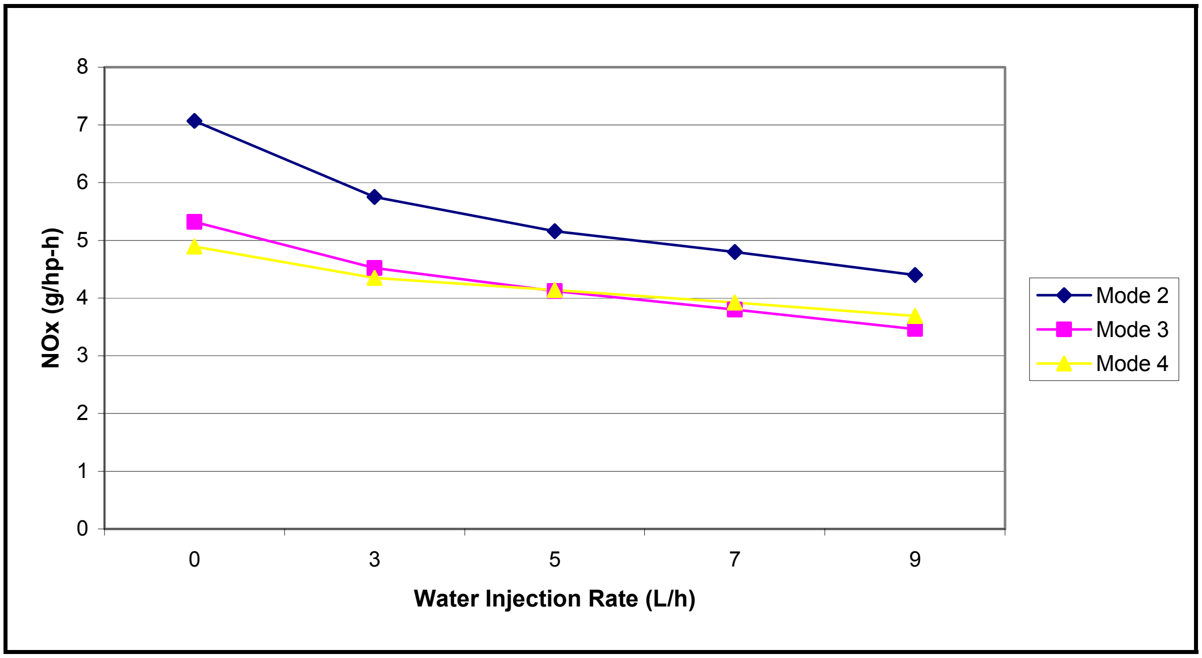

Figure 4.9 Impact of Water Injection Rate on NOx Emissions

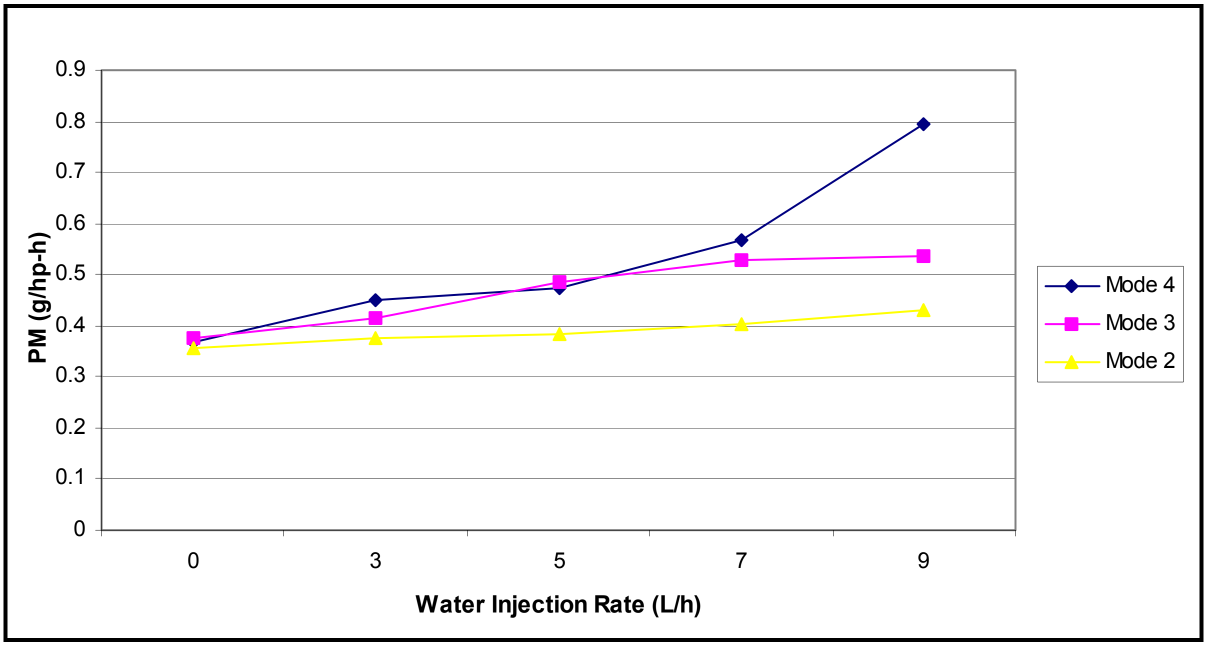

Figure 4.10 Impact of Water Injection Rate on PM Emissions

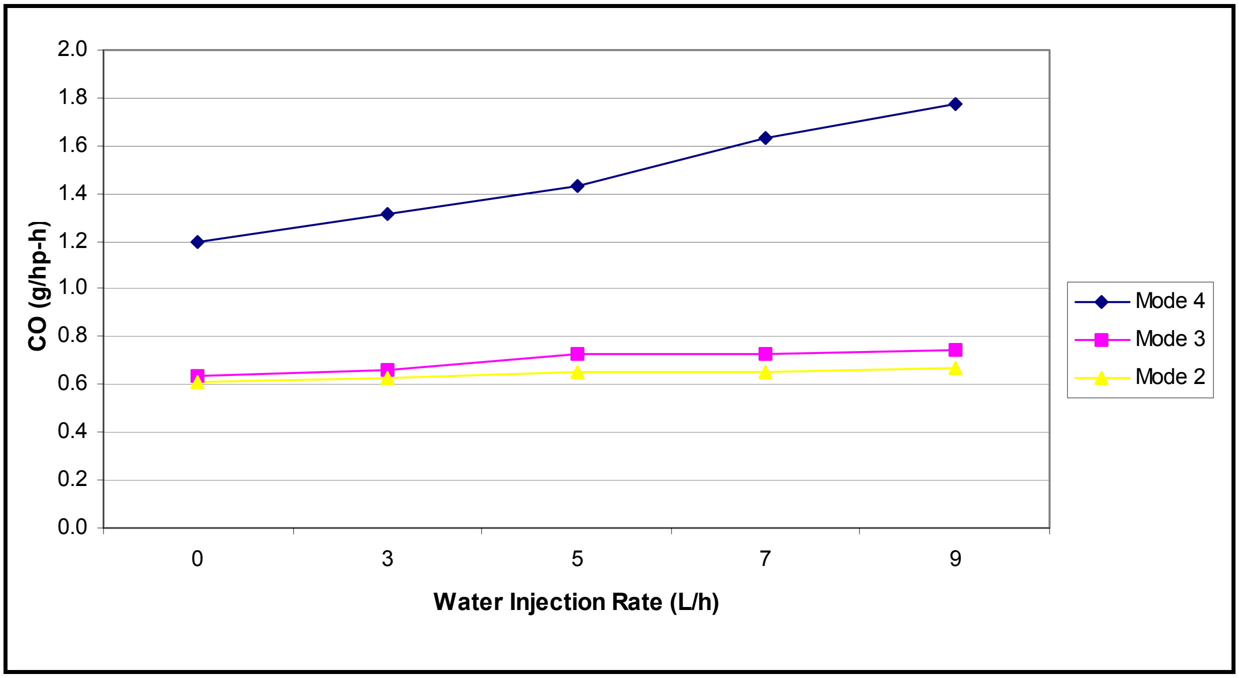

Figure 4.11 Impact of Water Injection Rate on CO Emissions

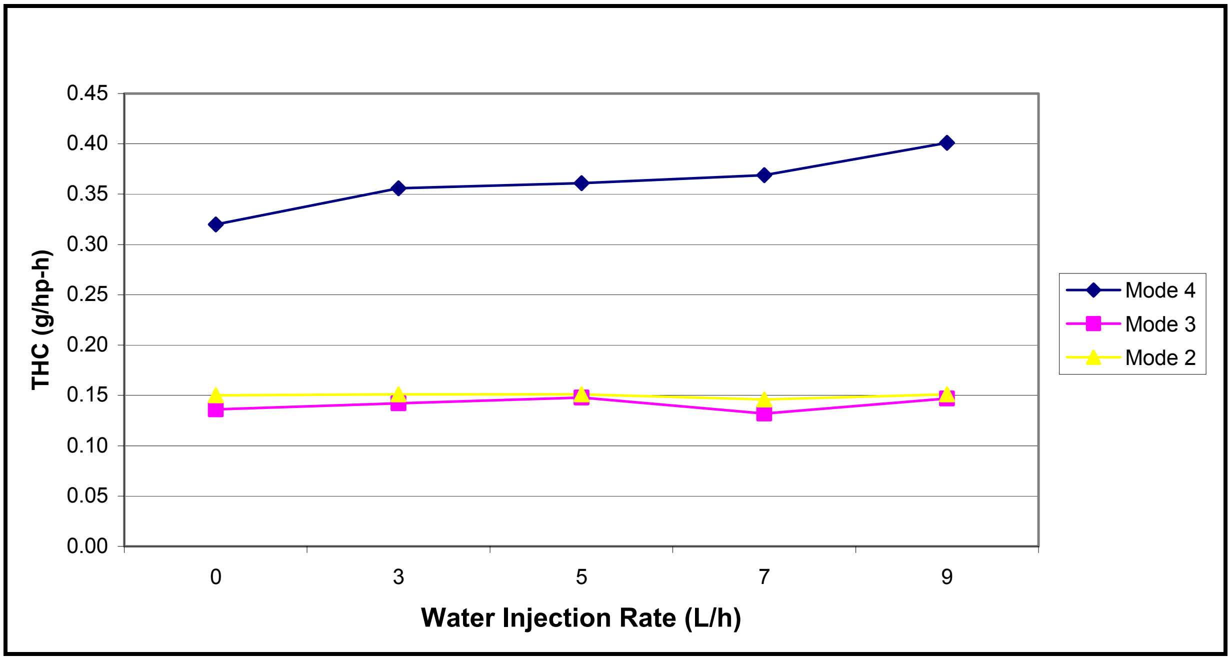

Figure 4.12 Impact of Water Injection Rate on THC Emissions

The data presented in the Table 4.9 indicates that the efficiency of the combustion process can be significantly affected with the introduction of too much water from the injection system. At the water injection rate of 27.0 L/h, with the engine operating at mode 4, the PM, THC and CO are increased by 110%, 25% and 39%, respectively. The calculated fuel consumption is increased by 1.3%.

The information from Table 4.9 can be used to select the optimum water injection rate for each of the modes at which the engine will be operating. For this to be done, it is necessary to predetermine the acceptable level of NOx reduction and the corresponding increases in PM, CO and THC. For this engine, the target for NOx reduction was a minimum of 20%. For PM, it is assumed that a maximum increase of 30% would be tolerated, as well as 10% to 15% for THC and CO. Using these criteria the ideal injection rates for the three modes are indicated in Table 4.10.

Table 4.10 Comparison of Emissions and Fuel Consumption versus Water Injection Rates

Mode	WIR (L/h)	NOx decrease	PM increase	THC increase	CO increase	FC increase
2	27.0	25%	21%	0.7%	9%	0.7%
3	16.7	23%	30%	15%	9%	0.5%
