APPENDIX F

Emission Test Report

On-Board ISO 8178-4 D2 Marine Engine Measurement of Emissions from Caterpillar Generator Engine Using ULSD and a 50/50 Blend of ULSD and Algal Based Biofuel

Report
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Disclaimer

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List of Acronyms

ºC	degree centigrade
C	carbon
CE-CERT	College of Engineering – Center for Environmental Research and Technology
CFO	critical flow orifice
CO	carbon monoxide
CO_2	carbon dioxide
DAF	dilution air filter
DNPH	dinitrophenylhydrazine
DoD	Department of Defense
DT	dilution tunnel
EC	elemental carbon
ECE	Economic Commission for Europe
EDG	emergency diesel generator
EFR	exhaust flow rate
EGA	exhaust gas analyzer
EMF	Electromotive Force
EP	exhaust pipe
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification
F.S./day	full scale per day
GM	General Motors
g/kW-hr	grams per kilowatt-hour
gph	gallons per hour
HC	hydrocarbon
HCLD	heated chemiluminescence detector
HEPA	high efficiency particulate air
HFID	heated flame ionization detector
hp	horsepower
hr	hour
ID	internal diameter
IMO	International Maritime Organization
ISO	International Organization for Standardization
kg/m^3	kilograms per cubic-meter
kPa	kilopascal
kW	kilowatt
l	liters
lpm	liters per minute
lb	pound
m	meter
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR.	maximum continuous rating
min	minutes
mm^2/s	square-millimeter per second

m/m	mass by mass
NDIR	non-dispersive infrared
ng	nanogram
NIOSH	National Institute of Occupational Safety and Health
NO	nitric oxide
NO_x	oxides of nitrogen
NO_2	nitrogen dioxide
OC	organic carbon
O_2	oxygen
PAHS	polynuclear aromatic hydrocarbons
PM	particulate matter
$PM_{2.5}$	particulate matter with a mean aerodynamic diameter less than 2.5 micron
PMD	paramagnetic detector
ppbc	parts per billion carbon
PTFE	polytetrafluoroethylene or Teflon Filter
ppm	parts per million
ppmv	parts per million by volume
psig	pound-force per square-inch gauge
QC/QA	quality control/quality assurance
RH	relative humidity
RIC	reciprocal internal combustion
rpm	revolutions per minute
scfm	standard cubic feet per minute
SMM	simplified measurement method
SO_2	sulfur dioxide
SP	sampling probe
VN	Venturi
T	temperature
TC	total carbon
TFE	Teflon™
TT	transfer tube
UCR	University of California, Riverside
ULSD	ultra low sulfur diesel
UN	United Nations
U.S.	United States
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification
VN	Venturi
vol%	volume %

Table of Contents

Disclaimer .... **i**

Acknowledgements .... **ii**

List of Acronyms .... **iii**

Table of Contents .... **v**

List of Figures .... **vii**

List of Tables .... **viii**

Executive Summary **1**

1 Introduction **2**

1.1 Alternative Fuels and Emission Regulations 2

1.2 Project Objectives 4

2 Project Approach **5**

2.1 Overview 5

2.2 In-use Emission Measurements Using IMO and ISO Methods 5

2.2.1 Test Vessel, Engine and Fuels 5

2.2.2 Operating Conditions of the Engine while Measuring Emissions 9

2.2.3 Engine Performance Measurements during Testing 10

2.2.4 Measurement of Gaseous and Particulate Matter Emissions 10

3 Data Analysis **12**

3.1 Calculation of Emission Factors 12

3.1.1 Calculation of the Exhaust Flow Rate by ISO 8178-2 12

3.1.2 Calculation of the Exhaust Flow Rate Assuming the Engine as an Air Pump 13

4 Results **14**

4.1 Exhaust Flow Rate 14

4.2 Test Fuels 14

4.3 Analysis of Emissions Factors 17

4.3.1 Operating Loads for the Engine when Emissions Measured 17

4.3.2 Carbon Dioxide Emissions 17

4.3.3 Quality Checks: Carbon Mass Balance: Fuel vs. Exhaust 19

4.3.4 NO_x Emissions 19

4.3.5 CO Emissions 20

4.3.6 SO_2 Emissions 20

4.3.7 Particulate Matter $PM_{2.5}$ Mass Emissions 21

4.3.8 PM Mass Fractionated into Elemental Carbon (EC) plus Organic Carbon (OC) 21

4.3.9 Quality Check: Conservation of $PM_{2.5}$ Mass Emissions 22

4.3.10 Fuel consumption by Carbon Balance 22

5 Discussion ... **24**

6 Conclusions ... **29**

7 References ... **30**

Appendix A - Test Cycles and Fuels for Different Engine Applications ... A-1

A.1 Introduction ... A-1

A.2 Constant speed ... A-1

A.3 Modes and Weighting Factors for Test Cycles ... A-2

A.4 Test Fuels ... A-2

Appendix B - Measuring Gaseous & Particulate Emissions ... B-1

B.1 Scope ... B-1

B.2 Sampling System for Measuring Gaseous and Particulate Emissions ... B-1

B.3 Dilution Air System ... B-2

B.4 Calculating the Dilution Ratio ... B-4

B.5 Dilution System Integrity Check ... B-4

B.6 Measuring the Gaseous Emissions: CO, CO_2, HC, NO_x, O_2, SO_2 ... B-5

B.6.1 Measuring Gaseous Emissions: ISO & IMO Criteria ... B-5

B.6.2 Measuring Gaseous Emissions: CE-CERT Design ... B-5

B.7 Measuring the Particulate Matter (PM) Emissions ... B-8

B.7.1 Added Comments about CE-CERT's Measurement of PM ... B-8

B.8 Measuring Non-Regulated Gaseous Emissions ... B-9

B.8.1 Flow Control System ... B-9

B.9 Measuring Non-Regulated Particulate Emissions ... B-10

B.9.1 Measuring the Elemental and Organic Carbon Emissions ... B-10

B.9.2 Measuring Real-Time Particulate Matter (PM) Emissions-DusTrak ... B-10

B.10 Quality Control/Quality Assurance (QC/QA) ... B-11

Appendix C Appendix C Raw Data, Analysis, Analysis Equations, and Calibration Data ... C-1

C.1 Data ... C-1

C.2 Calibration Data ... C-8

List of Figures

Figure 1-1: Navy Test Program Protocol 2
Figure 2-1: T/S State of Michigan 5
Figure 2-2: Caterpillar D398 Generator Set 7
Figure 2-3: T/S State of Michigan Engine Room - D398 Generator Sets 7
Figure 2-4: Propulsion System Layout 8
Figure 4-1: Exhaust Flow Rate by Engine as Air Pump versus by Carbon Balance 14
Figure 4-2: Engine Gaseous Emission Rate for CO_2 vs. Load 17
Figure 4-3: Engine Emission Factors for CO_2 vs. Load (g/kW-hr) 18
Figure 4-4: Average CO_2 Emission Factors for each mode and Overall Weighted Emission Factor 18
Figure 4-5: Carbon in the Exhaust versus Carbon in the Fuel 19
Figure 4-6: Average NO_x Emission Factors for each test mode and Overall Weighted Emission Factor 20
Figure 4-7: Average CO Emission Factors for each test mode and O verall Weighted Emission Factor 20
Figure 4-8: Total $PM_{2.5}$ Mass Emissions 21
Figure 4-9: PM Mass Fractioned into Elemental & Organic Carbon 22
Figure 4-10: Comparison of Mass on Teflon Filter & Cumulative Mass from Quartz Filter 23
Figure 4-11: Fuel Consumption as a Function of Engine Load 23
Figure 5-1: %Reduction in Pollutants by the 50/50 Blend 24
Figure 5-2: % Reduction in Fuel Consumption by the 50/50 Blend 25

Figure B-1: Partial Flow Dilution System with Single Venturi, Concentration Measurement and Fractional Sampling B-1
Figure B-2: Field Processing Unit for Purifying Dilution Air in Carrying Case B-2
Figure B-3: Setup Showing Gas Analyzer with Computer for Continuous Data Logging B-6
Figure B-4: Partial Flow Dilution System with Added Separation Stages for Sampling both Regulated and Non-regulated Gaseous and PM Emissions B-9
Figure B-5 Picture of Dustrak B-11
Figure C-1: NOx Calibration Data for Horiba PG 250 .... C-9
Figure C-2: CO Calibration Data for Horiba PG 250 .... C-9
Figure C-3: CO_2 Calibration Data for Horiba PG 250 .... C-10

List of Tables

Table 1-1: Marine Engine Categories 4
Table 2-1: Standard Cycle for Testing Steady-Speed Engines. 9
Table 2-2: Engine Parameters Measured and Recorded 10
Table 5-1: Gaseous Emission Factors (EF's) and %Reduction by 50/50 Blend versus ULSD 28
Table 5-2: Fuel Consumption and %Reduction by 50/50 Blend 28

Table A-1: Definitions Used Throughout ISO 8178-4 .... A-1
Table A-2: Combined Table of Modes and Weighting Factors A-3
Table A-3: Fuel Selection Criteria A-4
Table B-1: Components of a Sampling System: ISO/IMO Criteria & CE-CERT Design B-3
Table B-2: % Difference between Dilution Ratio by Carbon Dioxide and Nitrogen Oxides..... B-4
Table B-3: Detector Method and Concentration Ranges for Horiba PG-250............ B-7
Table B-4: Quality Specifications for the Horiba PG-250............ B-7
Table B-5: Measuring Particulate by ISO and CE-CERT Methods B-8
Table C-1: ULSD Gas Phase Emission Raw Data and Analysis C-1
Table C-2: 50/50 ULSD/Algal Biofuel Gas Phase Emission Raw Data and Analysis............ C-2
Table C-3: ULSD PM phase emissions raw data and analysis C-4
Table C-4: 50/50 ULSD/ALGAL PM phase emissions raw data and analysis C-6
Table C-5: Pre and Post Calibration of Horiba PG 250............ C-9

Executive Summary

Background: The United States Department of Transportation (U. S. DOT) / Maritime Administration, and the University of California, Riverside worked jointly with the Great Lakes Maritime Academy to study the impact of switching from Ultra Low Sulfur Diesel (ULSD) to a 50/50 blend of ULSD/Algal Biofuel. Many areas in the world are examining the use of alternative fuels as a replacement fuel to petroleum-derived fuel and to reduce emissions of gaseous and particulate matter which is harmful to health and/or the environment. The U. S. DOT / Maritime Administration is interested in assessing the impacts and operational consequences of switching to bio-based fuels.

Approach: The team decided to take a direct hands-on approach to determine the benefits of switching from ULSD to a 50/50 blend of ULSD/Algal Biofuel. The approach required a vessel for the test platform and the Great Lakes Maritime Academy provided a vessel representative of many U. S. DOT vessels that operate throughout inland and ocean waters of the United States. Testing took place as the vessel, T/S State of Michigan, operated on Lake Michigan. Sampling of the actual in-use emissions of gases (CO_2, CO, and NO_x) and particulate matter ($PM_{2.5}$) mass from one of the main generator engines was in compliance with the ISO 8178-2 protocol while the engine operating conditions followed the ISO 8178-4 D2 certification test cycle.

Results The gaseous and PM emissions were measured in triplicate for each of the five modes of the ISO 8178-4 D2 test cycle. For each fuel the emission measurements began when the engine was in stable operation at its maximum load (~100%). The load was then progressively reduced to ~75%, ~50%, ~25%, and ~10% and as stable operation was obtained the emissions were measured. This procedure was repeated until we had three emission measurements for each engine load. The goal of the project was to measure the changes brought about by switching from a ULSD to a 50/50 blend of ULSD/Algal Biofuel. The 50/50 blend had weighted emissions of NO_x, CO, and CO_2 that were 10%, 18%, and 5% lower than the emissions from the ULSD. Fuel switching also caused a significant reduction, up to 25%, in the weighted emissions of PM. Of the PM, the weighted EC fraction was 30% lower and the weighted OC fraction was 20% lower for the 50/50 blend relative to the ULSD. The weighted fuel consumption of the 50/50 blend was 4.5% lower than the ULSD weighted fuel consumption.

Based upon the measured amount of sulfur in the fuel the weighted emissions of SO_2 are calculated to be 0.0000 g/kW-hr. Based upon the regulated maximum content of sulfur in ULSD the maximum weighted emissions of SO_2 are calculated to be 0.0082 g/kW-hr. Assuming the algal biofuel has 0 sulfur the maximum weighted emissions of SO_2 for the 50/50 blend are calculated to be 0.0039 g/kW-hr

Conclusion: A 50/50 blend of ULSD/Algal Biofuel produces lower measured emissions of NO_x, CO, CO_2, PM, EC and OC relative to 100% ULSD and has slightly better fuel economy. The emissions of SO_2 are 0.00 g/kW-hr.

1 Introduction

1.1 Alternative Fuels and Emission Regulations

In 2009, Secretary of the Navy Ray Mabus established a goal of increasing the Navy and Marine Corps use of alternative energy to 50 percent by 2020. As part of this initiative, Secretary Mabus also announced a goal to demonstrate a green carrier strike group operating on 50% biofuels by 2012 and to sail that green carrier strike group by 2016. All Department of Defense (DoD) tactical fuel is purchased from competitive sources via several military specifications. These specifications were developed based upon the properties of petroleum derived fuels. As new non-petroleum sources of fuel are developed, they must be fully tested to ensure that they perform similar to or better than petroleum fuels in the Navy's various propulsion systems. To address these concerns, the Navy developed a fuel qualification plan. This plan was developed with input on current petroleum properties, discussions with prime mover manufacturers and internal Navy discussions. Figure 1, shows the fuel qualification process developed by the Navy. Included in the program is testing the fuel against the current specification, testing fit for purpose (FFP) property tests made up of testing for those things important to the Navy, but not included in the specification since they always fall in the acceptable range with petroleum, component and full scale testing, and platform and field testing. These tests include compatibility with current Navy fuels and fuel logistics, material compatibility, fire fighting, and long term storage as well as many others. The goal of this process is to ensure that any new fuel will be a drop-in replacement requiring no modifications to existing infrastructure or propulsion hardware.

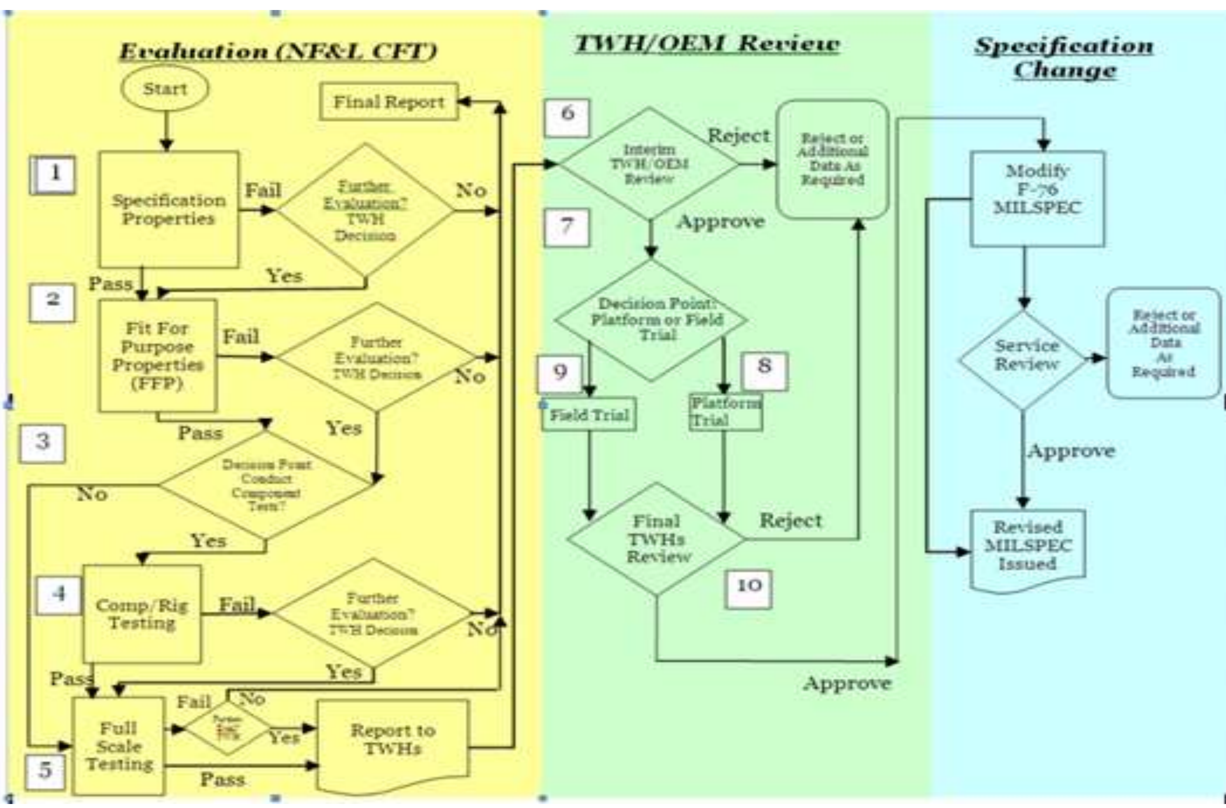

Figure 1-1: Navy Test Program Protocol

The first class of fuels being qualified for ship propulsion is hydrotreated renewable diesel (HRD) fuels. HRD derived from algal oils is being used as the representative feedstock to qualify this class of fuels. This fuel was produced to a Navy specification and was specifically designed and processed to be blended 50/50 by volume with NATO F-76 fuel which is the military diesel fuel typically used by the Navy for ship propulsion. The 50/50 blend of HRD with F-76 has already successfully completed specification, most FFP and component testing, and is currently under-going full scale engine testing and platform demonstrations.

One of the final steps in the qualification process for this renewable fuel blend is to perform platform and field testing. The Navy has begun testing on several craft and ship platforms. To further their knowledge of the fuel performance the Navy partnered with MARAD.

The U. S. Department of Transportation Maritime Administration (MARAD) has an ongoing program to evaluate alternative fuels for commercial marine fleets and as part of a cooperative effort with the U.S. Navy supported platform test of a fuel the Navy is evaluating. As part of this effort MARAD agreed to test a 50/50 blend of ULSD/Algal Biofuel in a combination of underway and pier side testing using one of the engines on their T/S State of Michigan vessel operated by the Great Lakes Maritime Academy in Traverse City, Michigan. As part of this evaluation they contracted with CE-CERT to measure the emissions and fuel economy while the engine was operated on 100% ULSD and then on 50/50 ULSD/algal Biofuel.

Emissions from engines on marine vessels are among the largest sources of uncontrolled mobile sources and present a significant health hazard to those living near the ports. Emissions from these sources, operating on the oceans, are controlled by the US Environmental Protection Agency (EPA) and the International Maritime Organization (IMO), which is an agency of the United Nations. For marine vessels operating on United States inland waterways emission regulations are enacted by the EPA.

The US EPA regulation[1] for newly manufactured engines, divides marine engines into three categories based on displacement (swept volume) per cylinder, as shown in Table 1-1. Categories 1 and 2 are further divided into subcategories, depending on displacement and net power output. The regulations are designed to substantially reduce nitrogen oxide (NO_x) and Particulate Matter (PM) emissions. Marine engines manufactured between 1973 and before the engines were subject to emission regulations may be subject to more stringent emission requirements when they are rebuilt.[2]

The engines on the T/S State of Michigan are subject to the emission requirements if they are rebuilt since they were originally manufactured in the mid 1980's.

[1] US Environmental Protection Agency (EPA), *40 Code of Federal Regulations, Part 1042 Control of Emissions*
[2] US Environmental Protection Agency (EPA), *40 Code of Federal Regulations, Part 1042, Subpart I Control of Emissions from New and In-use Marine Compression Ignition Engines and Vessels*

Category	Displacement per Cylinder (D)	
	Tier 1-2	Tier 3-4
1	$D < 5\ dm^3$†	$D < 7\ dm^3$
2	$5\ dm^3 \leq D < dm^3$	$7\ dm^3 \leq D < 30\ dm^3$
3	$D \geq 30\ dm^3$	

Table 1-1: Marine Engine Categories

1.2 Project Objectives

The goal of the CE-CERT portion of the project is to quantify the emissions impacts when switching from ULSD to a 50/50 blend of ULSD/Algal Biofuel. These measurements will allow quantification of the benefits of the fuel switching strategy for reducing emissions. The approach is to measure the emissions using the ISO 8178[3] guidelines and MARPOL Annex VI NO_x Technical Code for CO_2, CO, PM (2.5), NO_x, and SO_x emissions[4].

