In-use Emissions Test Program at VSR Speeds for Oceangoing Container Ship

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List of Acronyms

Al	Aluminum
ºC	degree centigrade
C	Carbon
CA	California
CARB	California Air Resources Board
CFO	Critical Flow Orifice
CFR	Code of Federal Regulation
CO	Carbon monoxide
CO_2	Carbon dioxide
DAF	Dilution Air Filter
DNPH	2,4Dinitrophenylhydrazine
DT	Dilution Tunnel
EC	Elemental Carbon
EGA	Exhaust Gas Analyzer
EP	Exhaust Pipe
EPA	Environmental Protection Agency
Ft	feet
FTIR	Fourier Transform Infra-Red
F.S./day	full scale per day
g/kW-hr	grams per kilowatt-hour
g/nmi	grams per nautical mile
HFO	Heavy Fuel Oil
Hz	Hertz
HCLD	heated chemiluminesence detector
HEPA	High Efficiency Particulate Air
H_2O	Water
$H_2SO_4.6.5H_2O$	hydrated sulfate or hydrated sulfuric acid
IMO	International Maritime Organization
ISO	International Organization for Standardization
kg/hr	kilograms per hour
kg/m^3	kilograms per cubic-meter
kg/nmi	kilograms per nautical mile
kW	kilowatt
lt	liters
lt/hr	liters per hour
m	meter
MDO	Marine Distillate Oil
MGO	Marine Gas Oil
MI	Michigan
min	minutes
MOUDI	Micro-Orifice Uniform Deposit Impactor
mm^2/s	square-millimeter per second

m/m	mass by mass
NDIR	Non-dispersive infra red
$(NH_2)_2CO$	Urea
NH_3	Ammonia
NIOSH	National Institute of Occupations Safety and Health
NO	Nitrogen monoxide
NO_x	Oxides of Nitrogen
NO_2	Nitrogen dioxide
N_2	Nitrogen
OC	Organic Carbon
PM	Particulate Matter
PTFE	Polytetrafluoroethylene or Teflon Filter
ppm	parts per million
ppmV	parts per million by volume
psig	pound-force per square-inch gauge
PUF	Poly Urethane Foam/XAD
QC/QA	Quality Control/Quality Assurance
RH	Relative Humidity
RPM	revolutions per minute
SCR	Selective Catalytic Reduction
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
SP	Sampling Probe
T	Temperature
TDL	Tunable Diode Laser
TDS	Thermal Desorption System
TT	Transfer Tube
UCR	University of California, Riverside
U.S.	United States
V	Volts
VN	Venturi
vol%	volume %
wt/wt%	weight by weight %
WI	Wisconsin

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Executive Summary

Background: California Air Resources Board (CARB) and the University of California, Riverside jointly worked with a shipping company to study the impacts of Vessel Speed Reduction (VSR) on the in-use emissions of ocean-going vessels. A voluntary VSR program is currently in place at the Port of Los Angeles and Port of Long Beach (POLA/POLB) and is implemented within 20 and 40 nautical miles (nm) from the ports. CARB has been evaluating the need for a VSR program which has been identified to improve the air quality along California's coastline communities. It has also been identified by several other ARB programs such as Diesel Risk Reduction Plan; the Goods Movement Emissions Reduction Plan, and Assembly Bill 32 - Greenhouse Gas Initiative. The VSR program offers emissions reductions of diesel particulate matter (PM), oxides of nitrogen (NO_x), oxides of sulfur (SO_x) and carbon dioxide (CO_2).

Approach: Two measurement voyages were performed at sea on a Panamax class container vessel (first vessel) in July and August 2009; two measurements would confirm the reproducibility of measured values. A third voyage was made in September 2010 on a modern Post Panamax vessel (second vessel) that was launched in 2010. The project measured emissions on the main engines while departing a southern California port and approaching another west coast port. The main engine on the first vessel had a maximum power rating of 37MW and the second vessel was 69MW. Measured emissions of gases (CO_2, CO, NO_x, and THC) and particulate matter ($PM_{2.5}$) mass from the main engine were performed in compliance with the ISO 8178-2 protocol while the engine operating conditions followed the ISO 8178-4 E3 certification test cycles. In addition, emission measurements were performed at low loads targeting lower vessel speeds to determine the potential emission reductions under the VSR mode. Tests were conducted on both high and low sulfur fuels, HFO and MGO.

Results: Table ES.1 summarizes the gaseous emissions and particulate matter mass in g/kW-hr obtained from the two measurement voyages of the first vessel. The results showed that the measurements repeated reasonably well during both voyages. It is to be noted that the results for EC and OC fractions are not available for the second voyage because of electrical difficulties. Table ES.2 summarizes the gaseous and particulate emissions in g/kW-hr from the second vessel. Table ES.3 summarizes the average reduction in gaseous and particulate emissions due to the reduction in vessel speed from cruise to 12 knots or less.

Table ES.1 Executive Summary Table for first Vessel

Test Set	Actual Speed (Knots)	Fuel	Target ISO Load	Actual Load	Gaseous and Particulate Emissions (g/kW-hr)							
					CO_2	NOx	CO	THC	$PM_{2.5}$	EC	OC	$SO_4^{2-}6H_2O$
Voyage 1												
VSR 12	12.0	HFO		10%	869	32.1	1.85	N/A	2.59	0.01	0.28	1.99
VSR 12	11.0	MGO		11%	777	24.9	2.07	1.94	0.25	0.01	0.10	0.02
VSR 15	15.0	MGO		21%	642	19.8	2.14	1.20	0.16	0.01	0.08	0.03
25%	17.0	HFO	25%	29%	577	19.5	0.57	0.30	1.19	0.01	0.15	0.89
50%	19.5	HFO	50%	52%	555	18.5	0.41	0.30	1.44	0.01	0.20	1.14
75%	23.0	HFO	75%	73%	561	19.5	0.36	0.26	2.14	0.01	0.23	1.64
85%	24.0	HFO	85%	81%	576	19.1	0.35	0.25	2.19	0.01	0.24	2.07
Overall Weighted Emission Factor					565	19.3	0.37	0.26	2.00	0.01	0.22	1.63
Voyage 2												
VSR 12	13.0	MGO		9%	828	25.5	2.10	2.44	N/A	N/A	N/A	N/A
VSR 15	14.0	MGO		17%	720	22.5	N/A	1.49	N/A	N/A	N/A	N/A
VSR 15	14.0	MGO		19%	709	21.9	1.50	N/A	0.18	N/A	N/A	N/A
25%	16.0	HFO	25%	28%	584	18.9	0.60	0.30	0.91	N/A	N/A	N/A
50%	19.5	HFO	50%	44%	533	16.6	0.44	0.28	1.07	N/A	N/A	N/A
75%	23.0	HFO	75%	69%	612	20.6	0.39	0.26	1.60	N/A	N/A	N/A
85%	24.0	HFO	85%	83%	579	19.0	0.35	0.22	1.56	N/A	N/A	N/A
Overall Weighted Emission Factor					593	19.6	0.40	0.26	1.49	N/A	N/A	N/A

Table ES.2 Executive Summary Table for second Vessel

Test Set	Speed (Knots)	Fuel	Target ISO Load	Actual Load	Gaseous Emissions (g/kW-hr)				$PM_{2.5}$ and Speciated $PM_{2.5}$ (g/kW-hr)			
					CO_2	NO_x	CO	THC	$PM_{2.5}$	EC	OC	SO_4^{2-}
VSR 12	12.0	MGO		12%	749	26.4	0.40	0.45	0.3	0.003	0.18	0.05
VSR 15	15.0	MGO		23%	672	16.8	1.89	0.34	0.3	0.003	0.17	0.08
25%	17.0	HFO	25%	24%	644	14.9	1.71	0.21	1.2	0.009	0.22	0.79
50%	21.8	HFO	50%	47%	626	14.4	1.23	0.14	1.2	0.006	0.19	0.94
75%	25.0	HFO	75%	75%	590	16.9	0.33	0.11	1.4	0.004	0.17	1.18
100%	26.5	HFO	100%	90%	600	15.2	0.36	0.12	1.5	0.004	0.16	1.34
Overall weighted emission factor					600	16.1	0.51	0.12	1.4	0.005	0.17	1.18

Table ES.3 Emissions Reduction due to VSR

Percent Reduction in Emissions due to VSR					
CO_2	NOx†	$PM_{2.5}$	EC	OC	$SO_4^{2-}H_2O$
61	56	69	53	70	75

†Note that the 56% reduction in NOx is attributed to change in fuel (HFO to MGO) and VSR

Conclusions: Two different emission measurements from the first vessel were within ~10% across all ISO load points. The overall in-use NOx emission factor from the second vessel was 5%, lower than the Tier 1 certification (17 g/kW-hr) and 14% lower than the benchmark value of 18.7 g/kW-hr commonly used for estimating emission inventories. Emissions rates were calculated in kilograms per nautical mile to evaluate emission benefits due to VSR. Based on measurements conducted in this study, approximately 61%, 56% and 69% reduction in CO_2, NOx and $PM_{2.5}$ was observed by reducing vessel speeds from cruise to 12 knots or less in the VSR zone, respectively.

1 Introduction

1.1 Background

Sea transport is now widely recognized as a considerable and increasing source of air pollution. Fuel consumption and emissions from international shipping have substantially increased over the past decade (Eyring et al., 2005). Several reviews have illustrated the magnitude of the problem on global (Corbett and Kohler, 2003; Endreson et al., 2003, 2007), regional (European Commission, 2002a) and local scales (Isakson et al., 2001; Saxe and Larsen, 2004). The principal exhaust gas emissions from ships include carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) (Lloyd's, 1995). It is well known that these emissions of exhaust gases and particles from ocean-going vessels (OGVs) affect the chemical composition of the atmosphere, climate and regional air quality and health.

A great majority of prime movers and auxiliary plants of ocean-going ships are diesel engines. As for large container ships, almost all are powered by slow-speed, two-stroke diesel engines. Diesel engines are used widely as power sources for coastal ships and international vessels primarily due to their high thermal efficiency, high fuel economy and durable performance. However, the gaseous and solid substances exhausted from diesel engines during the combustion process cause air pollution, in particular around harbor regions. Even though the containerships represent only 4% of the world's marine fleet, they are among the largest maritime emitters of CO_2 (Corbett, 2009). Despite their relatively small number, in 2007 they consumed over 70 million metric tons (Mmt) of bunker fuel and emitted over 230 Mmt of CO_2; this represents some 22% energy consumption and CO_2 emissions from international shipping (Buhaug et al., 2009). Compared to bulk shipping, crude oil tankers, and general cargo ships, CO_2 emissions from container ships are 1.3, 2.2 and 2.5 times greater. Emissions from container ships are expected to be the fastest growing segment of marine shipping (Ocean Policy Research Foundation, 2008).

One of the key challenges is to limit or reduce global anthropogenic NO_x and SO_2 emissions from OGVs as these have health and ecosystem consequences and can be transported large distances from their sources. NO_x emissions from shipping are relatively high because the internal combustion engines are designed to operate at high cylinder pressures and are without effective reduction technologies. SO_2 emissions are high because of high average sulfur content in marine heavy fuels used by most oceangoing ships (EPA, 2006; Endresen et al., 2005). Another challenge is the reduction of the emissions of greenhouse gases, in particular CO_2. For these reasons, shipping has been given increasing attention over the past few years and is recognized as a growing problem by both policy makers and scientists.

As a result of the emissions, it is necessary to understand technology-based approaches that are available to improve vessel efficiency and reduce emissions, including propeller re-design, anti-fouling measures for hulls, and improved engine operations. However, limitations of these measures have led to discussions about the potential for behavioral changes (operational changes and demand management) to achieve maximum mitigation targets more cost effectively (Buhaug et al., 2009). Speed reduction and switching to cleaner-burning fuels are such operational changes for potentially reducing PM, NO_x and SO_x, CO_2 emissions from international shipping near ports. The ports of Los Angeles and Long Beach are the entry point for almost half of all cargo containers entering the United States and an area where almost 20 million people live. Thus any controls in California will have a significant effect on improving the health of a sizable population.

1.2 POLA/POLB Voluntary VSR Program

The Ports of Los Angeles (POLA) and Long Beach (POLB) and the California Air Resources Board (CARB) are evaluating a number of initiatives to control OGV emissions near the coast. One initiative is a Voluntary Speed Reduction (VSR) program since all vessels can reduce speed and benefit from the reduced emissions of both NOx and PM at the lower speeds. Emissions from vessels are directly related to the energy required to move the vessel through water.

Since 2001, the POLA and POLB have carried out a successful VSR program where arriving or departing vessels slow to 12 knots within 20 nm of Point Fermin. In 2005, the Port of Long Beach further increased compliance by offering rewards to vessel operators for slowing to 12 knots or less within 40 nautical miles (nm) of Point Fermin. Because ships emit fewer emissions at slower speeds, the program results in an estimated reduction of up to 1,000 tons per year of smog-forming emissions and diesel particulates. According to the POLB web page, in 2009, more than 90% of vessels participated in the program, slowing their ships in the 20 nm zone, while more than 70% slowed down within the 40 nm zone. In return for their participation of at least 90 percent of the time in a calendar year, the vessel operators can earn up to a 25% reduction in dockage rates. The speed of every vessel in the speed reduction zone is measured and recorded by the Marine Exchange of Southern California.