4	11.2	19%	23%	3%	11%	0.4%

The water volumes that would be required for this optimized system as percentages of the total volume of fuel + water entering the combustion chamber would be:

$$[\text{Vol.}_{\text{water}} / (\text{Vol.}_{\text{fuel}} + \text{Vol.}_{\text{water}})] \times 100$$

Table 4.11 Water Requirements as a Percent Volume of the Fuel

	Mode 4	Mode 3	Mode 2
% water by vol.	44	34	35

Under these conditions with this engine operating 50% of the time, or approximately 84 hours per week, the following annual emissions changes would result:

NOx: (4.89 - 3.69 g/hp-h) x 274 hp x 4360 h → 1.435 t of NOx reduction

PM: (0.144 - 0.118 g/hp-h) x 274 hp x 4360 h → 31.1 kg of PM increase

THC: (0.151 - 0.150 g/hp-h) x 274 hp x 4360 h → 1.2 kg of THC increase

CO: (0.67 - 0.61 g/hp-h) x 274 hp x 4360 h → 71.8 kg of CO increase

FC: (160.75 - 159.69 g/hp-h) x 274 hp x 4360 h → 300 gal. increase

For a medium-speed marine diesel engine, assuming a similar emissions profile, the annual emissions changes that would result are presented in Table 12. These estimates were calculated based on actual exhaust emissions measurements conducted on one of the *MV Cabot*'s (Oceanex) medium-speed diesel propulsion engines. For these measurements, the engine operating parameters were intermediate rpm and 2/3 power (5475 hp).

Table 4.12 Extrapolated Exhaust Emissions Results from a Medium-Speed Diesel

Condition	NOx	CO	PM
Baseline (g/hp-h)	15	0.80	1.77
w/ water injection (g/hp-h)	12	0.87	2.14
Annual changes (tonnes)	-71.7	+1.67	+8.84

