Criteria Emissions from the Main Propulsion Engine of a Post-Panamax Class Container Vessel Using Distillate and Residual Fuels

Final Report (04_09_2009)
Contract # 06-412
Prepared for:
California Air Resources Board
1001 I Street,
Sacramento, CA 95814

Authors:

Dr. J. W. Miller
Mr. Harshit Agrawal
Mr. William A. Welch

University of California, Riverside
College of Engineering-Center for Environmental Research and Technology
Riverside, CA 92521

Disclaimer

This report was prepared as the result of work sponsored by the California Air Resources Board (CARB) and carried out with a major shipping company. As such the report does not necessarily represent the views of CARB and the partnering shipping company. Further the collective participants, its employees, contractors and subcontractors make no warrant, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has neither been approved nor disapproved by the collective group of participants nor have they passed upon the accuracy or adequacy of the information in this report.

Acknowledgements

The author expresses appreciation to the California Air Resources Board for funding the project and to the following associates who contributed much to the success of a project that enabled more to be learned about emissions from the main propulsion engines of a large container vessel. Not specifically mentioned below but essential to the success of this project was the support of the many people at the shipping company that volunteered their vessel and enabled this testing to be carried out. Their efforts started with the application to the Homeland Security Agency to gain permission to ride the vessel in the Pacific to modification of the operating conditions of the main engine during the voyage to allow emissions to be measured at the load points specified in the ISO E-3 certification cycle. Further the help of the crew on the vessel was a key to success in this project.

California Air Resources Board

- Ms. Bonnie Soriano
- Ms. Peggy Tarrico
- Mr. Paul Milkey

Table of Contents

Table of Figures

List of Tables

Executive Summary

The California Air Resources Board and the University of California, Riverside (UCR) partnered with a shipping company to measure the criteria gas and particulate matter ($PM_{2.5}$) emissions from the main engine of a Post Panamax Class container vessel running on 3.01 wt% sulfur Heavy Fuel Oil (HFO) and 0.2 wt% sulfur Marine Gas Oil (MGO). Exhaust sampling took place over a three day voyage from Los Angeles, CA to Seattle, WA during July, 2007

The project objectives were to:

1. Calculate emissions factors from the measured emissions of selected gases and particulate matter while the engine operates at the loads specified in the ISO 8178-E3 certification cycle.
2. Calculate emissions factors from the measured emissions of selected gases and particulate matter while the engine operates at the load needed to maintain a 12 knot speed (VSR mode).
3. Fractionate $PM_{2.5}$ mass into its major constituents: hydrated sulfate, organic carbon, inorganics (ash), and elemental carbon. .
4. Continuously monitor the gaseous and $PM_{2.5}$ emissions during the switch from MGO to HFO and calculate the difference in emission factors.
5. Model the $PM_{2.5}$ level changes during the fuel switching.
6. Comparison of exhaust flow rate calculations from different methods.
7. Comparison of emissions measurements done three years apart on the same vessel.

Emission factors determined from testing the main propulsion engine are presented in Table ES-1.

Table ES-1: Emission Factors for the Main Propulsion Engine

Load %	Fuel Type	CO_2	SO_2	CO	NO_x	$PM_{2.5}$
		(g/kWhr)	(g/kWhr)	(g/kWhr)	(g/kWhr)	(g/kWhr)
8%	MGO	578	0.72	0.54	15.34	0.57
13%	HFO	623	11.62	0.52	19.77	2.03
25%	HFO	678	12.66	0.41	21.33	2.22
50%	HFO	611	11.40	0.29	18.10	2.43
75%	HFO	604	11.28	0.28	20.08	2.91
90%	HFO	636	11.87	0.30	19.50	3.18

Continuous monitoring of $PM_{2.5}$ and SO_2 emissions during the fuel switching showed that it took about ninety minutes to stabilize after the fuel switch, indicative of the mixing in the fuel system. Results show that switching fuel from HFO to MGO during the VSR speed decreased the NO_x emission factor by 22 percent, which is much higher than expected. Thus, authors recommend a repeat of the measurement campaign to confirm these findings of fuel switching in this report.

1 Introduction

1.1 Background

Businesses at ports throughout the world are working with regulatory and community agencies to increase economic throughputs without increasing environmental impacts. Increased environmental impacts come mainly from increases in port activity and many ports are projecting substantial increases in activity. Increased port activity without further controls on new and legacy diesel engines will increase emissions in the communities near ports and the environmental impacts. An example of the projected emissions and their sources can be seen from the following figures for the Los Angeles area[1]. From these figures it is clear that the ships are the key contributors to the emission inventory in the future. However, little is known about the emissions from these sources, especially the actual in-use emissions.

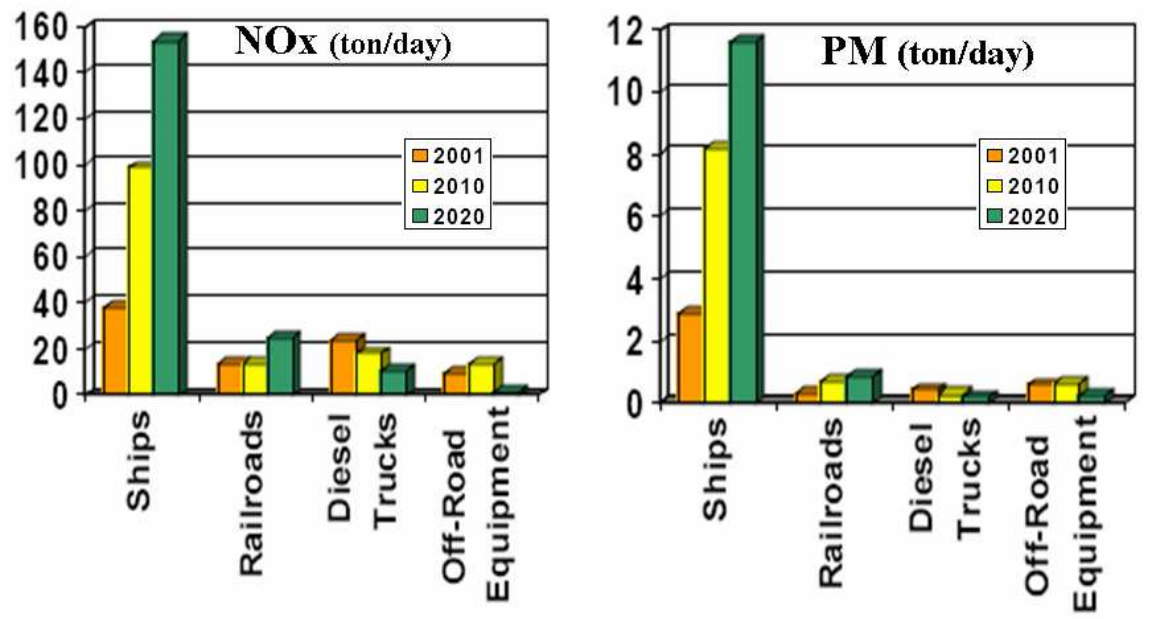


Figure 1-1 Trends for Various Port-Related Emissions (tons/day)

As ocean going vessels are one of the largest uncontrolled sources of pollutants and as emissions data from those sources are scarce, the California Air Resources Board, a major shipping company and UCR worked together on a project to measure emissions from the main engine on a Post-Panamax Class container vessel following the engine operating conditions specified in the ISO 8178 E-3 certification test and while following the voluntary Vessel Speed Reduction (VSR) program. The ISO 8178 E-3 certification conditions are defined later; VSR operations represent those times when ocean going vessel (OGV) voluntarily reduces their speed to 12 knots at a distance of 20 nautical

[1] Ref: *Goods Movement Action Plan* Phase I: Foundations (Sept 2005)

miles from the POLA/POLB. More detail on the VSR program is available on the ARB web site[2].

1.2 Project Objective

Given that background, the goals of the project are:

1. Calculate emissions factors from the measured emissions of selected gases and particulate matter while the engine operates at the loads specified in the ISO 8178-E3 certification cycle.
2. Calculate emissions factors from the measured emissions of selected gases and particulate matter while the engine operates at the load needed to maintain a 12 knot speed (VSR mode).
3. Fractionate $PM_{2.5}$ mass into its major constituents: hydrated sulfate, organic carbon, inorganics (ash), and elemental carbon. .
4. Continuously monitor the gaseous and $PM_{2.5}$ emissions during the switch from MGO to HFO and calculate the difference in emission factors.
5. Model the $PM_{2.5}$ level changes during the fuel switching.
6. Comparison of exhaust flow rate calculations from different methods.
7. Comparison of emissions measurements done three years apart on the same vessel.

Criteria pollutants measured include carbon monoxide (CO), oxides of nitrogen (NO_x), sulfur dioxide (SO_2) and particulate matter ($PM_{2.5}$). Based on previous studies by the authors[3], hydrocarbons emissions are observed to be low and near ambient levels for these engines and were excluded from the measurement campaign. The primary green house gas from ships, carbon dioxide (CO2), was also monitored. Measurements were made while the main engine operations approximated the ISO 8178 E-3 certification test modes, and while the vessel followed the 12 knot speed limit specified in the VSR program. Values from this study should be helpful in developing emission models and inventory calculations.

[2] See: http://www.arb.ca.gov/ports/marinevess/vsr/vsr.htm

[3] Agrawal H., Welch W.A., Miller J.W., Cocker D.R. (2008b) Emission measurements from a crude oil tanker at sea, *Environ. Sci. Technol., 42*, 7098-7103.

2 Test Plan

2.1 Overview

Prior to sailing, a detailed schedule for testing was developed by UCR and finalized with the Chief Engineer of the vessel. The plan included the location of specific sampling ports and engine operating conditions (rpm and load) as a function of time from the Port of Los Angeles. The test plan used information from the desired test matrix, including the number of repeat measurements, and the operational plan of sailing from Los Angeles to the Port of Tacoma. Subsequent discussions aligned and merged the two plans so everyone knew the operating plan for the voyage and for the testing.

The following sections provide detailed information on the test engine, test fuels and the engine conditions during the testing. Additional details on the test procedures are provided in Appendix A.

2.2 Test Fuels

While maneuvering out of the Port of Los Angeles to the 20 nautical mile limit of the VSR zone, the main engine operated on a Marine Gas Oil (MGO). Once the vessel reached 20 nm, the crew switched from the MGO to a heavy fuel oil (HFO) and the vessel sailed the reminder of the voyage on HFO, both fuels meeting ISO 8217 specifications. Both fuels were typical of normal supply and a one liter fuel sample of the MGO and HFO was withdrawn from the main engine final filter drain, immediately upstream of the injector rail, for subsequent analysis. The samples were analyzed after the voyage for a number of fuel properties. In addition to the samples, bunker delivery notes were collected as these provided independent analyses of the fuel properties for the HFO and MGO.