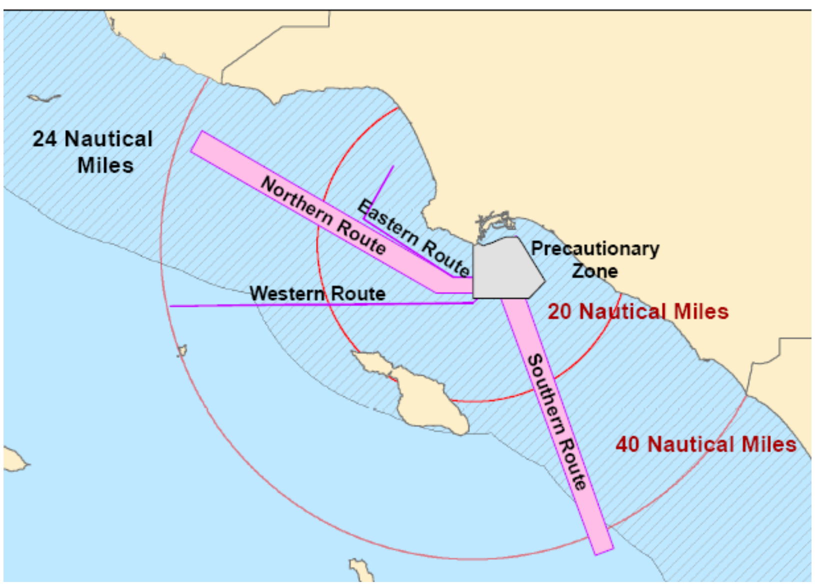

Figure 1-1 Map of Vessel Requirement Areas near Ports of Long Beach and Los Angeles

For 2010, the Port added a new option to allow a vessel operator to travel at an "Alternative Emission Reduction Speed" of more than 12 knots, after it is verified in the particular vessel that it is more efficient and less polluting than when operating at 12 knots or more.

1.3 Low-sulfur Fuel for Main Propulsion and Auxiliary Engines and Boilers

In July of 2008, CARB adopted a new regulation for fuel sulfur requirements for auxiliary and main propulsion engines and boilers of OGVs within 24 nm of the California coastline. Phase 1 of the regulation, which became effective on July 1, 2009 (13 CCR Section 2299.2), requires the use of ≤1.5% sulfur MGO or ≤ 0.5% sulfur MDO in auxiliary and main engines, and auxiliary boilers. Under Phase 2, the fuel sulfur limit for use in auxiliary and main engines and boilers will be 0.1% for MGO or MDO beginning January 1, 2012. On a per OGV call basis, reduction of 83% PM, 6% NOx, and 96% SOx operation is expected in 2013 due to switching fuel from HFO to MGO or MDO with 0.1% sulfur content over the distance the fuel is used.

1.4 Project Objectives

The VSR program approach can become an important element in improving air quality along coastline communities; however, few in-use emission studies on OGVs have been carried out in order to demonstrate the impact on emissions of operating the main propulsion engines at low speed. This study aims to measure the emission reductions that can be achieved through VSR based on actual in-use emission measurements. The primary objectives of the project are

- To determine the actual in-use emission of gases (CO_2, NO_x, CO, and THC) and particulate matter ($PM_{2.5}$) mass from the main propulsion engine of a Panamax class and Post Panamax class container vessels operating at loads close to ISO 8178-E3 certification cycle
- To determine emission reductions by reducing the vessel speed under the Vessel Speed Reduction (VSR) program
- To determine the effects of using either HFO or MGO.

2 Test Plan & Methods

2.1 Overview

Normally, emissions are measured in a laboratory where the engine is mounted on a dynamometer and emissions are measured at the ISO certification test points. For this project, the measured emissions were to be measured at sea while the engine operated at some of the ISO 8178-4 E3 certification conditions and at some of the VSR speeds specified by CARB and allowed by the vessel crew. The field measurement approach added complexity to the project since it was necessary to move a suite of laboratory-grade equipment onto the ships, find sampling locations, setup an on-site laboratory, calibrate the instruments and then test within the voyage time. The planning including the following elements:

1. Pre-test laboratory calibration of instruments, packaging of equipment for lifting and lowering on a vessel deck, preparation of PM filter media and laboratory notebook with the proposed test plan and operating points.
2. Design of final test plan. Upon boarding the vessel, first work with the Chief Engineer to identify the sampling ports and a final test plan that is consistent with their planned vessel schedule. This plan cannot change after this meeting since everyone is busy once at sea.
3. Operating the ship at specified test conditions. The vessel is operated at specified test conditions and times while recording the key engine parameters.
4. Measuring emissions. Emissions for CO, CO_2, NO_x and $PM_{2.5}$ were measured continuously at the desired vessel/engine operating conditions.
5. Calculating the emission factors while the vessel operated at the test conditions.
6. Analysis of the data and reporting.

The plan called for making multiple measurements at both the VSR and certification speeds and to make these measurements over three separate voyages.

2.2 Selecting Test Vessels and Engine

The plan called for measuring emissions on modern container ships that were 1) representative of those entering and leaving California and 2) left the San Pedro Ports for another location on the West Coast so the UCR crew could return to their home base. At the time of the vessel search many of the Post-Panamax ships with engines made after 2007 were now sailing directly to and from Asia so the selection was limited to Panamax vessels. One shipper provided a representative Panamax class container ship equipped with one main propulsion engine and four auxiliary engines. Another shipper offered a Post Panamax vessel that was put into service in 2010.

2.3 Test Fuel

Testing was performed using marine distillate oil (MDO)/marine gas oil (MGO) while maneuvering from the Port of Los Angeles to the 20 or 40 nautical mile limit of the VSR zone and a RM-grade fuel oil or heavy fuel oil (HFO) on the open seas. Basically HFO is petroleum derived liquid fuel, excluding marine fuel and gas oil, which less than 65% by volume (including losses) distils at 250°C by the ASTM D86 method. Fuel viscosity is the primary measurement for designating the fuel category.

Both fuels were expected to be typical of normal supply and meet the ISO 8217: 2005 specifications. Once on board, the Certificate of Analysis (C of A) for the fuels will be requested from the vessel owner; however, the plan is to take a fuel sample during testing for subsequent off-line analysis.

2.4 Test Cycle and Operating Conditions

The plan was to measure emissions while the engine operated at loads close to those specified in the ISO 8178-4 E3 certification cycle and at reduced vessel speeds of the VSR mode. Appendix A Test Cycles and Fuels for Different Engine Applications presents detailed information on the ideal Test Cycles and Fuels for Different Engine Applications as specified in the IMO and ISO protocols.

2.4.1 Operation at ISO 8178-4 E3 mode

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 will be carried out during a 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 8178-4 E3 marine certification test. For example, we know the Master/Captain will not operate the vessel at 100% power and data for that point are typically collected at 85% power. Further the Master usually limits the time at 85% power because of the high fuel consumption. All other test modes are easily incorporated into the vessel operation schedule as time permits.

Table 2-1 Engine Operating Conditions for the ISO 8178-4 E3 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 are determined at the time of testing and depended on several factors; including constraints by the times associated with the planned voyage, sea current, wave pattern, wind speed/direction, and cargo load. Efforts are made to conduct the emissions measurements at loads and RPM as close as possible to those specified in ISO 8178-4 E3.

2.4.2 Operation in the VSR mode

In addition to testing at the ISO certification conditions, the plan called for measuring emissions at the 12 and 15 knot speed limit in the VSR mode. For the present study, two VSR test opportunities were possible during the first voyage, first as the vessel left the Port of Los Angeles and second as the vessel approached the Port of Oakland. In the second voyage, emissions were measured at reduced speeds of 13 and 14 knots. In the third voyage, emissions were measured at 12 knots when the vessel was leaving the Port of Long Beach and entering the Port of Oakland. The key question for the VSR points was the time available for operating at the slow speed and the average speed needed to meet the operational schedule. Thus getting agreement at the slow speeds became more problematic that operating at the higher speeds.

2.4.3 Measuring Engine Load and Other Key Parameters

Determining the emission factors would require the measurement of a number of key engine parameters during the voyage and measurement time. Detailed instructions are provided for the required measurements for on-board testing[1] in Chapter 6: Procedures for demonstrating compliance with NOx emission limits on board. Some of the engine performance parameters measured or calculated for each mode during the emissions testing is shown in Table 2-2.

Table 2-2 Engine Parameters to be Measured and Recorded

Symbol	Parameter	Dimension
n_d	Engine speed	min^{-1}
p_C	Charge air pressure at receiver	kPa
P	Brake power (as specified below)	kW
P_{aux}	Auxiliary power (if relevant)	kW
T_{sc}	Charge air temperature at receiver (if applicable)	K
T_{caclin}	Charge air cooler coolant inlet temperature (if applicable)	K
$T_{caclout}$	Charge air cooler coolant outlet temperature (if applicable)	K
T_{Sea}	Seawater temperature (if applicable)	K
q_{mf}	Fuel oil flow (as specified below)	kg/h

The NTC points out that it is often difficult to measure some of the parameters in Table 2-2 for marine engines and some allowances are provided over measurements made in a test bed. For example: "The engine torque and engine speed shall be measured but the permissible deviations of instruments for measurement of engine-related parameters for on board verification purposes is different from those under the test bed testing method. If it is difficult to measure the torque directly, the brake power may be estimated by any other means."

Further the NTC reports that it is often impossible to measure the fuel oil consumption once an engine has been installed on board a ship (unlike the ECM output for an on-road engine). To simplify the on board procedure, the results of the measurement of the fuel oil consumption from an engine's pre-certification test bed testing may be accepted. Since the fuel oil flow rate used in the calculation (q_{mf}) must relate to the fuel oil

[1]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

composition determined in respect of the fuel sample drawn during the test, the measurement of q_{mf} from the test bed testing shall be corrected for any difference in net calorific values between the test bed and test fuel oils.

2.5 Emission Measurements

The emission testing of the main engine was performed using a partial dilution system that was developed based on the ISO 8178-2 protocol and detailed information are provided in Appendix B.

Emissions for CO, CO_2, NO_x and $PM_{2.5}$ were measured based on ISO -8178-2 protocols while the engine operated at the test modes specified in Table 2-1 or was following the VSR operating conditions. The measuring equipment and calibration frequencies met IMO Standards and details are provided in Appendix B. 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. Duplicate emission measurements were planned, as time permitted, to provide confidence limits.

2.6 Flow Rate Determination

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

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 section 13.1[2] and described below. Both methods are based on the measured exhaust gas concentrations and fuel consumption rate.

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, O and N in known proportions.

The carbon balance methods are 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 accurate fuel consumption data are available. The fuel consumption data were not available for the

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

first vessel so the carbon balance method could not be used. However, fuel consumption data were available for the second vessel and therefore, the carbon balance method was used to calculate exhaust flow rate.

2.6.2 Calculation of Exhaust Flow Rate, Assuming the Engine is an Air Pump

This method is widely used for calculating exhaust flow rate in diesel engines, especially stationary diesel engines. The 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. The method assumes the combustion air flow equals the total exhaust flow and that is a reasonable approximation. For example, diesel combustion is designed to operate with a large excess of air and an inert gas, nitrogen, that makes up 80% of the volume of the intake and exhaust air. Excessive oxygen goes through the engine and converted oxygen becomes carbon dioxide or water. Only the water will result in a volume expansion. At maximum load the water content is about 6 vol% and the exhaust expansion about 3 vol%, within the measurement error. At lower loads, the expansion will be proportionally smaller and the error less.

The main concern is that with 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 there the scavenger air flow is much smaller than the combustion air.

2.6.3 Calculation of the Exhaust Flow Rate from Proprietary Data

Various engine manufacture companies have proprietary knowledge and developed computer programs with 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 proprietary programs are checked against stoichiometric calculations based on carbon and oxygen balances; however, were not available in this study.

2.7 Test Protocol

Prior to sailing, a detailed schedule and final plan for testing was developed by UCR and 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 and Long Beach. The test plan used information from the UCR proposed test matrix, including the number of repeat measurements and the operational plan of sailing from Los Angeles to the Port of Oakland and Long Beach to the Port of Oakland. On-board discussions were conducted so everyone knew the operating plan for the voyage and for the testing.

In general, the sequential steps followed for each point in the test matrix was as follows:

- Once on-board and prior to sailing, UCR discussed their test plan with the crew.
- Once underway and upon achieving an engine set point, the gaseous emissions were monitored until they were stable for a minimum of fifteen (15) minutes
- Continuous and integrated gaseous measurements were acquired over consecutive test runs at each speed and load mode point to ensure adequate statistical analysis of the results. Consecutive data sets may be collected while the vessel is operating at a sustained speed and load point that falls within the certification cycle. The number of repeats would be determined by the vessel sailing schedule and the time at that mode. Also as mentioned earlier, the testing at 85% power would likely be time limited because of the high fuel consumption.
- Engine RPM, engine load, boost pressure and intake manifold temperature were recorded at each test mode in order to calculate the mass flow rate of the exhaust. If available, a fuel flow parameter would be recorded.
- Emission factors for each pollutant were calculated from the measured concentration data and calculated mass flow rate.