The water volume required for these reductions, based on estimates of fuel consumption (0.865 tonnes/h) and the assumption that the water volume percentages from the test engine can be extrapolated to the marine engine, would be 504 L/h.

Section 5 – Field Testing of WIS on the *Queen of New Westminster*

5.1 Introduction

Environment Canada, TDC, and BC Ferry Corporation have been collaborating on several programs to obtain exhaust emissions data from the fleet of ferries used on the coast of British Columbia. As part of the Marine Vessel Exhaust Emissions Program, a Water Injection System (WIS) was field tested on the *Queen of New Westminster.*

The emissions of concern to the IMO are NOx and PM. Other compounds related to the combustion of fossil fuels (THC, CO and CO_2) were also measured. Ocean-going tugs, 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.

Phase 2 of the Marine Vessel Exhaust Emissions Program, initiated after the development of the database of emissions from Canadian vessels, was designed to investigate new cost-effective 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 the IMO was in the process of setting guidelines for this emission. One of the programs developed under this theme was the laboratory evaluation of a Canadian manufactured continuous water injection (CWI) system, followed by installation of the technology on a BC ferry.

A prototype of the CWI, manufactured by M.A. Turbo/Engine Design, was laboratory tested at ERMD in 1998.[4] A recommendation from this work was to conduct field verification testing of the CWI system on a BC ferry engine.