2.3 Test Vessel and Engine

The sampling was conducted on a modern Post Panamax Class container ship that frequently calls on California ports and is representative of other modern container vessels. Properties of the vessel are provided in **Table 1**.

Vessel type:	Post-Panamax Class Container Ship
Shipyard:	Lindø
Built Year:	1998
Length (meters):	346.98
Beam (meters):	42.8
Speed (knots):	24.6
TEU: design/capacity:	6600/8680
Weight, GT	91,690
Date Entered Fleet:	1998-06-29

Table 1 Selected Properties of the Test Vessel

Modern container ships are large and have large engines that occupy over three stories of space on the vessel. The engine specifications are provided in **Table 2.**

Ship Type	Container vessel
Engine Type	12k90MC
Build	Hitachi MAN B&W 12K90Mk mk 6 (Build 1998)
Rated Power	54840 kW
Rated speed	94 r/min
Maximum pressure (at MCR)	141 bar

Table 2 Selected Data for the Main Propulsion Engine

According to the MAN web site[4] all MC engines "comply with the IMO speed dependent NO_x emission limitations, measured according to the ISO 8178 test cycles E2/E3 for Heavy Duty Diesel Engines."

2.4 Operating Cycles

Emission factors are dependent on the operating conditions of the vessel, for example load, rpm etc. The measurement were made both at operation of the vessel at ISO 8178-E-3 modes and actual in –use operation of the vessel at VSR mode.

2.4.1 Operation at ISO 8178-E3 modes

Normally, emissions from diesel engines are measured while the engine is in a laboratory and connected to an engine dynamometer. The engine operating conditions are set to match the recommended conditions specified in the regulation for certification. For this project, the testing was carried out during an actual sea voyage. This approach adds complexity, as it is often difficult to match "in-use" engine operating conditions with the operating conditions specified for the four modes in the ISO 8178 E-3 marine certification test.

Table 3 Engine Operating Conditions for the ISO 8178 E-3 Cycle

	Rated speed	Intermediate speed		
Speed, %	100	91	80	63
Power, %	100	75	50	25
Weighting factor	0.2	0.5	0.15	0.15

The achievable load points were determined at the time of testing and depended on several factors; including constraints by the schedule associated with the planned voyage, sea currents, wave patterns, wind speed/direction, and cargo load. Efforts were made to conduct the emissions measurements at loads and rpm as close as possible to those specified in ISO 8178 E-3.

[4] http://www.manbw.com/web/viewers/news/articleViewer.aspx?id=484

2.4.2 Operation in the VSR Mode

In addition to tests at the ISO conditions, the plan called for testing and measuring emissions at the 12 knot speed limit in VSR mode. Two VSR test opportunities were available. First when the vessel left the Port of Los Angeles, and second, when it sailed into the Port of Tacoma. In May 2001, a Memorandum of Understanding (MOU) was signed between the Ports of Los Angeles and Long Beach (POLA/POLB), the United States Environmental Protection Agency - Region 9, ARB, the South Coast Air Quality Management District, the Pacific Merchants Shipping Association, and the Marine Exchange of Southern California. This MOU requests OGV operators to voluntarily reduce their speed to 12 knots at a distance of 20 nautical miles from the POLA/POLB. Within the VSR boundary, it was expected that NO_x emissions would be significantly reduced and the reduction in NOx would help meet the goals of the 1994 ozone State Implementation Plan and 1997 South Coast Air Quality Management Plan.(VSR, 2001)

2.5 Emission Measurement

The test plan was designed to measure selected gaseous emissions, CO, NO_x, SO_2 and CO_2, while the main engine operated at or close to the certification conditions specified in ISO 8178 E-3, and during operation at the 12 knot VSR speed limit. In addition to gases, the test plan called for collecting filter samples on Teflon and quartz media for subsequent analysis of $PM_{2.5}$ mass, elemental carbon, organic carbon, ash and sulfate fractions. Continuous emissions monitoring of gases and $PM_{2.5}$ was carried out during the fuel switch.

2.5.1 Sampling Ports

As explained in Appendix A, a partial dilution system was connected directly to the exhaust and no transfer line was used. While the ISO 8178-1 allows a transfer line of up to 5 meters, the UCR protocol eliminates the transfer line wherever possible to minimize $PM_{2.5}$ losses. Earlier studies by UCR showed a transfer line of 5 meters could lower the $PM_{2.5}$ collected by up to 50%. Accordingly, measurements in this campaign were made without a transfer line between the raw exhaust and the partial dilution tunnel.

The sample port used for this work was installed prior to the campaign on the same vessel in 2004. It was located just before the waste heat boiler on the vessel. Sample probe access into the exhaust stream was gained by using the earlier probe sampling ports. The sampling probe extended over 30 cm into the raw exhaust stack; away from any conditions found near the stack wall boundary.

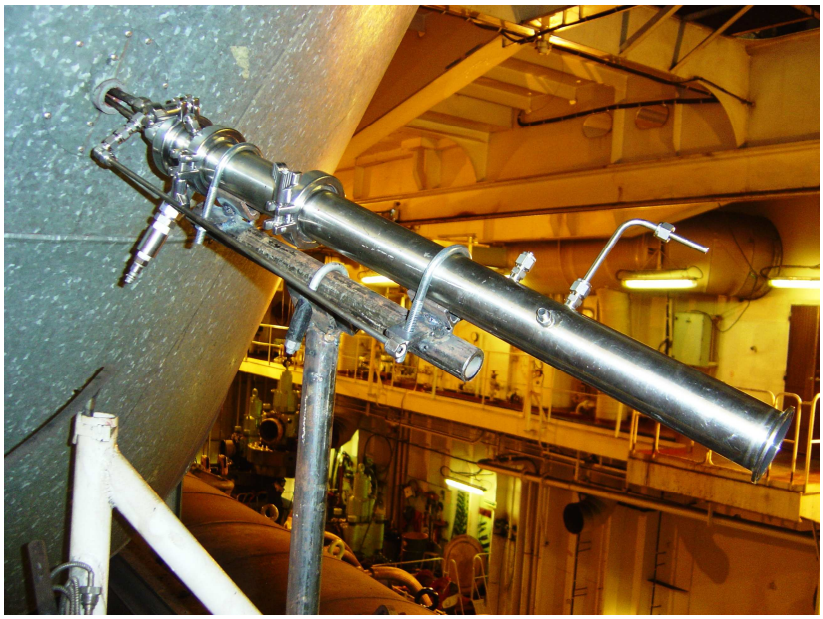


Figure 2-1 Example of a Sampling System where the Main Exhaust is Directly Connected with the Partial Dilution Tunnel

2.5.2 Measuring Gases and PM2.5 emissions

The concentrations of gases in the raw exhaust and the dilution tunnel were measured with a Horiba PG-250 portable multi-gas analyzer. In addition to the gaseous emissions, the test program determined load-specific particulate matter ($PM_{2.5}$) mass emissions while following the ISO and VSR modes. As described in Appendix A, the $PM_{2.5}$ mass was sampled from the main stream with a partial dilution method and collected on filter media. The real time $PM_{2.5}$ measurements were made with Dekati Mass Monitor. Measurement protocol is described in detail in Appendix A.

2.5.3 Calculation of Emission Factor

The emission factor at each mode is calculated from the measured gaseous and $PM_{2.5}$ 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 -E-3 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 (HC, CO, CO_2, $PM_{2.5}$, or NO_x) in g/kW-hr
g_i = Mass flow in grams per hour,
P_i = Power measured during each mode, including auxiliary loads, and
WF_i = Effective weighing factor.

2.6 Determining Exhaust Flow Rate

The calculated emission factor is strongly dependent on the mass flow of the exhaust. Accurate exhaust flow rate is needed to determine emission factors and various different approaches are described below. Appendix A of ISO 8178-1 describes two methods for calculating the exhaust gas mass flow and/or the combustion air consumption. A third approach calculated the air flow from the engine. The fourth approach uses proprietary data and was the method used in this report. Another approach is to measure the exhaust flow rate using a Pitot tube. These methods are described below.

2.6.1 Methods described in Appendix A of ISO 8178 -1

Two methods are described in Appendix A of ISO-8178-1. Both methods are based on measuring the exhaust gas concentrations and on the knowledge of the fuel consumption.

Method 1, Carbon Balance, calculates the exhaust mass flow based on the measurement of fuel consumption 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 consumption is measurable and the fuel composition and the concentration of the exhaust components are known. It is applicable for fuels containing H, C, S, 0, N in known proportions.

The carbon balance methods may be used to calculate exhaust flow rate when the fuel consumption 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 consumption data are available.

2.6.2 Determining exhaust flow rate from intake air

This method is 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 the cylinder volume, recorded rpm, and the temperature and pressure of the inlet air. The method assumes the combustion air flow equals the total exhaust flow. Low-speed, two stroke engines, usually has scavenged air flow while the piston is expanding and the exhaust valve is still open. The scavenger air would not be included in the air pump calculation leading to an under prediction of the total exhaust flow and the emission factors. The method works best for four stroke engines or for two-

stroke engines where there the scavenger air flow is much smaller than the combustion air[5].

2.6.3 Proprietary methods for determining total exhaust flow rate

Various engine manufacture companies, like MAN B&W, have developed proprietary knowledge and computer programs in the form of complex equations to calculate exhaust flow rates for their engines, including the low-speed, two stroke engines. Their complex equations provide an accurate value for the total exhaust flow, including both the combustion and the scavenger air flows. The programs are based on the load and the operating conditions of the engine and the turbochargers. Such programs were developed and checked against stoichiometric calculations based on carbon and oxygen balances. Since MAN supplied their proprietary data, the calculated total exhaust flow and subsequent emission factors in this report are based on the proprietary method.

2.6.4 Determination of stack gas velocity and volumetric flow rate by Pitot tube

In this method the average gas velocity in a stack is determined from the gas density and from measurement of the average velocity head with a Type S (Stausscheibe or reverse type) pitot tube. Details of this method are available in the ARB report on Method 2, Determination of Stack Gas Velocity and Volumetric Flow Rate (Type S Pitot Tube).

[5] Miller, J. W.; Durbin, T. D.; Johnson, K.; Cocker, D. R., III. Evaluation of Portable Emissions Measurement Systems (PEMS) for Inventory Purposes and the Not-To-Exceed Heavy-Duty Diesel Engine Regulation; Final Report for the California Air ResourceBoard, July, 2006.

3 Results and Discussion

3.1 Fuel Properties

Selected fuel properties from the certificate of analysis (COA) for the bunker oil and the marine gas oil are presented in Table 4.