2.8 Data Analysis – Emission Factors

Two types of emission factors were determined.

2.8.1 Modal Emission Factors

Emission factors in grams per unit time are calculated at each mode or load point from: 1) the measured gaseous and $PM_{2.5}$ concentration and 2) the calculated mass flow in the exhaust. These emission factors provide useful numbers for calculating the contribution to the inventory when a vessel enters a controlled area. The implications are significant if the modal emissions are twice at a certain load but the vessel speed is not twice as fast. Then the emission contribution to the inventory will be greater at the faster speed. We will see that speed and emissions vary non-linearly so emissions can be significantly greater in some cases.

2.8.2 Overall Emission Factors

Emission factors are calculated at each mode or load point from: 1) the measured gaseous and $PM_{2.5}$ concentration, 2) the calculated mass flow in the exhaust and 3) the reported engine load in kilowatt (kW). The emissions are reported in grams per unit work for each load and provide useful numbers for comparing with the certification values and with other vessels. An overall single emission factor representing the engine is determined by weighting the modal data according to the ISO 8178-4 E3 requirements and summing them. The equation used for the overall emission factor is as follows:

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

Where:

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

2.9 Data Analysis – Vessel Speed Effects on Emissions

A central portion of the analysis should deal with the relationship between vessel speed and emissions of criteria pollutants. The same principles apply to emissions of a greenhouse gas, CO_2, but that is of secondary consideration in this analysis. Because of the complexity of the analysis, some background is provided as insight into the analysis approach and the established relationship between vessel speed and power requirements.

2.9.1 Background on Power and Vessel Speed

Relationships between power and speed are not obvious. MAN B&W, the major builder of main propulsion engines for OGVs provides an introduction on their web page entitled: *Basic Principles of Ship Propulsion*[3] Excerpts from that memorandum are provided in Appendix E and included so as to provide some insight into the principles associated with figuring the effects of various resistive forces on vessel speed and the power required to achieve that speed.

To move a ship, it is necessary to overcome resistance, the forces working against its propulsion. The total resistance R_T can be divided into three main groups:

1) Frictional resistance, R_F;
2) Residual resistance made up of wave plus eddy resistances and
3) Air resistance.

Studies have shown that the frictional and wave resistances are the most important for container ships and make up over 80% of the resistive forces. Air and eddy resistances are minor contributors under most conditions.

The frictional resistance of the hull depends on the size of the hull's wetted area A_S, and on the specific frictional resistance coefficient C_F. As a ship is propelled through water, the frictional resistance increases at a rate that is equal to the square of the vessel's speed. Frictional resistance represents a considerable part of the ship's resistance, often some 70-90% of the ship's total resistance for low-speed ships (bulk carriers and tankers) and sometimes ≤ 40% for high-speed ships (cruise liners and passenger ships). The frictional resistance is found as follows: $\mathbf{R_F = C_F \times K}$

Wave resistance refers to the energy loss caused created by the waves generated as the vessel moves through the water. At low speeds wave resistance is proportional to the square of the speed but wave resistance increases much faster at higher speeds. In principle, this means that a speed barrier is imposed, so that a further increase of the ship's propulsion power will not result in a higher speed as all the power will be

[3] From MAN web page: *Basic Principles of Ship Propulsion* http://www.mandieselturbo.com/1005405/Press/Publications/Technical-Papers/Marine-Power/Low-Speed/Low-Speed-Archive/Ship-Propulsion.html

converted into wave energy. The residual resistance normally represents 8-25% of the total resistance for low-speed ships, and up to 40-60% for high-speed ships.

2.9.2 Analysis Relating Emissions, Fuel Consumption and Vessel Speed

References, such as MAN, discuss the propeller law and how the fuel consumed relates to the velocity or speed of the vessel. MAN points out that resistance (R) for lower ship speeds is proportional to the square of the ship's speed (V), i.e. $\mathbf{R = c \times V^2}$ where **c** is a constant. Thus the necessary power requirement (P)… $\mathbf{P = R^* V = c \times V}^3$.

For a ship equipped with a fixed pitch propeller, the ship speed **V** is proportional to the rate of revolution, **n**. Since the vessel speed varies linearly with engine RPM, the equation for the power required is: $\mathbf{P = c\ {*}n^{3.}}$ This equation is the propeller law, which states that "the necessary power delivered to the propeller is proportional to the rate of revolution to the power of three". Experience based on actual measurements shows that the power and engine speed relationship for a given weather condition are fairly reasonable; however, the power and ship speed relationship are often seen with an exponent greater than three. A reasonable relationship to be used for estimations in the normal ship speed range could be as follows:

- For large, high-speed ships like container vessels: $\mathbf{P = c{*}V^{4.5}}$
- For medium-sized, medium-speed ships like feeder container ships, reefers, RoRo ships, etc.: $\mathbf{P = c\ {*}V^{4.0}}$
- For low-speed ships like tankers and bulk carriers, and small feeder container ships, etc.: $\mathbf{P = c\ {*}V^{3.5}}$

2.10 Reporting

Toward the goal of reporting comparative emissions for ships at various speeds, UCR will compile and report measured emissions and engine operating data and the calculated or measured flow rates for two ships. These raw data lead to calculated modal and overall emission factors, the basis of the comparison. UCR plans to report emission factors with confidence limits based on the repeated test results. Either brake specific or fuel specific emission factors based on the CO_2 emissions might be used as basis for comparing the emissions from the various speeds and fuels. In any case, an overall emission factor will be estimated and compared with the certification values to illustrate that the results are representative of a properly functioning engine.

3 Results for the First Vessel

This section presents results and some analysis of the measured emissions of criteria pollutants as a function of fuel type and engine load for the two separate voyages on the same vessel. Using the same vessel allowed a better determination of the confidence limits for the data. For the most part the final plan developed with the crew on first vessel was the same carried out for the second sailing, except during the second voyage the UCR vacuum pumps overloaded the electrical circuits so UCR discontinued taking PM samples on the quartz media to reduce load. UCR took samples with Teflon media to measure the PM mass. Both voyages made a number of measurements at sea to include loads specified by ISO at the certification points and VSR speeds specified by CARB. The results for gaseous and $PM_{2.5}$ emissions are discussed in the following sections.

3.1 Test Schedule

The primary goal of this project was to determine the actual in-use emission of gases (CO_2, NO_x, CO, and THC) and particulate matter ($PM_{2.5}$) mass from the main engine of a Panamax Class container vessel following the ISO certification cycle and some speed under the California VSR program. Two measurement voyages between the Ports of Los Angeles and Oakland were undertaken for this purpose, one in July 2009 and the other in August 2009, each of which lasted for 3 days. Details of the test schedule for both the measurement voyages are given in

Table 3-1 Test Schedule

Voyage	Date	Fuels	Planned Test Points; Fuel & Load
Voyage 1 (First Vessel)	07/01/2009	HFO & MGO	HFO: RT & ISO: 100%, 75%, 50% & 25% & VSR 12 knots (Into Oakland Port) MGO: VSR 11 & 15 knots (Out of POLA)
Voyage 2 (First Vessel)	08/01/2009	HFO & MGO	HFO: RT & ISO: 100%, 75%, 50% & 25% MGO: VSR 13, 14(out of POLA) & 14 knots (Into Oakland Port)

Notes:

- RT: Real Time Monitoring and Recording of Gaseous Emission Samples;
- ISO: Filter samples taken in accordance with ISO 8178-4 E3.

3.2 First Test Vessel and Engine

The plan called for measuring emissions on a modern container ship that was 1) representative of those entering and leaving California and 2) left the San Pedro Ports for another location on the West Coast so the UCR crew could return to their home base. At the time of the vessel search many of the Post-Panamax ships with engines made after 2007 were now sailing directly to and from Asia so the selection was limited to Panamax vessels. One shipper provided a representative Panamax class container ship equipped with one main propulsion engine and four auxiliary engines. Some properties of the vessel are presented in Table 3-2.

Table 3-2 Selected Technical Parameters of the First Vessel

Vessel Type	Panamax Class Container Ship
Shipyard	Ishikajima-Harima Heavy Industries Co. Ltd, Japan
Year Built	1997
Length (m)	292
Beam (m)	32
Dead weight (ton)	59,840
Gross tonnage (ton)	49,995
Maximum TEU capacity	4,062
Maximum speed (knots)	24.5
Maximum draught (m)	13

The main propulsion engine was a Sulzer RTA84C type engine that was widely used and is a low-speed, direct-reversible, single-acting, two-stroke engine, comprising crosshead-guided running gear, hydraulically operated poppet-type exhaust valves, turbocharged uniflow scavenging system and oil-cooled pistons. The Sulzer RTA84C is designed for running on a wide range of fuels from marine gas oil (MGO) to heavy fuel oils (HFO) of different qualities. It is massive in size and stands more than four stories as shown in Figure 3-1. Some technical parameters of the Sulzer engine are given in Table 3-3

Table 3-3 Selected Technical Parameters of the First Test Engine

Manufacturer/Model	Sulzer/9RTA84C
Technology	2-stroke
Number of Cylinders	9
Speed (MCR)	102 rpm
Maximum Power Rating	36,740 kW
Power (MCR)	4050 kW/cyl
Mean effect. press	17.9 bar
Bore	840 mm
Stroke	2400 mm
Displacement	11,970.4 liters
Mean piston speed	8.2 m/s

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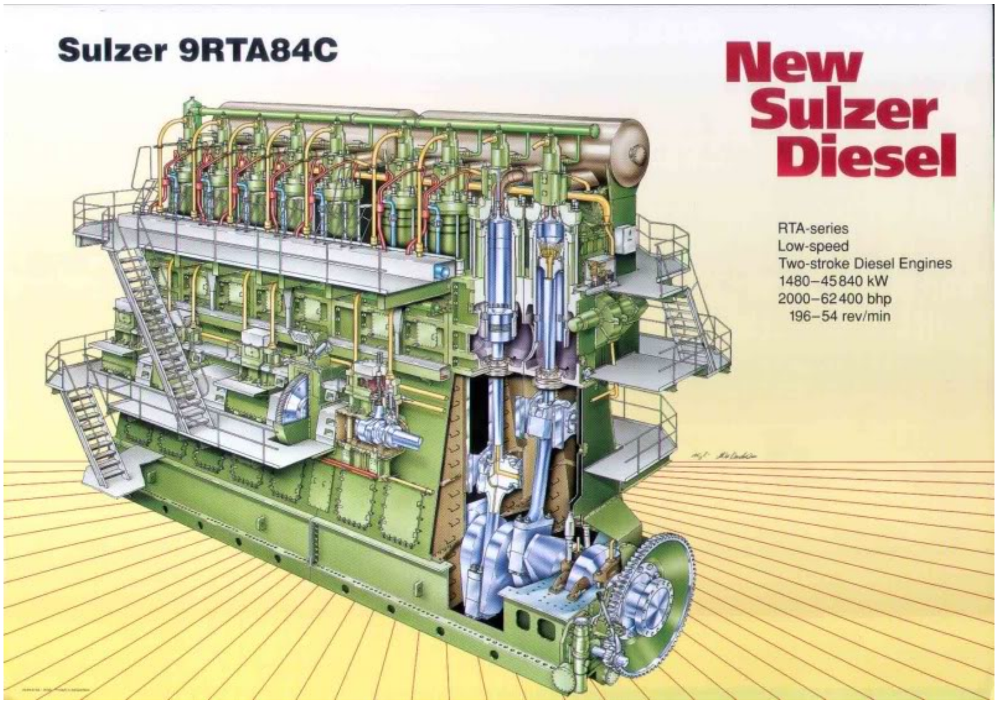

Figure 3-1 Picture of the Main Propulsion Engine

Fuels for both voyages were typical of normal supply and met the ISO 8217: 2005 specifications. Both Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO) were used during the testing and two different fuel analyses were available. One analysis was performed by the fuel supplier and presented to the ship owner in the format of a Certificate of Analysis (C of A). The C of A provided by the fuel supplier is presented in Appendix C. The other analysis was performed on a one liter fuel sample taken directly from the fueling system during the measurement voyage and analyzed by a different lab. Selected properties of the fuel from both the analyses are presented in Table 3-4.