The exhaust emissions from the #4 main engine of the *Queen of New Westminster* were tested on two separate occasions, July 1999 and January 2000, while on route from Vancouver to Vancouver Island and on the return runs. This engine had previously been installed with a CWI system. Emissions testing was performed with and without the CWI in operation, and emissions of CO, CO_2, NOx and PM were collected. The remainder of this section details the test plan and procedures, and includes a comparison of the criteria pollutant emissions with and without the CWI installed.

5.2 Objective

The objective of the third part of Phase 2 of the Marine Vessel Exhaust Emissions Program was to compare criteria pollutants from one main engine of the *Queen of New Westminster* with and without the CWI system installed.

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[4] Marine Vessel Exhaust Emissions – Phase II, ERMD Report #98-26781, Transport Canada Report TP 13445E.

5.3 Vessel and Engine Data

Tables 5.1 and 5.2 list the details of the *Queen of New Westminster* and its main engines, respectively.

Table 5.1 Ship Description

Ship Description	***Queen of New Westminster***
Length (m)	129.9
Beam (m)	23.2
Ship Displacement (load tons)	5360
Gross Tonnage	8750
Propeller Type	Constant Pitch
Launch Date	1964

Table 5.2 Main Engine Description

Engine Description	***Queen of New Westminster***
Manufacturer	Wartsila 9R32D
Type	Turbo diesel
Bore x Stroke	320 x 350 mm
Max. Cont. Rating	3375 KW/750 rpm
Number/Configuration of Cylinders	9 in-line
Fuel Type	Diesel No. 2

5.4 Test Procedure

A test procedure was developed by ERMD to evaluate the exhaust emissions from one of the main engines during typical operation of the vessel while it was in normal cruise in open water. This section describes the test schedule, emissions sampling, and emissions calculation.

5.4.1 Test Matrix

Genesis Engineering provided the lead contact with the ferry operators to coordinate the test schedule. M.A. Turbo/Engine Design provided engine operational data during the tests.

Table 5.3 lists the schedule that was completed for the testing. Three baseline tests were performed without the CWI system, followed by four tests with the CWI system installed and different water injection flows, and finally re-baseline testing without the CWI system.

Table 5.3 Test Matrix for the *Queen of New Westminster*

Test #	Engine Mode	Location	CWI	Samples collected
99-1	Cruise	Nanaimo to Tsawwassen	OFF	CO, CO_2, NOx
99-2	Cruise	Nanaimo to Tsawwassen	ON	CO, CO_2, NOx
99-3	Cruise	Nanaimo to Tsawwassen	OFF	CO, CO_2, NOx
00-1	Cruise	Swartz Bay to Tsawwassen	OFF	CO_2, NOx, PM
00-2	Cruise	Swartz Bay to Tsawwassen	ON	CO_2, NOx, PM
00-3	Cruise	Tsawwassen to Swartz Bay	OFF	CO_2, NOx, PM
00-4	Cruise	Tsawwassen to Swartz Bay	ON	CO_2, NOx, PM

5.4.2 Exhaust Emissions Sampling Methodology and Procedures

The exhaust sampling and analysis system was prepared by ERMD to provide accurate and repeatable data comparable to a more permanent installation of analyzers that would be typical of a standardized test bench configuration. To achieve these criteria, ERMD utilized a portable, commercial, continuous emissions monitor (ECOM-AC) for the measurement of CO, CO_2, NOx, and O_2. Coupled with the emissions analyzer were stainless steel particulate filters holders, a vacuum pump, and a mass flow controller used to collect total PM. PM emissions rates were obtained by directing the exhaust through pre-weighed 47 mm Pallflex™ filters, allowing particles to be deposited. Prior to the test, all filters were stored in a desiccator where the conditions were maintained at 40±10% humidity and 24°C. After this stabilization period, the filters were weighed on a Mettler AE240 balance readable to 0.01 mg. The filters were then stored in covered petri dishes for transfer to the test site. After the testing, the filters were returned to the petri dishes and sealed for transfer back to the analysis lab. Prior to weighing, the filters were re-stabilized in the desiccator for 12 to 24 hours and then re-weighed to determine the net mass of diesel particulate emissions. This mass, plus the measurement data, was used to calculate the PM emissions rate in kg/tonne fuel.

Table 5.4 outlines the sampling media and analysis methodology as well as the flow rates used during the testing.

Table 5.4 Emissions Sampling and Analysis

Component	Sample/analysis	Flow Rate (L/min)
CO, CO_2, NOx, O_2	Continuous electrochemical sensors	1.5
Total Particulate Mass	47 mm diameter filters/ Gravimetric method	16.5

With the repeat tests that were performed in January 2000, an OTC MicroGas portable emissions analyzer was used instead of the ECOM. The CO measurements from tests read with the OTC MicroGas were at the instrument detection limits. The CO measurement range of the instrument is 0 to 15%. Also, with repeat tests, a 9.5 mm diameter stainless tube connected to a heated sample line was used to draw sample to the emissions analyzer to reduce the moisture content of the exhaust. This change may have had an impact on the total PM measurements.