Table 4 Selected Properties of the Fuel Used on the Vessel

Fuel	Units	Heavy Fuel Oil (HFO)	Marine Gas Oil (MGO)
Density @ 15C	kg/m^3	988.5	863.8
Viscosity @ 50C	mm^2/s	290.6	180
Sulfur	%m/m	3.01	0.2
Ash	%m/m	0.05	< 0.01
Vanadium	mg/kg	75	< 1
Nickel	mg/kg	29	< 1

3.2 Test plan and operating conditions

As mentioned in the prior section, an emissions measurement plan, which fitted the voyage and engine operating plan, was developed before leaving port. While the measurement plan called for following the ISO modes, the actual loads when testing an engine on a vessel differed from the ISO protocol due to practical considerations. For example, the main propulsion engine was not tested at 100% load as specified in the ISO protocol because company policy precludes operation above 90% load.

VSR modes were tested. While leaving the Port of Los Angeles the vessel operated in VSR mode (12 knots, ~8% engine load) on MGO and while entering the Port of Seattle the engine operated on HFO at 15 knots and ~13% load. The final test schedule is shown in Table 5

Table 5 Test Schedule for the Main Propulsion Engine

Condition	Fuel	Date
VSR ~8%	MGO	7/16/2007
ISO 90%	HFO	7/16/2007
ISO 75%	HFO	7/16/2007
ISO 50%	HFO	7/16/2007
ISO 25%	HFO	7/16/2007
VSR ~13%	HFO	7/18/2007

3.3 Exhaust Flow Rate

As described in the last section, the exhaust gas analyzers measure concentration and accurate exhaust flow rates are needed to figure the emission factor for each mode. Three recognized approaches to calculating the exhaust flow rate were described in that section: carbon balance, model combustion as pump, and proprietary data. Figure 3-1 compares the flow figured with each of the methods.

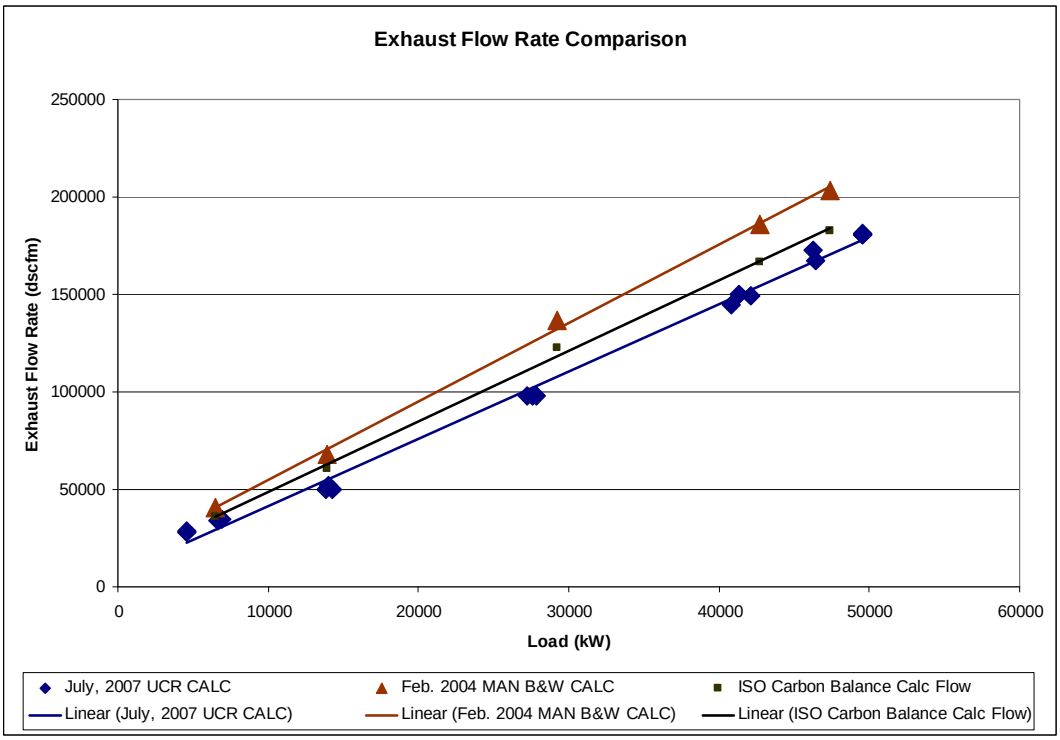


Figure 3-1 Comparison of Exhaust Flow Rates using different methods

Table 3- shows the exhaust flow rate from the proprietary data is higher than the flow rate calculated by the air pump method by about 16.7%. We used the flow rate from the proprietary data to calculate emission factors in this report.

Table 3-3 Exhaust Flow Rate Comparison

	Exhaust Flow rate (dry scfm)		
Engine Load %	**Air pump**	**Proprietary Data**	**% Difference**
10	35,018	40,556	13.7
25	52,265	67,815	22.9
50	100,924	136,401	26.0
75	157,459	186,261	15.5
85	174,212	203,149	14.2
		Weighted difference	**16.7**

4 Results and Discussions - Regulated Emissions

The first goal of this study was to determine the emission factor for the gaseous and $PM_{2.5}$ pollutants from the container vessel at each of the ISO 8178 certification modes for comparison with the other data. Gaseous and $PM_{2.5}$ measurements were conducted in triplicate (consecutive) and the results are presented in following sections.

4.1 Gaseous Emissions

The gaseous emissions of interest in this study were: CO_2, CO, SO_2 and NO_x. All of the gaseous emissions were measured using instruments specified in the ISO protocol, except for SO_2. ISO 8178-1 Chapter 7.4.3.7 *Sulfur dioxide (SO_2) analysis* specifies: "The SO_2 concentration shall be calculated from the sulfur content of the fuel used, since experience has shown that using the direct measurement method for SO_2, does not give more precise results." This approach is valid as most (>95%) of the fuel sulfur is converted to SO_2 in the combustion process.

The modal gaseous emissions factors for CO_2, CO, NO_x and SO_2 in terms of g/kW-hr are presented in Figure 4-1. Triplicate measurements were made for each set of load conditions and the error bars on the figure represent the confidence limits for the data gathered and analyzed. Calculated values of the coefficient of variation (CV) show the average for the NO_x and CO_2 was about 3%, very good precision for field studies.
Numeric results are also presented in Table 6 for the modal and weighted emission factors.

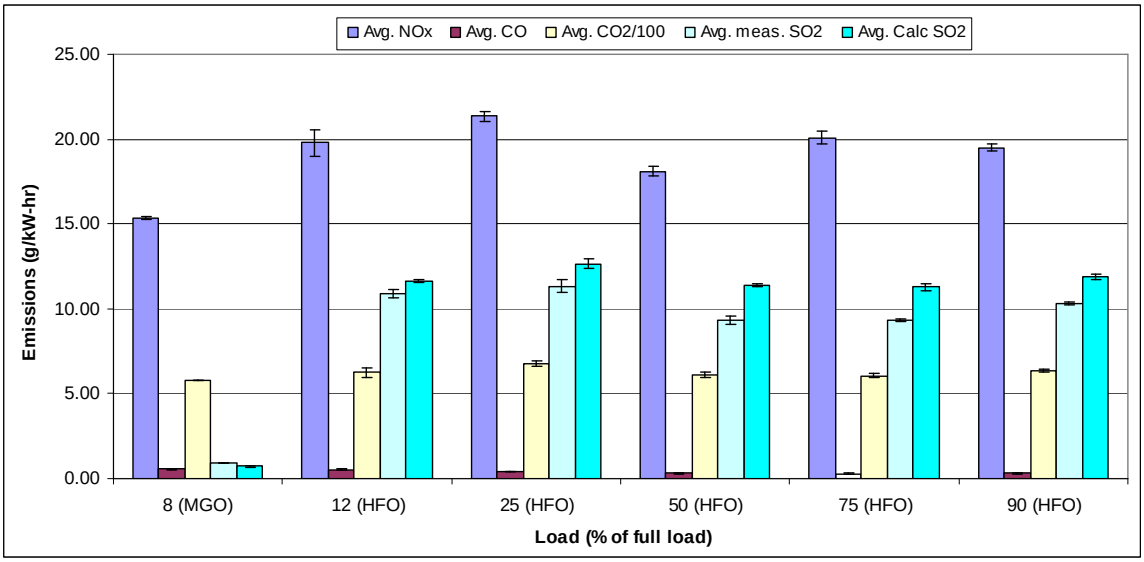


Figure 4-1 Emission Factor for Different Gases for Main Engine

Table 6 Emission factor of Different Gases for Main Propulsion Engine

Load (%)	CO_2	SO_2	CO	NO_x
	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr
VSR-8 (MGO)	578	0.72	0.54	15.34
VSR 12 (HFO)	623	11.62	0.52	19.77
25 (HFO)	678	12.66	0.41	21.33
50 (HFO)	611	11.40	0.29	18.10
75 (HFO)	604	11.28	0.28	20.08
90 (HFO)	636	11.87	0.30	19.50
ISO weighted	622			19.85

4.2 Particulate Matter ($PM_{2.5}$) Emission Factors

In addition to the gaseous emissions, the test program determined load-specific particulate matter ($PM_{2.5}$) mass emissions while following the ISO and VSR modes. As described in Appendix A, the $PM_{2.5}$ mass was sampled from the main stream with a partial dilution method and collected on filter media. The $PM_{2.5}$ mass emissions for the main engine are presented in Table 4-. Triplicate measurements were made and error bars are presented in Figure 4-2, providing an indication of the confidence limits. The coefficient of variation for the $PM_{2.5}$ mass was about 5%; excellent precision value for field studies.