Table 3-4 Selected Properties of the Fuels Used on the Vessel

Fuel Property	Units	Voyage 1				Voyage 2			
		Analysis(CoA)		Analysis (UCR)		Analysis(CoA)		Analysis (UCR)	
		HFO	MGO	HFO	MGO	HFO	MGO	HFO	MGO
Density at 15°C	kg/m^3	990.3	842.8	-	-	990.6	842.8	-	-
Density at 15.5°C	kg/m^3	-	-	950.1	842.3			962.2	842.7
Viscosity at 50°C	mm^2/s	262.3	-	-	-	367		-	-
Viscosity at 40°C	mm^2/s	-	2.7	-	-		2.7	-	-
Sulfur	%m/m	3.44	< 0.05	3.14	-	2.5	< 0.05	2.15	-
Sulfur	ppmw	-	-	31,442.7	6.5		-	21,534.3	94.2
Ash	%m/m	0.07	< 0.01	-	-	0.03	< 0.01	-	-
Vanadium	mg/kg	276	1	-	-	57	1	-	-
Nickel	mg/kg	56	< 1	-	-	21	< 1	-	-

Notes:

- Analysis 1 was the Certificate of Analysis (C of A) provided to the ship operator.
- Analysis 2 was the values for the UCR fuel sample taken during the voyage.

3.3 Operating Conditions for Vessel during Emissions Testing

The emission testing was conducted with the engine operating at some ISO certification loads and between 10-21% of full load to represent the VSR mode. The operating conditions are presented in Table 3-5. UCR members went to the engine control room to manually read the engine operating conditions from the instrument panel and recorded then on data sheets. Some of the operating conditions included the load, RPM, boost pressure and temperature. Electronic monitoring and recording was not available.

Table 3-5 Engine Operating Conditions for the Present Study

Voyage 1							
Load (%)	11	19	29	52	73	81	10
Load (kW)	3,948	6,898	10,790	18,960	26,717	29,688	3,760
Engine Speed (rpm)	50	61	68	84	94	98	47
Voyage 2							
Load (%)	9	19	28	44	69	83	17
Load (kW)	3,300	6,700	10,095	16,627	25,025	30,260	6,240
Engine Speed (rpm)	45	58	65	79	93	98	55

3.4 Sampling Ports

The raw exhaust from the main engine was sampled before the waste heat boiler by replacing four existing thermocouples with 3/8” diameter stainless steel tubing that extended over 30 cm into the raw exhaust stack. With sampling before the waste heat boiler, PM is unchanged and with 30cm probes, the distance is sufficient to free any effects from stack wall boundary conditions. One of the four ports was used for dilution tunnel and the other three were used for continuous monitoring of the raw exhaust.

Figure 3-2 Installed Sampling System on Vessel #1

3.5 Determining the Exhaust Flow Rate

An accurate calculation of exhaust flow rate is essential for calculating emission factors and as presented in the background, there are several approaches that can be used. For this study, the exhaust flow rate was determined from the intake air flow by assuming that the engine operates as an air pump and the air flow into the engine equals the air flow out of the engine. The flow rate of the intake air was determined from the displaced cylinder volume, recorded rpm, temperature, and boost pressure of the inlet air. Figure 3-3 shows the calculated exhaust flow rate against the engine load for both voyages.

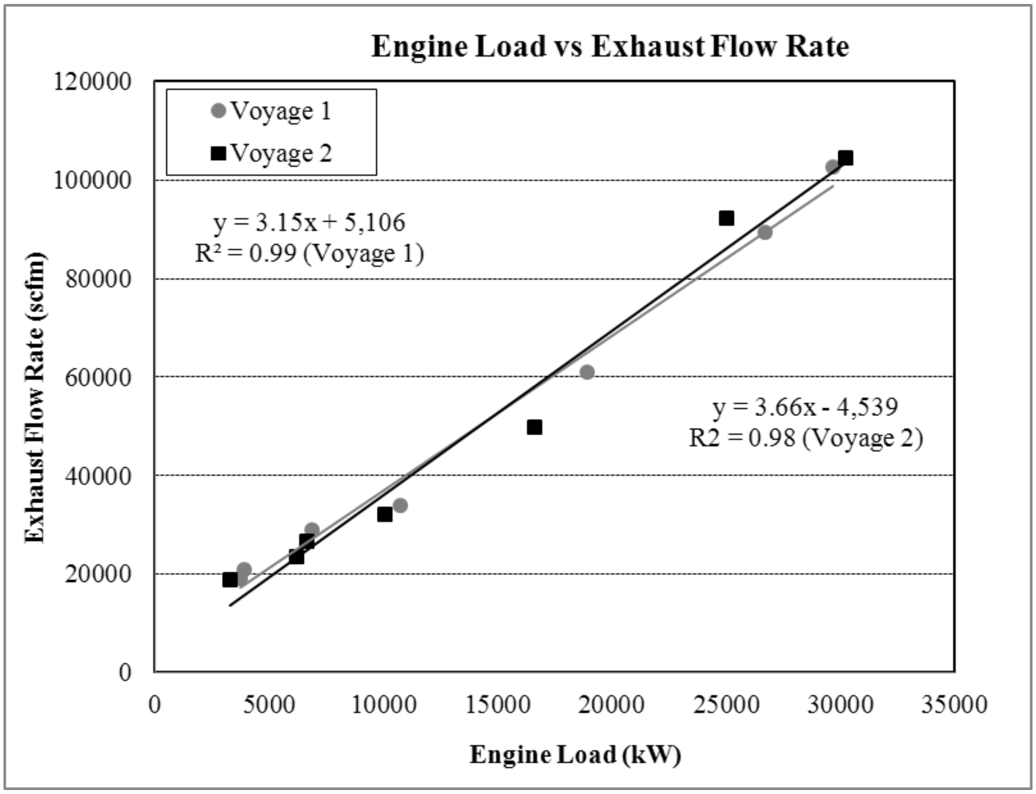

Figure 3-3 Engine Load vs. Exhaust Flow Rate

3.6 Gaseous Emissions – IMO Methods

The gaseous emissions of interest in this study were CO_2, NO_x, CO and THC. All the gaseous emissions were measured by instruments in compliance with the IMO standard specification and a detailed list of the gaseous emissions from both the measurement voyages are presented in kg/hr and g/kW-hr in this section. Three sets of consecutive readings were measured for every test condition, where each reading by itself was a five to seven minute average of one hertz data obtained from the instrument. The error bars in the figures represent the confidence limit of the analyzed data. Data were taken while operating on either heavy fuel oil or marine gas oil.

3.6.1 Carbon Dioxide Emissions

Carbon dioxide (CO_2) emissions were checked first as they 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 fuel consumption reported by the engine manufacturer.

The gaseous emissions for CO_2 from both voyages in kg/hr are presented in Figure 3-4 and Figure 3-5. The results in Figure 3-4 show that CO_2 emission increases as the load increases due to higher fuel consumption, as expected. The error bars in the figure represent the confidence limits of the data gathered and analyzed. The results from both the voyages showed good repeatability of the measured values.

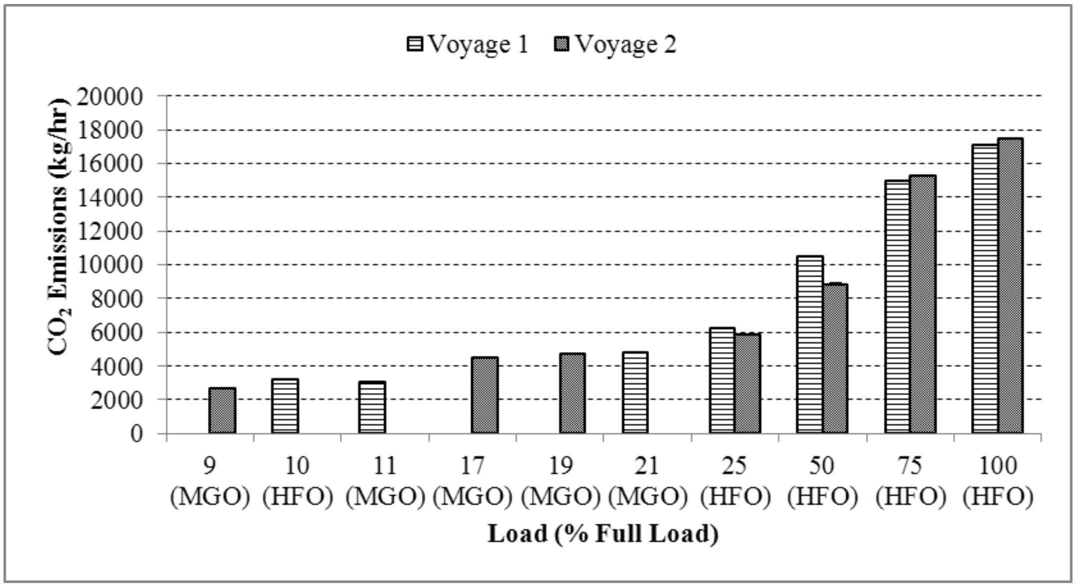

Figure 3-4 Modal Emission Rates for CO_2 in kg/hr

Another graphical representation of the fuel consumption data as a function of engine load is presented in Figure 3-5. The coefficient of determination (R^2) value is quite linear as expected.

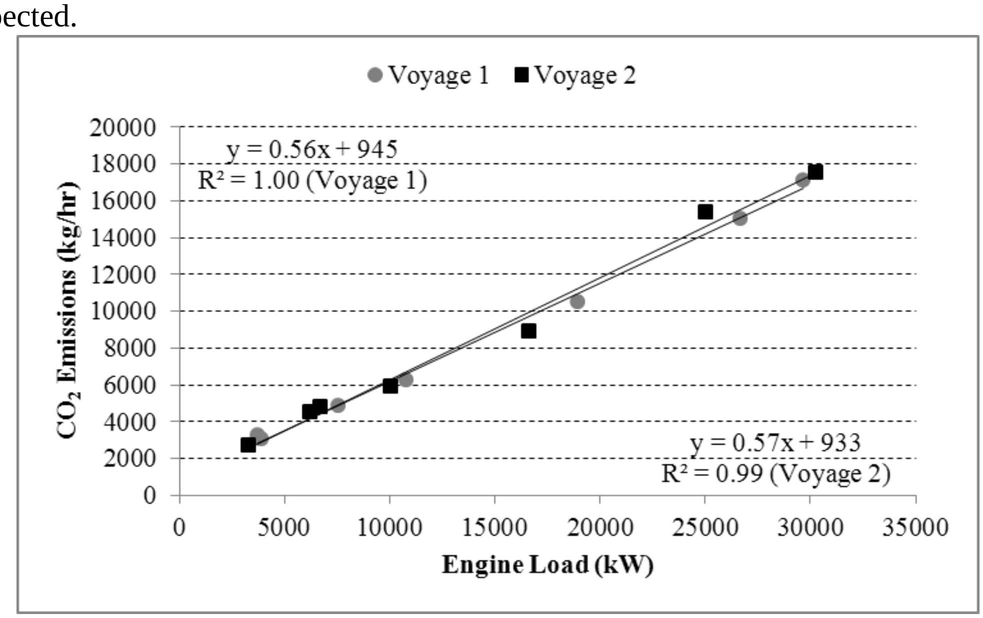

Figure 3-5 Engine Load vs. Modal CO2 Emissions (kg/hr)

The emission factors from both the voyage given in g/kW-hr in are shown in Figure 3-6 and near the 600 g/kW-hr at the higher load points that are expected for two-stroke, slow-speed diesel engines. As expected, emission factors at lower load are higher than 600 g/kW-hr as the engine is not operating efficiently at those low speeds. CO_2 emission factors across ISO load points are within ~10% for two voyages.

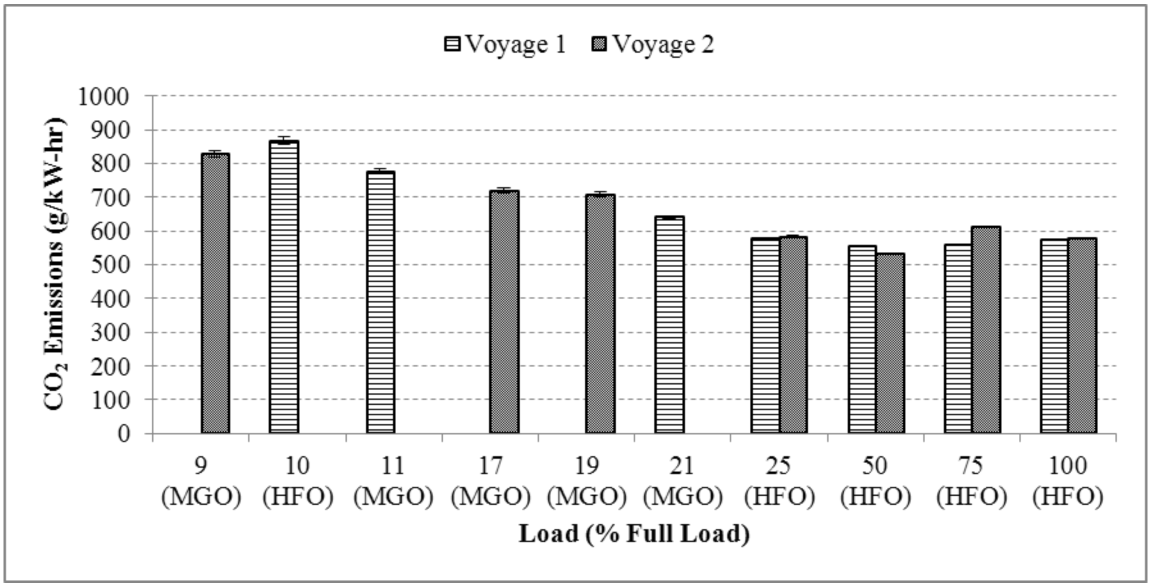

Figure 3-6 Modal Emission Factors for CO_2 in g/kW-hr

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

As part of the UCR's QA/QC, the carbon mass balance was checked between the fuel and the measured carbon in the exhaust. During the emission testing, the fuel flow rate was not directly measured, but was calculated in liters per minute (LPM) from the fuel consumption data over time. The fuel consumed was determined from the control panel displays of fuel and return meter readings in the engine room. These data were available only for second voyage so the carbon mass balance was performed only for Voyage 2. Based on the typical carbon content of HFO and MGO fuels which are 86 and 87 % wt/wt respectively, the carbon content of the fuel in kg/hr was estimated by using the fuel flow rate and density of the fuel obtained from the fuel analysis. The amount of carbon in the exhaust was calculated from the CO_2 and CO emissions and Figure 3-7 shows the carbon mass balance between the fuel and the exhaust for the second voyage. The R^2 value is quite good.