CE-CERT carried out all items in the Scope of Work on Saturday, September 10 and Sunday, September 11, 2011 as the T/S State of Michigan was operating on Lake Michigan with the test engine being operated on the test fuels loaded by MARAD onto the ship and at the specified ISO 8178-4 D2 test conditions.

[3] ISO 8178-2 & ISO 8178-4, Reciprocating internal combustion engines – Exhaust Emission measurement – Part 2: Measurement of gaseous and particulate exhaust emissions at site and Part 4: Test cycles for different engine applications, First Edition, 1996-08-15

[4] International Maritime Organization, *Annex VI of MARPOL 73/78 "Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code*".

2 Project Approach

2.1 Overview

The overall plan was designed to meet the requirements specified in the MARAD solicitation order number DTMA-91-V-2011-0251. The heart of the work was the measurement of the gaseous and particulate emissions, including: carbon oxides (CO, CO_2,), oxides of nitrogen (NO_x) and particulate matter (PM), while the chosen engine operated at the steady-state conditions specified in the Statement Of Work with ULSD and later with the 50/50 ULSD/algal Biofuel. Measurement methods were IMO and ISO compliant for both the gases and PM. The following sections provide detailed information.

2.2 In-use Emission Measurements Using IMO and ISO Methods

The project description involved simultaneous measurement of NO_x, CO, CO_2 from a marine generator engine exhaust using the in-use Simplified Measurement Methods (SMM) system that is compliant with the International Maritime Organization (IMO) NO_x Technical Code. Further, CE-CERT proposed using ISO methods to measure PM mass.

2.2.1 Test Vessel, Engine and Fuels[5]

The vessel selected for the test program is the T/S State of Michigan, which is a retired Stalwart Class (T-AGOS 1) Modified Tactical General Ocean Surveillance Ship built by Tacoma Boat. The vessel was commissioned in August 1985 as PERSISTENT (T-AGOS 6) and was struck and transferred to Great Lakes Maritime Academy in 2002 and renamed the T/S State of Michigan. The vessel is an electric drive vessel with 4 propulsion generators and two propulsion motors. In 2009-2010 the control system was upgraded and the tankage was modified during a yard period. Figure 2-1, shows the vessel. The vessel is owned by MARAD and operated by the Great Lakes Maritime Academy in Traverse City, Michigan. It is used in the training of individuals for a career in the merchant marine.

Figure 2-1: T/S State of Michigan

[5] Descriptions and Figures taken from U.S. Department of Transportation Maritime Administration (MARAD) Alternative Fuel for Marine Application Test Plan, 8/23/11 Revised DRAFT

The T/S State of Michigan has four main propulsion diesel generators that are electrically interconnected via a bus to drive two 1,600 kW propulsion motors and provide electrical power for the ship. Each propulsion diesel generator is a Caterpillar D398 Engine that is:

• 12-Cylinder, V-12, 4-Stroke Configuration
• 6.25 in bore, 8.00 in stroke, 2,945 cu in displacement (48.3 liters)
• 600 kW (800 hp) – fuel rate 47.6 gph[6]
• Turbocharged, aftercooled configuration

The Navy currently uses this engine on their remaining T-AGOS 1 Class vessels in service as well as Emergency Diesel Generator (EDG) service on some older ships in the fleet. Figure 2-2 shows the engine configuration and Figure 2-3 shows the engines as they are currently installed on the ship.

To ensure removal of any engine-to-engine variability a single engine was selected for the test. Figure 2-4 shows the propulsion system layout. During a July 2011 meeting with T/S State of Michigan operational staff, Navy, and MARAD it was determined that Ship Service Diesel Generator (SSDG) #4 would be the best candidate to perform the testing. The fuel service system is capable of being isolated to run on either service tank and can be split to operate SSDG #2 and #4 on the port service tank and SSDG #1 and #3 on the starboard service tank.

[6] Fuel rate based on fuel oil having a higher heat value (HHV) of 19,590 Btu/lb and weighing 7.076 lb/gal.

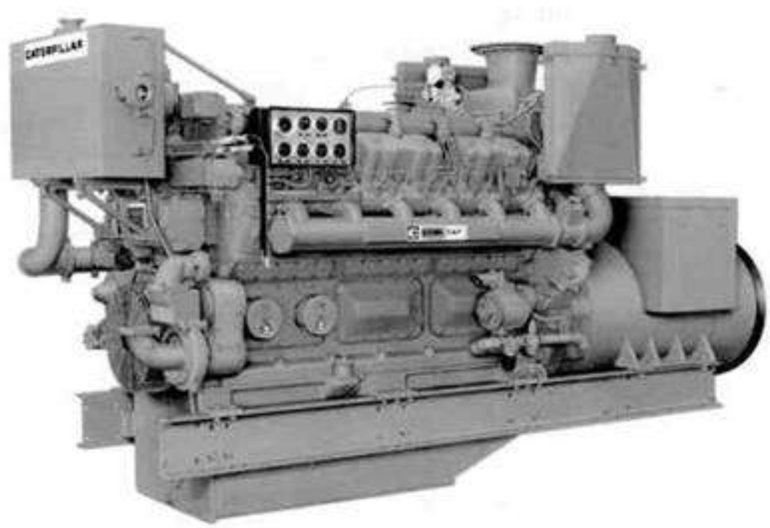

Figure 2-2: Caterpillar D398 Generator Set

Figure 2-3: T/S State of Michigan Engine Room - D398 Generator Sets

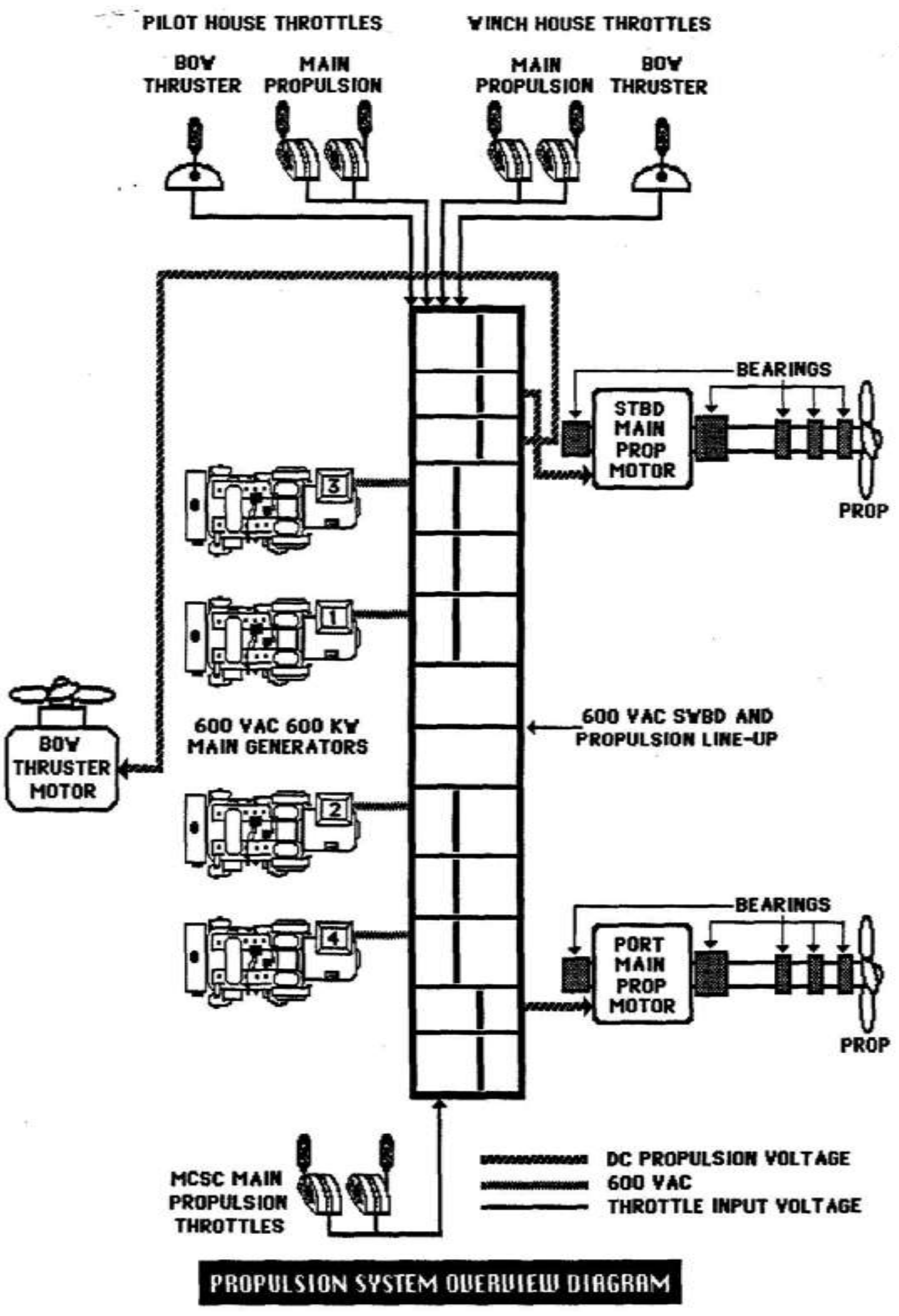

Figure 2-4: Propulsion System Layout

Appendix A discusses the ISO recommendations for selecting fuels and test cycles for different engine applications. Since this test is a Research & Development program the fuel selection is to suit the purpose of the test. Two fuels were selected for the testing. The base fuel is Ultra Low Sulfur Diesel (ULSD) which is the standard fuel used for the operation of this vessel. The second fuel was a 50/50 blend of the ULSD with an algal Biofuel. The Navy supplied the hydrotreated algal Biofuel. It was shipped from a facility in Pasadena Texas to Crystal Flash Energy, a local fuel sales company in Traverse City, Michigan. Crystal Flash blended the algal Biofuel with the ULSD and added Lubrizol 539D, a lubricity additive, in sufficient volume to meet the lubricity requirements of the blend of ULSD and algal Biofuel. Steam cleaned tank trucks were used to transport the blended fuel from Crystal Energy to the ship. Samples of the fuels were taken at various points in the distribution of the fuels and sent to the Naval Air Systems Command (NAVAIR) for testing.

2.2.2 Operating Conditions of the Engine while Measuring Emissions

The Caterpillar D398 engines on this vessel drive generators to power the electric motors which propel the vessel. Therefore the appropriate test procedure for these engines is with the engine operating according to the 5-modes of the ISO-8178-4 D2 cycle shown in Table 2-1.

Mode	1	2	3	4	5
Speed	rated speed				
Load	100%	75%	50%	25%	10%
Weighting Factor	0.05	0.25	0.3	0.3	0.1

Table 2-1: Standard Cycle for Testing Steady-Speed Engines.

For the ISO cycles, the engine is run for about 30 minutes at rated speed and the highest power possible to warm the engine and stabilize emissions. A plot or map of the peak power at each engine RPM is determined starting with the rated speed. If CE-CERT suspects the 100% load point at rated speed is unattainable, then we select the highest possible load on the engine as Mode 1.

The Emissions are measured while the engine operates according to the requirements of ISO-8178-D2. For a diesel engine the highest power mode is run first and then each mode is run in sequence The minimum time for samples is 5 minutes and if necessary, the time is extended to collect sufficient particulate sample mass or to achieve stabilization with large engines. The gaseous exhaust emission concentration values are measured and recorded for the last 3 minutes of the mode.

Engine speed, displacement, boost pressure, and intake manifold temperature are measured in order to calculate the gaseous flow rate. Emissions factors are calculated in terms of grams per kilowatt hour for each of the operating modes and fuels tested, allowing for emissions comparisons of each fuel relative to the baseline fuel.

As configured, the control system for the D398 engines only permitted each engine to operate at ~50% of their Maximum Continuous Rating (MCR) of 600 kW. However, the company that upgraded the propulsion machinery control system, Technical Marine Services, indicated that it was possible to remove this limiting function so that the engines could operate at nearly 100% MCR. Therefore MARAD had Technical Marine Service send an engineer to the ship to make this change for the emissions portion of the testing. With the change the engine operated at ~92% of the rated load while the vessel operated on Lake Michigan. The achievable load points were determined at the time of testing and depended on several factors; including constraints by current, wave pattern, and wind speed/direction. Efforts were made to conduct the emissions measurements at loads and RPM as close as possible to those specified in ISO 8178 D-2. As operated, the modes were at 92, ~81, ~61, ~27, and ~16 % of the rated speed for modes 1, 2, 3, 4, and 5, respectively.

2.2.3 Engine Performance Measurements during Testing

Chapter 6 of the NO_x Technical Code[7], "Procedures for demonstrating compliance with NO_x emission limits on board" provides detailed instructions for the required measurements for on-board testing. Some of the engine performance parameters measured or calculated for each mode during the emissions testing are shown in Table 2-2.

Parameter	Units
Load	kW
Engine Speed	RPM
Generator Output	Amps
Fuel supply	gph
Fuel return	gph
Air intake pressure	psi
Air intake temperature	°F

Table 2-2: Engine Parameters Measured and Recorded

2.2.4 Measurement of Gaseous and Particulate Matter Emissions

The emission measurements were performed using a partial dilution system that was developed based on the ISO 8178-1 protocol and detailed information is provided in Appendix B, "Measuring Gaseous & Particulate Emissions".

In measuring the gaseous and particulate emissions, CE-CERT followed ISO 8178-2 and Chapter 5 of the NO_x Technical Code as they provide the general requirements for onboard measurements. The concentrations of gases in the raw exhaust and the dilution tunnel were measured with a Horiba PG-250 portable multi-gas analyzer. The PG-250 can simultaneously measure up to five separate gas components. The signal output of the instrument is interfaced directly with a laptop computer through an RS-232C interface to record measured values continuously. However, in the present program the computer stopped functioning, apparently

[7]International Maritime Organization, Marine Environment Protection Committee: *Prevention Of Air Pollution From Ships; Report of the Working Group on Annex VI and the NOx Technical Code* (MEPC 57/Wp.7/Add.2 3) April 2008

because the EMF from the generator fried the hard drive, and thus all readings had to be recorded manually. Although the two CE-CERT personnel could have hand recorded all of the data by themselves, for efficiency two other personnel recorded data from instruments which were not within the immediate vicinity of the emission testing equipment. Since all data is obtained under steady state operating conditions hand recording the data is no problem. Major features of the PG-250 include a built-in sample conditioning system with sample pump, filters, and a thermoelectric cooler. The performance of the PG-250 was tested and verified under the U.S. Environmental Protection Agency Environmental Technology Verification (EPA ETV) program.

Emissions were measured while the engine operated at the test modes specified in ISO 8178-4, Table 2-1. The measuring equipment and calibration frequencies met IMO Standards. The details of the CE-CERT equipment are provided in Appendix B, “Measuring Gaseous & Particulate Emissions” and the calibrations are provided in Appendix C, “Raw Data, Analysis, Analysis Equations, and Calibration Data”. In addition to measuring criteria emissions, the project measured:

1. PM continuously with a monitor to check on whether the PM concentration was constant while the filters were being loaded.
2. PM mass fractionated into the elemental and organic fractions as an internal mass balance.

3 Data Analysis

After returning from the on-board measurement testing the instrument calibration and raw test data was placed in an Excel file. The calibration and raw test data was then post processed in this file to produce QC summaries and final results summaries for review by the Project Manager. The raw data, post processed data, equations for the post processing, and calibration data are in Appendix C, "Raw Data, Analysis, Analysis Equations, and Calibration Data".

3.1 Calculation of Emission Factors

The emission factors at each mode are calculated from the measured gaseous concentration, the reported engine load in kilowatts (kW) and the calculated mass flow in the exhaust. An overall single emission factor representing the engine is determined by weighting the modal data according to the ISO 8178-4 D2 requirements and summing them. The equation used for the overall emission factor is as follows:

$$A_{WM} = \frac{\sum_{i=1}^{i=n}(g_i \times WF_i)}{\sum_{i=1}^{i=n}(P_i \times WF_i)}$$

Where:

A_{WM} = Weighted mass emission level (CO, CO_2, $PM_{2.5}$, or NO_x) in g/kW-hr
g_i = Mass flow in grams per hour at the i^{th} mode,
P_i = Power measured during each mode, and
WF_i = Effective weighing factor.

3.1.1 Calculation of the Exhaust Flow Rate by ISO 8178-2

Clearly the calculated emission factor is strongly dependent on the mass flow of the exhaust. Two methods for calculating the exhaust gas mass flow and/or the combustion air consumption are described in ISO 8178-2 Appendix A[8]. Both methods are based on the measured exhaust gas concentrations and fuel usage rate. The two ISO methods are described below.

Method 1, Carbon Balance, calculates the exhaust mass flow based on the measurement of fuel usage and the exhaust gas concentrations with regard to the fuel characteristics (carbon balance method). The method is only valid for fuels without oxygen and nitrogen content, based on procedures used for EPA and ECE calculations.

Method 2, Universal, Carbon/Oxygen-balance, is used for the calculation of the exhaust mass flow. This method can be used when the fuel usage is measurable and the fuel composition and the concentration of the exhaust components are known. It is applicable for fuels containing H, C, S, O, N in known proportions.

[8] *International Standards Organization, IS0 8178-1,* Reciprocating internal combustion engines - Exhaust emission measurement -Part 2: Measurement of gaseous particulate exhaust emissions at site, *First edition 1996-08-l5*

The carbon balance methods may be used to calculate exhaust flow rate when the fuel usage is measured and the concentrations of the exhaust components are known. In these methods, flow rate is determined by balancing carbon content in the fuel to the measured carbon dioxide in the exhaust. This method can only be used when the fuel usage data are available.

3.1.2 Calculation of the Exhaust Flow Rate Assuming the Engine as an Air Pump

This method has been widely used for calculating exhaust flow rate in diesel engines, especially stationary diesel engines. This method assumes the engine is an air pump, and the flow rate is determined from displacement of the cylinder, recorded rpm, with corrections for the temperature and pressure of the inlet air. This method assumes the combustion air flow equals the total exhaust flow. However, for low-speed, two stroke engines, there could be scavenger air flow while the piston is expanding and the exhaust valve is still open. This scavenger air would not be included in the air pump calculation leading to under predicting the total exhaust flow and the emission factors. The method works best for four stroke engines or for two-stroke engines where the scavenger air flow is much smaller than the combustion air.

4 Results

This section presents the results and analysis of the measured emissions of pollutants as a function of fuel type and engine load.

4.1 Exhaust Flow Rate

We used the carbon balance method and the engine as an air pump to calculate the exhaust flow rate. There was very good agreement between the two methods as can be seen in Figure 4-1. In Figure 4-1 EFR I is the Exhaust Flow Rate by carbon balance and EFR II is the Exhaust Flow Rate by engine as air pump. Because the preferred method of calculating exhaust flow rate is the carbon balance method we will present and discuss emission factors based on EFR I only. Appendix C. "Raw Data, Analysis, Analysis Equations, and Calibration Data" contains the raw data and all calculated results based upon EFR I and EFR II.

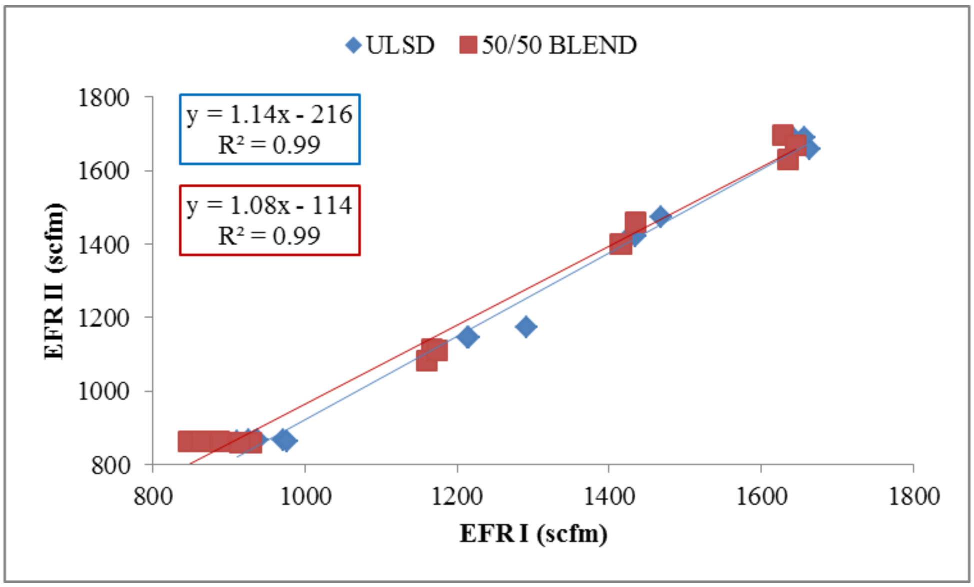

Figure 4-1: Exhaust Flow Rate by Engine as Air Pump versus by Carbon Balance

4.2 Test Fuels

Multiple samples of the ULSD and the 50/50 blend of ULSD with the algae Biofuel were analyzed by the Navy. Average results from these analyses are presented in Tables 4-1 and 4-2, respectively. The Navy highlighted in yellow those properties which were less than the minimum or more than the maximum specification.