Table 4-5 $PM_{2.5}$ Emission Factors in g/kW-hr & Standard Deviation

Load (% rated)	$PM_{2.5}$ (g/kW-hr)	SD
8 (MGO)	0.57	0.05
12 (HFO)	2.03	0.01
25 (HFO)	2.22	0.06
50 (HFO)	2.43	0.12
75 (HFO)	2.91	0.08
90 (HFO)	3.18	0.05
ISO weighted	2.79	

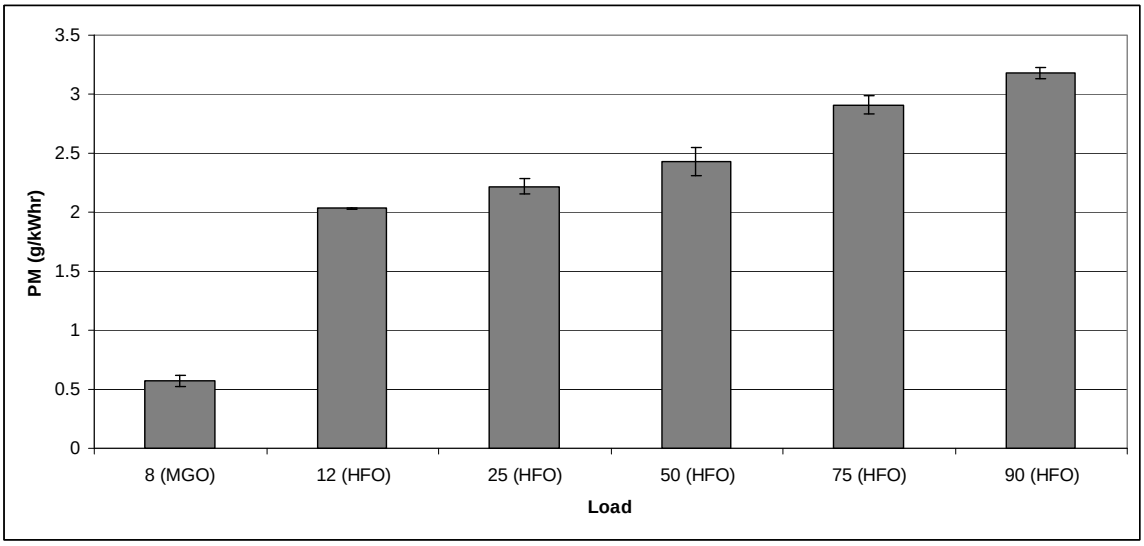


Figure 4-2 Emission Factor (g/kW-hr) for Particulate Matter from the Main Engine as a Function of Load

4.3 Discussion of Emission factors during VSR operation

In May 2001, a Memorandum of Understanding (MOU) between the Ports of Los Angeles and Long Beach (POLA/POLB), the United States Environmental Protection Agency - Region 9, ARB, the South Coast Air Quality Management District, the Pacific Merchants Shipping Association, and the Marine Exchange of Southern California was signed (it was later extended through 2004). This MOU specifically requests OGVs to voluntarily reduce their speed to 12 knots at a distance of 20 nautical miles from the POLA/POLB. In doing so, significant reductions in NOx emissions would occur and help meet the goals of the 1994 ozone State Implementation Plan and 1997 South Coast Air Quality Management Plan.(VSR , 2001)[6]

The VSR mode testing at MGO was conducted while leaving the port in California, and the HFO was conducted while entering the port of Seattle. It was not possible, during the operational limitation of the vessel, to get the exact same load while leaving the Port of Los Angeles and while entering port of Seattle. The VSR load while leaving the POLA was 8 percent of full power with engine running on MGO, while the lowest stable load for the heavy fuel oil combustion in the main engine was 13%.

The emission factors are affected significantly by changes in load when the engine power is below 20% of maximum. The emission factors for NO_x is found to increase with

[6] Vessel Speed Reduction (VSR) for ocean going vessels, http://www.arb.ca.gov/ports/marinevess/vsr/vsr.htm

decrease in engine load. This study provides a conservative estimate of the decrease in NO_x by switching the fuel from HFO to MGO on the main engine of container vessels.
It is found that a 22 percent decrease in NO_x emissions is observed with switching the fuel from HFO to MGO at VSR mode. This increase is much higher than can be attributed to the fuel NO_x (5 – 10%) which is due to differences in the nitrogen contents of the fuels. Further tests are required to confirm this finding.
There is a very minor CO_2 decrease which can be attributed to the differences in engine load to an extent. A decrease of 70% in PM emission factors was observed mainly due to the differences in level of sulfur in the fuel.

4.4 Emission Factors Compared: August 2007 and February 2004 Voyages

Since the engine and vessel tested in this report was also tested in Feb 2004, it was valuable to compare the measured values for the two campaigns. There were differences; however. In February 2004, MAN was the lead group for testing and used their instruments and dilution tunnel for measuring the gaseous and $PM_{2.5}$ emissions. During August 2007, UCR measured the emissions with different instruments and dilution tunnel. However both teams followed the protocols outlined in ISO 8178-1. Figure 4-3 presents the comparison of the CO_2 concentrations from the two emission tests and show that the concentrations of CO_2 were within 8% at the different load points for the two separate tests. This finding provides confidence in the consistency of the test methods and the engine operation at various engine load conditions. The sulfur level in the fuel for the Feb 2004 and the Aug 2007 were 2.4% and 3.01%, respectively. It is observed that the NO_x emissions at lower loads are within up to 25% of the two tests. PM emission normalized by the corresponding sulfur levels in the fuels, are around 6% to 22% lower for Feb 2004 test. In Feb 2004 test a 5m transfer line was used. The losses in this transfer line can explain the lower PM levels observed for the Feb 2004 test.

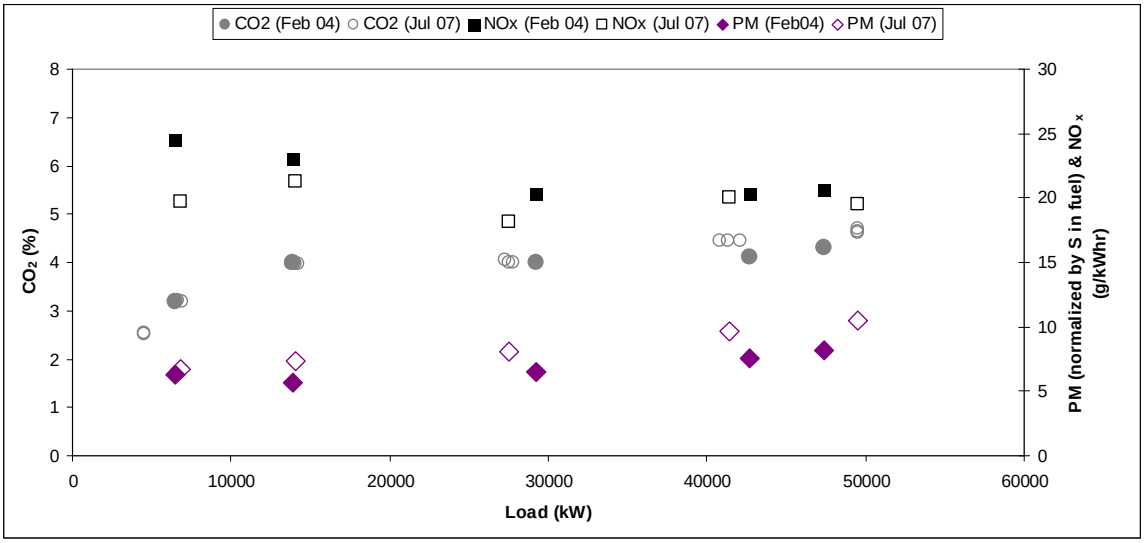


Figure 4-3 Comparison of CO_2, NO_x, $PM_{2.5}$ Concentration vs Load, Feb 2004 vs July 2007 Voyages

5 Results and Discussion – Unregulated Emissions

In addition to measuring the criteria pollutants and carbon dioxide, the project was aimed at measuring the various components of the $PM_{2.5}$ mass into its major fractions. There are very few data from marine engines where the $PM_{2.5}$ mass is fractionated into its major constituent groups: sulfate, organic and elemental carbon. As shown in the following sections, for the high sulfur fuel (3.01 wt. % S) used in the ship tested, the main fraction of $PM_{2.5}$ mass consists primarily of hydrated sulfate followed by organic carbon and finally, elemental (black) carbon. The remaining $PM_{2.5}$ mass includes chemical constituents in the fuel that are found in the parts-per-million range, like vanadium, in fuel that forms ash during the combustion process and contribute a minor amount to the $PM_{2.5}$ mass.

5.1 Emissions of Sulfate

Sulfate was extracted from the Teflon filter as described in Appendix A and the extract analyzed for sulfate ions with an ion chromatograph. The sulfate analyses are shown in Figure 5-1 and relate to the level of sulfur in the fuel. The bunker fuel sulfur content was 3.01% and the MGO sulfur content was 0.2 %.

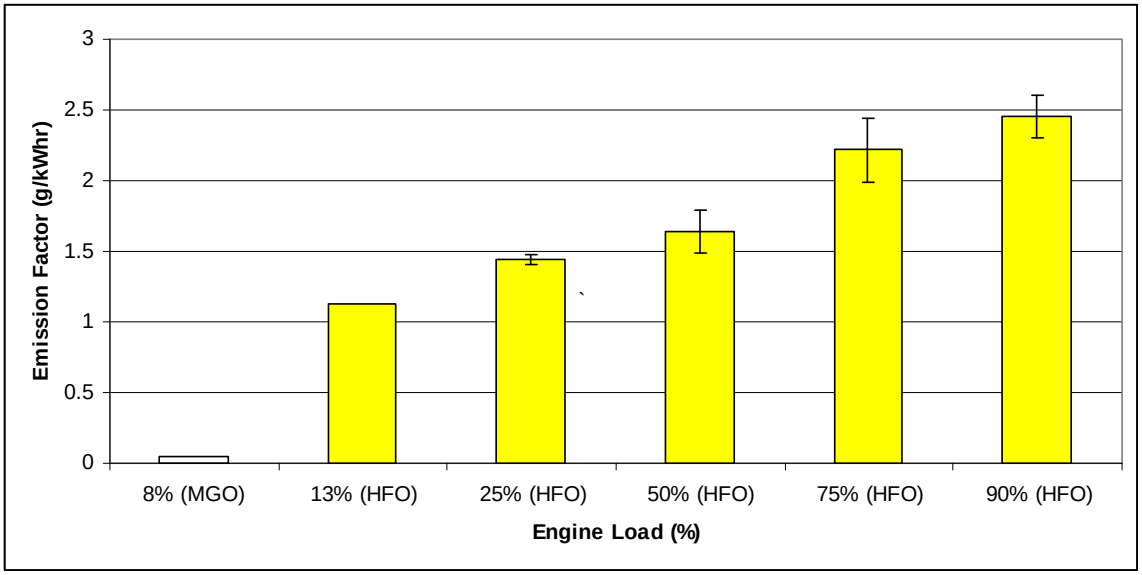


Figure 5-1 Figure of the Sulfate Emissions vs. Engine Load

The same sulfate data at each operating mode are provided in numerical form in Table 7. The calculation assumed that the sulfate was in the form of hydrated sulfuric acid, where 6.5 water molecules were combined with each sulfuric acid molecule.
The emission factor of sulfate is significantly lower when the engine is running on low sulfur marine gas oil. Previous studies[7] have shown that sulfur from fuel to sulfate conversion increases with the engine load, which is the primary reason for the increase in hydrated sulfate emission factor as engine load increases.

Table 7 Sulfate Emissions (g/kW-hr) for the Main Engine

Engine Type	Load %	Unit	Hydrated Sulfate
Main Engine	8 (MGO)	g/kW-hr	0.05
Main Engine	12 (HFO)	g/kW-hr	1.13
Main Engine	25 (HFO)	g/kW-hr	1.44
Main Engine	50 (HFO)	g/kW-hr	1.64
Main Engine	75 (HFO)	g/kW-hr	2.22
Main Engine	90 (HFO)	g/kW-hr	2.46

5.2 Elemental and Organic Carbon

The organic carbon (OC) and elemental carbon (EC) fractions originate mainly from the unburned fuels and lubrication oils. The emissions of elemental and organic carbon (OC/EC) for the main engine are reported in Figure 5-2. Note that the OC levels are greater than ten times the EC levels and increase significantly at the lowest power. The OC and EC emission factors are often used in source apportionment research so determining the OC and EC levels was important for other studies.