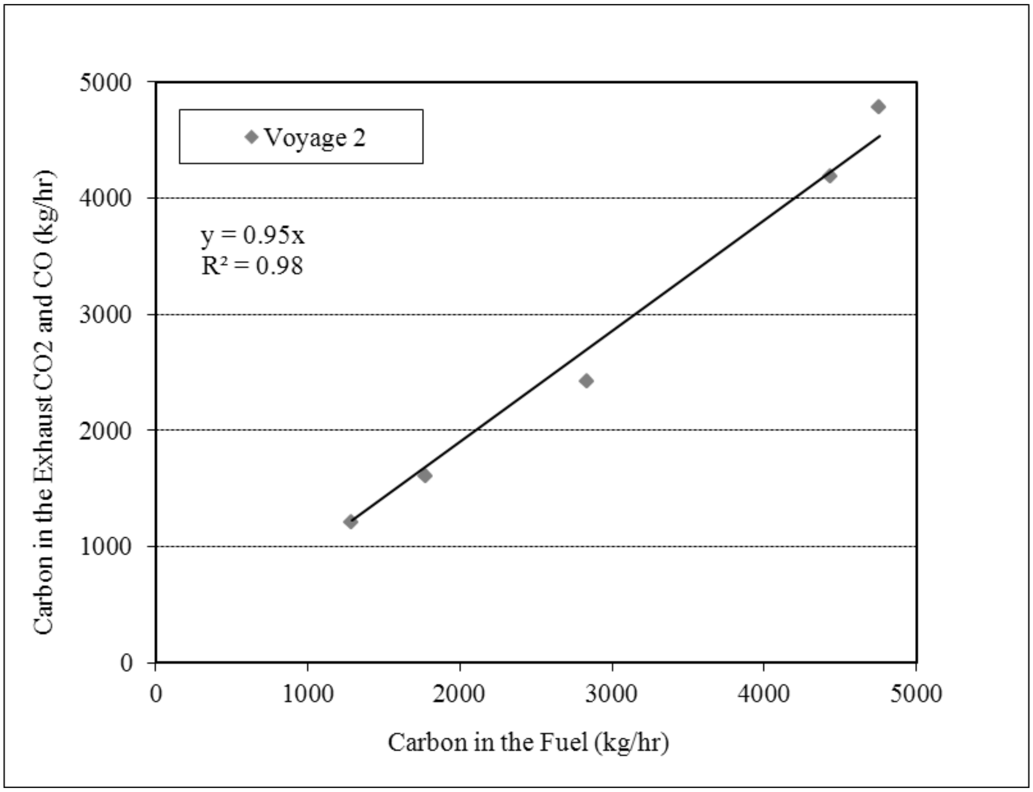

Figure 3-7 Carbon Mass Balance between Fuel and Exhaust

3.6.3 Quality Checks: CO_2 Emissions vs. Engine and Vessel Speed

Another check of the data is the plot of fuel consumed or power versus the propeller/engine speed. As described in Section 2.81, *Analysis Relating Emissions, Fuel Consumption and Vessel Speed,* one would expect the data to fit an equation where the power would vary with the cube of the speed. Basically more and more fuel is required as the vessel speeds up. The data in Figure 3-8 fall on a cubic line with an R^2 ~1 thus indicating a good fit for the engine data during both voyages. A plot of engine and vessel speed is shown in Figure 3-9 and is linear, as expected.

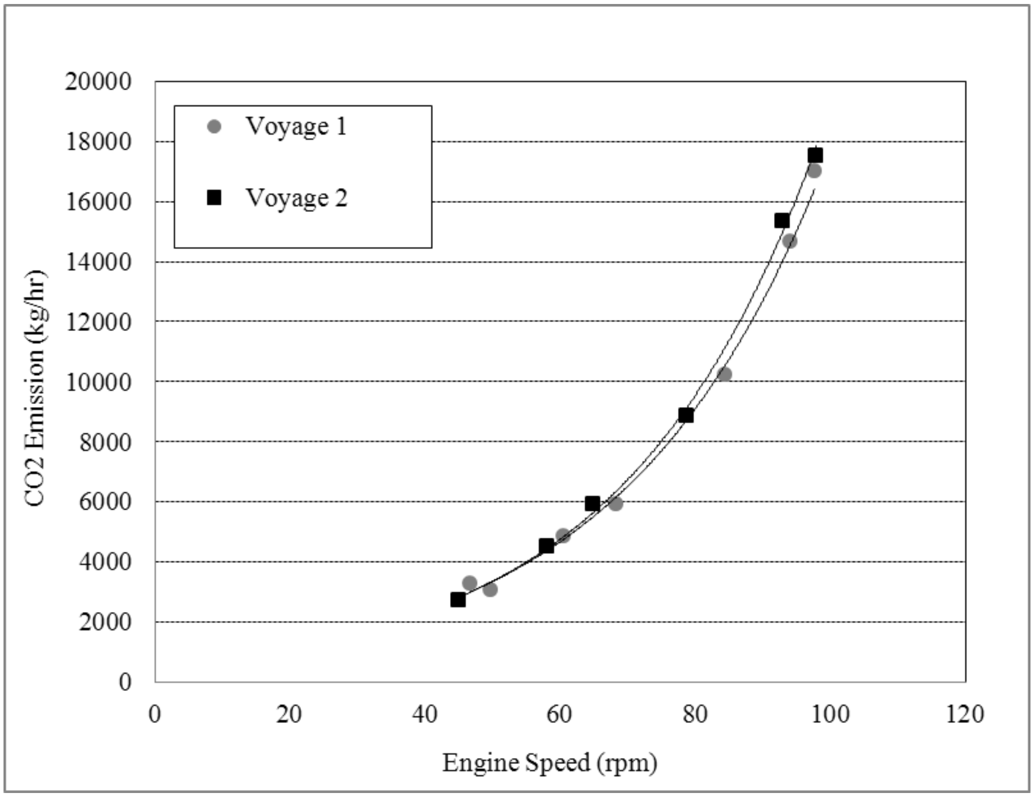

Figure 3-8 Emissions of CO2 (kg/hr) vs. Engine Speed

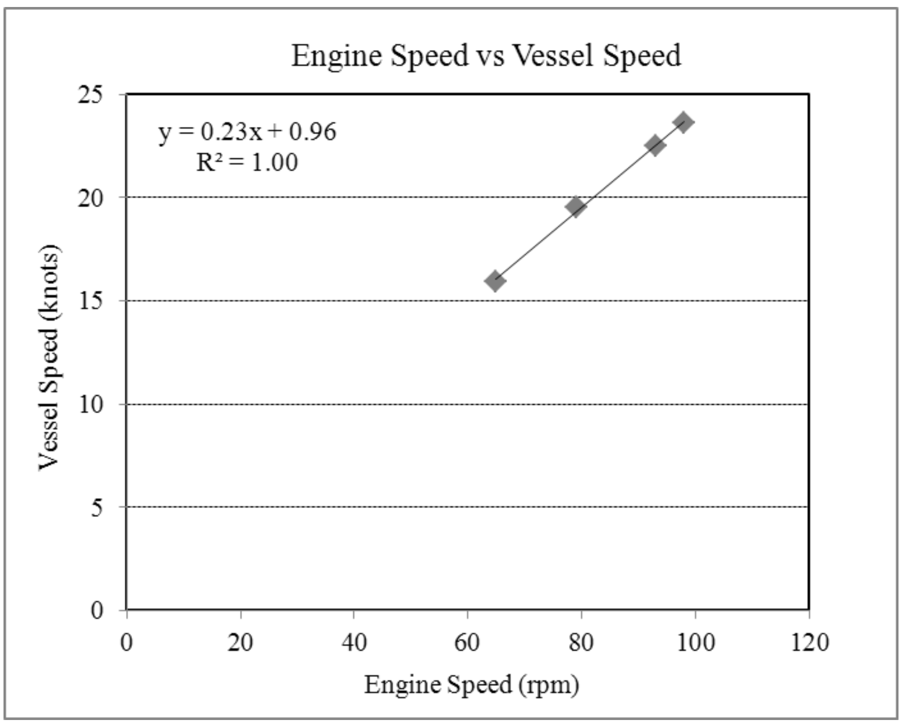

Figure 3-9 Engine Speed (RPM) vs. Vessel Speed (knots)

3.6.4 NO_x Emissions

NOx emission rates and factors are the second parameters of interest in air basins that are environmentally sensitive. The gaseous emissions for NO_x from both voyages are presented in kg/hr in Figure 3-10.

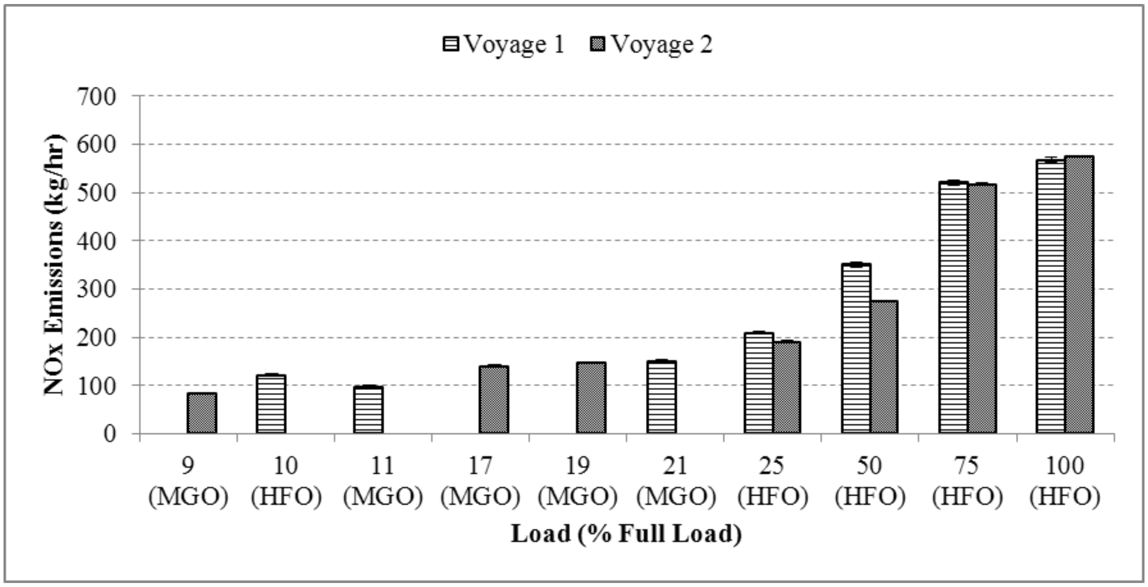

Figure 3-10 Modal Emission Rates for NOx in kg/hr

Plots of NOx modal emission factors in g/kW-hr are shown in Figure 3-11. The variation of NO_x emissions in kg/hr across the loads is similar to CO_2 emissions. The NO_x emission factors in g/kW-hr are within the typical range as expected for both voyages for ISO load points. Note that the NOx emission factors are higher at lower loads than ISO load points. However, NOx emissions in kg/hr are relatively very low at lower loads, suggesting reduction in NOx emissions on lowering vessel engine load.