5.4.3 Emissions Calculations

The mass emissions calculations were based on those outlined in ISO 8178-1.[5] In this method the calculations are based on carbon balance between the fuel and exhaust. It was assumed in the calculations that ambient levels of the pollutants were negligible. In addition, as all comparative tests were conducted on the same runs, an assumption was made that the humidity level was constant. Table 5.5 lists the inputs and outputs of the emissions calculations.

Table 5.5 Emissions Calculations

Inputs	Outputs
Fuel density and fuel fraction carbon Exhaust concentration of CO_2 Fuel flow rate	Exhaust flow rate
Exhaust flow rate Exhaust emissions concentration Component density	Mass emissions rate of exhaust
Mass emissions rate & Engine power setting or fuel rate	Power-specific emissions rate g/kW•h Fuel-specific emissions rate kg/tonne

5.5 Results and Discussion

The results of the emissions testing are listed in Tables 5.6 through 5.9 in kg/tonne fuel for the July 1999 testing.

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[5] ISO 8178-1:1996(E) Reciprocating internal combustion engines - Exhaust emission measurement. Part 1: Test bed measurement of gaseous and particulate exhaust emissions

Table 5.6 Baseline Emissions Rates Without CWI System (kg/t fuel)

Configuration	CO	CO_2	NOx
Baseline #1	2.18	3124	75.5
Baseline #2	2.18	3127	74.5
Baseline #3	2.12	3128	74.4
Average	2.16	3126	74.8
Standard Deviation	0.03	2.08	0.61
% Covariance	1.60	0.07	0.81

Table 5.7 Emissions Rates with CWI System (kg/t fuel)

Configuration	Condition	Water Flow* (L/min)	CO	CO_2	NOx
CWI Test #1	Nozzle #26, 60 psig	1.3	2.15	3127	67.4
CWI Test #2	Nozzle #26, 68 psig	1.5	2.18	3127	67.0
CWI Test #3	Nozzles #22 and D, 40 psig	2.1	2.12	3127	63.3
CWI Test #4	Nozzles #22 and D, 40 psig: #26 50 psig	3.3	2.21	3127	58.3

**data provided by M.A. Turbo/Engine Design*

Table 5.8 Repeat Baseline Emissions Rates Without CWI System (kg/t fuel)

Configuration	CO	CO_2	NOx
Baseline #4	2.18	3127	74.7
Baseline #5	2.18	3127	74.8
Baseline #6	2.25	3128	75.4
Average	2.20	3127	75.0
Standard Deviation	0.04	0.58	0.38
% Covariance	1.83	0.02	0.81

Table 5.9 Exhaust Emissions Summary for January 2000

TEST	CO_2 (kg/t fuel)	NOx (kg/t fuel)	PM (kg/t fuel)
1. CWI-off	3149	63.36	0.227
1. CWI-off	3115	63.36	0.209
Average	**3132**	**63.36**	**0.218**
1. CWI-on	3136	53.88	0.189
1. CWI-on	3112	53.94	0.164
Average	**3124**	**53.91**	**0.177**
2. CWI-off	2801	51.84	0.245
2. CWI-off	2797	54.11	0.167
Average	**2799**	**52.98**	**0.206**
2. CWI-on	2801	45.55	0.163
2. CWI-on	2791	48.47	0.164
Average	**2796**	**47.01**	**0.164**

Due to the small data set, statistical analysis of the results is limited. The results for the baseline tests were repeatable. The CWI tests for the July 1999 testing were taken with different nozzle pressures and water flow rates, and only one test per condition. Therefore, it was not possible to determine the repeatability or statistical significance of these tests. For the January 2000 testing, the data that is reported in Table 5.9 represents the exhaust emissions at a constant flow rate and pressure.

There was no significant difference between the CO and the CO_2 emissions rates with and without the CWI system in operation. However, differences in the NOx emissions rates with and without the system in place were observed.

A direct comparison of the results, as simply the percent relative difference was calculated and is presented in Table 5.10, which lists the percent relative difference of the average baseline NOx, value (i.e., 75 kg/tonne fuel) compared with the individual tests taken with the CWI.

Table 5.10 Relative Difference of the Average Baseline NOx Values to the CWI NOx Values

Avg Baseline vs. CWI Test 1-99	-10.1
Avg Baseline vs. CWI Test 2-99	-10.7
Avg Baseline vs. CWI Test 3-99	-15.6
Avg Baseline vs. CWI Test 4-99	-22.3

For the 1999 testing, the average relative percent difference in NOx emissions with and without the CWI was 15%, without a change in CO or CO_2 emissions. In the January 2000 testing, the NOx emissions were reduced by 11 to 15% without affecting the fuel consumption.

The PM emissions were measured during the January 2000 testing as indicated in Table 5.9. The data illustrates a reduction in the PM for all of the measured runs. The average reduction for all of the tests with the CWI operational was 19.8%. Table 5.11 summarizes the average exhaust emissions results for the testing conducted for this period.