[7] Agrawal H., Malloy Q., Welch W.A., Miller J.W., Cocker D.R.(2008a) In-Use Gaseous and Particulate Matter Emissions from a Modern Ocean Going Container Vessel, *Atmos. Environ., 42*, 5504-5510

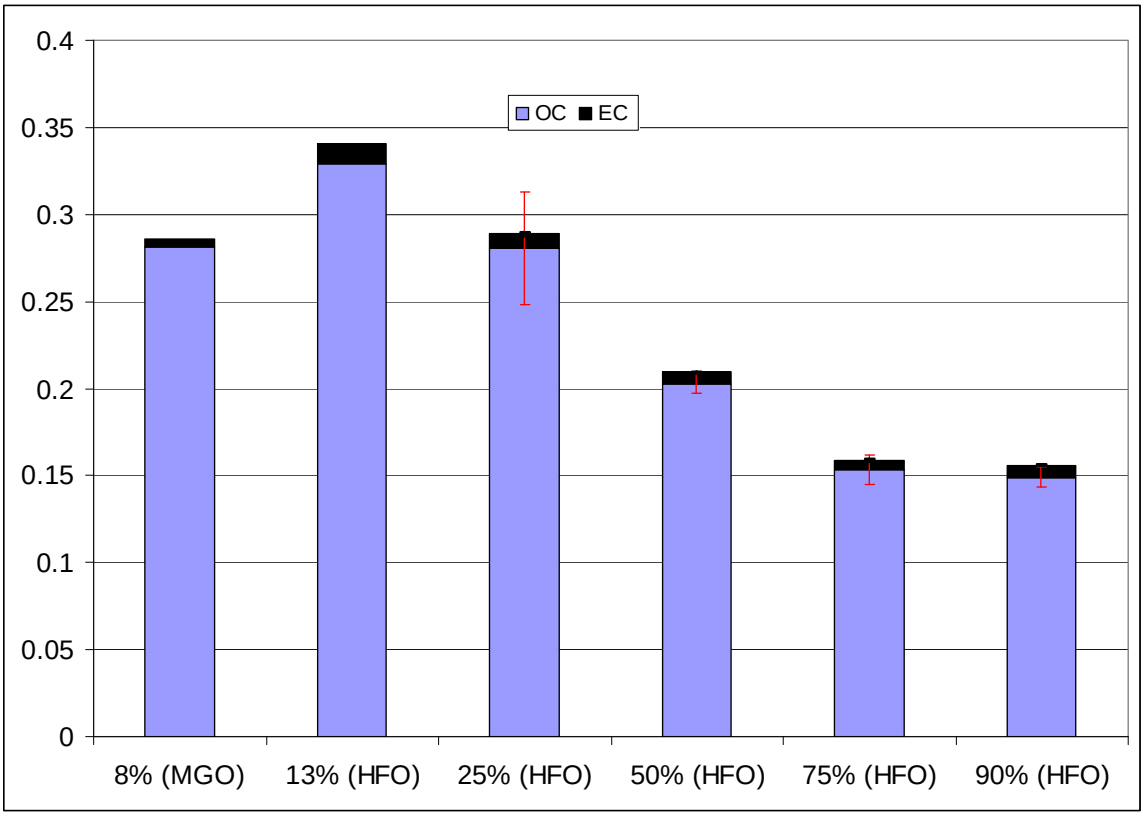


Figure 5-2 Emission Factors in g/kW-hr for the Elemental & Organic Carbon $PM_{2.5}$ fractions

5.3 Quality Check for Conservation of $PM_{2.5}$ Mass Emissions

An important element in UCR's analysis is a check that the total $PM_{2.5}$ mass collected on the Teflon filter equals the the sum of the masses independently measured as sulfate, organic and elemental carbon and estimated ash. The results of the QA/QC for main engine are presented in **Table 8.** The comparison of results between the two methods shows a bias or systematic error with the Teflon mass always being bigger than the composited mass. As shown in **Table 8,** the sulfate fraction represents from 56 to 77% of the $PM_{2.5}$ emissions for the main engine when operating on HFO with 3.01 wt% sulfur.

Table 8 Comparison of $PM_{2.5}$ Emission Factors with EC+OC+ Hydrated Sulfate Emission Factors for Main Engine

[redacted]	[redacted]	$PM_{2.5}$ (g/kWhr)	OC (g/kWhr)	EC (g/kWhr)	Ash (g/kWhr)	Hydrated Sulfate (g/kWhr)
MGO	8%	0.57	0.2815	0.0042	N/A	0.05
HFO	13%	2.03	0.3292	0.0116	0.099	1.13
HFO	25%	2.22	0.2673	0.0081	0.108	1.44

HFO	50%	2.43	0.1997	0.0064	0.097	1.64
HFO	75%	2.91	0.1482	0.0057	0.096	2.22
HFO	90%	3.18	0.1459	0.0068	0.101	2.46

Another perspective is shown in **Figure 5-3** where the total $PM_{2.5}$ measured on the Teflon is compared with the sum of the weights for sulfate, elemental and organic carbon. Clearly this figure shows the Teflon mass is always greater than the sum of the constituent masses suggesting a bias or systematic error in the data.

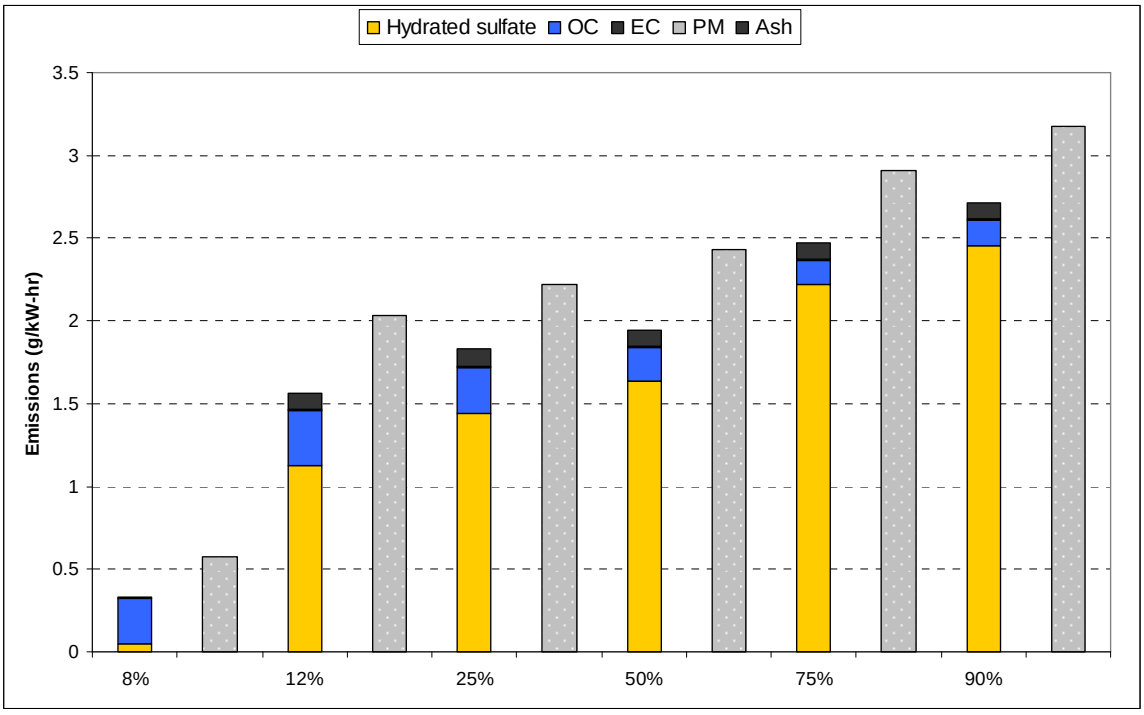


Figure 5-3 Comparative Plots of Total $PM_{2.5}$ Emissions with Composite $PM_{2.5}$ Emissions

6 Results and Discussion – Fuel Switching

6.1 Real Time Emissions Monitoring of Gases and $PM_{2.5}$ during Fuel Switching from MGO to HFO and the Effect on Emission Factor

The vessel voluntarily operates its main propulsion engine on MGO fuel within 20 nautical miles of port. After the vessel was beyond 20 nautical miles, the fuel into the main engine was switched to HFO and the engine load increased from 8% to 57%. Figure 6-1 presents a chart showing the continuous concentration of gases and $PM_{2.5}$ emissions (from the Dekati DMM) during the period of the fuel switch and increase in the engine load. The plot shows that the effect of fuel switching. Note for the gases -- NO_x, CO_2, and CO – the change was almost instantaneous, but for the SO_2 and $PM_{2.5}$ emissions the change took over one and half hour to stabilize.

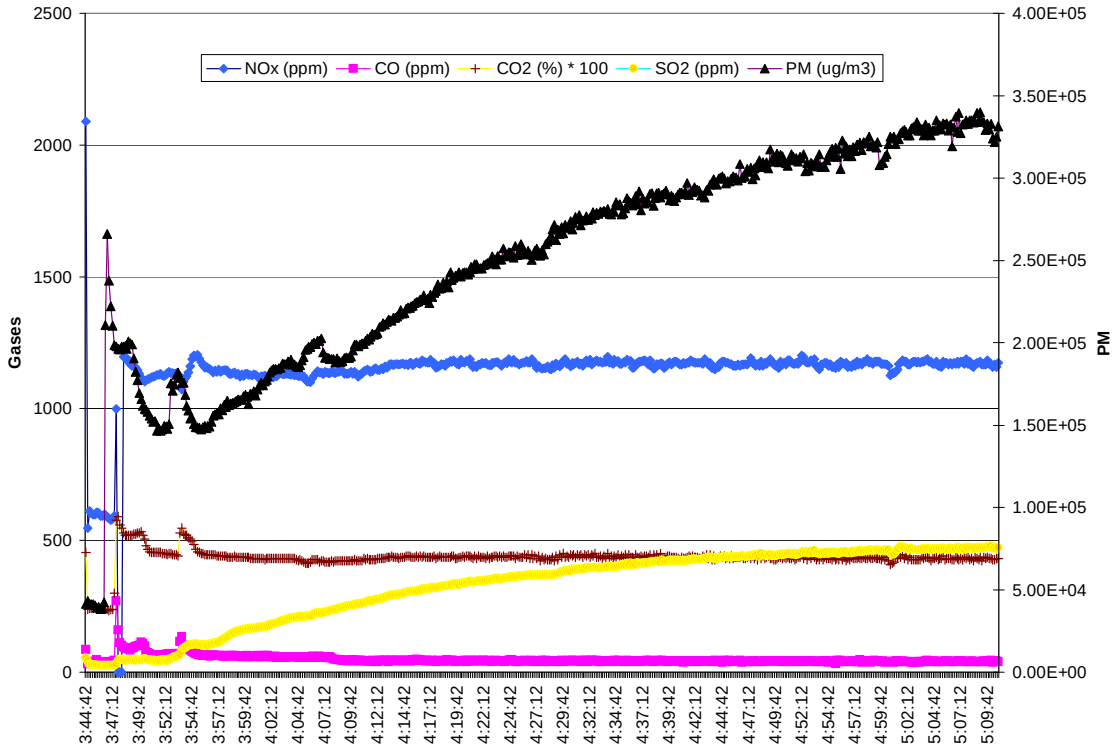


Figure 6-1 Continuous Monitoring of Gaseous and $PM_{2.5}$ Emissions during the Fuel Switch from MGO to HFO