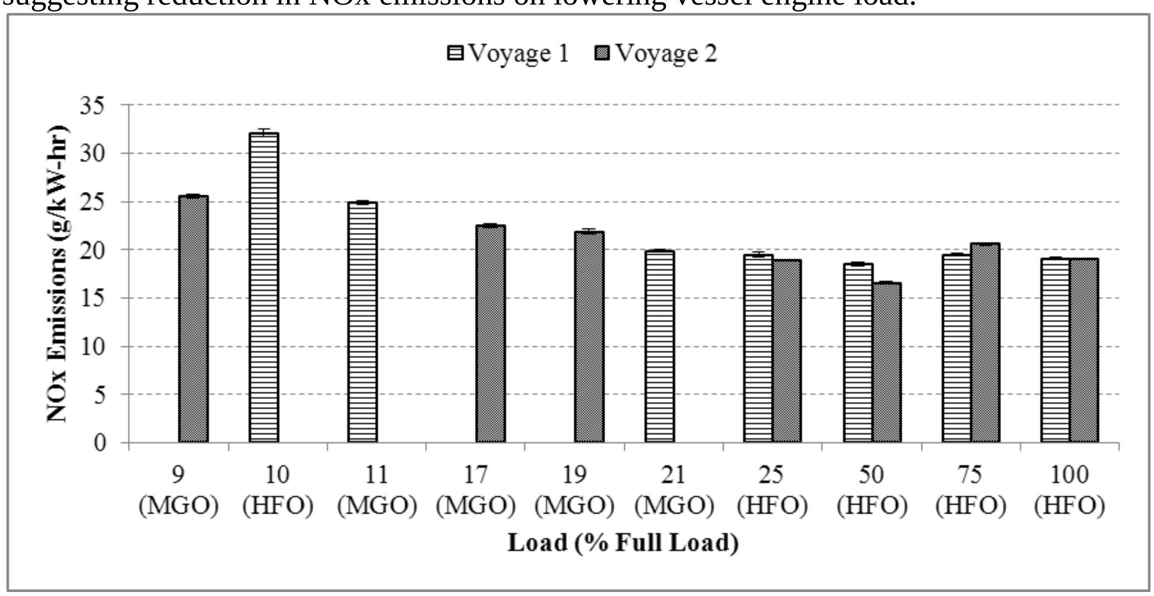

Figure 3-11 Modal Emission Factors for NOx in g/kW-hr

3.6.5 CO Emissions

The gaseous emissions for CO in kg/hr for both voyages are shown in Figure 3-12. Carbon monoxide forms under fuel-rich combustion conditions due to insufficient oxygen to complete the reaction to CO_2. CO emissions are similar across ISO load points for both voyages.

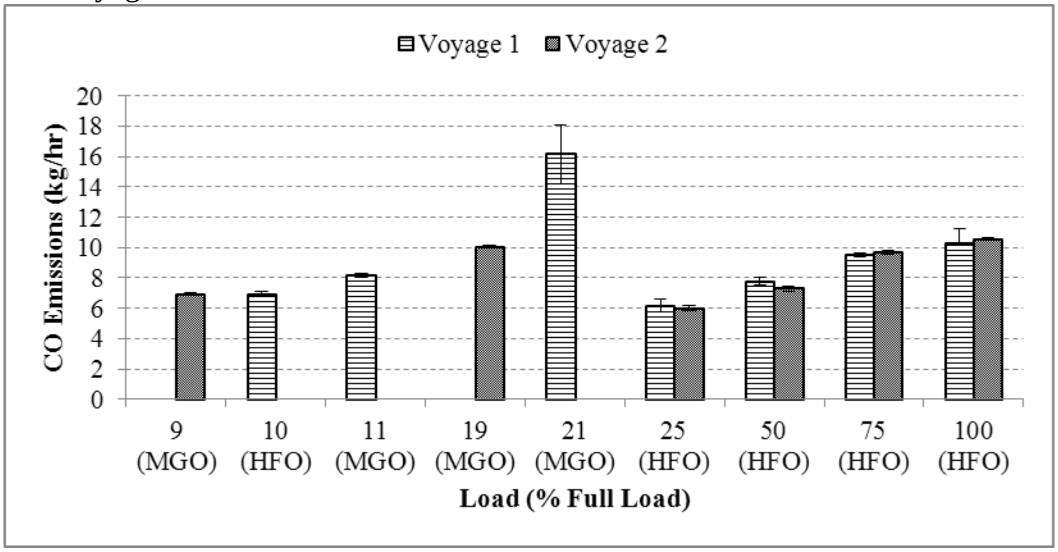

Figure 3-12 Modal Emission Rates for CO in kg/hr

The CO modal emission factors in g/kW-hr in Figure 3-13 are found to be the highest at low power conditions, where burning rates and peak temperatures are relatively low. Values are within the typical range as expected for both the voyage.

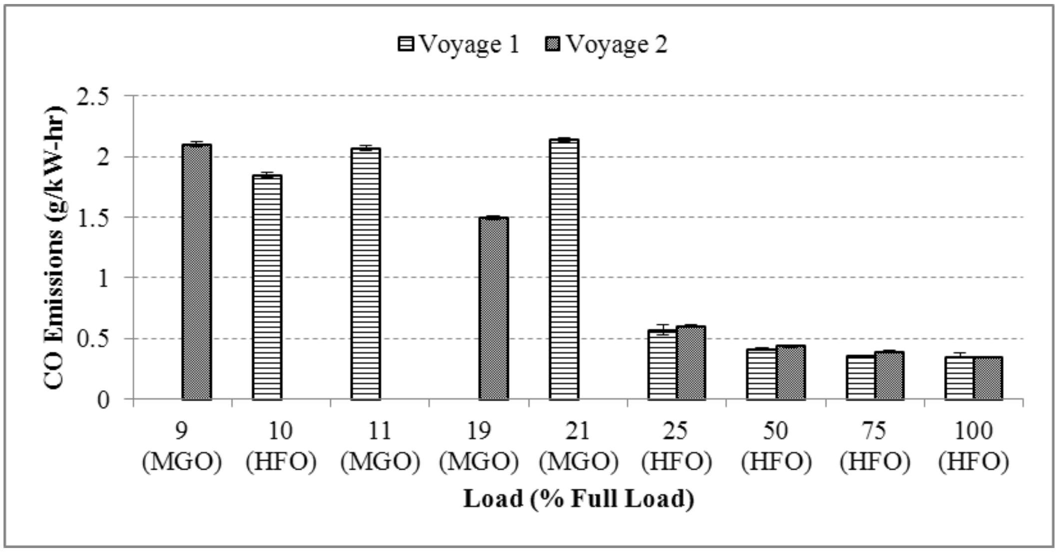

Figure 3-13 Modal Emission Factors for CO in g/kW-hr

3.6.6 Total Hydrocarbon (THC) Emissions

The modal emissions and emission factors for THCs for both voyages are shown in respectively. Higher THC emissions (kg/hr) are observed at lower loads than ISO load points. However, emissions of THC are low across all load points.

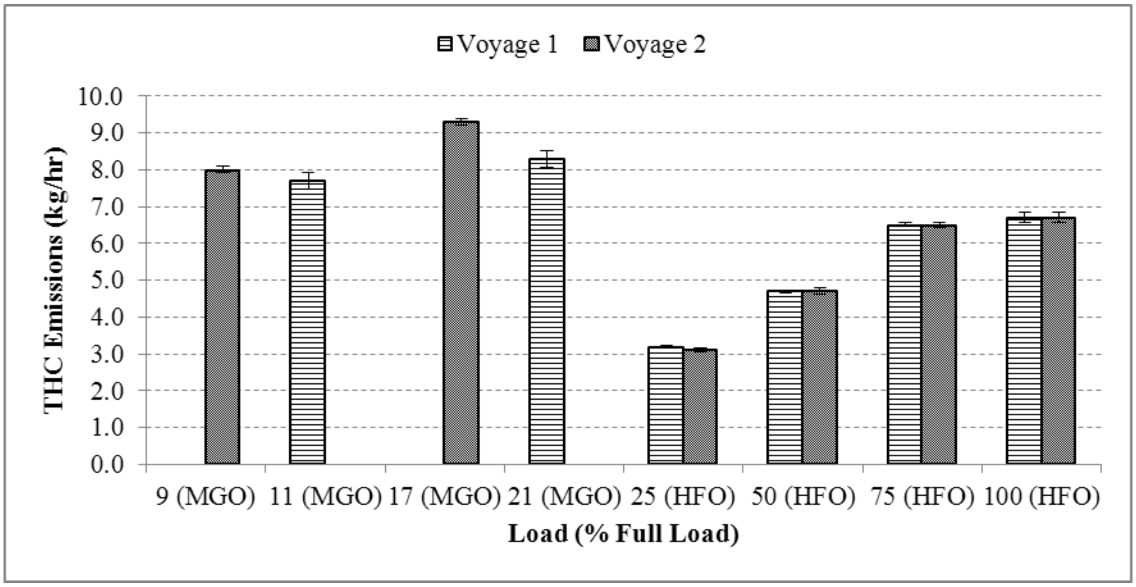

Figure 3-14 Modal Emission Rates for THC in kg/hr

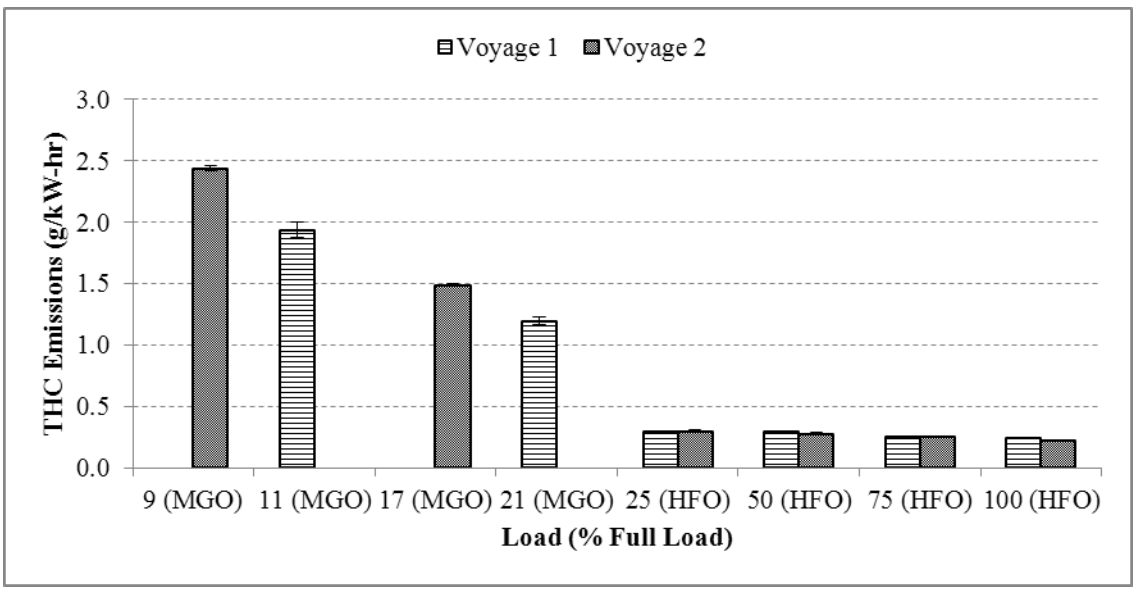

Figure 3-15 Modal Emission Factors for THC in g/kW-hr

3.6.7 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. Voyage 1 sulfur contents for HFO and MGO were 3.14% and 0.00065%, respectively. Voyage 2 sulfur contents for HFO and MGO were 2.15% and 0.0094%, respectively. Table 3-6 presents SO_2 emission factors for both voyages.

Table 3-6 SO_2 Emission Factors (g/kW-hr) for both Voyages

Voyage 1							
VSR 12	VSR 12	VSR 15	25%	50%	75%	85%	Overall Weighted
HFO	MGO	MGO	HFO	HFO	HFO	HFO	HFO
17.1	0.00	0.00	11.4	10.9	11.0	11.3	11.1
Voyage 2							
VSR 12	VSR 15	VSR 15	25%	50%	75%	85%	Overall Weighted
MGO	MGO	MGO	HFO	HFO	HFO	HFO	HFO
0.05	0.04	0.04	7.9	7.2	8.3	7.8	8

3.6.8 Tabulated Gaseous Emissions Data

The gaseous emissions of interest in this study are CO_2, NO_x, CO and THC. All the gaseous emissions were measured by instruments in compliance with the IMO standard specification (Appendix A.2.1). A detailed list of the gaseous emissions from both measurement voyages is presented in kg/hr and g/kW-hr for all the test conditions and is provided in Table 3-7 and Table 3-8 respectively. Three sets of consecutive readings were measured for every test condition, where each reading by itself was a five to seven minute average of one hertz data obtained from the instrument and the average of these is shown in Table 3-7 and Table 3-8.