Table 5.11 Average Exhaust Emissions Percent Differences with the Use of the CWI

Test	CO_2	NOx	PM
	kg/t fuel	kg/t fuel	kg/t fuel
1-00	.25	14.9	19.0
2-00	.11	11.3	20.6
Avg	**.18**	**13.1**	**19.8**

Listed in Table 5.7 are the water flows that were used for each of the tests with the CWI**.** This data was not recorded by ERMD but was provided by M.A. Turbo/Engine Design. Figure 5.1 provides a graphical display of the emissions reductions in NOx, with the CWI, from Table 5.8, versus the water flow.

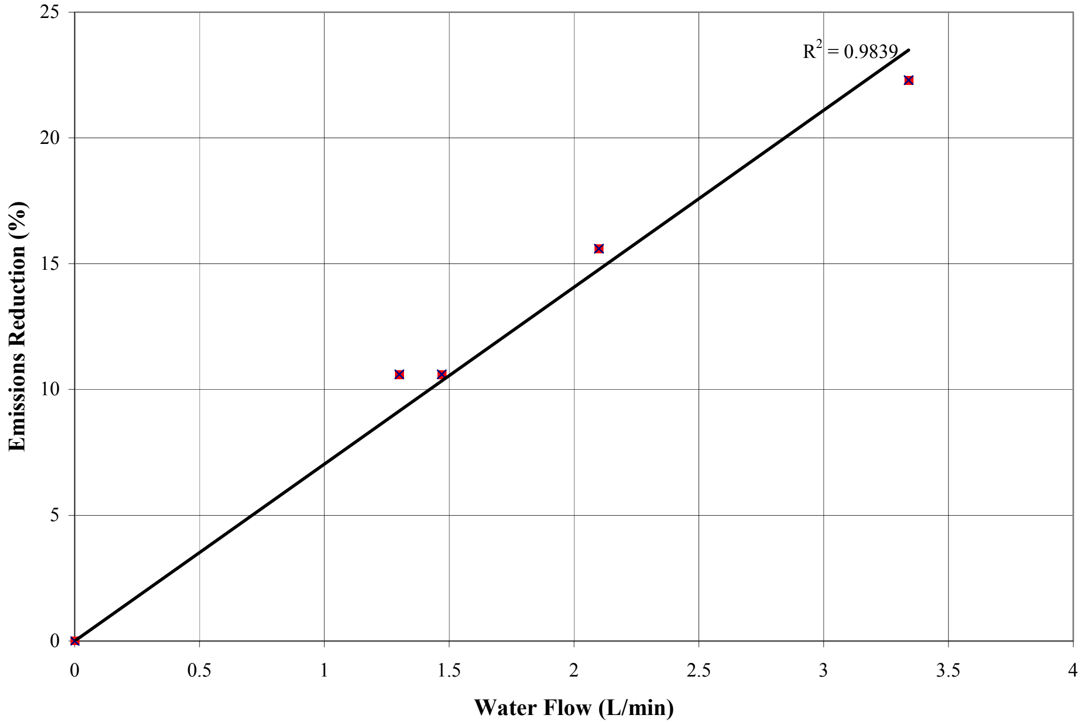

Figure 5.1 Influence of Water Injection on NOx Emissions

A linear trend line was plotted through the emissions reductions resulting in an R^2 value of 0.99. This indicates a linear relationship exists between the amount of water injected and the emissions reduction in NOx.

Additional engine and vessel operational data was recorded during testing by M.A. Turbo/Engine Design and is provided in Table 5.12. Table 5.13 lists the percent relative difference between operating conditions with and without the CWI.

Table 5.12 Specific Operating Conditions of the Engine During Testing

	Time	**Load**	**Shaft**	**P_S**	**T_S**	**T_O**	**T_C**	**T_{exh}**	**Fuel Rate**	**SFC**
		hp	**rpm**	**bar**	**^{0}C**	**^{0}F**	**^{0}C**	**^{0}F**	**L/min**	**L/hp-h**
Baseline Test #										
1	13:40	3325	272	1.5	56	82	427	760	8.42	-
2	13:45	3326	272	1.5	57	82	428	761	8.39	-
3	13:50	3322	272	1.49	57	82	428	760	8.36	-
Average		3324	272	1.5	57	82	428	760	8.39	0.1514
Water Injection Conditions										
1. Nozzle # 26, 60 psig	13:55	3350	272	1.52	49	82	416	752	8.38	-
2. Nozzle #26, 68 psig	14:00	3360	272	1.54	48	82	415	751	8.39	-
3. Nozzles #22 and D, 40 psig	14:05	3360	272	1.55	48	83	415	751	8.39	-
4. Nozzles #22 and D, 40 psig #26 50 psig	14:10	3365	272	1.55	48	83	415	750	8.40	
Average										0.149
Baseline Test #										
4	14:21	3320	272	1.45	56	83	425	760	8.40	-
5	14:26	3320	272	1.45	57	83	428	761	8.37	-
6	14:31	3322	272	1.46	57	84	429	761	8.36	-
Average		3321	272	1.45	57	83	427	761	8.38	0.151
Average Baseline Tests		**3323**	**272**	**1.48**	**57**	**83**	**428**	**760**	**8.39**	**0.1512**