Certificate of Analysis
T/S SOM ULSD Control Fuel
(with Lubrizol 539D)
LIMS # 11281-04190

Conformance to F-76 Chemical and Physical Properties per MIL-DTL-16884L

Test	Parameter	Method	Units	Minimum	Maximum	Petroleum Diesel (F-76)
Lubricity, HFRR	Wear Scar	D6079	µm		460	320
Appearance at 25°C		D4176	-----	Clear & Bright		Clear & Bright
Demulsification at 25°C		D1401	minutes		10	4
Density at 15°C		D4052	kg/m^3			829
Distillation	10% Recovered	D86	°C	Report		205
	50% Recovered		°C	Report		251
	90 % Recovered		°C		357	310
	End Point		°C		385	333
	Reside + Loss		Volume %		3.0	1.5
Cloud Point		D5773	°C		-1	-18
Color		D1500	-----		3	5.8
Flash Point		D93	°C	60		59
Particulate Contamination		D5452	mg/L		10	In progress
Pour Point		D5949	°C		-6	-27
Viscosity at 40°C		D445	mm^2/s	1.7	4.3	2.3
Acid Number		D974	mg KOH/g		0.30	0.05
Ash		D482	Mass %		0.005	0.001
Carbon Residue	10% Bottom	D524	Mass %		0.20	0.07
Copper Strip Corrosion at 100 °C		D130	-----		No. 3	1a
Hydrogen Content		D7171	Mass %	12.5		13.6
Ignition Quality	Cetane Index	D976	-----	40		51
Storage Stability	Total Insolubles	D5304	mg/100 mL		3.0	0.6
Sulfur Content		D4294	Mass %		0.5	0.0
Trace Metals	Ca	D7111	mg/kg		1.0	0.0
	Pb	D7111	mg/kg		0.5	0.0
	Na + K	D7111	mg/kg		1.0	0.3
	V	D7111	mg/kg		0.5	0.1

Provided by: Naval Fuels & Lubricants Cross Functional Team, AIR-4.4.5.1

Table 4-1: Average Properties of ULSD Fuel

Certificate of Analysis

T/S SOM 50% Algae HR-76/ 50% ULSD Blend

(with Lubrizol 539D)

LIMS #11289-04207

Conformance to F-76 Chemical and Physical Properties per MIL-DTL-16884L

Test	Parameter	Method	Units	Minimum	Maximum	Petroleum Diesel (F-76)
Lubricity, HFRR	Wear Scar	D6079	µm		460	310
Appearance at 25°C		D4176	-----	Clear & Bright		Clear & Bright
Demulsification at 25°C		D1401	minutes		10	3
Density at 15°C		D4052	kg/m^3			804
Distillation	10% Recovered	D86	°C	Report		218
	50% Recovered		°C	Report		270
	90 % Recovered		°C		357	297
	End Point		°C		385	320
	Reside + Loss		Volume %		3.0	1.6
Cloud Point		D5773	°C		-1	-11
Color		D1500	-----		3	4.8
Flash Point		D93	°C	60		61
Particulate Contamination		D5452	mg/L		10	1.2
Pour Point		D5949	°C		-6	-18
Viscosity at 40°C		D445	mm^2/s	1.7	4.3	2.5
Acid Number		D974	mg KOH/g		0.30	0.06
Ash		D482	Mass %		0.005	0.000
Carbon Residue	10% Bottom	D524	Mass %		0.20	0.01
Copper Strip Corrosion at 100 °C		D130	-----		No. 3	1a
Hydrogen Content		D7171	Mass %	12.5		14.1
Ignition Quality	Cetane Index	D976	-----	40		65
Storage Stability	Total Insolubles	D5304	mg/100 mL		3.0	0.2
Sulfur Content		D4294	Mass %		0.5	0.0
Trace Metals	Ca	D7111	mg/kg		1.0	0.0
	Pb	D7111	mg/kg		0.5	0.0
	Na + K	D7111	mg/kg		1.0	0.3
	V	D7111	mg/kg		0.5	0.1

Provided by: Naval Fuels & Lubricants Cross Functional Team, AIR-4.4.5.1

Table 4-2: Average Properties of 50/50 Blend of ULSD and Algae Fuel

4.3 Analysis of Emissions Factors

A key element of the test program was to measure emission from the engine with both the ULSD fuel and the 50/50 blend of ULSD and algal Biofuel. The following analysis presents the emission factors at the average of the measured loads for the ULSD and the 50/50 blend.

4.3.1 Operating Loads for the Engine when Emissions Measured

During the emission measurements, the engine was operated at load points close to those specified in ISO 8178-4 D2 with both fuels. The actual loads in Table 4-3 are typical of the type of deviation from the specified loads when trying to hit the set points while operating at sea.

Fuel	Engine					
ISO 8178-4 D2	Load (%)	100	75	50	25	10
ULSD	Load (%)	92	82	60	26	17
ULSD	Load (kW)	554	490	359	159	101
50/50 ULSD/Algal Biofuel	Load (%)	92	80	61	28	15
50/50 ULSD/Algal Biofuel	Load (kW)	551	482	368	167	91

Table 4-3: Load Points (%Load and kW) for Engine

4.3.2 Carbon Dioxide Emissions

Carbon dioxide (CO_2) emissions are checked first as these values provide insight into the accuracy and representativeness of the data. Specifically, the data are reviewed to determine if the numbers are repeatable and accurate when compared with the measured fuel consumption (FC). Values for both fuels are plotted in Figure 4-2 and are nearly linear, as expected.

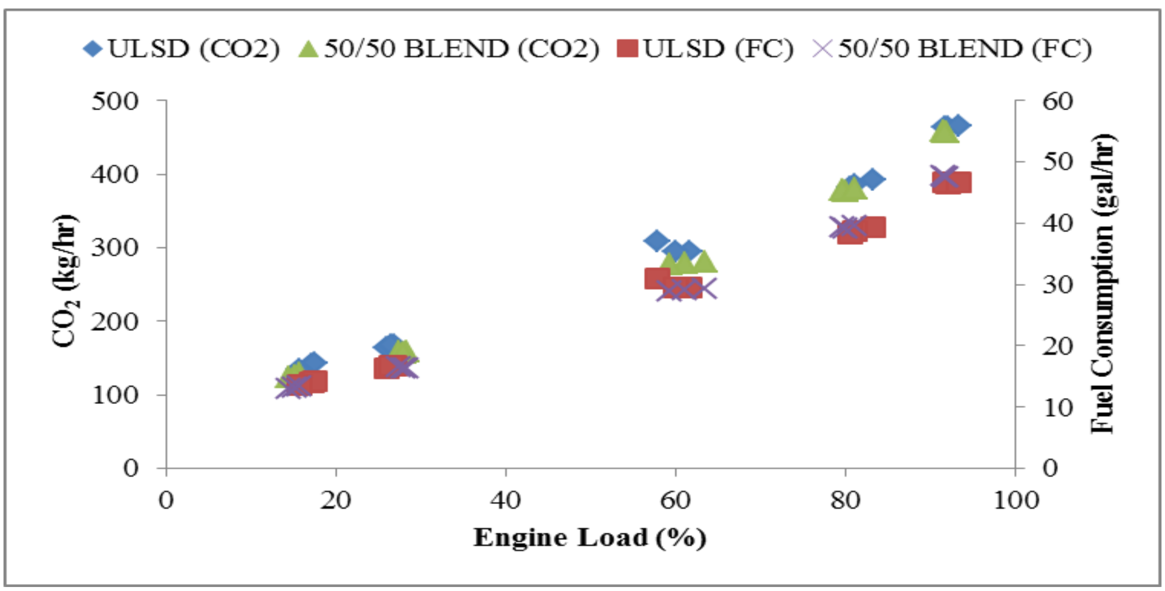

Figure 4-2: Engine Gaseous Emission Rate for CO_2 vs. Load

The CO_2 emission factors are provided in Figure 4-3. Values obtained during this project, ~ 800 g/kW-hr, are about the expected values for a medium speed diesel engine. Notice the emissions factor increases significantly as the power decreases from the 50% load point. A ~25% increase in fuel consumption when going from 50% to 25% power is similar to what we have observed before. Figure 4-4 presents these emission factors at different engine loads and includes the overall average weighted emission factor. Overall a 5% reduction in CO_2 was observed for the 50/50 blend versus the ULSD. Since 99%+ of the carbon in the fuel is converted to CO_2 a ~5% reduction in fuel consumption is expected for the 50/50 blend versus the ULSD. The Navy recently reported that the heating values of these fuels are 42.934 MJ/kg for the ULSD and 43.400 MJ/kg for the 50/50 ULSD/algal Biofuel blend. Because the blend has a higher heating value than the ULSD it is expected to have slightly better fuel economy.

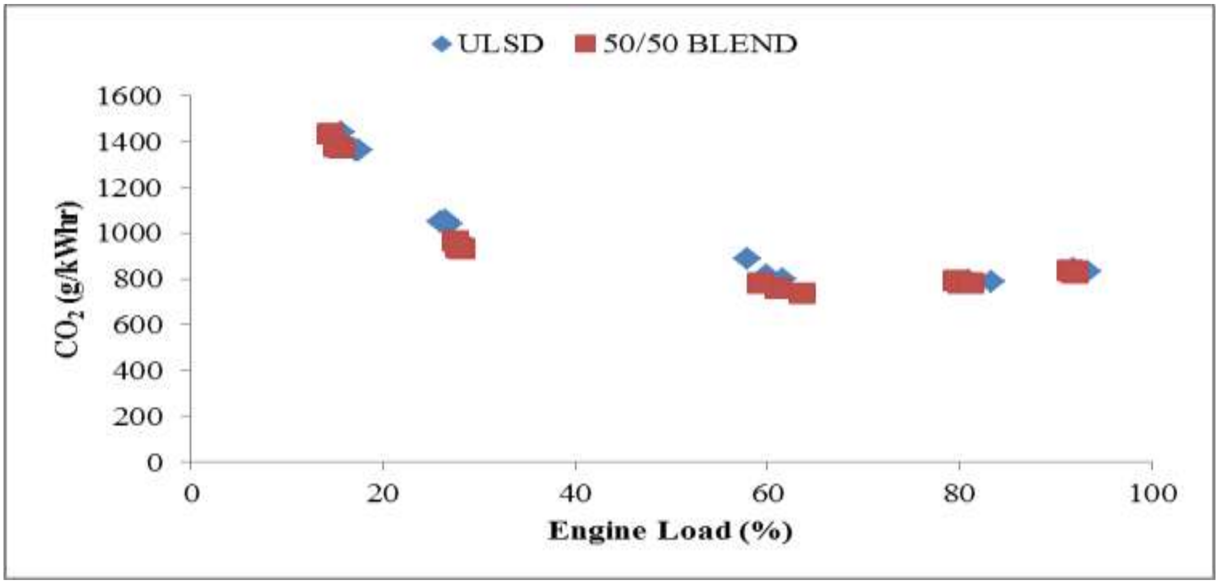

Figure 4-3: Engine Emission Factors for CO_2 vs. Load (g/kW-hr)

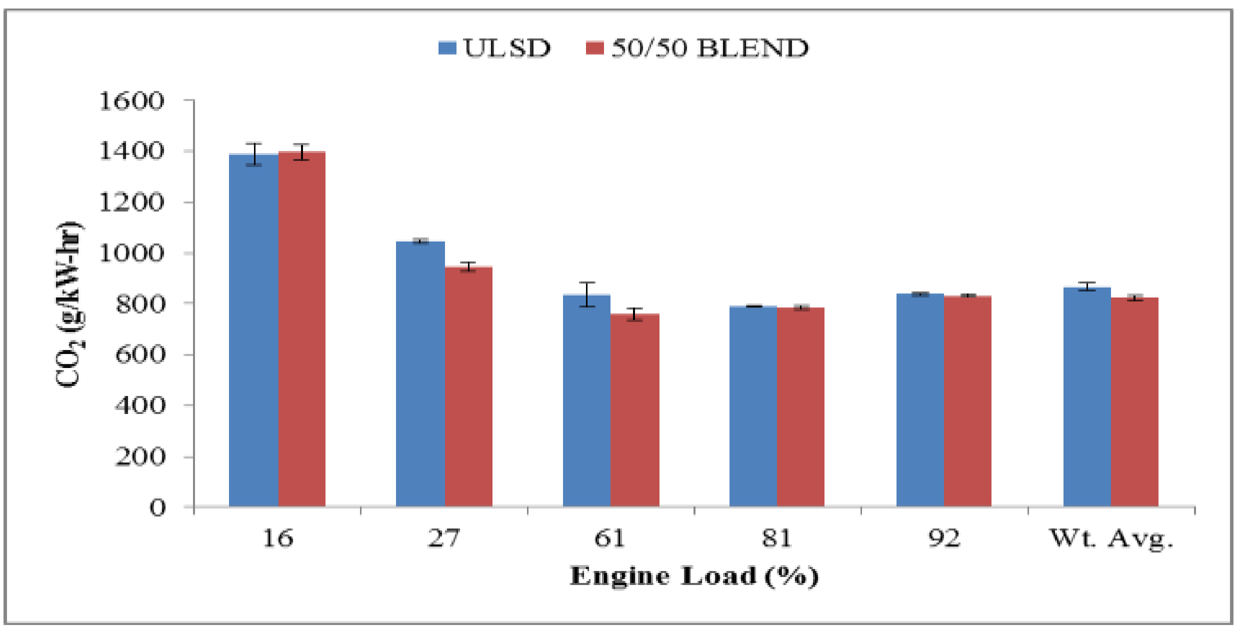

Figure 4-4: Average CO_2 Emission Factors for each mode and Overall Weighted Emission Factor

4.3.3 Quality Checks: Carbon Mass Balance: Fuel vs. Exhaust

As part of CE-CERT's QA/QC, the carbon mass balance is checked by comparing the carbon flow from the fuel with the measured carbon in the exhaust gases. Figure 4-5 shows that there is essentially a one to one comparison thus confirming the QA/QC. When forced through zero, carbon balance was within 1% for both fuels. Note that the EFR II is Exhaust Flow Rate by engine as an air pump.

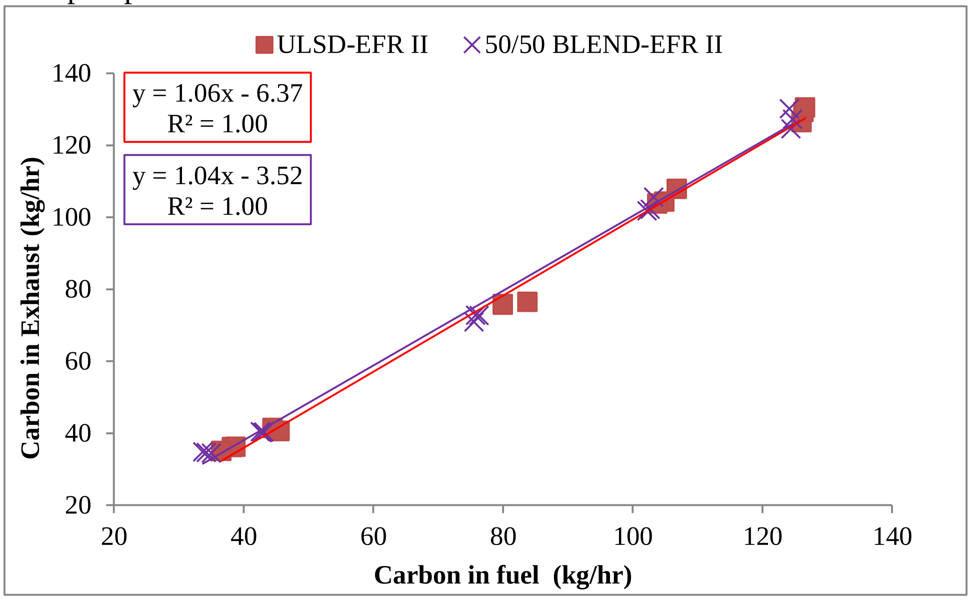

Figure 4-5: Carbon in the Exhaust versus Carbon in the Fuel

4.3.4 NO_x Emissions

NO_x emission rates and factors are the second parameters of interest in air basins that are environmentally sensitive. The gaseous emission factors for NO_x are presented in g/kW-hr in Figure 4-6. Overall a 10% reduction in NO_x emissions was observed.

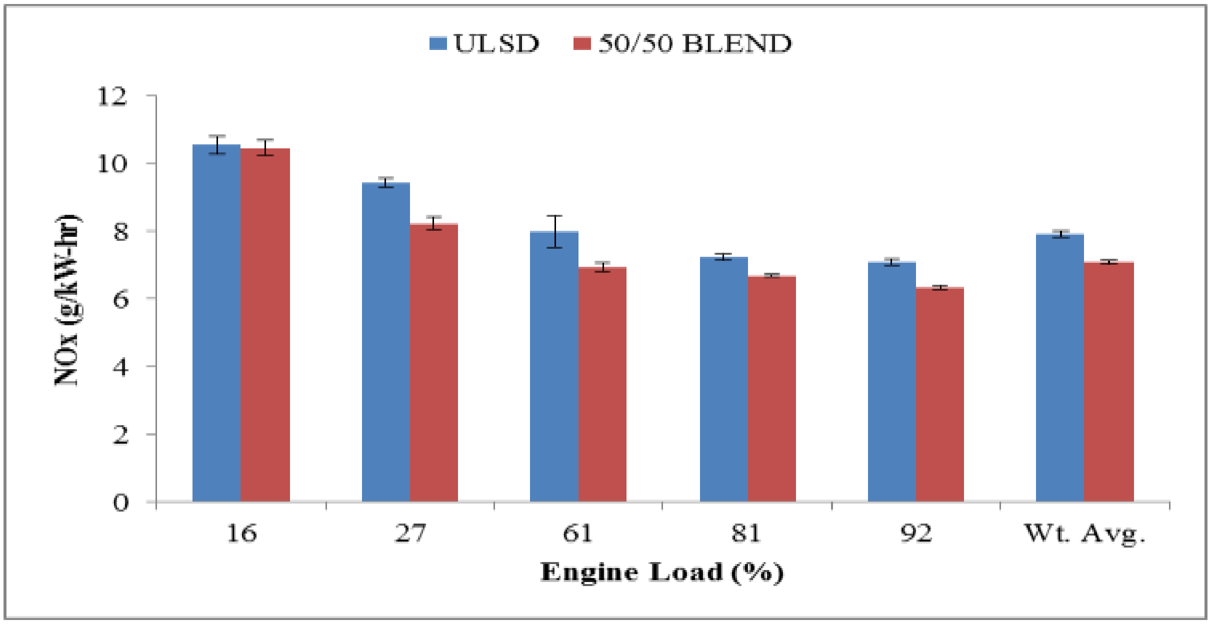

Figure 4-6: Average NO_x Emission Factors for each test mode and Overall Weighted Emission Factor

4.3.5 CO Emissions

CO emission rates and factors are presented in g/kW-hr in Figure 4-7. CO emissions were low across all load points which is typical of diesel engines. Overall a reduction of 18% was found for the 50/50 blend versus the ULSD.