Table 3-7 Gaseous Emissions (kg/hr)

Test Set	Actual Speed (Knots)	Fuel	Target ISO Load	Actual Load	Gaseous Emissions				Standard Deviation			
					CO_2	NOx	CO	THC	CO_2	NOx	CO	THC
					kg/hr							
Voyage 1												
VSR 12	12	HFO		10%	3,266	121	6.9	N/A	10.74	2.60	0.15	N/A
VSR 12	11	MGO		11%	3,067	98	8.2	7.7	58.25	1.86	0.16	0.22
VSR 15	15	MGO		21%	4,855	150	16.2	8.3	99.90	3.09	1.93	0.23
25%	17	HFO	25%	29%	6,231	210	6.2	3.2	17.44	0.91	0.40	0.04
50%	20	HFO	50%	52%	10,521	351	7.8	5.7	42.43	5.33	0.25	0.04
75%	23	HFO	75%	73%	14,992	521	9.5	6.8	22.6	5.04	0.13	0.05
85%	24	HFO	85%	81%	17,102	567	10.3	7.5	39.9	4.9	0.98	0.14
Voyage 2												
VSR 12	13	MGO		9%	2,733	84	6.9	8	27.33	0.84	0.07	0.08
VSR 15	14	MGO		17%	4490	140	N/A	9.3	44.90	1.40	N/A	0.09
VSR 15	14	MGO		19%	4752	147	10.0	N/A	47.52	1.47	0.10	N/A
25%	16	HFO	25%	28%	5,898	191	6.0	3.1	31.68	1.13	0.13	0.06
50%	20	HFO	50%	44%	8,864	275	7.3	4.7	30.44	1.66	0.16	0.09
75%	23	HFO	75%	69%	15,326	531	9.7	6.5	27.08	2.64	0.13	0.07
85%	24	HFO	85%	83%	17,513	575	10.6	6.7	39.46	1.78	0.06	0.13

Table 3-8 Gaseous Emission Factors (g/kW-hr)

Test Set	Actual Speed (Knots)	Fuel	Target ISO Load	Actual Load	Gaseous Emissions				Standard Deviation			
					CO_2	NOx	CO	THC	CO_2	NOx	CO	THC
					g/kW-hr							
Voyage 1												
VSR 12	12.0	HFO		10%	869	32.1	1.85	N/A	10.74	0.40	0.02	N/A
VSR 12	11.0	MGO		11%	777	24.9	2.07	1.94	8.22	0.26	0.02	0.06
VSR 15	15.0	MGO		21%	642	19.8	2.14	1.20	3.78	0.12	0.01	0.03
25%	17.0	HFO	25%	29%	577	19.5	0.57	0.30	1.62	0.28	0.04	0.00
50%	19.5	HFO	50%	52%	555	18.5	0.41	0.30	2.24	0.19	0.01	0.00
75%	23.0	HFO	75%	73%	561	19.5	0.36	0.26	0.85	0.17	0.00	0.00
85%	24.0	HFO	85%	81%	576	19.1	0.35	0.25	1.34	0.15	0.03	0.00
Overall Weighted Emission Factor					565	19.3	0.37	0.26				
Voyage 2												
VSR 12	13.0	MGO		9%	828	25.5	2.10	2.4	8.28	0.26	0.02	0.02
VSR 15	14.0	MGO		17%	720	22	N/A	1.49	7.20	0.22	N/A	0.01
VSR 15	14.0	MGO		19%	709	21.9	1.50	N/A	7.09	0.22	0.01	N/A
25%	16.0	HFO	25%	28%	584	18.9	0.60	0.30	3.14	0.11	0.01	0.01
50%	19.5	HFO	50%	44%	533	16.6	0.44	0.28	1.83	0.1	0.01	0.01
75%	23.0	HFO	75%	69%	612	20.6	0.39	0.26	1.08	0.11	0.01	0.00
85%	24.0	HFO	85%	83%	579	19.0	0.35	0.22	1.3	0.06	0.00	0.00
Overall Weighted Emission Factor					593	19.6	0.40	0.26				

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 sulfate, elemental and organic carbon while the engine operated at the ISO and VSR modes. As described in Appendix B: *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 DustTrak during both voyages. The total and speciated $PM_{2.5}$ mass emissions from both measurement voyages are presented in kg/hr and g/kW-hr for the specified test modes. Triplicate measurements were made as in the case of gaseous emissions and the error bars presented in the following figures are at one-sigma to provide an indication of confidence limits.

3.7.1 Total $PM_{2.5}$ Mass Emissions

Total $PM_{2.5}$ mass emissions from both voyages are presented in kg/hr and g/kW-hr for all the test modes in Figure 3-16 and Figure 3-17. The $PM_{2.5}$ mass emissions in kg/hr increased with engine load due to increase in fuel consumption. The difference in the amount of PM between marine gas oil and heavy fuel oil is primarily due to the differences in the sulfur content of the heavy fuel oil. The variation in $PM_{2.5}$ between two voyages across ISO load points is also due to different sulfur content. Sulfur content in HFO for voyage 1 and 2 were 3.14% and 2.15%, respectively. Therefore, higher $PM_{2.5}$ emissions are observed for voyage 1 than voyage 2.

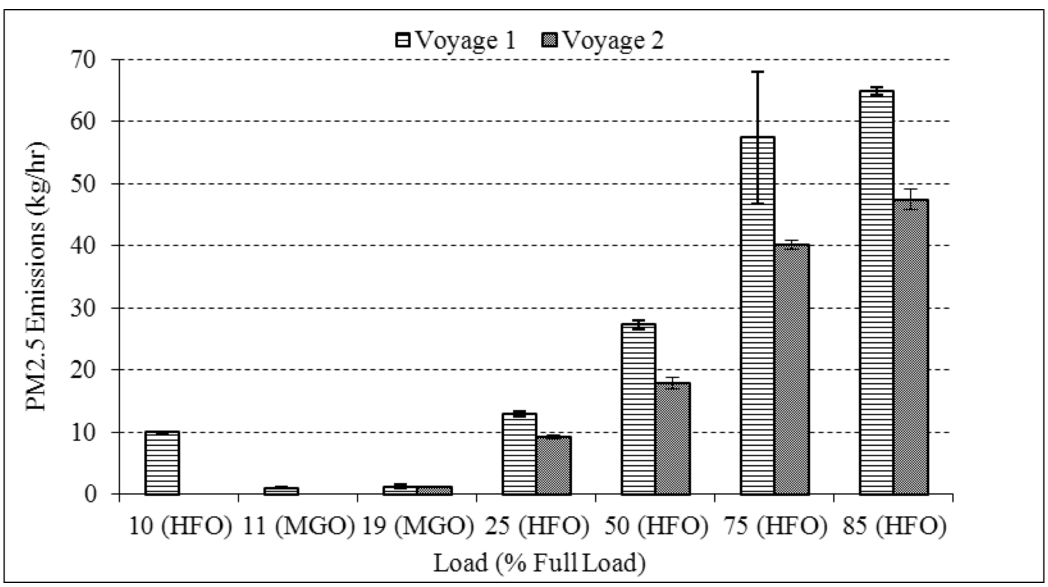

Figure 3-16 Modal Emission Rates for Total $PM_{2.5}$ in kg/hr

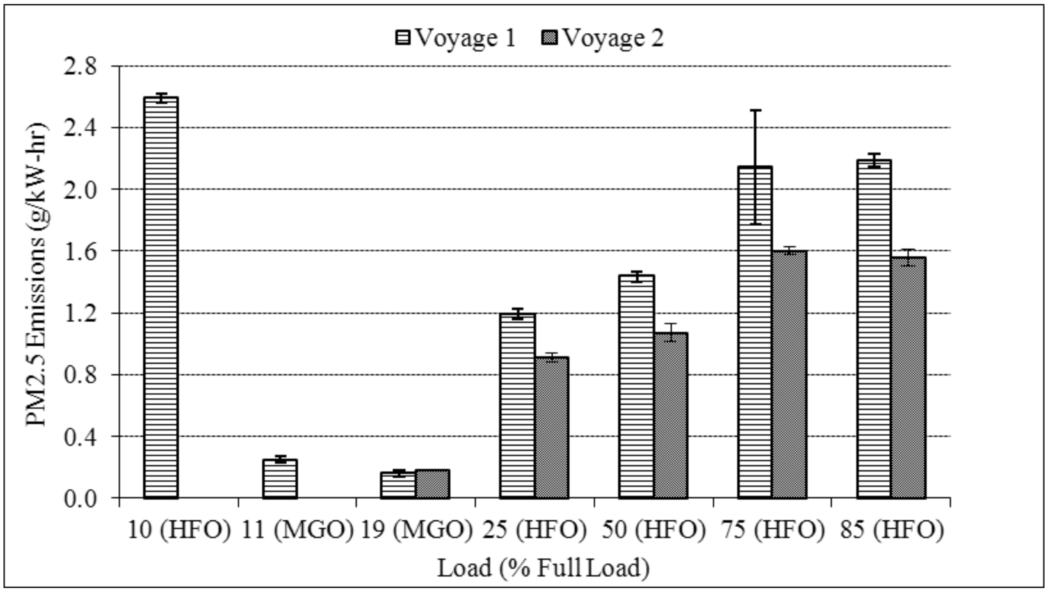

Figure 3-17 Modal Emission Factors for Total $PM_{2.5}$ Mass in g/kW-hr

3.7.2 Elemental Carbon (EC) Emissions

The elemental carbon (EC) fraction of the $PM_{2.5}$ mass emissions in kg/hr and g/kW-hr are shown in Figure 3-18 and Figure 3-19. Note that the EC emission factors are low in comparison to $PM_{2.5}$. EC fraction of $PM_{2.5}$ is within ~1% across ISO load points. The EC fractions are shown only for Voyage 1 as there were major power issues (tripping of circuit breakers etc) and electrical problems that prevented UCR from running their vacuum pump to obtain samples on quartz media during the second voyage.

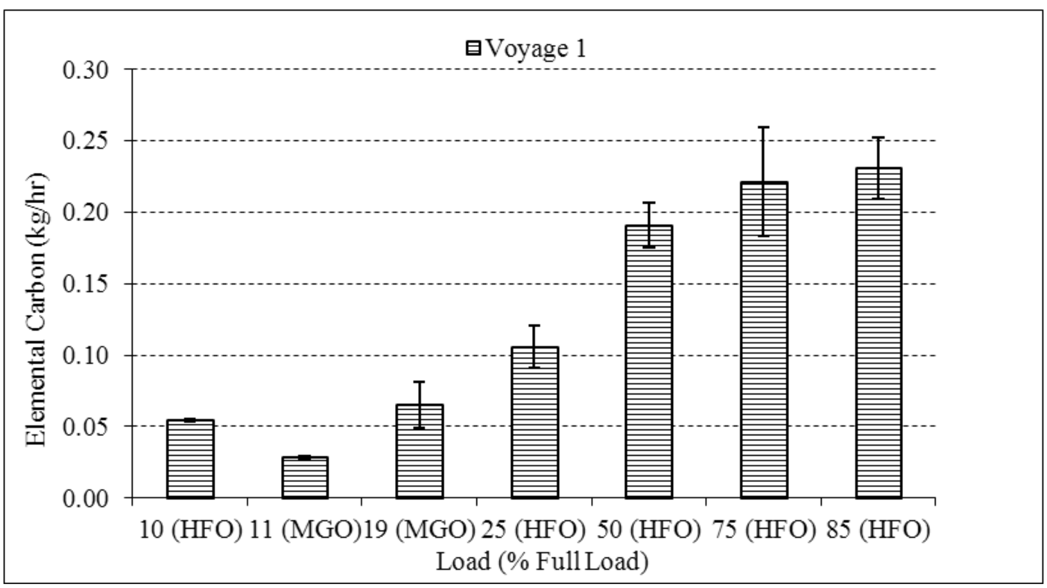

Figure 3-18 Modal Emission Rates for EC in kg/hr

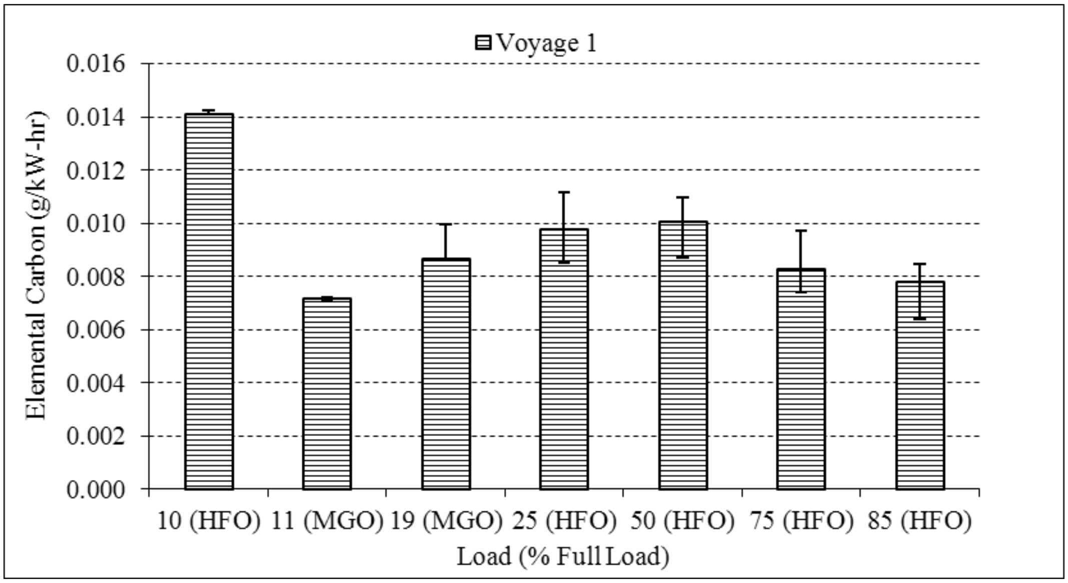

Figure 3-19 Modal Emission Factors for EC in g/kW-hr

3.7.3 Organic Carbon (OC) Emissions

The organic carbon fraction of the $PM_{2.5}$ mass emissions in kg/hr and g/kW-hr are shown in Figure 3-20 and Figure 3-21. OC fractions were only available for Voyage 1. OC fraction of $PM_{2.5}$ varies between 11-14% across ISO load points.