Legend:

P_S – scavenging air pressure
Ts – scavenging air temperature
T_0 – engine room air temperature
T_C – average exhaust gas temperature after cylinders
T_{exh} – exhaust gas temperature after turbocharger
SFC – specific fuel consumption

Table 5.13 Percent Relative Difference in Operating Conditions with and without CWI

	Load hp	Shaft rpm	P_S bar	T_S ^{0}C	T_O ^{0}F	T_C ^{0}C	T_{exh} ^{0}F	Fuel Rate L/min	SFC L/hp-h
Baseline vs. CWI Test # 1	0.8	0	2.7	-13.6	-1.2	-2.7	-1.1	-0.1	0.9 to 1.05
Baseline vs. CWI Test # 2	1.1	0	4	-15.3	-1.2	-2.9	-1.2	0	
Baseline vs. CWI Test # 3	1.1	0	4.5	-15.3	0	-2.9	-1.2	0	
Baseline vs. CWI Test # 4	1.4	0	4.5	-15.3	0	-2.9	-1.4	0.1	

The largest percent difference was seen with the scavenging air temperature: it was reduced with the use of the CWI by ~15%. Slight differences were seen in the other parameters; however, the parameter of most concern was the engine load (hp), which was consistently increased by ~1.1%, and specific fuel consumption (L/h), which was decreased by ~1.0%.

The focus of the testing was to investigate the impact of the CWI on the exhaust emissions from the propulsion engine while operating under normal service conditions. Other relevant factors that need to be addressed concerning the installation of a CWI system for continuous operation are the long-term effect of the water system on the engine components, and details relating to the water volume, storage, and availability.

5.6. Summary

The emissions rates from the *Queen of New Westminster* were tested while the ferry was under normal cruise operations. Emissions of CO, CO_2, NOx and PM were measured with and without a CWI system installed on one of the main engines.

With the limited tests that were performed, a decrease of 10% to 22% in NOx emissions was noted with the water injection system with varying water volumes being injected. The maximum reduction in NOx was 22% with nozzles #22 at 40 psig, and nozzles #26 at 50 psig and a water flow rate of 3.3 L/min. A linear relationship was shown to exist between the amount of water injected and the decrease in NOx emissions. The emissions rates of CO and CO_2 were not affected with the use of the water injection system. The PM was reduced by an average of 19.8% based on a total of four separate runs with the water injection rate at a constant flow and pressure.

Engine parameters and ambient conditions such as fuel flow rate, specific fuel consumption, exhaust gas temperature after cylinders and after turbocharger, engine room air temperature and scavenging air pressure were measured with and without the CWI and were provided by M.A. Turbo/Engine Design. Scavenging air temperature was reduced with the CWI. Engine load or horsepower was increased by ~1% with the CWI, resulting in a decrease in specific fuel consumption by ~1%. An investigation of the changes in load and specific fuel consumption with the use of the CWI is recommended.

Section 6 – Summary and Conclusions

6.1 Phase 1 – Characterization of Exhaust Emissions from the *MV Cabot*

Phase 1 of the Marine Vessel Exhaust Emissions Program involved the collaboration of ERMD, TDC, and Oceanex on a project to measure the exhaust emissions of a cargo vessel (the *MV Cabot*) under normal operation. Measurements to determine the level of NOx, CO, CO_2, O_2 and PM were completed during each of the engine trial runs. Table 6.1 presents the primary results of the *MV Cabot* exhaust emissions testing.

Table 6.1 Emissions Rates During Cruise Conditions in g/hp-h

Sample	Engine operation	CO	NOx	CO_2	PM
1	Leaving port	1.3	18.5	2982	n/a
2	Low-speed cruise	1.3	16	2932	n/a
3	Intermediate speed	0.7	15	2951	n/a
4	Intermediate speed	1.4	13	2927	1.14
5	Intermediate speed	0.8	12	2918	1.19
6	High speed	0.8	15	2902	1.77
7	High speed	0.8	9.3	2902	1.66

These results formed baseline emissions for comparison with future testing of the *MV Cabot* with a WIS in place. In addition, the NOx emissions were compared to IMO standards. The emissions results, though based on estimates of fuel consumption and engine power, indicated that the NOx exceeded regulated levels for six of the seven different measurement points during the transit from Montreal to Trois Rivières. Only the second high-speed run met the IMO standard for NOx emissions.

The repeatability of the data was somewhat varied. The CO emissions for the high-speed cruise and the NOx emissions for the intermediate-speed cruise tests compared well. The NOx emissions for the high-speed cruise and the CO emissions for the intermediate-speed cruise tests did not compare favorably with relative deviations of greater than 30%. The PM results for both the intermediate and high-speed tests were repeatable within ~5%.

6.2 Phase 2 – Part 1: Laboratory Testing of Water Emulsified Fuels

Phase 2 – Part 1 of the Marine Vessel Exhaust Emissions Program involved the collaboration of ERMD and TDC on a project to measure the effect of fuel emulsions on marine exhaust emissions. Measurements to determine the level of NOx, CO, CO_2, THC and PM were taken for four separate fuel emulsions.