6.2 Theory to explain delay time for the SO_2 & $PM_{2.5}$ transient behavior on the fuel switch

One of the interesting observations was the fact that the SO_2 and $PM_{2.5}$ apparently took about 90 minutes to stabilize after the fuel switch as compared with about 5 minutes for

the carbon and nitric oxide gases. Since the SO_2 took the same time as the $PM_{2.5}$ as shown in Figure 6-3, it is clear that the observed transient behavior of the data can be explained by the time required for the fuel mixing and change out from the MGO to HFO in the fuel system. The ships fuel oil system is perhaps one of the most complicated systems on board (Appendix C). The fuel oil system comprises of bunkering, settling, centrifuging and service tank system for MDO and HFO fuels. Appendix C describes the fuel oil system and the complexity associated with the mixing of two different fuels during fuel switching. The observed behavior in mixing is an unsteady case and follows a logarithmic increment as shown in Figure 6-2.

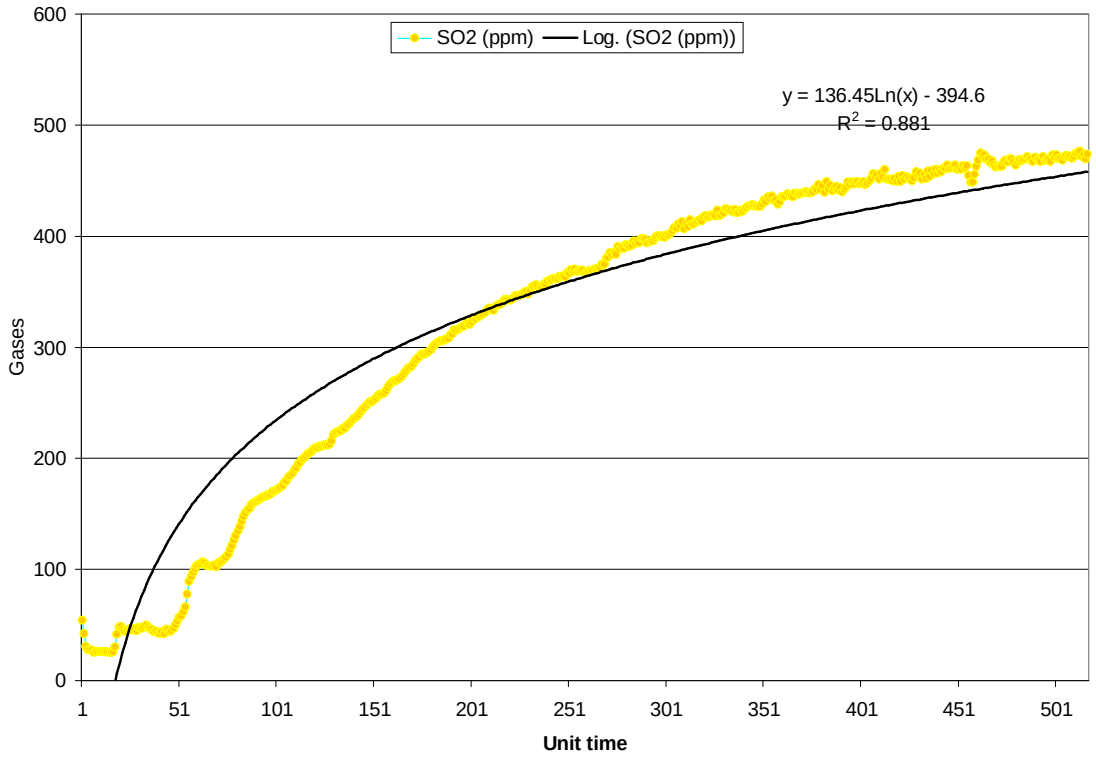


Figure 6-2 Mixing Function fit for the SO_2 concentration change with time during fuel switching

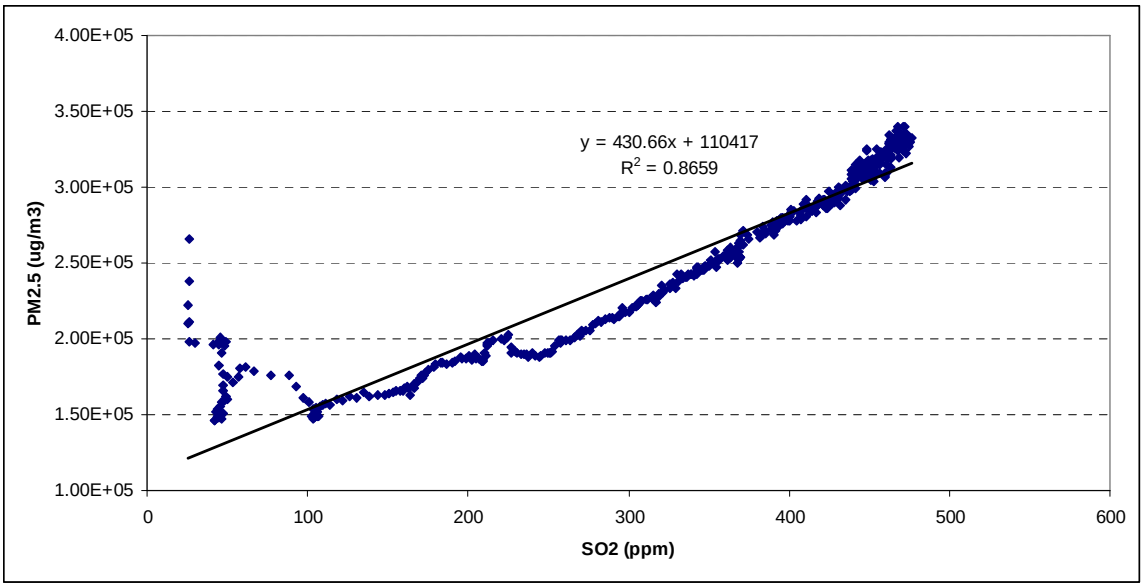


Figure 6-3 $PM_{2.5}$ vs SO_2 concentrations during the fuel switching

7 Findings and Recommendations

The California Air Resources Board and the University of California, Riverside (UCR) partnered with the shipping company to measure the criteria pollutant and particulate matter ($PM_{2.5}$) emissions from the main engine of a Post Panamax Class container vessel running on 3.01 wt% sulfur Heavy Fuel Oil (HFO) and 0.2 wt% sulfur Marine Gas Oil (MGO). Exhaust sampling took place over a three day voyage from Los Angeles, CA to Seattle, WA during July, 2007

Emission factors determined from testing of the main propulsion engine are presented in Table ES-1.

Table ES-1: Emission Factors for the Main Propulsion Engine

Load %	Fuel Type	CO_2	SO_2	CO	NO_x	$PM_{2.5}$
		(g/kWhr)	(g/kWhr)	(g/kWhr)	(g/kWhr)	(g/kWhr)
8%	MGO	578	0.72	0.54	15.34	0.57
13%	HFO	623	11.62	0.52	19.77	2.03
25%	HFO	678	12.66	0.41	21.33	2.22
50%	HFO	611	11.40	0.29	18.10	2.43
75%	HFO	604	11.28	0.28	20.08	2.91
90%	HFO	636	11.87	0.30	19.50	3.18

Results show that switching fuel from HFO to MGO during the VSR speed decreased the NOx emission factor by 22 percent and the $PM_{2.5}$ by 72%; the latter is mainly due to the sulfur reduction in the fuel. The NO_x reduction of 22% is much higher than expected due to the fuel switching. Thus, authors recommend a repeat of the measurement campaign to confirm these findings of fuel switching in this report.

Furthermore, continuous monitoring showed it took about ninety minutes for the $PM_{2.5}$ and SO_2 emissions to stabilize after the fuel switch, indicative of the mixing in the fuel system.

The authors recommend a repeat of the measurement campaign to confirm the findings in this report. Additionally, emission measurements at all the ISO certification loads and at the same VSR loads comparing HFO and MGO fuels can provide insightful information on fuel switching.

Appendix A

A.1 Certification Test Protocol for Emissions from Marine Engines

In 2003, the US EPA[8] published the compliance limits, the test protocols and measurement methods for large marine engines in the Code of Federal Regulations. EPA recognized the duty cycle used in determination of compliance with emission standards was critical and specified a duty cycle intended to simulate in-use operation. Testing consisted of exercising the engine over a prescribed duty cycle of speeds and loads. To address operational differences between engines, EPA adopted two different duty cycles. One for engines that operate on a fixed-pitch propeller curve (E3) and the other for propulsion engines that operates at a constant speed (E2). These are the same duty cycles specified by International Organization for Standardization[9] (ISO) and IMO Annex VI and shown in **Error! Reference source not found.** below.

Table A- 1 ISO Test Cycles type "E" for Marine Applications

Mode number (cycle B)	1	2	3	4	5	6	7	8	9	10	11
Mode number (cycle E1)	**1**	**2**					**3**	**4**			**5**
Speed	Rated speed					Intermediate speed					Low-idle speed
Torque [1], %	100	75					75	50			0
Weighting factor	0,08	0,11					0,19	0,32			0,3
Mode number (cycle E2)	**1**	**2**	**3**	**4**							
Speed	Rated speed					Intermediate speed					Low-idle speed
Torque [1], %	100	75	50	25							
Weighting factor	0,2	0,5	0,15	0,15							
Mode number (cycle E3)	**1**					**2**		**3**		**4**	
Speed [1], %	100					91		80		63	
Power, %	100					75		50		25	
Weighting factor	0,2					0,5		0,15		0,15	

For this vessel, UCR followed the E3 cycle as closely as practical. Usually the engine is not operated at 100% power so UCR measured the vessel at the highest power possible.