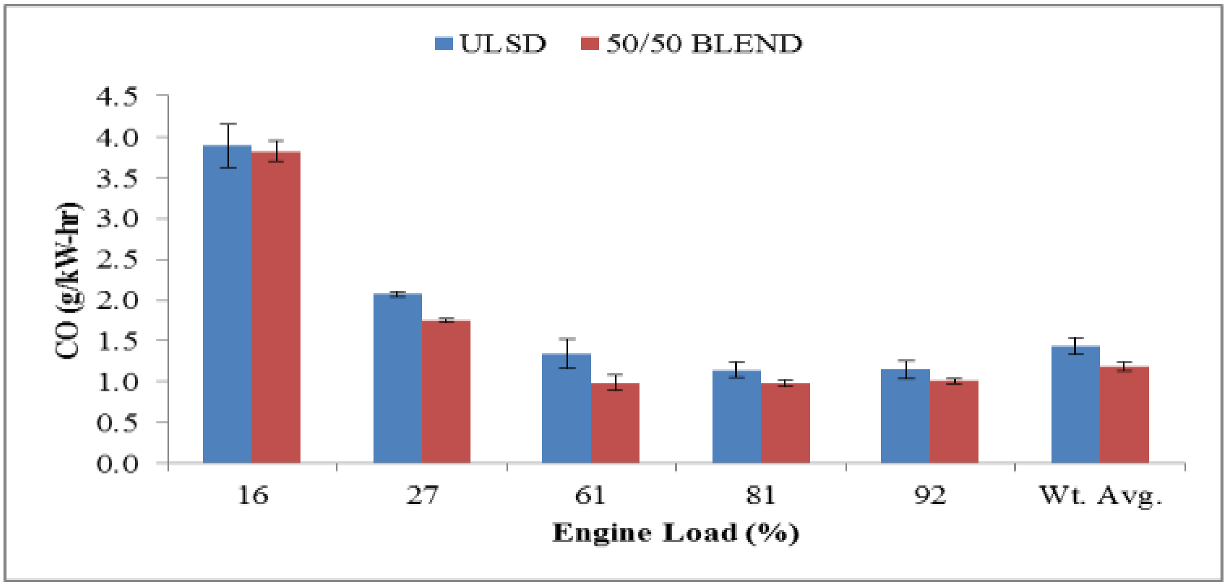

Figure 4-7: Average CO Emission Factors for each test mode and O verall Weighted Emission Factor

4.3.6 SO_2 Emissions

Sulfur oxides (SO_x) emissions are formed during the combustion process of a diesel engine from the oxidation of sulfur contained in the fuel. The emissions of SO_x are predominantly in the form of SO_2. On an average more than 95% of the fuel sulfur is converted into SO_2 and the rest is further oxidized to SO_3.and sulfate particles. Per ISO 8178-1 sulfur oxides concentrations are calculated based on the sulfur content in the fuel. The reported sulfur content for both fuels is 0.0 mass % (Table 4-1 and 4-2). The fuels used in this program were ULSD and a 50/50 blend of ULSD and algal biofuel. By regulation, ULSD has a maximum sulfur content of 15 ppm (0.0015 mass %) and algal biofuel presumably has a sulfur content of 0 ppm.

Per ISO 8178-1 the emissions of SO_2 are estimated by the following formula:

$GSO_2 = (MWSO_2/AWS)(GFuel)(GAM)(1000)$

Where:
GSO_2 = grams per hour of SO_2
$MWSO_2$ = molecular weight of SO_2 = 64.0588
AWS = Atomic weight of S = 32.06
GFuel = fuel mass flow (kg/hr)
GAM = sulfur content of fuel (m/m)

Assuming a sulfur content of 15 ppm for the ULSD and a sulfur content of 7.5 ppm for the 50/50 blend the maximum weighted emissions of SO_2 for the ULSD are 0.0080 g/bhp-hr and for the 50/50 blend they are 0.0038 g/bhp-hr.

4.3.7 Particulate Matter $PM_{2.5}$ Mass Emissions

In addition to the gaseous emissions, the test program measured emissions of the $PM_{2.5}$ mass and $PM_{2.5}$ emissions fractionated into elemental and organic carbon.

Total $PM_{2.5}$ mass emissions from both fuels are presented in g/kW-hr for all the test modes in Table 5-1 and the data is plotted in Figure 4-8. A significant overall reduction of 25% was observed for the 50/50 blend versus the ULSD. Higher reductions (up to 35%) were found at engine loads of 50% and below where the generator is typically set to run most of the time.

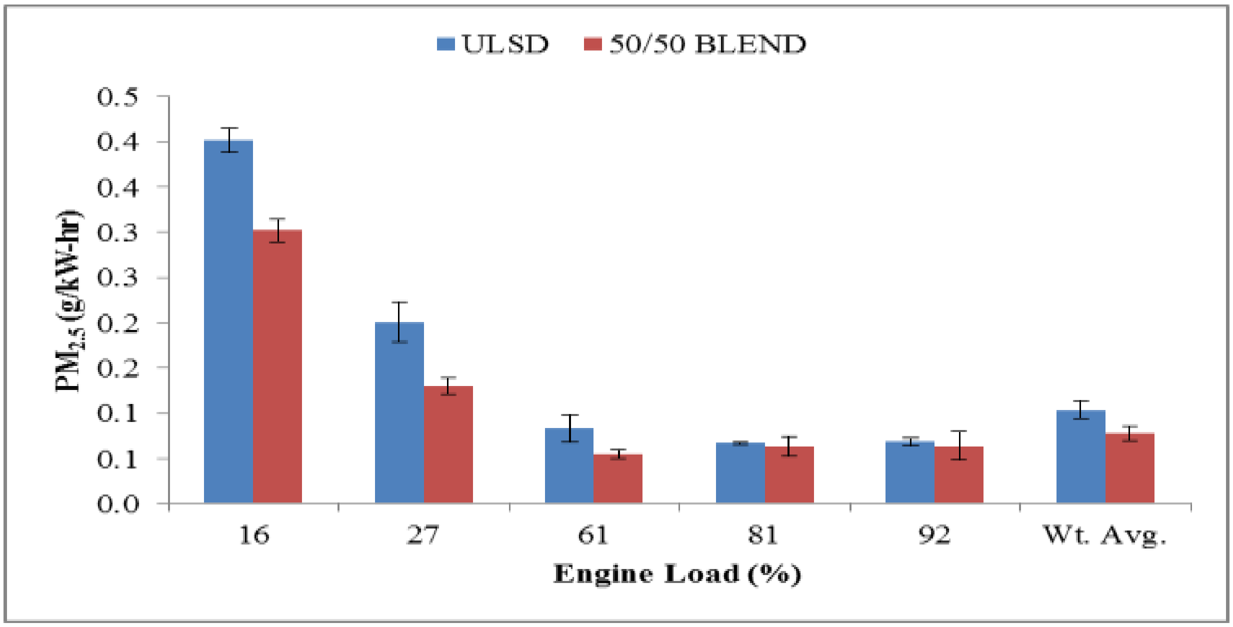

Figure 4-8: Total $PM_{2.5}$ Mass Emissions

4.3.8 PM Mass Fractionated into Elemental Carbon (EC) plus Organic Carbon (OC)

The PM mass was fractioned into elemental plus organic carbon to determine the composition of the mass. In this second measurement approach, a quartz filter captured the PM emissions from the same sample line used for the Teflon PM mass determination. The quartz filter was post processed into elemental carbon (EC) and an organic fraction (OC) of the PM. Figure 4-9 represents EC/OC measurements across all loads for both fuels. On an average the OC fraction accounts for approximately 85% of the total PM mass. The fraction of EC increases as the load increases irrespective of fuel type. As described in - Measuring Gaseous & Particulate Emissions”, $PM_{2.5}$ in the raw exhaust was sampled using a partial dilution system and the PM was collected on filter media. Simultaneous, real-time PM measurements were made using TSI’s

DusTrak. However, this data is not available because of the destruction of the hard drive of the computer. The total and speciated $PM_{2.5}$ mass emissions for both fuels across all load points, and percent reduction in elemental and organic carbon are presented in Appendix C, "Raw Data, Analysis, Analysis Equations, and Calibration Data".

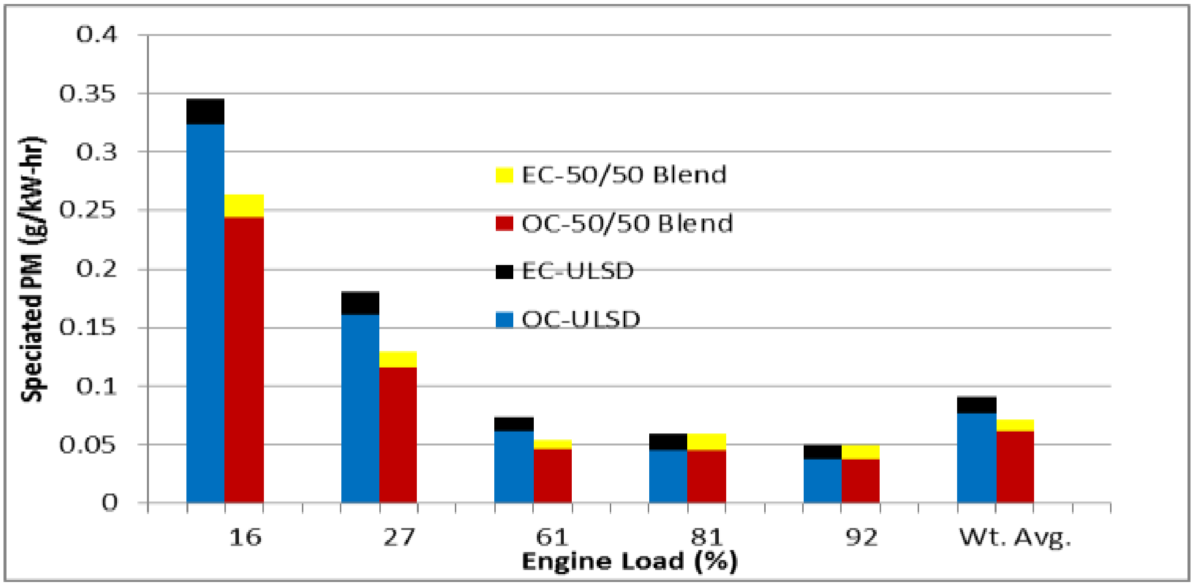

Figure 4-9: PM Mass Fractioned into Elemental & Organic Carbon

4.3.9 Quality Check: Conservation of $PM_{2.5}$ Mass Emissions

An important element of CE-CERT's field program and analysis is the QA/QC check with independent methods. For example, the total $PM_{2.5}$ mass collected on the Teflo® filter should agree with the sum of the masses independently measured as elemental carbon and organic carbon. To account for hydrogen and oxygen in the organic carbon, the organic carbon is multiplied by a factor of 1.2[9]. The plot showing the parity and the cumulative mass is provided below as Figure 4-10. Both lines are nearly linear showing good agreement between the independent methods for measuring PM.

4.3.10 Fuel consumption by Carbon Balance

Since 99+% of the carbon in the fuel is converted to CO_2 the grams of CO_2 can be used to calculate fuel consumption in g/kW-hr by multiplying the grams of CO_2 by the ratio of molecular weight of C to molecular weight of CO_2 and by 100 divided by the % of C in the fuel. The fuel consumption for both fuels across all loads is shown in Figure 4-11. Overall the fuel consumption for the 50/50 blend is 4.5% less than the ULSD.

[9] Shah, S.D., Cocker, D.R., Miller, J.W., Norbeck, J.M. Emission rates of particulate matter and elemental and organic carbon from in-use diesel engines. *Environ. Sci. & Technology*, **2004**, 38 (9), pp 2544-2550.

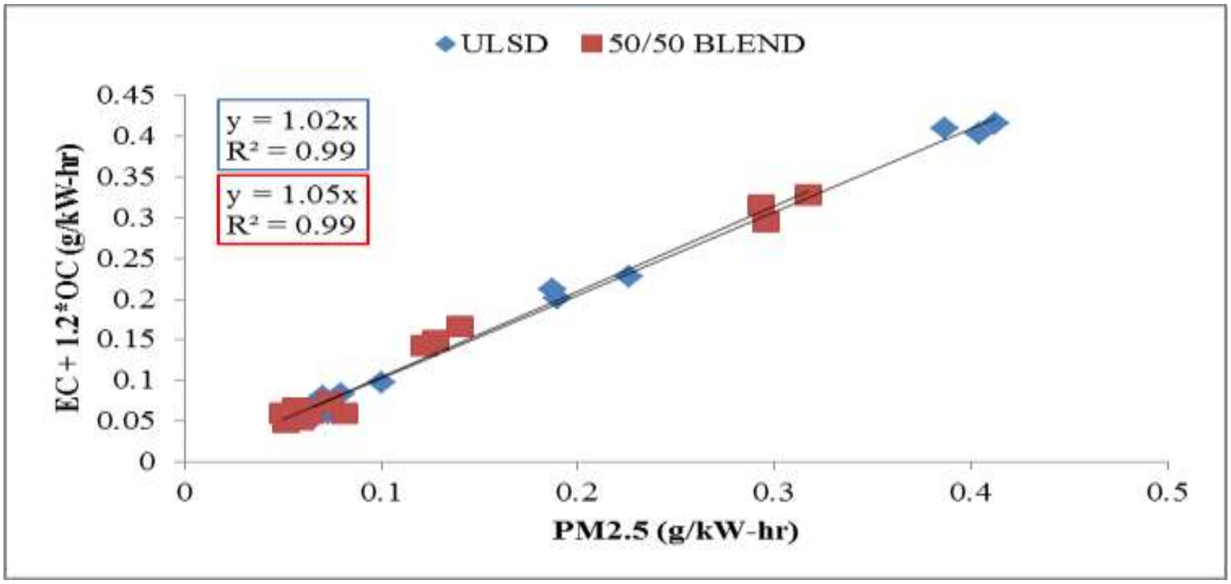

Figure 4-10: Comparison of Mass on Teflon Filter & Cumulative Mass from Quartz Filter

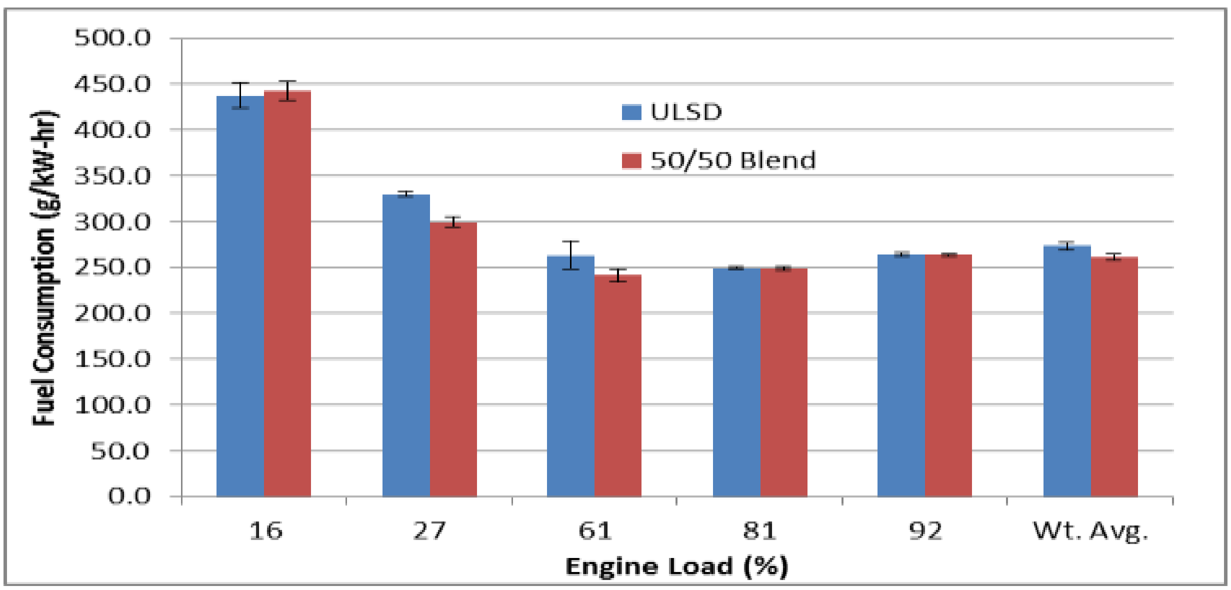

Figure 4-11: Fuel Consumption as a Function of Engine Load

5 Discussion

A primary objective for the CE-CERT portion of this project was to determine the effect on emission factors by switching from ULSD to the 50/50 blend of ULSD and algal Biofuel. Modal and weighted emission factors for NO_x, CO, CO_2, $PM_{2.5}$, EC and OC from both fuels are provided in table 5-1. Based on the average results the percentage reductions for the gaseous and particulate emissions for the individual modes and the overall weighted emissions are shown in Figure 5-1. With the exception of CO_2 at 16% engine load and OC at 92% engine load all pollutants show a reduction by the 50/50 blend relative to the ULSD. However, based on the overlap of the standard deviations for the averages the reductions are not statistically significant at engine loads of 81 and 92% for CO_2, $PM_{2.5}$, EC, and OC. At an engine load of 16% the reductions are not statistically significant for NO_x, CO, CO_2, and EC. At all other engine loads, and for the weight average load, the reductions are statistically significant.

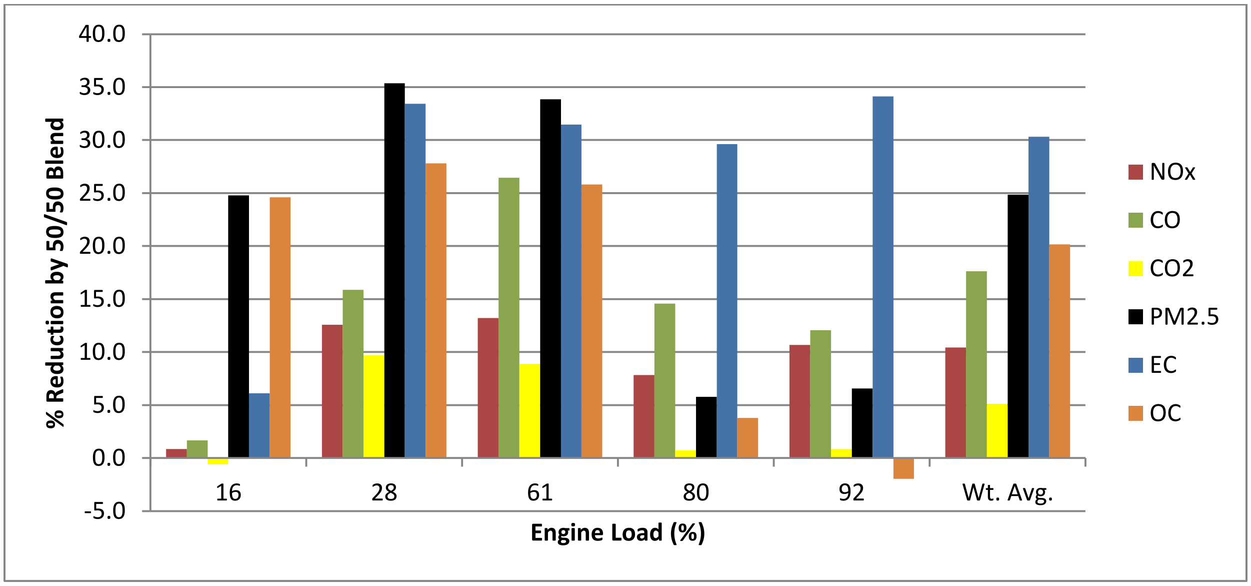

Figure 5-1: %Reduction in Pollutants by the 50/50 Blend

A secondary objective of the CE-CERT portion of this program was to determine the effect on fuel consumption by switching from ULSD to the 50/50 blend of ULSD and algal Biofuel. Table 5-2 summarizes the percentage reduction of fuel consumption for the 50/50 blend versus the ULSD. Based on the average results, the percentage reductions in the fuel consumption for the individual modes and the overall weighted emissions are shown in Figure 5-2. Based on the overlap of the standard deviations for the averages the reductions are not statistically significant at engine loads of 16, 81 and 92%. They are statistically significant at engine loads of 28 and 61%, and for the overall weighted average.

With the exception of the $PM_{2.5}$ and OC, the emissions and the fuel consumption show little differences between the ULSD and the 50/50 blend at very light loads such as 16% of maximum engine load. With the exception of CO and NO_x the emissions and the fuel consumption show little differences between the ULSD and the 50/50 blend at heavy loads such as 80 and 92% of maximum engine load. The ISO 8178 D2 cycle, which was developed based upon normal in-use engine operation, indicates that 85% of the time the engine operation is in the range of 25% to 75% of the maximum engine load. Therefore it is reasonable to expect that the weighted average results, and the percentage reduction of the weighted average results, for the 50/50 blend relative to the ULSD is applicable to generator engines which operate primarily in this engine load region. Clearly, the majority of the fuel benefits are for intermediate loads where the engine spends a significant amount of time under normal operation conditions. However, to more accurately quantify actual fuel benefits over a period of time, in-use engine activity data has to be determined and then be coupled with the emission factors measured in this study.