The work conducted during this part of Phase 2 focused on the measurement of the exhaust emissions and fuel consumption of a heavy-duty on-road diesel engine (operated under IMO marine cycle 8178-4 E3) with four fuel emulsions ranging from 5% to 20% water, emulsified with low-sulphur diesel. By varying the water content and the fuel injection timing, the project was designed to investigate the potential for an optimized exhaust emissions reduction and minimal power loss combination.

The primary results of the testing were the following;

- With the engine operating using the standard fuel injection timing, the 20% fuel emulsion results indicate the greatest exhaust emissions reductions for all four modes. The only exceptions are the THC and CO measurements during Mode 4.
- Advancing the timing resulted in the expected increases in efficiency and NOx. The addition of the fuel emulsion did not, however, provide enough of a reduction in the combustion temperature to reduce the NOx emissions below the base fuel base timing conditions.
- 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%. Operating the engine on fuel emulsions decreased the emissions that had increased due to the timing change.

It is assumed that the effects on the exhaust emissions of retarding the timing and operating on fuel emulsion is very engine specific. Therefore, it would be difficult to translate these results to other engines; however, it is evident that a combination of the two will result in significant emissions reductions to engines operating under a marine cycle. For this particular engine, retarding the timing by less than the 9 degrees may result in an acceptable loss of power and efficiency while maintaining the significant gains in emissions reductions.

6.3 Phase 2 – Part 2: Laboratory Testing of a Water Injection System

Phase 2 – Part 2 of the Marine Vessel Exhaust Emissions Program involved the collaboration of ERMD and TDC on a project to measure the effect of a water injection system on a diesel engine operating in a marine cycle. Measurements to determine the level of NOx, CO, CO_2, THC and PM were compared over numerous separate operating conditions.

The work conducted during this part of Phase 2 focused on the measurement of the exhaust emissions and fuel consumption of a heavy-duty on-road diesel engine (operated under IMO marine cycle 8178-4 E3) with five different water injection rates over several operating modes. By varying the water injection rate over the operating modes described in IMO 8178-4 E3, the project was designed to investigate the effect of water injection on exhaust emissions over a wide variety of operating conditions. Additionally, both multi-point and single-point injection were investigated.

Table 6.2 presents an overview of the relative change in exhaust emissions between the baseline (no water injection) emissions and various multi-point water injection rates. In addition to these results, it was also determined that multi-point injection achieved approximately 15% to 20% lower NOx and PM emissions than single-point injection in almost all scenarios.

Table 6.2 Comparison of Emissions and Fuel Consumption versus Water Injection Rates

Mode	WIR (L/h)	NOx decrease	PM increase	THC increase	CO increase	FC increase
2	27.0	25%	21%	0.7%	9%	0.7%
3	16.7	23%	30%	15%	9%	0.5%
4	11.2	19%	23%	3%	11%	0.4%

It was apparent from these results that water injection is a valid method of reducing NOx emissions in marine engines at the cost of some increases in other emissions. Noteworthy is that NOx emissions (by mass) are several orders of magnitude greater than the emissions of PM, THC and CO, thus a 20% decrease in NOx compared to a 20% increase in, say, PM emissions is not "offsetting". The overall mass reduction in each species (per unit fuel or annum of operation) must be compared. Additionally, further investigation into other conditions related to the use of the WIS, such as the volume of the water required, cost of the water, associated costs of using the injection system and the long-term effects of using water on the engine components, should be undertaken.

6.4 Phase 2 – Part 3: Field-testing of a Water Injection System

Phase 2 – Part 3 of the Marine Vessel Exhaust Emissions Program involved the collaboration of ERMD, TDC, and the BC Ferry Corporation on a project to measure the exhaust emissions of the *Queen of New Westminster* with and without the use of a water injection system. The exhaust emissions from the #4 main engine of the *Queen of New Westminster* of the BC Ferry Corporation were tested on two separate occasions, July 1999 and January 2000, while on route from Vancouver to Vancouver Island and on the return runs. This engine had previously been installed with a water injection system.

Emissions testing was performed with and without the water injection system in operation, and emissions of CO, CO_2, NOx and PM were collected. Water injection rates and pressures were varied over a number of test runs.

With the limited tests that were performed, a decrease of 10% to 22% in NOx emissions was noted with the water injection system with varying water volumes being injected. The maximum reduction in NOx was 22%, with two different nozzle configurations at a water flow rate of 3.3 L/min. A linear relationship was shown to exist between the amount of water injected and the decrease in NOx emissions. The emissions rates of CO and CO_2 did not show any statistical variation with the use of the water injection system.

PM was reduced by an average of 19.8% based on a total of four separate runs with the water injection rate at a constant flow and pressure. This is in contrast to the bench-scale tests performed in Phase 2 – Part 2, which demonstrated an increase of PM with the addition of a water injection system. These differences may be explained in part by real-world operating conditions, engine specifications and fuel differences. It would, however, add more weight to the value of the bench-scale water injection results if the trends observed for each species (between baseline and water injection) were similar.