[8] US Environmental Protection Agency, 40 CFR Parts 9 and 94 *Control of Emissions From New Marine Compression-Ignition Engines at or Above 30 Liters Per Cylinder*; Final Rule, February 28, 2003

[9] International Standards Organization, IS0 8178-4 First edition, 1996-08-l 5, *Reciprocating Internal Combustion Engines - Exhaust Emission Measurement -Part 4: Test Cycles for Different Engine Applications* Reference number IS0 8178-4:1996(E)

Measurements were also made at the speed of 12 knots required for the Voluntary Speed Reduction (VSR) program.

A.2 Measuring Gaseous and $PM_{2.5}$ Emissions from Marine Diesel Engines

UCR selected methods for sampling and analysis of the gases and particulate matter ($PM_{2.5}$) to conform to the requirements of ISO 8178-1[10]. The approach involved the use of a partial flow dilution system with single Venturi as shown in Figure A-1. Raw exhaust gas was transferred from the exhaust pipe (EP) to the dilution tunnel (DT) through the sampling probe (SP) due to the negative pressure created by the Venturi (VN) in DT.

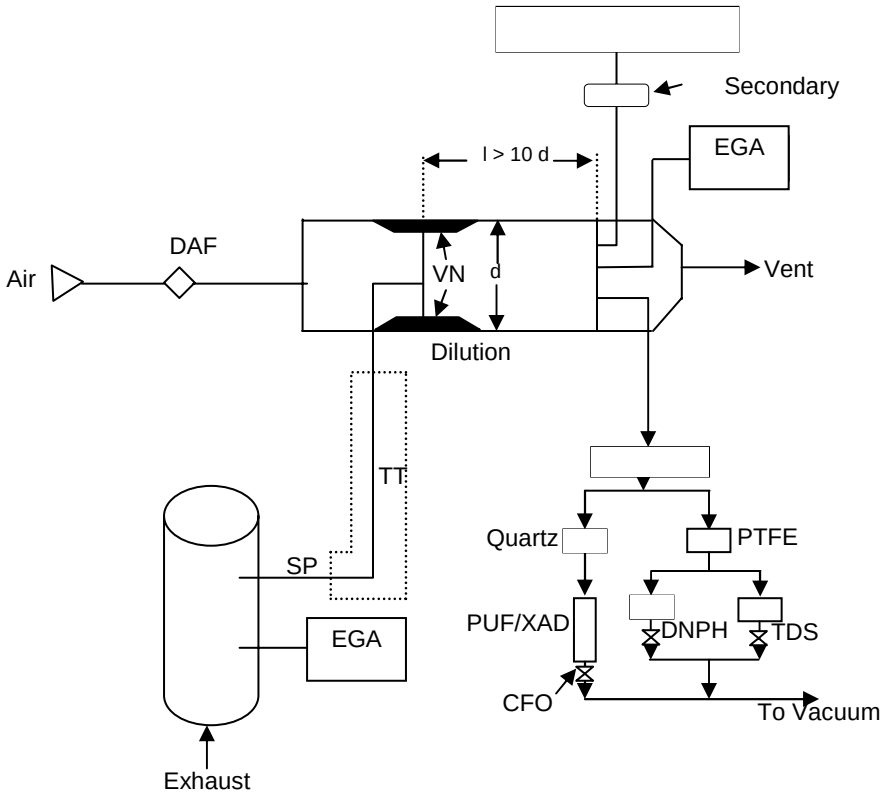


Figure A- 1 Partial Flow Dilution System with Single Venturi, Concentration Measurement and Fractional Sampling

The gas flow rate through SP depends on the momentum exchange at the Venturi zone and is therefore affected by the absolute temperature of the gas at the exit of tube in the Venturi. 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. The tracer gas concentrations (CO_2 or NO_x) are measured in the raw exhaust gas, the diluted exhaust gas

[10] *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*

and the dilution air using the exhaust gas analyzer (EGA), and the dilution ratio is calculated from the measured values.

In order to apply the ISO approach in the field, UCR designed a portable set of equi$PM_{2.5}$ent that is field deployable. The equi$PM_{2.5}$ent fits into several metal cases with an interior of foam molding to allow sensitive equi$PM_{2.5}$ent, like computers, to be easily transported or even be lifted and dropped into cargo areas on a vessel without harm to the contents. For practical purposes, the design includes pieces of equi$PM_{2.5}$ent that allow the use of a range of common electrical (120/240V, 50/60Hz) and supply air utilities. For example, while UCR tries to obtain instrument grade pressurized air for dilution air, we further process any supply air through a field processing unit to assure the quality of the dilution air. The processing air takes the supply air through a number of steps including reducing the pressure to about 30psig as that allows a dilution ratio of about 5/1 in the geometry of our system. The next stages, in sequence, for conditioning the supply air included: 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 campaign Figure A- 2 below shows the unit for processing the dilution air.

Figure A- 2 Field Processing Unit for Purifying Dilution Air in Transport Case

A.2.1 Measuring the Gaseous Emissions

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 using the measurement methods recommended by the EPA. The signal output of the instrument was interfaced directly

with a laptop computer through an RS-232C interface to record measured values continuously (Figure A-3). 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. EPA ETV program.

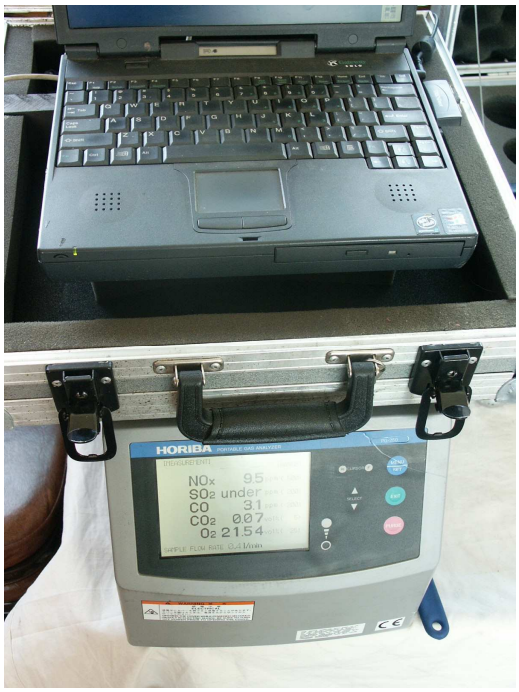


Figure A- 3 In-field Illustration of Continuous Gas Analyzer and Computer for Data Logging

Details of the gases and the ranges for the Horiba instrument are shown in **Error! Reference source not found.**. Note that the Horiba instrument measured sulfur oxides (SO_2); however, the ISO reference reports: "The SO_2, concentration shall be calculated from the sulfur content of the fuel used, since experience has shown that using the direct measurement method for SO_2, does not give more precise results."

Table A- 2 Detector Method and Concentration Ranges for Monitor

Component	Detector	Ranges
Nitrogen Oxides (NOx)	Heated Chemiluminescence Detector (HCLD)	0-25, 50, 100, 250, 500, 1000, & 2500 $pPM_{2.5}v$
Carbon Monoxide (CO)	Non dispersive Infrared Absorption (NDIR)	0-200, 500, 1000, 2000, & 5000 $pPM_{2.5}v$
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 $pPM_{2.5}v$
Oxygen	Zirconium oxide sensor	0-10, & 25 vol%

For quality control, UCR carried 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 by Praxair (Los Angeles, CA). Drift was determined to be within manufacturer specifications of ± 1% full scale per day, except for SO_2 set at ± 2% F.S./day. Other specifications of the instruments are provided in Error! Reference source not found. below.

Table A- 3 Quality Specifications for the Horiba PG-250

Repeatability	±0.5% F.S.(NOx : ≦100ppm range CO : ≦1000ppm range) ±1.0% F.S.
Linearity	±2.0% F.S.
Drifft	±1.0% F.S./day(SO_2 : ±2.0%F.S./day)

A.2.2 Measuring the Particulate Matter ($PM_{2.5}$) Emissions

A raw particulate sampling probe was fitted close to and upstream of the raw gaseous sample probe in the exhaust. In order to measure $PM_{2.5}$, a sampling probe was inserted into the end of the dilution tunnel (>10 diameters downstream) and directed to a $PM_{2.5}$ sample splitter that allowed up to three samples to be collected. For the particulate samples, we used one of the $PM_{2.5}$ lines and directed it to a cyclone separator, sized to

remove particles >$_{2.5}$um. From the separator, we added two lines with 47 Gelman filter holders, one for collecting $PM_{2.5}$ on a Teflon filter and the other for collecting $PM_{2.5}$ on a quartz filter. Thus the flow in the dilution tunnel was split into two fractions, a smaller flow for measuring $PM_{2.5}$ mass and $PM_{2.5}$ properties and a much larger flow that was vented outside the vessel. Note with the partial dilution approach for measuring gases and $PM_{2.5}$ that it is critical for the dilution ratio be determined very accurately.

UCR collected simultaneous Teflon and quartz filters at each operating mode and analyzed them according to standard procedures. The simultaneous collection of quartz and Teflon filters allows an internal quality check of the $PM_{2.5}$ mass. Teflon (Teflo) filters used to acquire $PM_{2.5}$ mass were weighted following the procedure of the Code of Federal Regulations (CFR) (40 CFR Part 86). Briefly, total $PM_{2.5}$ were collected on Pall Gelman (Ann Arbor, MI) 47 mm Teflo filters and weighed using a Cahn (Madison, WI) C-35 microbalance. Before and after collection, the filters were conditioned for 24 hours in an environmentally controlled room (RH = 40%, T = 25 °C) and weighed daily until two consecutive weight measurements were within 3 µg.

$PM_{2.5}$ samples were 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 $PM_{2.5}$ filters were sealed in containers immediately after sampling, and kept chilled until analyzed.

A.3 Quality Control/Quality Assurance (QC/QA)

Each of the laboratory methods for $PM_{2.5}$ mass and chemical analysis has a standard operating procedure including the frequency of running the standards and the repeatability that is expected when the standard is 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.

- For the ISO cycles, run the engine at rated speed and the highest power possible to warm the engine and stabilize emissions for about 30 minutes.
- Determine a plot or map of the peak power at each engine $RPM_{2.5}$, starting with rated speed. UCR suspected the 100% load point at rated speed was unattainable with propeller torque so Mode 1 would represent the highest attainable $RPM_{2.5}$/load.
- Emissions were measured while the engine operates according to the requirements of ISO-8178-E3. For the main engine first run was made for 50% load which was also the mode running on the 12 knots speed for Vehicle Speed Reduction (VSR), The minimum time for main engine samples were 5 minutes and if necessary, the

time was extended to collect sufficient particulate sample mass or to achieve stabilization with large engines.

- The gaseous exhaust emission concentration values were measured and recorded for the last 3 min of the mode.
- Engine speed, displacement, boost pressure, and intake manifold temperature were 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.