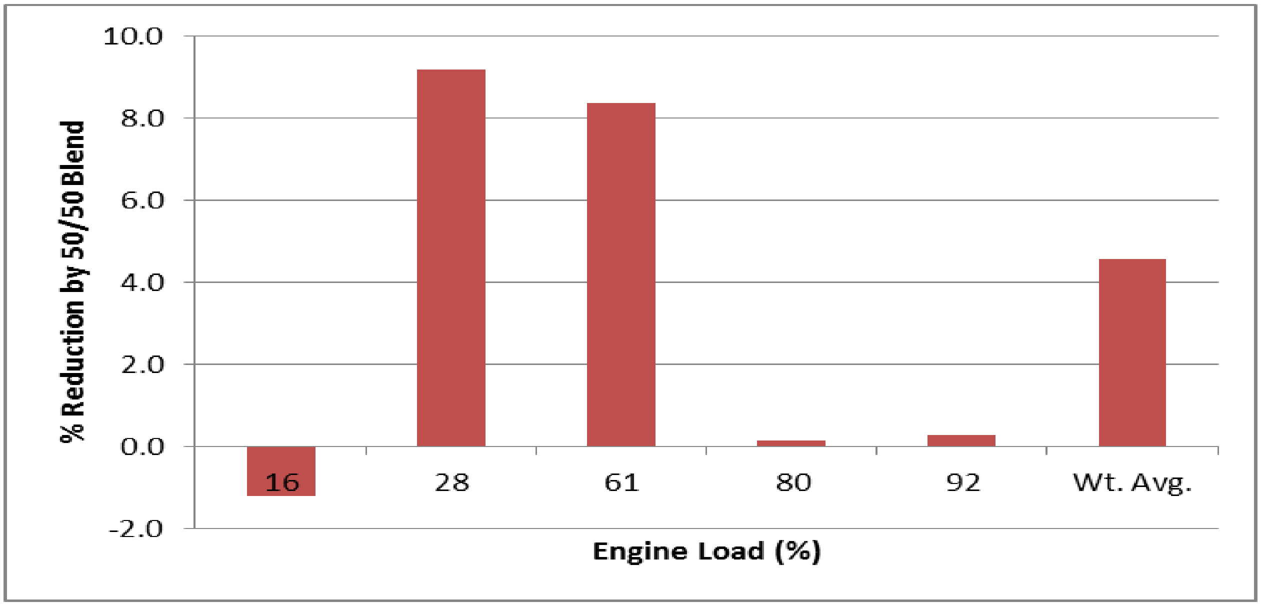

Figure 5-2: % Reduction in Fuel Consumption by the 50/50 Blend

As noted above, most of the significant reduction in gaseous and particulate emissions on switching from ULSD (B0) to50/50 blend of ULSD and algal biofuel (B50) were observed at 28% and 61% loads. At 16% engine load, significant reduction up to 25% was observed for $PM_{2.5}$ whereas no significant reduction was observed for gaseous emissions. This trend of emissions reductions as a function of load is similar to those seen in other marine test campaigns with biodiesel fuel.[12-14] The Tier 1 engine had overall weighted average NO_x emission factors using ULSD and 50/50 blend of 7.8 and 7.2 g/kW-hr, respectively. This is compared to the MARPOL Annex VI NOx emission limit for a 600 kW engine of 12.2 g/kW-hr. In terms of overall weighted NO_x and $PM_{2.5}$ emission factors, the engine is comparable to similar sized off-road and marine applications.[12-14]

Quantification of trade-off between NO_x and PM from diesel engines has always been challenging for researchers. Most of studies[1-11] on biodiesel fuels focus on engine/chassis dynamometer tests of on-road engines operating predominantly on transient cycles. These studies show an increase in NO_x (-5.9% to 6.6% for B20 and 2%-17% for B50) emissions and large reductions in CO (3-30% for B20 and 18-40% for B50) and PM (4-37% for B20 and 4-63% for B50) mass emissions relative to petroleum diesel. Research on biodiesel effects on marine diesel engines is limited. Roskilly et. al.[12] found reductions in NO_x up to ~24% and ~3% increase in CO_2 emissions from small marine craft diesel engines (21.3 and 38 kW) on consuming B100 (recycled cooking fat and vegetable oil). In a more comparable study[13] with maximum engine power of 500 hp on a ferry consuming B50 blend of soy-based biodiesel and ULSD, Jayaram et. al., found 7% and 25% reduction in CO and $PM_{2.5}$, respectively, with no significant change in NO_x emissions. A recent study[14] on a one cylinder 400 kW marine diesel engine found NO_x as well as PM emissions to be similar for low-sulfur fossil fuels and biogenic fuels (Petzold et. al.).

Previous studies[15-16] have shown trends of decreasing NO_x emissions with increasing cetane index for both diesel and biodiesel fuels. Fuels with higher cetane index have shorter ignition delays, providing more time for the fuel combustion process to be completed. Density is another fuel property that has been shown to impact NO_x emissions. Higher densities have been correlated with higher NO_x emissions for both diesel and biodiesel fuels.

An extensive study of biodiesels was carried out for the Naval Facilities Engineering Command by Jack, et. al.[17] The study involved 5 fuels: an ULSD, JP-8, a soy based diesel, and two yellow grease based biodiesels identified as YGA and YGB. The biodiesels were tested at the 20%, 50%, 70%, and 100% levels. Ten different diesel engine types were used in the study but not all fuels were tested in every engine. The engines included a 5.9L Cummins in a Thomas Bus, a GM 6.5L Model A2 in a Humvee, a GM 6.2L Model A1 M998 in a Humvee, a Cummins C6 3.9L in a Harlan Aircraft Tug, a Cummins 5.9L 175 HP in a Stake Truck, Ford F700 Series, a Caterpillar 3406C in a Tractor, Ford L-9000, a Perkins 2.6L -55 HP in a Hyster 65 Forklift Model H65XM, a Navistar 7.3L in a Ford F-350 Pickup, a Caterpillar 3126 330 HP in a Thomas Bus, a Kamatzu SA60125E-2 Portable 250 KW Generator, and a Lippy MEP-806A 60 KW Tactical Generator. "The project results for the regulated emissions were that at the B20 level, there were no consistent trends over all applications tested. Within the context of the test matrix, no differences were found between the different YGA, YGB, and soy-based biodiesel feedstocks. The results of more extensive statistical analyses also indicated no statistically significant differences in CO, HC, NOx and PM emissions between the B20-YGA and the ULSD." "Thus the air pollution performance objectives outlined in the project's demonstration plan were not met. Although these results were not expected, they are not necessarily a disappointment since the baseline USLD fuel proved to be greatly superior to existing on-road Diesel No. 2." Because of the more extensive processing to produce ULSD, relative to higher sulfur diesel, ULSD tends to have a lower aromatic content, a lower density, and a higher cetane index and cetane number. All of these factors tend to produce lower emissions of NO_x, CO, and $PM_{2.5}$, relative to higher sulfur diesel fuel.

In the current study, the ULSD had a high cetane index and a density near the minimum for a No. 2 diesel. The 50/50 blend of ULSD and algal fuel had a cetane index 14 numbers higher than the ULSD and a density well into the range of No. 1 diesel (Table 4-2 and 4-3). Although aromatic content was not directly measured the cetane index and density are indicative of the aromatic content being considerably lower than for higher sulfur number 2 diesel fuel. Based on the density and cetane index of the 50/50 blend its aromatic content is less than the ULSD. Aromatic content in the fuel contributes to incomplete fuel oxidation in the locally fuel rich zones which leads to the formation of carbon monoxide and $PM_{2.5}$. These factors lead one to expect lower emissions from the 50/50 blend relative to the ULSD and the measurements for the

600 kW engine on the T/S State of Michigan clearly shows that on consuming a blend of ULSD and algal fuel, an overall reduction of ~10% and ~25% can be achieved for NO_x and $PM_{2.5}$, respectively.

There were a few issues encountered during field testing that merit discussion. The location of the sampling port was approximately three (3) duct diameters downstream of the turbocharger outlet. Ideally, the sample port would be located at least eight (8) duct diameters downstream of any flow disturbance. The geometry of the engine room layout made it impractical to locate the sample port at the ideal location. The location chosen, however, did meet the minimum requirement of at least two (2) diameters downstream of any flow disturbance. There were differences between the target engine load points and actual load points (Table 4-1). This is typical of variances seen in engine loads when trying to achieve a specific operating mode on a vessel at sea. As emission factors for NO_x and $PM_{2.5}$ are fairly flat across the mid-load operating range for diesel engines, the impact on the results is minimal. Finally, the data acquisition computer failed prior to sampling. Therefore, instrument readings were acquired manually in a laboratory log book. A minimum of six (6) readings were obtained from all engine operating and emissions instrumentation at each mode point. As the samples are collected at steady-state mode points, the impact of the computer failure on results is minimal. The major effect is that the standard deviations are greater than they would have been if the computer had continued to function simply because there would have been more values to average.

Emissions from ULSD and a 50/50 Blend of ULSD/Algal Biofuel

Engine Mode	Engine Load (ULSD)	Engine Load (50/50 Blend)	Emission Factors (ULSD)						Emission Factors (50/50 Blend)						% Reduction					
			NO_X	CO	CO_2	$PM_{2.5}$	EC	OC	NO_X	CO	CO_2	$PM_{2.5}$	EC	OC	NO_X	CO	CO_2	$PM_{2.5}$	EC	OC
	(%)	(%)	g/kW-hr						g/kW-hr											
100	92	92	7.1	1.15	838	0.068	0.011	0.038	6.3	1.01	831	0.064	0.008	0.039	10.68	12.05	0.85	6.57	34.13	-1.96
75	82	80	7.2	1.15	790	0.067	0.014	0.046	6.7	0.98	784	0.063	0.010	0.044	7.84	14.56	0.73	5.79	29.61	3.78
50	60	61	8.0	1.34	834	0.083	0.012	0.062	6.9	0.99	760	0.055	0.008	0.046	13.22	26.46	8.89	33.85	31.47	25.82
25	26	28	9.4	2.07	1046	0.201	0.020	0.161	8.2	1.74	944	0.130	0.013	0.117	12.57	15.87	9.70	35.35	33.43	27.80
10	17	15	10.5	3.89	1387	0.401	0.021	0.324	10.5	3.83	1396	0.302	0.020	0.244	0.85	1.68	-0.61	24.78	6.12	24.59
Average Weighted Emission Factors			7.9	1.44	866	0.104	0.014	0.077	7.1	1.19	822	0.078	0.010	0.061	10.44	17.61	5.09	24.85	30.33	20.16

Table 5-1: Gaseous Emission Factors (EF's) and %Reduction by 50/50 Blend versus ULSD

Engine Mode	Engine Load (ULSD)	Engine Load (50/50 Blend)	Fuel Consump-tion (ULSD)	Fuel Consump-tion (50/50 Blend)	% Reduction
	(%)	(%)	g/kW-hr	g/kW-hr	
100	92	92	265	264	0.3%
75	82	80	249	249	0.2%
50	60	61	263	241	8.4%
25	26	28	330	300	9.2%
10	17	15	438	443	-1.2%
Average Weighted Fuel Consumption			273	261	4.5%

Table 5-2: Fuel Consumption and %Reduction by 50/50 Blend

6 Conclusions

Based upon the ISO 8178-4 D2 cycle the 50/50 blend of ULSD/Algal Biofuel produces lower measured average weighted emissions of NO_x, CO, CO_2, $PM_{2.5}$, EC, and OC relative to 100% ULSD. The 50/50 blend also had lower weighted average fuel consumption (4.5%) relative to 100% ULSD.

- The overall reduction of ~10% in NO_x emissions is mostly attributed to higher cetane index and lower density of the 50/50 blend.
- The significant reduction up to 25% in $PM_{2.5}$ is attributed to the higher cetane index and lower density of the 50/50 blend relative to the ULSD.
- The CO emission reductions of ~18% are attributed to the higher cetane index of the 50/50 blend. Higher cetane index promotes shorter ignition delay and more time for the fuel combustion process.
- The emission benefits and fuel consumption benefits are at their maximum value at the engine loads where the engine operates the majority of the time.
- The weighted average emission reduction of EC is 30%.
- The weight average emission reduction of OC is 20%.
- The amount of OC fraction (78-94%) in the total PM (EC+OC) was predominant for both fuels. Although EC and OC emission factors increased with decrease in load for both fuels, only the EC fraction of the total PM decreased with decrease in load whereas OC fraction increased.

7 References

1. McCormick, R.L.; Tennant, C.J.; Hayes, R.R., Regulated Emissions from Biodiesel Tested in Heavy-Duty Engines Meeting 2004 Emission Standards. Society of Automotive Engineers 2005, SAE 2005-01-2200.
2. Sze, C.; Whinihan, J.K.; Olson, B.A.; Schenk, C.R., Impact of Test Cycle and Biodiesel Concentration on Emissions. Society of Automotive Engineers 2007, SAE 2007-01-4040.
3. McCormick, R.L.; Williams, A.; Ireland, J., Effects of Biodiesel Blends on Vehicle Emissions. National Renewable Energy Laboratory 2006, NREL/MP-540-40554.
4. U.S. Environmental Protection Agency, A comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions. Draft Technical Report 2002, EPA420-P-02-001.
5. Sharp, C.A.; Howell, S.A.; Jobe, J., The effect of Biodiesel Fuels on Transient Emissions from Modern Diesel Engines, Part I Regulated Emissions and Performance. Society of Automotive Engineers 2000, SAE 2000-01-1967.
6. Graboski, M.S.; Ross, J.D.; McCormick, R.L., Transient Emissions from No. 2 Diesel and Biodiesel Blends in a DDC Series 60 Engine. Society of Automotive Engineers 1996, SAE 961166.
7. Schumacher, L.G.; Borgelt, S.C., Fosseen, D., Heavy-duty engine exhaust emission tests using methyl ester soybean oil/diesel fuel blends. Bioresour. Technology. 1996, 57(1), 31-36.
8. Alam, M.; Song, J.; Acharya, R., Combustion and Emissions Performance of Low Sulfur, Ultra Sulfur and Biodiesel Blends in a DI Diesel Engine. Society of Automotive Engineers 2004, SAE 2004-01-3024.
9. Cheng, A.S.; Buchholz, B.A.; Dibble, R.W., Isotopic Tracing of Fuel Carbon in the Emissions of a Compression-Ignition Engine Fueled with Biodiesel Blends. Society of Automotive Engineers 2003, SAE 2003-01-2282.
10. Durbin, T.D.; Cocker, D.R.; Sawant, A.A., Regulated Emissions from Biodiesel Fuels from on/off-road Applications. Atmospheric Environment. 2007, 41 (27), 5647-5658.
11. Eckerle, W.A.; Lyford-Pike, E.J.; Stanton, D.W., Effects of Methyl Ester Biodiesel Blends on NOx Emissions. Society of Automotive Engineers 2008-01-0078.
12. Roskilly A. P.; Nanda, S.K.; Wang, Y.D., The Performance and the Gaseous Emissions of Two Small Marine Craft Diesel Engines Fuelled with Biodiesel. Appl. Therm. Eng. 2008, 28 (8-9), 872-880.
13. Jayaram, V.; Agrawal, H.; Welch, W.A.; Miller, J.W.; Cocker, D.R., Real-Time Gaseous, PM and Ultrafine Particle Emissions from a Modern Engine Operating on Biodiesel. Environmental Science and Technology, 2011, 45, 2286-2292.
14. Petzold, A.; Lauer, P.; Fritsche, U., Operation of Marine Diesel Engines on Biogenic Fuels: Modification of Emissions and Resulting Climate Effects. Environmental Science and Technology, 2011.
15. McCormick, R.L.; Graboski, M.S.; Alleman, T.L., Impact of Biodiesel Source Material and Chemical Structure on Emissions of Criteria Pollutants from a Heavy-Duty Engine. Environmental Science and Technology, 2001, 35, 1742-1747.
16. Graboski, M.S.; McCormick, R.L., Combustion of Fat and Vegetable Oil Derived Fuels in Diesel Engines. Progress in Energy and Combustion Science 1998, 24, 125-164.
17. Holden, B., Jack, J., Miller, W., Durbin, T., Effect of Biodiesel on Diesel Engine Nitrogen Oxide and Other Regulated Emissions, Technical Report TR-2275-ENV, Project No. WP-0308, Navel Facilities Engineering Command, May 2006

Appendix A - Test Cycles and Fuels for Different Engine Applications

A.1 Introduction

Engines for off-road use are made in a much wider range of power output and used in more applications than engines for on-road use. The objective of IS0 8178-4[10] is to provide the minimum number of test cycles by grouping applications with similar engine operating characteristics. IS0 8178-4 specifies the test cycles while measuring the gaseous and particulate exhaust emissions from reciprocating internal combustion (RIC) engines coupled to a dynamometer or at the site. The tests are carried out under steady-state operation using test cycles representative of given applications. Table A-1 gives definitions used throughout ISO 8178-4.

Test cycle	A sequence of engine test modes each with defined speed, torque and weighting factor, where the weighting factors only apply if the test results are expressed in g/kWh.
Preconditioning the engine	1) Warming the engine at the rated power to stabilize the engine parameters and protect the measurements against deposits in the exhaust system. 2) Period between test modes which has been included to minimize point-to-point influences.
Mode	An engine operating point characterized by a speed and a torque.
Mode length	The time between leaving the speed and/or torque of the previous mode or the preconditioning phase and the beginning of the following mode. It includes the time during which speed and/or torque are changed and the stabilization at the beginning of each mode.
Rated speed	Speed declared by engine manufacturer where the rated power is delivered.
Intermediate speed	Speed declared by the manufacturer, taking into account the requirements of ISO 8178-4 clause 6.

Table A-1: Definitions Used Throughout ISO 8178-4

A.2 Constant speed

For engines designed to operate at a constant speed, such as generator sets with intermittent load, the torque figures, with the engine operating at rated speed, are percentage values of the torque corresponding to the prime power rating as defined in ISO 8528-1[11].

[10] International Standards Organization, IS0 8178-4, Reciprocating internal combustion engines - Exhaust emission measurement - Part 4: Test cycles for different engine applications, First edition IS0 8178-4:1996(E)

[11] International Standards Organization, IS0 8528-1:2005, Reciprocating internal combustion engine driven alternating current generating sets -- Part 1: Application, ratings and performance

A.3 Modes and Weighting Factors for Test Cycles

The combined table of modes and weighting factors is shown in Table A-2. Most test cycles were derived from the 13-mode steady state test cycle (UN-ECE R49). Apart from the test modes of cycles E3, E4 and E5, which are calculated from propeller curves, the test modes of the other cycles can be combined into a universal cycle (B) with emissions values calculated using the appropriate weighting factors. Each test shall be performed in the given sequence with a minimum test mode length of 10 minutes or enough to collect sufficient particulate sample mass. The mode length shall be recorded and reported and the gaseous exhaust emission concentration values shall be measured and recorded for the last 3 min of the mode. The completion of particulate sampling ends with the completion of the gaseous emission measurement and shall not commence before engine stabilization, as defined by the manufacturer.

A.4 Test Fuels

Fuel characteristics influence engine emissions so ISO 8178-2 provides guidance on the characteristics of the test fuel. Where fuels designated as reference fuels in IS0 8178-5 are used, the reference code and the analysis of the fuel shall be provided. For all other fuels the characteristics to be recorded are those listed in the appropriate universal data sheets in IS0 8178-5. The fuel temperature shall be in accordance with the manufacturer’s recommendations. The fuel temperature shall be measured at the inlet to the fuel injection pump or as specified by the manufacturer, and the location of measurement recorded. The selection of the fuel for the test depends on the purpose of the test. Unless otherwise agreed by the parties the fuel shall be selected in accordance with Table A-3.

B-Type mode number	1	2	3	4	5	6	7	8	9	10	11
Torque	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated speed					Intermediate speed					Low idle
Off-road vehicles											
Cycle C1	0,15	0,15	0,15		0,1	0,1	0,1	0,1			0,15
Cycle C2				0,06		0,02	0,05	0,32	0,3	0,1	0,15
Constant speed											
Cycle D1	0,3	0,5	0,2								
Cycle D2	0,05	0,25	0,3	0,3	0,1						
Locomotives											
Cycle F	0,25							0,15			0,6
Utility, lawn and garden											
Cycle G1						0,09	0,2	0,29	0,3	0,07	0,05
Cycle G2	0,09	0,2	0,29	0,3	0,07						0,05
Cycle G3	0,9										0,1
Marine application											
Cycle E1	0,08	0,11					0,19	0,32			0,3
Cycle E2	0,2	0,5	0,15	0,15							
Marine application propeller law											
Mode number E3	**1**					**2**		**3**		**4**	
Power (%)	100					75		50		25	
Speed (%)	100					91		80		63	
Weighting factor	0,2					0,5		0,15		0,15	
Mode number E4	**1**					**2**		**3**		**4**	**5**
Speed (%)	100					80		60		40	Idle
Torque (%)	100					71,6		46,5		25,3	0
Weighting factor	0,06					0,14		0,15		0,25	0,4
Mode number E5	**1**					**2**		**3**		**4**	**5**
Power (%)	100					75		50		25	0
Speed (%)	100					91		80		63	Idle
Weighting factor	0,08					0,13		0,17		0,32	0,3

Table A-2: Combined Table of Modes and Weighting Factors

Test purpose	Interested parties	Fuel selection
Type approval (Certification)	1. Certification body 2. Manufacturer or supplier	Reference fuel, if one is defined Commercial fuel if no reference fuel is defined
Acceptance test	1. Manufacturer or supplier 2. Customer or inspector	Commercial fuel as specified by the manufacturer[1)]
Research/development	One or more of: manufacturer, research organization, fuel and lubricant supplier, etc.	To suit the purpose of the test

1) Customers and inspectors should note that the emission tests carried out using commercial fuel will not necessarily comply with limits specified when using reference fuels.

When a suitable reference fuel is not available, a fuel with properties very close to the reference fuel may be used. The characteristics of the fuel shall be declared.

Table A-3: Fuel Selection Criteria

Appendix B- Measuring Gaseous & Particulate Emissions

B.1 Scope

ISO 8178-1[12] and ISO 8178-2[13] specify the measurement and evaluation methods for gaseous and particulate exhaust emissions when combined with combinations of engine load and speed provided in IS0 8178- *Part 4: Test cycles for different engine applications*. The emission results represent the mass rate of emissions per unit of work accomplished. Specific emission factors are based on brake power measured at the crankshaft, the engine being equipped only with the standard auxiliaries necessary for its operation. Per ISO, auxiliary losses are <5 % of the maximum observed power. IMO ship pollution rules and measurement methods are contained in the "International Convention on the Prevention of Pollution from Ships", known as MARPOL 73/78[14], and sets limits on NO_x and SO_x emissions from ship exhausts. The intent of this protocol was to conform as closely as practical to both the ISO and IMO standards.

B.2 Sampling System for Measuring Gaseous and Particulate Emissions

A properly designed sampling system is essential for accurate collection of a representative sample from the exhaust and subsequent analysis. ISO points out that particulate must be collected in either a full flow or partial flow dilution system and CE-CERT chose the partial flow dilution system with single venturi as shown in Figure B-1.

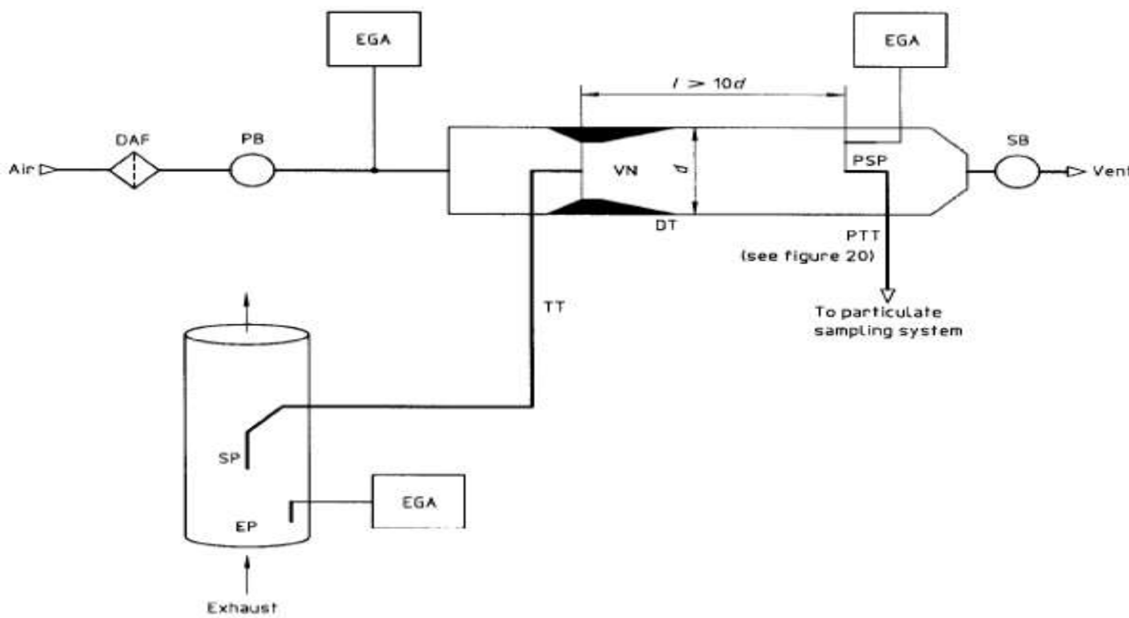

Figure B-1: Partial Flow Dilution System with Single Venturi, Concentration Measurement and Fractional Sampling

[12] International Standards Organization, IS0 8178-1, Reciprocating internal combustion engines - Exhaust emission measurement -Part 1: Test-bed measurement of gaseous particulate exhaust emissions, First edition 1996-08-l5

[13] International Standards Organization, IS0 8178-2, Reciprocating internal combustion engines - Exhaust emission measurement -Part 2: Measurement of gaseous and particulate exhaust emissions at site, First edition 1996-08-l5

[14] International Maritime Organization, Annex VI of MARPOL 73/78 "Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code".

A partial flow dilution system was selected based on cost and the impossibility of a full flow dilution for “medium and large” engine testing on the test bed and at site. The flow in the dilution system eliminates water condensation in the dilution and sampling systems and maintains the temperature of the diluted exhaust gas at <52°C before the filters. ISO cautions the advantages of partial flow dilution systems can be lost to potential problems such as: losing particulates in the transfer tube, failing to take a representative sample from the engine exhaust and inaccurately determining the dilution ratio.

An overview of CE-CERT’s partial dilution system in Figure B-1 shows that raw exhaust gas is transferred from the exhaust pipe (EP) through a sampling probe (SP) and the transfer tube (TT) to a dilution tunnel (DT) due to the negative pressure created by the venturi (VN) in DT. The gas flow rate through TT depends on the momentum exchange at the venturi zone and is therefore affected by the absolute temperature of the gas at the exit of TT. Consequently, the exhaust split for a given tunnel flow rate is not constant, and the dilution ratio at low load is slightly lower than at high load. More detail on the key components is provided in Table B-1.

B.3 Dilution Air System

A partial flow dilution system requires dilution air and CE-CERT uses compressed air in the field as it is readily available. ISO recommends the dilution air be at 25 ± 5°C, filtered and charcoal scrubbed to eliminate background hydrocarbons. The dilution air may be dehumidified. To ensure the compressed air is of a high quality CE-CERT processes any supplied air through a field processing unit that reduces the pressure to about 30 psig as that level allows a dilution ratio of about 5/1 in the geometry of our system. The next stages, in sequence, include: a liquid knock-out vessel, desiccant to remove moisture with silica gel containing an indicator, hydrocarbon removal with activated charcoal and a HEPA filter for the fine aerosols that might be present in the supply air. The silica gel and activated carbon are changed for each field voyage. Figure B-2 shows the field processing unit in its transport case. In the field the case is used as a framework for supporting the unit

Figure B-2: Field Processing Unit for Purifying Dilution Air in Carrying Case

Section	Selected ISO and IMO Criteria	CE-CERT Design
Exhaust Pipe (EP)	In the sampling section, the gas velocity is > 10 m/s, except at idle, and bends are minimized to reduce inertial deposition of PM. Sample position is 6 pipe diameters of straight pipe upstream and 3 pipe diameters downstream of the probe.	CE-CERT follows the ISO recommendation, as closely as practical.
Sampling Probe (SP) -	The minimum inside diameter is 4 mm and the probe is an open tube facing upstream on the exhaust pipe centerline. No IMO code.	CE-CERT uses a stainless steel tube with diameter of 8mm placed near the center line.
Transfer Tube (TT)	As short as possible and < 5 m in length; Equal to/greater than probe diameter & < 25 mm diameter; TTs insulated. For TTs > 1m, heat wall temperature to a minimum of 250°C or set for < 5% thermophoretic losses of PM.	CE-CERT no longer uses a transfer tube.
Dilution Tunnel (DT)	shall be of a sufficient length to cause complete mixing of the exhaust and dilution air under turbulent flow conditions; shall be at least 75 mm inside diameter (ID) for the fractional sampling type, constructed of stainless steel with a thickness of > 1.5 mm.	CE-CERT uses fractional sampling; stainless steel tunnel has an ID of 50mm and thickness of 1.5mm.
Venturi (VN) --	The pressure drop across the venturi in the DT creates suction at the exit of the transfer tube TT and gas flow rate through TT is basically proportional to the flow rate of the dilution air and pressure drop.	Venturi proprietary design provided by MAN B&W; provides turbulent mixing.
Exhaust Gas Analyzers (EGA)	One or several analyzers may be used to determine the concentrations. Calibration and accuracy for the analyzers are like those for measuring the gaseous emissions.	CE-CERT uses a 5-gas analyzer meeting IMO/ISO specs

Table B-1: Components of a Sampling System: ISO/IMO Criteria & CE-CERT Design

B.4 Calculating the Dilution Ratio

According to ISO 8178, "it is essential that the dilution ratio be determined very accurately" for a partial flow dilution system such as CE-CERT uses. The dilution ratio is simply calculated from measured gas concentrations of CO_2 and/or NO_x in the raw exhaust gas versus the concentrations in the diluted exhaust gas. CE-CERT has found it useful to independently determine the dilution ratio from both CO_2 and NO_x and compare the values to ensure that they are within ±10%. CE-CERT's experience indicates the independently determined dilution ratios are usually within 5%. Table B-2 presents the % difference for the current data. At systematic deviations within this range, the measured dilution ratio can be corrected, using the calculated dilution ratio. According to ISO, dilution air is set to obtain a maximum filter face temperature of <52°C and the dilution ratio shall be > 4.

Test Mode	ULSDFM	50/50 Blend
100	-10.1	-6.2
100	-7.2	-5.4
100	-4.6	-2.0
75	-7.4	-4.1
75	-7.1	-4.5
75	-7.0	-4.7
50	-5.2	-4.3
50	-5.1	-3.4
50	-5.5	-4.0
25	3.0	-1.1
25	-1.1	0.2
25	0.0	0.1
10	11.5	8.3
10	14.2	7.8
10	9.1	5.6

Table B-2: % Difference between Dilution Ratio by Carbon Dioxide and Nitrogen Oxides

B.5 Dilution System Integrity Check

ISO describes the necessity of measuring all flows accurately with traceable methods and provides a path and metric to quantifying the leakage in the analyzer circuits. CE-CERT has adopted the leakage test and its metrics as a check for the dilution system. According to ISO the maximum allowable leakage rate on the vacuum side shall be 0.5 % of the in-use flow rate for the portion of the system being checked. Such a low leakage rate allows confidence in the integrity of the partial flow system and its dilution tunnel. Experience has taught CE-CERT that the flow rate selected should be the lowest rate in the system under test.

B.6 Measuring the Gaseous Emissions: CO, CO_2, HC, NO_x, O_2, SO_2

Measurement of the concentration of the main gaseous constituents is one of the key activities in measuring emission factors. This section covers the ISO/IMO protocols and that used by CE-CERT. For SO_2, ISO recommends and CE-CERT concurs that the concentration of SO_2 is calculated based on the fact that 95+% of the fuel sulfur is converted to SO_2.

B.6.1 Measuring Gaseous Emissions: ISO & IMO Criteria

ISO specifies that either one or two sampling probes located in close proximity in the raw gas can be used and the sample split for different analyzers. However, in no case can condensation of exhaust components, including water and sulfuric acid, occur at any point of the analytical system. ISO specifies the analytical instruments for determining the gaseous concentration in either raw or diluted exhaust gases. These instruments include:

- Heated flame ionization detector (HFID) for the measurement of hydrocarbons;
- Non-dispersive infrared analyzer (NDIR) for the measurement of carbon monoxide and carbon dioxide;
- Heated chemiluminescent detector (HCLD) or equivalent for measurement of nitrogen oxides;
- Paramagnetic detector (PMD) or equivalent for measurement of oxygen.

ISO states the range of the analyzers shall accurately cover the anticipated concentration of the gases and recorded values between 15% and 100% of full scale. A calibration curve with five points is specified. However, with modern electronic recording devices, like a computer, ISO allows the range to be expanded with additional calibrations. ISO details instructions for establishing a calibration curve below 15%. In general, calibration curves must be < ±2 % of each calibration point and be < ±1 % of full scale zero.

ISO outlines their verification method. Each operating range is checked prior to analysis by using a zero gas and a span gas whose nominal value is more than 80 % of full scale of the measuring range. If, for the two points considered, the value found does not differ by more than ±4 % of full scale from the declared reference value, the adjustment parameters may be modified. If >4%, a new calibration curve is needed.

ISO & IMO specify the operation of the HCLD. The efficiency of the converter used for the conversion of NO_2 into NO is tested prior to each calibration of the NO_x analyzer. The efficiency of the converter shall be > 90 %, and >95 % is strongly recommended.

ISO requires measurement of the effects from exhaust gases on the measured values of CO, CO_2, NO_x, and 0_2. Interference can either be positive or negative. Positive interference occurs in NDIR and PMD instruments where the interfering gas gives rise to the same effect as the gas being measured, but to a lesser degree. Negative interference occurs in NDIR instruments due to the interfering gas broadening the absorption band of the measured gas, and in HCLD instruments due to the interfering gas quenching the radiation. Interference checks are recommended prior to an analyzer’s initial use and after major service intervals.

B.6.2 Measuring Gaseous Emissions: CE-CERT Design

The concentrations of CO, CO_2, NO_x and O_2 in the raw exhaust and in the dilution tunnel are measured with a Horiba PG-250 portable multi-gas analyzer. The PG-250 simultaneously measures five separate gas components with methods recommended by the ISO/IMO and U.S. EPA. The signal output of the instrument is connected to a laptop computer through an RS-232C interface to continuously record measured values. Major features include a built-in sample conditioning system with sample pump, filters, and a thermoelectric cooler. The performance of the PG-250 was tested and verified under the U.S. EPA Environmental Technology Verification (ETV)[15] program. Figure B-3 is a photo showing a common setup of this system.

Figure B-3: Setup Showing Gas Analyzer with Computer for Continuous Data Logging

Details of the gases and the ranges for the Horiba instrument are shown in Table B-3. Note that the Horiba instrument measures sulfur oxides (SO_2); however, the CE-CERT follows the protocol in ISO and calculates the SO_2 level from the sulfur content of the fuel as the direct measurement for SO_2 is less precise than calculation.

[15] http://www.epa.gov/etv/verificationprocess.html

Component	Detector	Ranges
Nitrogen Oxides (NOx)	Heated Chemiluminescence Detector (HCLD)	0-25, 50, 100, 250, 500, 1000, & 2500 ppmv
Carbon Monoxide (CO)	Non dispersive Infrared Absorption (NDIR)	0-200, 500, 1000, 2000, & 5000 ppmv
Carbon Dioxide (CO_2)	Non dispersive Infrared Absorption (NDIR)	0-5, 10, & 20 vol%
Sulfur Dioxide (SO_2)	Non dispersive Infrared Absorption (NDIR)	0-200, 500, 1000, & 3000 ppmv
Oxygen	Zirconium oxide sensor	0-5, 10, & 25 vol%

Table B-3: Detector Method and Concentration Ranges for Horiba PG-250

For quality control, CE-CERT carries out analyzer checks with calibration gases both before and after each test to check for drift. Because the instrument measures the concentration of five gases, the calibration gases are a blend of several gases (super-blend) made to within 1% specifications. Experience has shown that the drift is within manufacturer specifications of ±1% full scale per day shown in Table B-4. The PG-250 meets the analyzer specifications in ISO 8178-1 Section 7.4 for repeatability, accuracy, noise, span drift, zero drift and gas drying.

Repeatability	±0.5% F.S. (NO_x: </= 100ppm range CO: </= 1,000ppm range) ±1.0% F. S.
Linearity	±2.0% F.S.
Drift	±1.0% F. S./day (SO_2: ±2.0% F.S./day)

Table B-4: Quality Specifications for the Horiba PG-250

B.7 Measuring the Particulate Matter (PM) Emissions

ISO 8178-1 defines particulates as any material collected on a specified filter medium after diluting exhaust gases with clean, filtered air at a temperature of </= 52ºC, as measured at a point immediately upstream of the primary filter. The particulate consists of primarily carbon, condensed hydrocarbons and sulfates, and associated water. Measuring particulates requires a dilution system and CE-CERT selected a partial flow dilution system. The dilution system design completely eliminates water condensation in the dilution/sampling systems and maintains the temperature of the diluted exhaust gas at < 52°C immediately upstream of the filter holders. IMO does not offer a protocol for measuring PM. A comparison of the ISO and CE-CERT practices for sampling PM is shown in Table B-5.

	ISO	CE-CERT
Dilution tunnel	Either full or partial flow	Partial flow
Tunnel & sampling system	Electrically conductive	Same
Pretreatment	None	Cyclone, removes >2.5µm
Filter material	Fluorocarbon based	Teflon (TFE)
Filter size, mm	47 (37mm stain diameter)	Same
Number of filters in series	Two	One
Number of filters in parallel	Only single filter	Two; 1 TFE & 1 Quartz
Number of filters per mode	Single or multiple	Multiple
Filter face temp. °C	< 52	Same
Filter face velocity, cm/sec	35 to 80.	~33
Pressure drop, kPa	For test <25	Same
Filter loading, µg	>500	500-1,000 + water w/sulfate
Weighing chamber	22±3°C & RH= 45%± 8	Same
Analytical balance, LDL µg	10	0.5
Flow measurement	Traceable method	Same
Flow calibration, months	< 3months	Every voyage

Table B-5: Measuring Particulate by ISO and CE-CERT Methods

Sulfur content. According to ISO, particulates measured using IS0 8178 are "conclusively proven" to be effective for fuel sulfur levels up to 0.8%. CE-CERT is often faced with measuring PM for fuels with sulfur content exceeding 0.8% and has extended this method to those fuels as no other method is prescribed for fuels with a higher sulfur content.

B.7.1 Added Comments about CE-CERT's Measurement of PM

In the field CE-CERT uses a raw particulate sampling probe fitted close to and upstream of the raw gaseous sample probe and directs the PM sample to the dilution tunnel. There are two gas stream leaving the dilution tunnel; the major flow vented outside the tunnel and the minor flow directed to a cyclone separator, sized to remove particles >2.5um. The line leaving the cyclone separator is split into two lines; each line has a 47 mm Gellman filter holder. One holder collects PM on a Teflon filter and the other collects PM on a quartz filter. CE-CERT simultaneously collects PM on Teflon and quartz filters at each operating mode and analyzes them according to standard procedures.

Briefly, total PM is collected on Pall Gellman (Ann Arbor, MI) 47 mm Teflo filters and weighed using a Cahn (Madison, WI) C-35 microbalance. Before and after collection, the filters are conditioned for 24 hours in an environmentally controlled room (RH = 40%, T= 25 °C) and weighed daily until two consecutive weight measurements are within 3 µg or 2%. It is important to note that the simultaneous collection of PM on quartz and Teflon filters provides a comparative check of PM mass measured by two independent methods and serves as an important Quality Check for measuring PM mass.

B.8 Measuring Non-Regulated Gaseous Emissions

Neither ISO nor IMO provide a protocol for sampling and analyzing non-regulated emissions. CE-CERT uses peer reviewed methods adapted to their PM dilution tunnel. The methods rely on added media to selectively collect hydrocarbons and PM fractions during the sampling process for subsequent off-line analysis. A secondary dilution is constructed to capture real time PM as shown in Figure B-4.