Appendix B- Test Data and Calculations

B.1 Detailed Engine Operational Results

test set	fuel type	Engine type	Load %	Load	Dilution Ratio (Primary)	$RPM_{2.5}$	scavenge air pressure	scavenge air temp	Displacement Liters	Std Correct (Pa*Tstd)/(Pstd*Ta)	Calc Flow scfm	Corrected Flow scfm
				MW			bar	C				
VSR	MGO	ME	8	4.549	4.592593	43.35	0.1	34	17558.4	1.048637	28183.63	32694.0819
VSR	MGO	ME	8	4.549	4.592593	43.6	0.1	34	17558.4	1.048637	28346.16	32694.0819
ISO	HFO	ME	90	49.55	4.070796	94	2.36	41	17558.4	3.107132	181079.9	139149.331
ISO	HFO	ME	90	49.55	4.070796	93.8	2.36	41	17558.4	3.107132	180694.6	139149.331
ISO	HFO	ME	90	49.55	4.070796	93.8	2.36	41	17558.4	3.107132	180694.6	139913.72
ISO	HFO	ME	75	40.786	3.990826	87.9	1.82	36	17558.4	2.651904	144520.5	213737.605
ISO	HFO	ME	75	42.117	3.990826	88.7	1.89	36	17558.4	2.717429	149439.2	213737.605
ISO	HFO	ME	75	41.323	3.990826	88.7	1.9	36	17558.4	2.72679	149954	213737.605
ISO	HFO	ME	50	27.567	4.28866	77.8	1.12	30	17558.4	2.036169	98214.59	178479.1566
ISO	HFO	ME	50	27.825	4.28866	77.3	1.12	29	17558.4	2.042908	97906.35	180639.5613
ISO	HFO	ME	50	27.232	4.28866	77.6	1.12	29	17558.4	2.042908	98286.32	183833.9027
ISO	HFO	ME	25	14.025	4.354167	63.1	0.39	31	17558.4	1.334905	52223.06	123950.0592
ISO	HFO	ME	25	14.25	4.354167	62.1	0.37	33	17558.4	1.307279	50331.82	125297.7977
ISO	HFO	ME	25	13.812	4.354167	61.8	0.37	33	17558.4	1.307279	50088.67	126335.7575
VSR test	HFO	ME	13	6.893	5.54386	49.65	0.17	32	17558.4	1.121894	34534.54	69960.0572
VSR test	HFO	ME	12	6.679	5.54386	49.6	0.16	33	17558.4	1.108777	34096.4	70816.9775

C- Modeling the fuel switching

Figure C-1 describes that the ship's fuel oil system is perhaps one of the most complicated systems on board. Naturally, introducing multiple fuel oil system implies considerable additional complexity to the ship design in general and to the engine room design in particular[11].

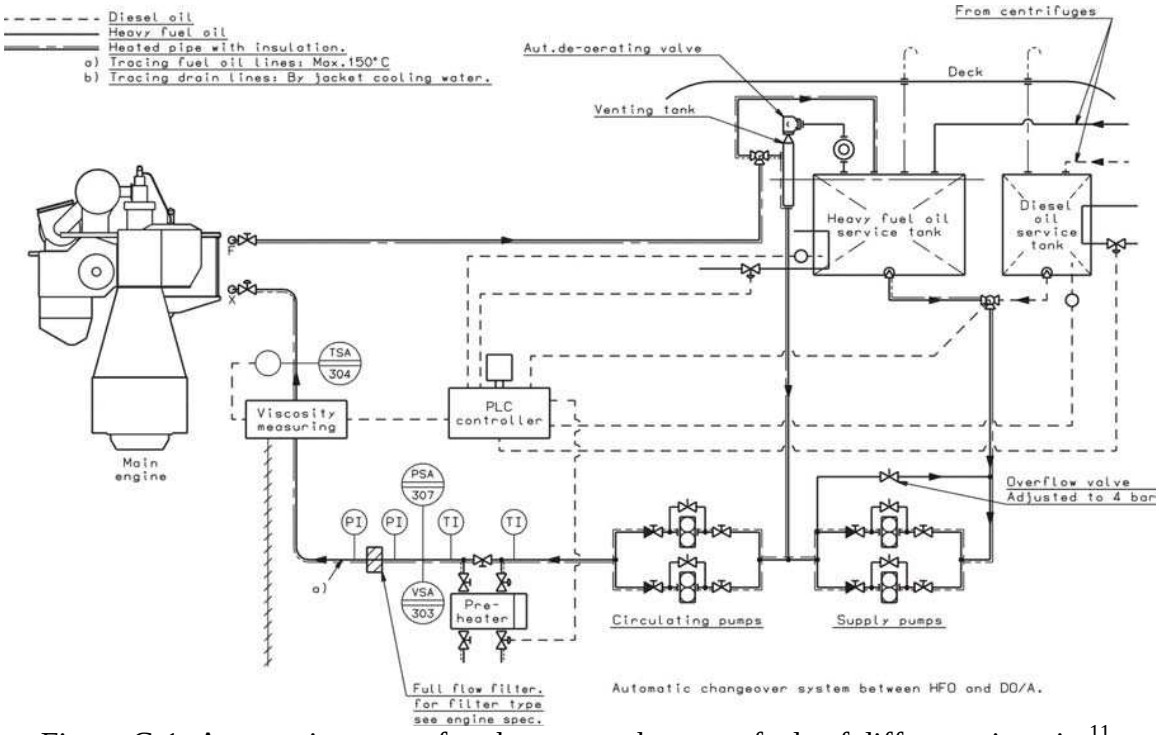


Figure C-1: Automatic system for changeover between fuels of different viscosity[11].

A typical fuel oil system for changeover has separate bunkering, settling, centrifuging and service tank system for MDO and for HFO (Figure C-2). More details of the fuel system are provided in documents from engine manufacturer[12]. Briefly, during operation at sea the fuel from the bunker tanks is first treated in centrifugal seperators before entering the service tanks. From the service tanks, the fuel enters the supply system. In the supply system, the fuel is pumped by the supply pump into a circulating system.The circulating system is followed by a pre heater (which heats the HFO until it reaches the necessary viscosity) and a fuel filter. Excess fuel oil supplied to the engines is re-circulates via the venting box.

[11] Operation on Low –Sulphur Fuels : Two Stroke Engines, MAN Diesel A/S Copenhagen, Denmark, http://www.manbw.com/article_005271.html

[12] Uni-concept Auxiliary Systems for Two-stroke Main Engines and Four-stroke Auxiliary Engines, MAN Diesel A/S Holeby, Denmark, http://www.manbw.com/files/news/filesof1418/19992814.pdf.

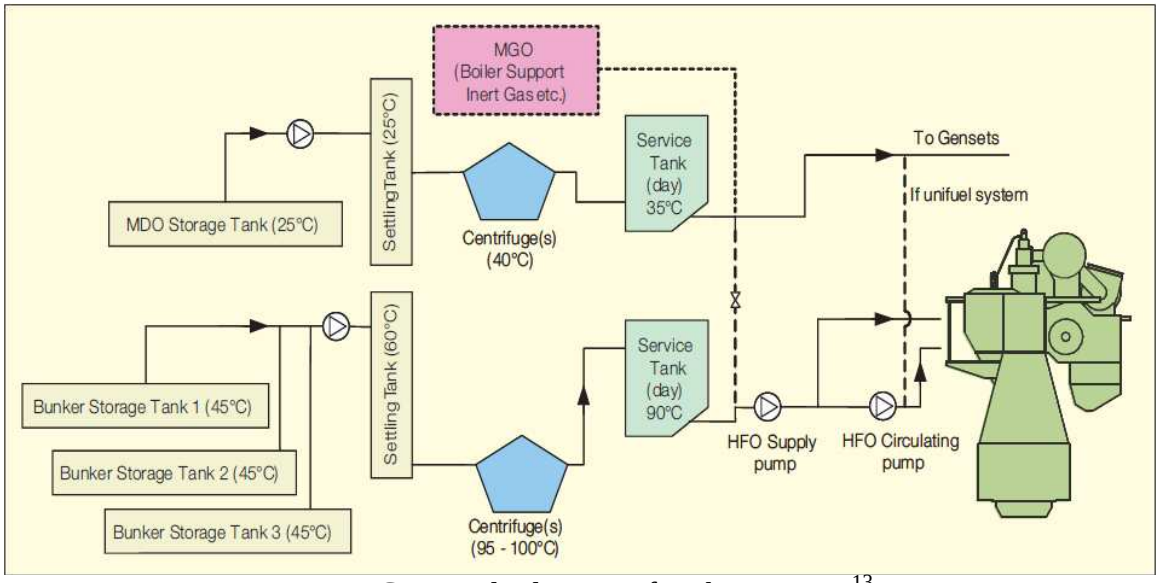
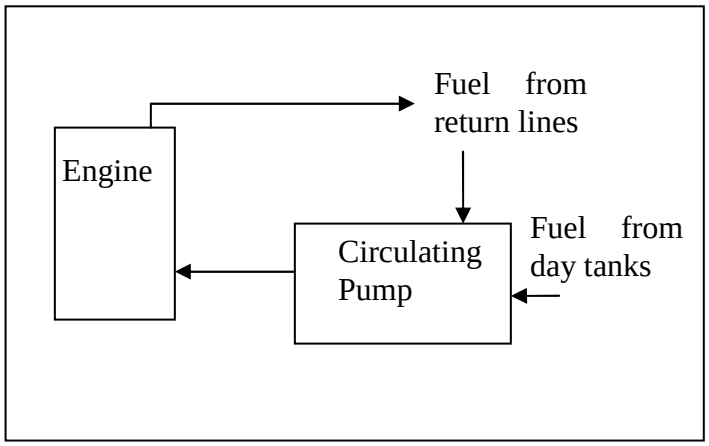


Figure C-2: Fuel oil system for changeovers[13]

It has been observed in this study that the SO_2 and $PM_{2.5}$ took about 90 minutes to stabilize after the fuel switch as compared with about 5 minutes for the carbon and nitric oxide gases. The time taken for stabilization of SO_2 and $PM_{2.5}$ can only be explained by the mixing of two fuels with different sulfur levels in the fuel oil system. Since there are separate service tanks (day tanks) for different fuels equipped with three way valves as described in Figure C-1, the mixing of two fuels would happen in the fuel lines from service tanks to the engine and the re-circulation line from the engine to the circulating pumps (Figure C-3).



.Figure C-3: Mixing in the Fuel System

The lack of understanding of fuel flow rates in the return lines and the feed in the pumps, restrict us to accurately model the mixing.

[13] Operation on Low –Sulphur Fuels : Two Stroke Engines, MAN Diesel A/S Copenhagen, Denmark http://www.manbw.com/article_005271.html