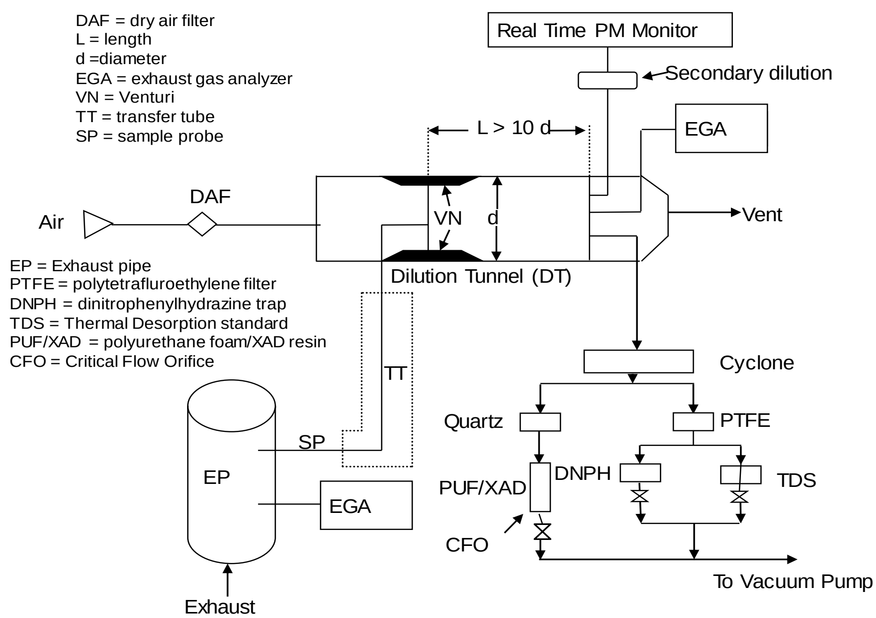

Figure B-4: Partial Flow Dilution System with Added Separation Stages for Sampling both Regulated and Non-regulated Gaseous and PM Emissions

B.8.1 Flow Control System

Figure B-4 shows the sampling system and media for sample collection. Critical flow orifices are used to control flow rates through all systems and all flows are operated under choked conditions (outlet pressure << 0.52 * inlet pressure). Thermocouples and absolute pressure gauges are used to correct for pressure and temperature fluctuations in the system. On the C_4-C_{12} line (TDS tube line) and DNPH line, flows are also metered as differential pressure through a laminar flow element. Nominal flow rates are 20 liters per minute (lpm) for the quartz and Teflon media, 1 lpm for the DNPH and 0.2 lpm for the TDS line. Each flow rate is pressure and temperature corrected for the sampling conditions encountered during the operating mode.

B.9 Measuring Non-Regulated Particulate Emissions

B.9.1 Measuring the Elemental and Organic Carbon Emissions

CE-CERT collected simultaneous Teflo™ and Quartz filters at each operating mode and analyzed them according to standard procedures. PM samples are collected in parallel on 2500 QAT-UP Tissuquartz Pall (Ann Arbor, MI) 47 mm filters that were preconditioned at 600°C for 5 h. A 1.5 cm^2 punch is cut out from the quartz filter and analyzed with a Sunset Laboratory (Forest Grove, OR) Thermal/Optical Carbon Aerosol Analyzer according to the NIOSH 5040 reference method (NIOSH 1996). All PM filters are sealed in containers immediately after sampling, and kept chilled until analyzed.

B.9.2 Measuring Real-Time Particulate Matter (PM) Emissions-DusTrak

In addition to the filter-based PM mass measurements, CE-CERT takes continuous readings with a Nephelometer (TSI DustTrak 8520, Figure B-5) so as to capture both the steady-state and transient data. The DustTrak is a portable, battery-operated laser photometer that gives real-time digital readout with the added benefits of a built-in data logger. The DustTrak/nephelometer is fairly simple to use and has excellent sensitivity to untreated diesel exhaust. It measures light scattered by aerosol introduced into a sample chamber and displays the measured mass density in units of mg/m^3. As scattering per unit mass is a strong function of particle size and refractive index of the particle size distributions and as refractive indices in diesel exhaust strongly depend on the particular engine and operating condition, some scientists question the accuracy of PM mass measurements. However, CE-CERT always references the DustTrak results to filter based measurements and this approach has shown that mass scattering efficiencies for both on-road diesel exhaust and ambient fine particles have values around $3m^2/g$. For these projects, a TSI DustTrak 8520 nephelometer measuring 90° light scattering at 780nm (near-infrared) is used.

Figure B-5: Picture of TSI DustTrak

B.10 Quality Control/Quality Assurance (QC/QA)

Each of the laboratory methods for PM mass and chemical analysis has a standard operating procedure including the frequency of running the standards and the repeatability that is expected with a standard run. Additionally the data for the standards are plotted to ensure that the values fall within the upper and lower control limits for the method and that there is no obvious trends or bias in the results for the reference materials. As an additional quality check, results from independent methods are compared and values from this work are compared with previously published values, like the manufacturer data base.

Appendix C Appendix C Raw Data, Analysis, Analysis Equations, and Calibration Data

C.1 Data

Tables C-1 and C-2 contain gas phase raw data and processed results for the ULSD and the 50/50 blend of ULSD / Algal biofuel.

ULSDFM						Measured Dilute			Measured Raw			Dilute Concentration			Raw Concentration			Dilution Ratio		Fuel Con-sump-tion
Date	Test Mode	RPM	Amps	Load	Load	NOX	CO	CO2	NOX	CO	CO2	NOX	CO	CO2	NOX	CO	CO2	CO2	NOX	
				(kW)	(%)	(ppm)	(ppm)	(%)	(ppm)	(ppm)	(%)	(ppm)	(ppm)	(%)	(ppm)	(ppm)	(%)			(gph)
9/10/2011	100	1179	700	552.6	92.1	196	61.6	2.60	719	208	8.56	203	62.2	2.75	740	213	9.12	3.32	3.65	46.5
9/10/2011	100	1179	698	551.1	91.8	206	58.7	2.66	726	194	8.61	213	59.3	2.81	747	198	9.18	3.27	3.50	46.6
9/10/2011	100	1179	709	559.7	93.3	206	54.5	2.64	723	178	8.70	214	54.9	2.78	744	181	9.27	3.33	3.49	46.7
9/10/2011	75	1179	633	499.7	83.3	199	60.5	2.41	739	215	8.22	206	61.1	2.55	760	219	8.76	3.44	3.69	39.4
9/10/2011	75	1179	616	486.3	81.1	204	56.8	2.43	754	192	8.27	211	57.3	2.57	776	196	8.81	3.43	3.68	38.7
9/10/2011	75	1179	613	483.9	80.7	202	52.3	2.40	754	181	8.23	209	52.7	2.53	776	185	8.77	3.47	3.71	38.3
9/10/2011	50	1179	440	347.4	57.9	183	58.9	2.06	698	209	7.33	190	59.4	2.17	718	214	7.81	3.60	3.78	30.9
9/10/2011	50	1179	468	369.5	61.6	181	54.5	2.04	707	194	7.44	188	54.9	2.15	728	198	7.93	3.69	3.88	29.5
9/10/2011	50	1179	456	360.0	60.0	180	49.4	2.05	705	181	7.46	187	49.7	2.15	725	185	7.94	3.69	3.89	29.5
9/10/2011	25	1179	198	156.3	26.1	125	48.8	1.42	469	172	5.38	129	49.0	1.48	484	175	5.72	3.85	3.74	16.4
9/10/2011	25	1179	204	161.1	26.8	126	48.3	1.44	479	173	5.29	130	48.5	1.50	493	177	5.62	3.74	3.78	16.7
9/10/2011	25	1179	202	159.5	26.6	122	46.8	1.41	471	173	5.29	127	47.0	1.47	485	176	5.62	3.81	3.81	16.8
9/10/2011	10	1179	131	103.4	17.2	102	61.5	1.23	355	212	4.69	106	62.1	1.28	366	217	4.98	3.90	3.46	14.1
9/10/2011	10	1179	133	105.0	17.5	108	56.8	1.27	353	209	4.72	112	57.3	1.32	364	214	5.01	3.78	3.25	14.3
9/10/2011	10	1179	119	93.9	15.7	94	62.8	1.19	339	218	4.57	98	63.4	1.24	350	223	4.85	3.92	3.57	13.5

Intake Air (IA)				Engine Dis-place-ment					% Diff	Calculations using EFR_1						Calculations using EFR_2					
Left	Right	Left	Right		EFR_1	V_E	S_C	EFR_2	EFR-1, EFR_2	NOX	CO	CO2	NOX	CO	CO2	NOX	CO	CO2	NOX	CO	CO2
psi	psi	°F	°F	(l)	(scfm)	(l/min)		(scfm)		(g/hr)	(g/hr)	(g/hr)	(g/kWh)	(g/kWh)	(g/kWh)	(g/hr)	(g/hr)	(g/hr)	(g/kWh)	(g/kWh)	(g/kWh)
15.5	13.5	170	180	48.26	1664	28449	1.65184	1660	0.3%	3932	687	463617	7.12	1.24	839	3923	686	462458	7.10	1.24	837
16.0	14.0	170	180	48.26	1658	28449	1.68013	1688	-1.8%	3956	638	464606	7.18	1.16	843	4028	650	473067	7.31	1.18	858
16.0	14.0	171	180	48.26	1644	28449	1.67881	1687	-2.6%	3907	580	465587	6.98	1.04	832	4009	595	477707	7.16	1.06	853
12.0	10.0	164	174	48.26	1468	28449	1.46768	1475	-0.4%	3565	626	392882	7.13	1.25	786	3580	629	394494	7.16	1.26	789
10.5	9.5	163	173	48.26	1435	28449	1.41281	1419	1.1%	3553	546	385895	7.31	1.12	794	3515	541	381739	7.23	1.11	785
11.0	9.0	164	173	48.26	1426	28449	1.41168	1418	0.5%	3531	513	381912	7.30	1.06	789	3512	511	379871	7.26	1.06	785
6.5	4.5	156	167	48.26	1292	28449	1.16744	1173	9.2%	2964	537	308252	8.53	1.54	887	2690	487	279760	7.74	1.40	805
6.0	4.0	156	167	48.26	1215	28449	1.13853	1144	5.9%	2826	469	294269	7.65	1.27	796	2659	441	276918	7.20	1.19	749
6.0	4.0	156	167	48.26	1214	28449	1.13853	1144	5.7%	2811	437	294268	7.81	1.21	817	2649	412	277356	7.36	1.14	770
0.0	0.0	145	160	48.26	937	28449	0.86197	866	7.6%	1447	319	163834	9.26	2.04	1048	1337	295	151359	8.55	1.89	968
0.0	0.0	146	160	48.26	972	28449	0.86126	865	10.9%	1530	334	166846	9.50	2.07	1036	1362	298	148598	8.46	1.85	923
0.0	0.0	147	161	48.26	977	28449	0.85986	864	11.6%	1514	335	167845	9.49	2.10	1052	1338	296	148356	8.39	1.86	930
0.0	0.0	147	158	48.26	927	28449	0.86197	866	6.5%	1083	391	140968	10.47	3.78	1363	1012	365	131741	9.79	3.53	1274
0.0	0.0	149	159	48.26	934	28449	0.85986	864	7.5%	1085	388	142962	10.33	3.70	1362	1004	359	132266	9.56	3.42	1260
0.0	0.0	150	159	48.26	911	28449	0.85916	863	5.3%	1017	395	134991	10.83	4.20	1437	963	374	127857	10.25	3.98	1361

Table C-1: ULSD Gas Phase Emission Raw Data and Analysis

50/50 blend						Measured Dilute			Measured Raw			Dilute Concentration			Raw Concentration			Dilution Ratio		Fuel Consumption
Date	Test M	RPM	Amps	Load	Load	NOX	CO	CO2	NOX	CO	CO2	NOX	CO	CO2	NOX	CO	CO2	CO2	NOX	
				(kW)	(%)	(ppm)	(ppm)	(%)	(ppm)	(ppm)	(%)	(ppm)	(ppm)	(%)	(ppm)	(ppm)	(%)			(gph)
9/11/2011	100	1179	699	551.8	92.0	183.4	53.85	2.5957	656.4	178	8.62	189.9	54.24	2.74	675.7	181.83	9.186	3.35	3.56	47.5
9/11/2011	100	1179	696	549.5	91.6	184.3	50.73	2.6127	646.1	168.63	8.566	190.7	51.03	2.759	665.2	172.19	9.128	3.31	3.49	47.7
9/11/2011	100	1179	698	551.1	91.8	189.9	50	2.623	644.1	166.42	8.602	196.5	50.28	2.77	663.2	169.93	9.167	3.31	3.37	47.6
9/11/2011	75	1179	609	480.8	80.1	188.1	50	2.355	689.9	173.4	8.167	194.7	50.28	2.483	710.2	177.1	8.701	3.5	3.65	39.1
9/11/2011	75	1179	606	478.4	79.7	186.2	49	2.372	683.5	166.63	8.203	192.7	49.26	2.501	703.6	170.14	8.74	3.49	3.65	39.3
9/11/2011	75	1179	617	487.1	81.2	189.1	47.27	2.36	693.4	161.77	8.136	195.7	47.48	2.488	713.8	165.15	8.668	3.48	3.65	39.5
9/11/2011	50	1179	464	366.3	61.1	172.2	46.27	2	672.6	167.28	7.35	178.3	46.45	2.103	692.4	170.81	7.827	3.72	3.88	29
9/11/2011	50	1179	451	356.1	59.3	170.2	44.3	2.021	653.3	158.63	7.368	176.3	44.42	2.126	672.5	161.92	7.846	3.69	3.81	28.9
9/11/2011	50	1179	483	381.3	63.6	174.3	41.55	2.027	670.4	144	7.361	180.5	41.6	2.132	690.1	146.89	7.839	3.68	3.82	29.2
9/11/2011	25	1179	209	165.0	27.5	115.7	45.2	1.392	455	158	5.267	120.3	45.35	1.453	468.9	161.27	5.598	3.85	3.9	16.5
9/11/2011	25	1179	215	169.7	28.3	116.5	44.27	1.4018	447	160.77	5.246	121.1	44.39	1.463	460.7	164.12	5.576	3.81	3.8	16.4
9/11/2011	25	1179	212	167.4	27.9	118.3	43.64	1.404	457.1	158.57	5.286	122.9	43.74	1.465	471.1	161.86	5.618	3.83	3.83	16.3
9/11/2011	10	1179	110	86.8	14.5	90.17	60.17	1.1708	330.6	203.28	4.527	94.07	60.73	1.216	341	207.81	4.807	3.95	3.63	12.9
9/11/2011	10	1179	119	93.9	15.7	91.9	58.08	1.199	328	204.86	4.492	95.86	58.58	1.246	338.4	209.43	4.769	3.83	3.53	13.4
9/11/2011	10	1179	116	91.6	15.3	90.5	59.33	1.175	339	197.38	4.508	94.42	59.87	1.22	349.7	201.74	4.786	3.92	3.7	13.1

Intake Air (IA)				Engine					% Diff												
Left	Right	Left	Right	Displacement	EFR_1	VE	S_C	EFR_2	EFR-1, EFR_2	NOX	CO	CO2	NOX	CO	CO2	NOX	CO	CO2	NOX	CO	CO2
psi	psi	°F	°F	(l)	(scfm)	(l/min)		(scfm)		(g/hr)	(g/hr)	(g/hr)	(g/kWh)	(g/kWh)	(g/kWh)	(g/hr)	(g/hr)	(g/hr)	(g/kWh)	(g/kWh)	(g/kWh)
16.5	14.0	172	181	48.26	1628	28449	1.69029	1698.1	-4.3%	3512	575	456638	6.36	1.04	827	3664	600	476411	6.64	1.09	863
16.0	13.5	172	181	48.26	1645	28449	1.66206	1669.8	-1.5%	3494	550	458570	6.36	1.00	835	3547	559	465510	6.45	1.02	847
15.0	13.0	172	180	48.26	1635	28449	1.621	1628.5	0.4%	3461	540	457602	6.28	0.98	830	3448	538	455925	6.26	0.98	827
11.0	8.5	165	174	48.26	1415	28449	1.39517	1401.7	0.9%	3208	487	375953	6.67	1.01	782	3178	482	372484	6.61	1.00	775
11.0	8.5	165	174	48.26	1416	28449	1.39517	1401.7	1.0%	3180	468	377871	6.65	0.98	790	3149	463	374133	6.58	0.97	782
11.5	10.0	165	174	48.26	1435	28449	1.45225	1459	-1.7%	3270	460	379805	6.71	0.95	780	3325	468	386245	6.83	0.96	793
5.5	3.5	158	167	48.26	1167	28449	1.10785	1113	4.6%	2580	387	278948	7.04	1.06	761	2461	369	266061	6.72	1.01	726
5.0	3.0	158	168	48.26	1160	28449	1.07812	1083.1	6.6%	2491	365	277984	7.00	1.03	781	2326	341	259541	6.53	0.96	729
5.5	3.5	159	168	48.26	1173	28449	1.10607	1111.2	5.3%	2585	335	280870	6.78	0.88	737	2449	317	266042	6.42	0.83	698
0.0	0.0	150	162	48.26	929.6	28449	0.85707	861.05	7.4%	1392	291	158955	8.43	1.77	963	1289	270	147227	7.81	1.64	892
0.0	0.0	151	162	48.26	927.8	28449	0.85637	860.35	7.3%	1365	296	157995	8.04	1.74	931	1265	274	146517	7.46	1.62	863
0.0	0.0	152	162	48.26	915.1	28449	0.85568	859.66	6.1%	1376	288	157025	8.22	1.72	938	1293	270	147513	7.73	1.62	881
0.0	0.0	148	160	48.26	847.3	28449	0.85986	863.86	-2.0%	923	342	124384	10.62	3.94	1432	941	349	126818	10.83	4.02	1460
0.0	0.0	148	160	48.26	887.1	28449	0.85986	863.86	2.6%	958	361	129212	10.20	3.84	1375	933	352	125830	9.94	3.74	1339
0.0	0.0	148	160	48.26	864.2	28449	0.85986	863.86	0.0%	965	339	126316	10.54	3.70	1379	965	339	126268	10.53	3.70	1379

Table C-2: 50/50 ULSD/Algal Biofuel Gas Phase Emission Raw Data and Analysis

Tables C-3 and C-4 contain PM phase raw data and processed results for the ULSD and the 50/50 blend of ULSD and Algal biofuel.

Teflon ID	Quartz ID	Teflon Duration	Quartz Duration	Teflon flow	Quartz flow	$PM_{2.5}$	EC	OC	TC
		(mins)	(mins)	(lpm)	(lpm)	(mg)	(ug)	(ug)	(mg)
T110366	SSQM001	5.0	4.9	15.7	18.1	0.340	66.1	210.4	0.276
T110251	SSQM006	6.0	5.9	15.6	18.0	0.376	54.3	252.4	0.307
T110391	SSQM011	5.0	5.0	15.4	17.3	0.309	71.0	181.2	0.252
T110305	SSQM002	5.1	5.0	15.5	17.9	0.318	59.2	261.7	0.321
T110269	SSQM007	5.0	4.9	15.5	18.0	0.304	60.3	247.9	0.308
T110387	SSQM012	5.0	5.0	15.4	17.8	0.295	95.7	202.6	0.298
T110260	SSQM003	5.0	5.0	15.6	17.9	0.347	49.9	276.0	0.326
T110255	SSQM008	5.1	5.0	15.4	17.8	0.305	60.9	253.1	0.314
T110388	SSQM013	5.0	4.9	15.4	17.7	0.260	40.6	244.9	0.286
T110261	SSQM004	5.0	5.0	15.3	17.8	0.446	33.2	403.0	0.436
T110392	SSQM009	5.0	5.0	15.4	17.8	0.385	38.3	355.2	0.394
T110384	SSQM014	5.0	5.0	15.3	17.7	0.364	61.4	341.5	0.403
T110385	SSQM005	7.0	6.9	15.5	17.9	0.760	43.5	694.7	0.738
T110393	SSQM010	7.0	7.0	15.4	17.8	0.772	58.5	685.3	0.744
T110381	SSQM015	7.0	6.9	15.2	17.6	0.644	29.7	626.7	0.656

Calculations using EFR I											
$PM_{2.5}$	EC	OC	OC_corrected for H/O	TC_corrected for H/O	TC	$PM_{2.6}$	EC	OC	OC_corrected for H/O	TC_corrected for H/O	TC
(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/kWh)	(g/kWh)	(g/kWh)	(g/kWh)	(g/kWh)	(g/kWh)
40.2	6.9	22.0	26.4	33.3	28.9	0.07	0.01	0.04	0.05	0.06	0.05
36.7	4.6	21.5	25.9	30.5	26.2	0.07	0.01	0.04	0.05	0.06	0.05
36.9	7.6	19.4	23.3	30.8	27.0	0.07	0.01	0.03	0.04	0.06	0.05
34.3	5.6	24.9	29.8	35.4	30.5	0.07	0.01	0.05	0.06	0.07	0.06
32.4	5.6	23.1	27.8	33.4	28.8	0.07	0.01	0.05	0.06	0.07	0.06
31.9	9.0	19.1	22.9	31.9	28.1	0.07	0.02	0.04	0.05	0.07	0.06
34.9	4.4	24.3	29.2	33.6	28.7	0.10	0.01	0.07	0.08	0.10	0.08
29.3	5.1	21.4	25.6	30.8	26.5	0.08	0.01	0.06	0.07	0.08	0.07
25.3	3.5	21.0	25.2	28.7	24.5	0.07	0.01	0.06	0.07	0.08	0.07
35.3	2.3	27.8	33.4	35.6	30.1	0.23	0.01	0.18	0.21	0.23	0.19
30.5	2.7	24.7	29.6	32.3	27.3	0.19	0.02	0.15	0.18	0.20	0.17
29.8	4.4	24.4	29.3	33.7	28.8	0.19	0.03	0.15	0.18	0.21	0.18
42.7	2.1	34.1	40.9	43.1	36.2	0.41	0.02	0.33	0.40	0.42	0.35
42.5	2.8	32.9	39.5	42.3	35.7	0.40	0.03	0.31	0.38	0.40	0.34
36.3	1.5	30.9	37.1	38.5	32.4	0.39	0.02	0.33	0.39	0.41	0.34

Calculations using EFR II							
$PM_{2.5}$	EC	OC	TC	$PM_{2.6}$	EC	OC	TC
(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/kWh)	(g/kWh)	(g/kWh)	(g/kWh)
40.1	7.8	24.8	32.6	0.07	0.01	0.04	0.06
37.3	5.4	25.1	30.5	0.07	0.01	0.05	0.06
37.8	8.7	22.2	30.8	0.07	0.02	0.04	0.06
34.5	6.4	28.4	34.8	0.07	0.01	0.06	0.07
32.0	6.3	26.1	32.4	0.07	0.01	0.05	0.07
31.7	10.3	21.8	32.1	0.07	0.02	0.05	0.07
31.6	4.5	25.2	29.7	0.09	0.01	0.07	0.09
27.5	5.5	22.9	28.4	0.07	0.01	0.06	0.08
23.8	3.7	22.5	26.2	0.07	0.01	0.06	0.07
32.7	2.4	29.5	32.0	0.21	0.02	0.19	0.20
27.2	2.7	25.0	27.7	0.17	0.02	0.16	0.17
26.3	4.4	24.7	29.2	0.17	0.03	0.16	0.18
39.9	2.3	36.5	38.7	0.39	0.02	0.35	0.37
39.3	3.0	34.9	37.9	0.37	0.03	0.33	0.36
34.4	1.6	33.5	35.0	0.37	0.02	0.36	0.37

Table C-3: ULSD PM phase emissions raw data and analysis

Teflon ID	Quartz ID	Teflon Duration	Quartz Duration	Teflon flow	Quartz flow	$PM_{2.5}$	EC	OC	TC
		(mins)	(mins)	(lpm)	(lpm)	(mg)	(ug)	(ug)	(mg)
AT11063	SSQM016	5.0	4.966667	15.0	17.9	0.367	35.6	238.6	0.274
AT11062	SSQM021	5.0	5.0	15.0	17.9	0.264	37.9	199.1	0.237
T110376	SSQM026	5.0	5.0	15.0	17.8	0.235	47.5	178.7	0.226
AT11070	SSQM017	5.0	5.0	15.0	18.0	0.275	34.1	228.0	0.262
T100724	SSQM022	5.0	5.0	14.9	17.7	0.318	54.6	267.5	0.322
T110370	SSQM027	5.0	5.0	15.0	17.7	0.225	59.8	175.2	0.235
AT11069	SSQM018	5.0	5.0	14.9	17.7	0.220	40.7	208.1	0.249
T100725	SSQM023	5.0	5.0	14.9	17.7	0.209	41.4	202.1	0.243
T110375	SSQM028	5.0	5.0	15.0	17.7	0.197	28.0	204.9	0.233
AT11068	SSQM019	5.0	5.0	14.9	17.6	0.286	32.1	305.2	0.337
T110386	SSQM024	5.0	5.0	14.9	17.5	0.272	39.5	277.0	0.317
AT11061	SSQM029	5.0	5.0	14.9	17.7	0.258	24.4	276.3	0.301
AT11066	SSQM020	7.0	7.0	14.9	17.6	0.511	37.5	484.7	0.522
T110377	SSQM025	7.0	7.0	14.9	17.6	0.508	46.1	456.9	0.503
AT11064	SSQM030	7.0	7.0	14.9	17.6	0.491	32.2	491.4	0.524

Calculations using EFR I											
$PM_{2.5}$	EC	OC	OC_corrected for H/O	TC_corrected for H/O	TC	$PM_{2.6}$	EC	OC	OC_corrected for H/O	TC_corrected for H/O	TC
(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/kWh)	(g/kWh)	(g/kWh)	(g/kWh)	(g/kWh)	(g/kWh)
44.9	3.7	24.7	29.6	33.3	28.3	0.08	0.01	0.04	0.05	0.06	0.05
32.3	3.9	20.6	24.7	28.6	24.5	0.06	0.01	0.04	0.05	0.05	0.04
28.4	4.9	18.5	22.2	27.1	23.4	0.05	0.01	0.03	0.04	0.05	0.04
30.6	3.2	21.3	25.5	28.7	24.4	0.06	0.01	0.04	0.05	0.06	0.05
35.4	5.2	25.3	30.4	35.6	30.5	0.07	0.01	0.05	0.06	0.07	0.06
25.3	5.7	16.8	20.1	25.8	22.5	0.05	0.01	0.03	0.04	0.05	0.05
21.5	3.4	17.3	20.8	24.2	20.7	0.06	0.01	0.05	0.06	0.07	0.06
20.1	3.4	16.6	19.9	23.3	20.0	0.06	0.01	0.05	0.06	0.07	0.06
19.0	2.3	16.9	20.3	22.6	19.2	0.05	0.01	0.04	0.05	0.06	0.05
23.1	2.2	21.0	25.2	27.4	23.2	0.14	0.01	0.13	0.15	0.17	0.14
21.7	2.7	18.9	22.7	25.4	21.6	0.13	0.02	0.11	0.13	0.15	0.13
20.4	1.6	18.6	22.3	23.9	20.2	0.12	0.01	0.11	0.13	0.14	0.12
27.5	1.7	22.3	26.8	28.5	24.0	0.32	0.02	0.26	0.31	0.33	0.28
27.8	2.2	21.3	25.6	27.8	23.5	0.30	0.02	0.23	0.27	0.30	0.25
26.8	1.5	22.8	27.4	28.9	24.3	0.29	0.02	0.25	0.30	0.32	0.27

Calculations using EFR II							
$PM_{2.5}$	EC	OC	TC	$PM_{2.6}$	EC	OC	TC
(g/hr)	(g/hr)	(g/hr)	(g/hr)	(g/kWh)	(g/kWh)	(g/kWh)	(g/kWh)
46.9	4.5	30.5	35.0	0.085	0.008	0.055	0.063
32.8	4.7	24.7	29.4	0.060	0.009	0.045	0.053
28.3	5.7	21.5	27.2	0.051	0.010	0.039	0.049
30.3	3.8	25.2	28.9	0.063	0.008	0.052	0.060
35.1	6.0	29.5	35.5	0.073	0.013	0.062	0.074
25.7	6.8	20.0	26.8	0.053	0.014	0.041	0.055
20.5	3.8	19.4	23.2	0.056	0.010	0.053	0.063
18.8	3.7	18.2	21.9	0.053	0.010	0.051	0.061
18.0	2.6	18.8	21.3	0.047	0.007	0.049	0.056
21.4	2.4	22.8	25.2	0.130	0.015	0.138	0.153
20.1	2.9	20.5	23.4	0.118	0.017	0.121	0.138
19.1	1.8	20.5	22.3	0.114	0.011	0.123	0.134
28.1	2.1	26.6	28.7	0.323	0.024	0.306	0.330
27.0	2.5	24.3	26.8	0.288	0.026	0.259	0.285
26.8	1.8	26.8	28.6	0.293	0.019	0.293	0.312

Table C-4: 50/50 ULSD/ALGAL PM phase emissions raw data and analysis

Equations for calculations in Tables 9-1 through 9-4.

1. Load (kW) = Amps / (760)(600)

Where: Amps as measured
760 = Maximum amps generated by engine
600 = Maximum kW generated by engine

2. Load (%) = Load (kW) / 600

3. Dilute Concentrations, DC_x (Based on Calibration Curves, see 9.2)
   a. DC_{NOx} = 1.0273(Measured Dilute NO_x) + 1.447
   b. DC_{CO} = 1.0277(Measured Dilute CO) – 1.1023
   c. DC_{CO2} = 1.0699(Measured Dilute CO_2) – 0.0367

4. Raw Concentrations, RC_x (Based on Calibration Curves)
   a. RC_{NOx} = 1.0273(Measured Raw NO_x) + 1.447
   b. RC_{CO} = 1.0277(Measured Raw CO) – 1.1023
   c. RC_{CO2} = 1.0699(Measured Raw CO_2) – 0.0367

5. Dilution Ratios
   a. Based on CO_2 = RC_{CO2} / DC_{CO2}
   b. Based on NO_x = RC_{NOx} / DC_{NOx}

6. Exhaust Flow Rate in scfm
   a. EFR I= $C_F(24.47)F_C(3.785)\rho_F(1000)(0.03531)(0.001) / (12(RC_{CO2} - 0.03)(60))$
   b. EFR II= $V_E(0.03531)(S_C)$

Where: By Carbon Balance
C_F = Carbon content of fuel = 100 – measured Hydrogen content of fuel
24.47 = Volume in liters of 1 mole of gas
F_C = Fuel consumption in gph
3.785 = liters/gal
ρ_F = density of fuel in kg/m^3
1000 = g/kg
0.03531 = ft^3/l
0.001 = m^3/l
12 = molecular weight of carbon in g
0.03 = Background concentration of CO_2
60 = minutes per hour

Where: By Engine as air pump
V_E = Volume of exhaust in l/min = 48.26*rpm/2
48.26 = engine displacement in l
2 = Number of cylinder revolutions per displacement
0.03531 = ft^3/l
S_C = correction to standard temperature and pressure conditions
$S_C = (293.15((IA_P)(0.06894)+1.013)) / ((1.013((IA_T+459.67)(5/9))))$
293.15 = standard temperature in °K
IA_P = Inlet Air Pressure in psi = Average of left and right intake air
0.06894 = conversion of psi to bar
1.013 = standard atmospheric pressure in bar

IA_T = Inlet Air Temperature in °F
$(IA_T + 459.67)(5/9)$ converts °F to °K

7. % Diff = % difference between EFR I and EFR II= 100(EFR I– EFR II) / EFR II

8. Emissions (E_{gx}) in g/hr
   a. $E_{gNOx} = (10^{-6})(46) / 24.47$(EFR I or EFR II)(60) / (0.035325)
   b. $E_{gCO} = (10^{-6})(28) / 24.47$(EFR I or EFR II)(60) / (0.035325)
   c. $E_{gCO2} = RC_{CO2}(10^{-2})(44) / 24.47$(EFR I or EFR II)(60) / (0.035325)
   d. $E_{gPM2.5}$ = (mg/filter)(DR_CO_2)(EFR I or EFR II)(0.028)(60)/(T_t)/(T_f)
   e. E_{gEC} = (ug/filter)(DR_CO_2)(EFR I or EFR II)(0.028)(60)/(Q_t)/(Q_f)/1000
   f. E_{gOC} = (ug/filter)(DR_CO_2)(EFR I or EFR II)(0.028)(60)/(Q_t)/(Q_f)/1000

Where: 10^{-6} for RC_{NOx} and RC_{CO} converts ppm to moles
10^{-2} for RC_{CO2} converts % to moles
46, 28, 44 = g/mole for NO_x, CO, and CO_2, respectively
60 = min/hr
.035325 = ft^3/l
DR_CO_2 = Dilution ratio based on CO2 concentrations in raw and diluted exhaust
mg/filter = Teflon final weight
T_t = sampling duration for Teflon filter
T_f = flow through the Teflon filter in lt/min
ug/filter = EC/OC mass collected on Quartz filter
Q_t = sampling duration of Quartz filter
Q_f = flow through the Quartz filter in lt/min
0.028 = m^3/ft^3
1000 = mg/ug

9. Emissions (E_x) in g/kW-hr
   a. $E_{NOx} = E_{gNOx}$ / Load
   b. $E_{CO} = E_{gCO}$ / Load
   c. $E_{CO2} = E_{gCO2}$ / Load
   d. $E_{PM2.5} = E_{gPM2.5}$/ Load
   e. $E_{EC} = E_{gEC}$/ Load
   f. $E_{OC} = E_{gOC}$/ Load

10. Fuel Consumption (FC) in g/kW-hr
    a. FC = [CO_2 (g/hr)][(MW C)/MW CO_2][100/%C in fuel]
    b. MW C = Molecular weight of C = 12
    c. MW CO_2 = Molecular weight of CO_2 = 44
    d. %C in fuel = % carbon in fuel

C.2 Calibration Data

Table C-5 presents the pre and post calibration data for the Horiba PG-250 and Figures C-1 through C-3 presents the plots of the calibration data and the regression equations for the calibration data.

NO_X Calibration Gas Concentration (ppm)	Measured NO_x Pre Calibration (ppm)	Measured NO_x Post Calibration (ppm)	Average Measured NO_x Calibration	CO Calibration Gas Concentration (ppm)	Measured CO Pre Calibration (ppm)	Measured CO Post Calibration (ppm)	Average Measured CO Calibration	CO_2 Calibration Gas Concentration (%)	Measured CO_2 Pre Calibration (ppm)	Measured CO_2 Post Calibration (ppm)	Average Measured CO_2 Calibration
0	0.32	0.25	0.285	0	-0.3	-0.55	-0.425	0	0	0	0
156	150	148.925	149.4625	25.5	27.3	26.6	26.95	1.54	1.47	1.4425	1.45625
575	543	569	556	51	51	51.975	51.4875	2.06	2.01	2.035	2.0225
918	877	910.6	893.8	202	196.8	197.76	197.28	9.83	9.21	9.212	9.211

Table C-5: Pre and Post Calibration of Horiba PG 250

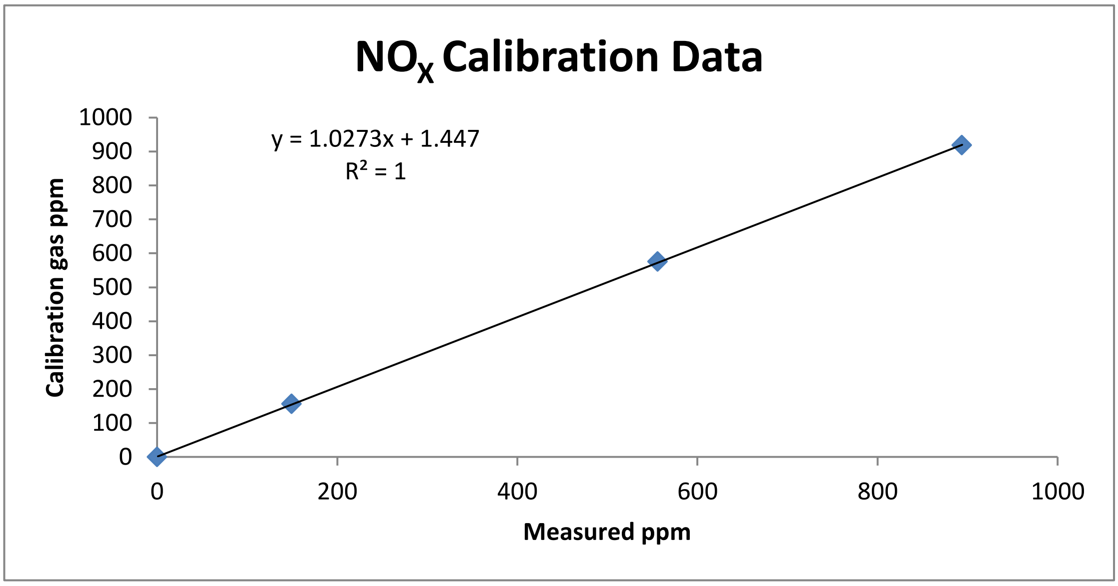

Figure C-1: NOx Calibration Data for Horiba PG 250

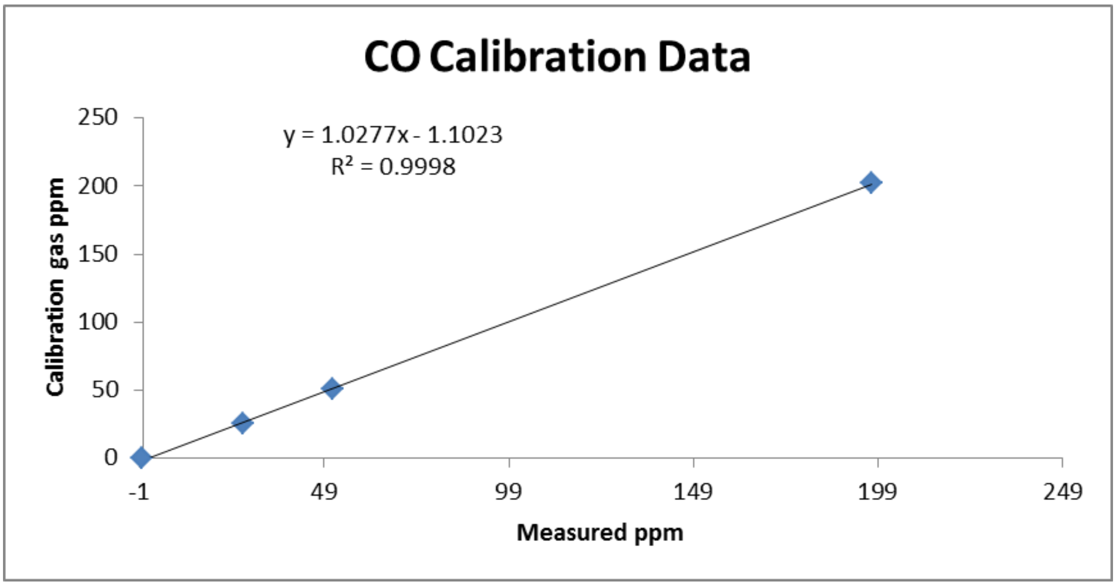

Figure C-2: CO Calibration Data for Horiba PG 250

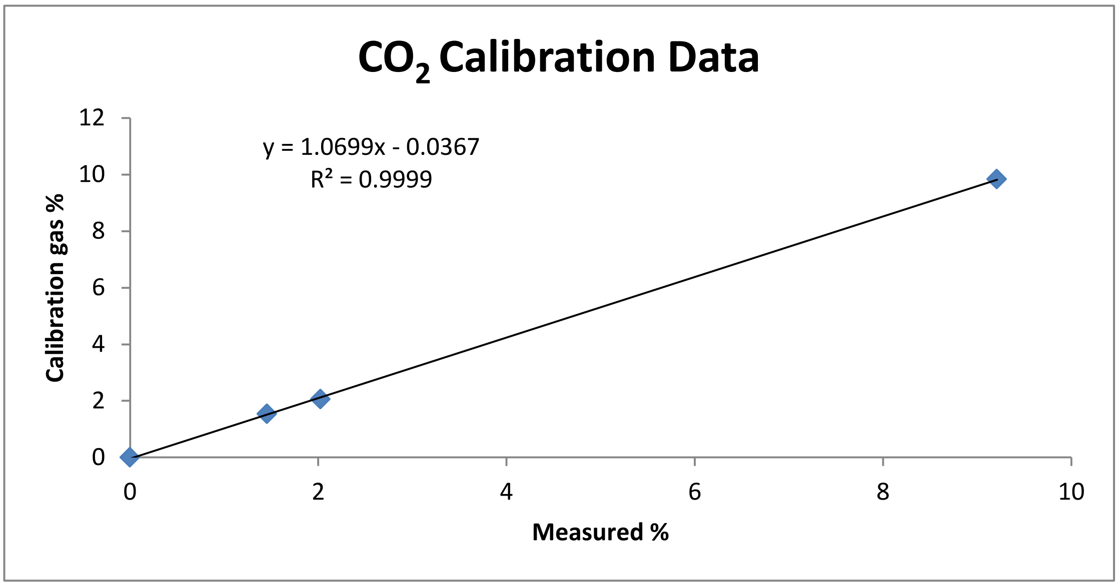

Figure C-3: CO_2 Calibration Data for Horiba PG 250