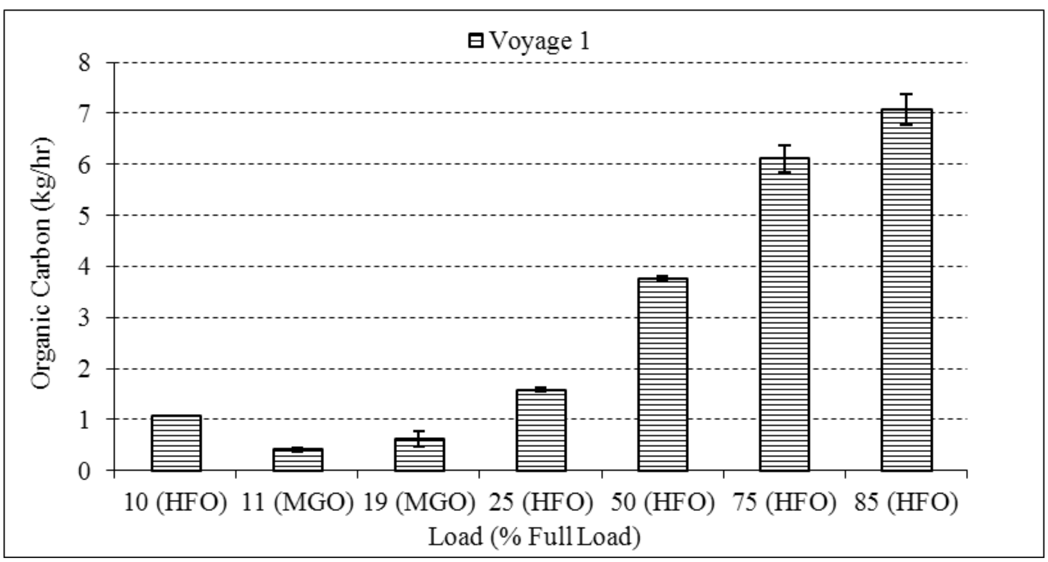

Figure 3-20 Modal Emission Rates for OC in kg/hr

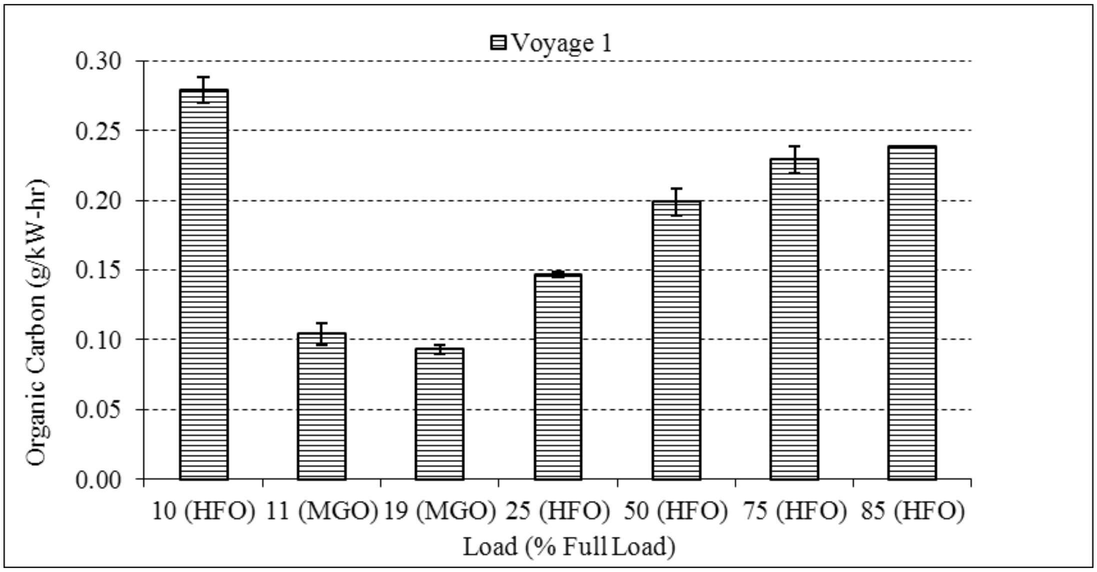

Figure 3-21 Modal Emission Factors for OC in g/kW-hr

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

An important element of UCR'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 with the sum of the carbon masses independently measured as elemental and organic carbon and hydrated sulfate fraction. That plot is shown below as Figure 3-22 and the fit (R^2 value) to a linear equation is very good.

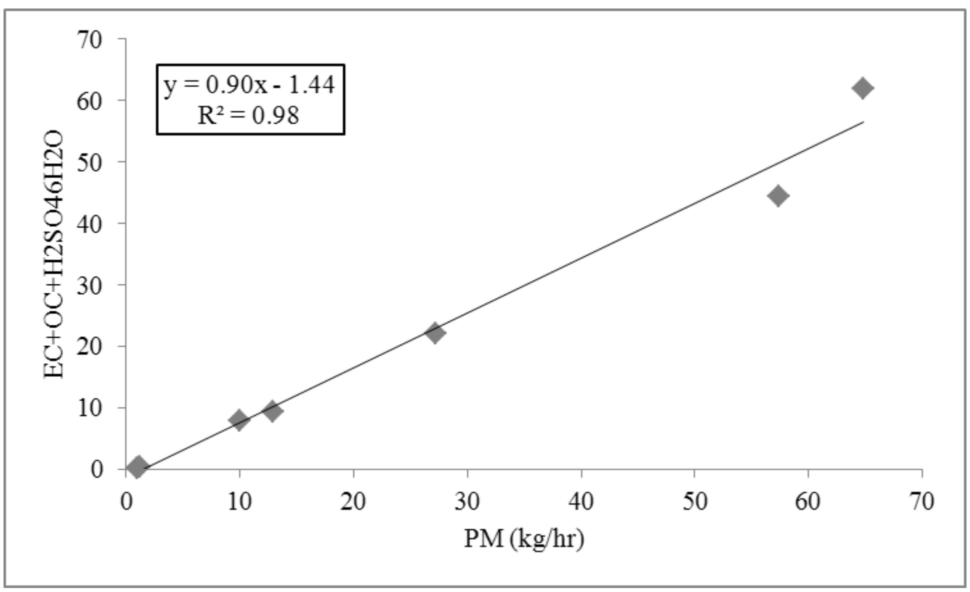

Figure 3-22 $PM_{2.5}$ Mass Balance

The highest portion of PM mass emissions from large marine diesels operating on HFO is the sulfate contribution. Figure 3-23 below shows the balance when the sulfate mass, expressed as H_2SO_4 $6H_2O$, is added to the elemental and organic carbon masses. Sulfate fraction is obtained from Teflo® filters which were extracted with HPLC grade water and isopropyl alcohol and analyzed for sulfate ions using a Dionex DX-120 ion chromatograph. A factor of 2.15 was applied to the mass of sulfate ions as sulfate on the Teflo® filter and was assumed to be in hydrated form ($H_2SO_4.6H_2O$) as predicted using the aerosol thermodynamic model ISORROPIA[x, y, z]. The hydrated sulfate fraction dominated the total PM and it increased from 0.70 to 0.95 as load increased from 25% to 100%.Fuel sulfur conversion to sulfate increased from 2.3% to 5.5% as the engine load increased from 29% to 81%, consistent with previous studies.

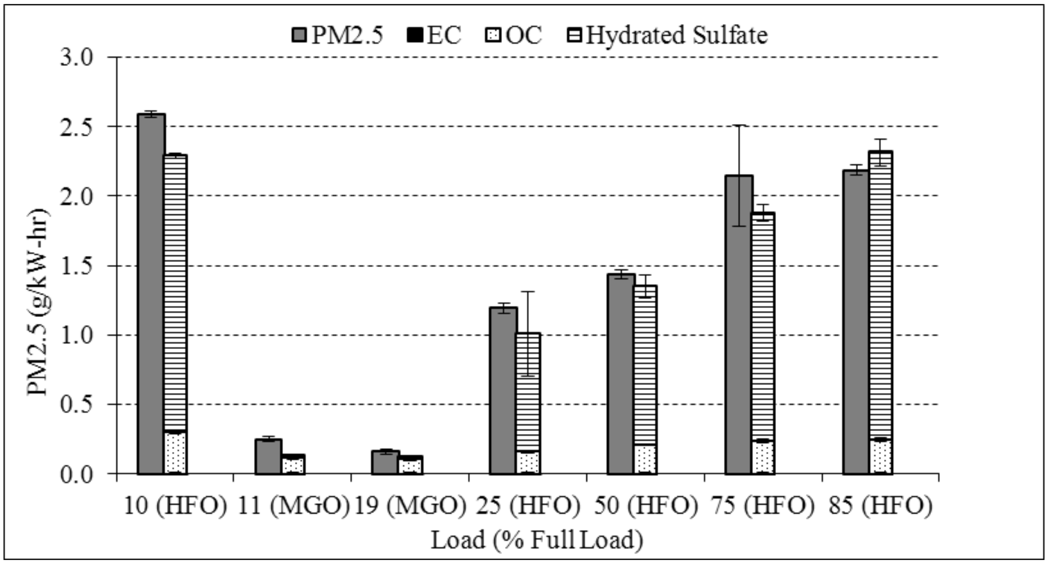

Figure 3-23 Mass Balance: Total and Speciated $PM_{2.5}$ Mass

3.7.5 Tabulated Particulate Emissions Data

The total and speciated $PM_{2.5}$ mass emissions from both measurement voyages are presented in kg/hr and g/kW-hr for the test modes and given in Table 3-9 and Table 3-10, respectively. Triplicate measurements were made for PM as in the case of gaseous emissions and the error bars presented in the following tables are at one-sigma and provide an indication of confidence limits.

[x] Nenes, A., Pilinis, C., Pandis, S.N. (1998) ISORROPIA: A New Thermodynamic Model for Multiphase Multicomponent Inorganic Aerosols, Aquat. Geochem., 4, 123-152.

[y] Fountoukis, C. and Nenes, A. (2007) ISORROPIA II: A Computationally Efficient Aerosol Thermodynamic Equilibrium Model for K^+ - Ca^{2+} - Mg^{2+} - NH_4^+ - SO_4^{2-} - NO_3^- - - Cl^- - H_2O Aerosols, Atmos. Chem. Phys., 7, 4639-4659.

[z] ISORROPIA. http://nenes.eas.gatech.edu/ISORROPIA.

[b] Agrawal, H., et al., In-use gaseous and particulate matter emissions from a modern ocean going container vessel. *Atmospheric Environment*, **2008**. 42(21): p. 5504-5510

[c] Agrawal, H., Welch, W.A., Henningsen, S., Miller, J.W., Cocker, D.R. Emissions from Main Propulsion Engine on Container Ship at Sea. *Journal of Geophysical Research*, vol 115, D23205, 7 PP., **2010**

Table 3-9 Total and Speciated Particulate Matter (PM2.5) Emissions (kg/hr)

Test Set	Actual Speed (Knots)	Fuel	Target ISO Load	Actual Load	Particulate Emissions (kg/hr)				Standard Deviation			
					$PM_{2.5}$	EC	OC	$SO_4^{2-}6H_2O$	$PM_{2.5}$	EC	OC	$SO_4^{2-}6H_2O$
Voyage 1												
VSR 12	12.0	HFO		10%	10.0	0.054	1.07	7.67	0.10	0.00	0.01	0.08
VSR 12	11.0	MGO		11%	0.99	0.028	0.41	0.070	0.10	0.00	0.05	0.03
VSR 15	15.0	MGO		21%	1.23	0.065	0.62	0.190	0.28	0.02	0.15	0.06
25%	17.0	HFO	25%	29%	12.9	0.106	1.58	9.560	0.37	0.01	0.04	3.46
50%	19.5	HFO	50%	52%	27.2	0.191	3.77	21.6	0.76	0.02	0.04	1.53
75%	23.0	HFO	75%	73%	57.3	0.222	6.11	43.8	10.6	0.04	0.26	1.54
85%	24.0	HFO	85%	81%	64.8	0.231	7.06	61.3	0.64	0.02	0.30	2.62
Voyage 2												
VSR 12	13.0	MGO		9%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
VSR 15	14.0	MGO		17%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
VSR 15	14.0	MGO		19%	1.22	N/A	N/A	N/A	0.01	N/A	N/A	N/A
25%	16.0	HFO	25%	28%	9.20	N/A	N/A	N/A	0.29	N/A	N/A	N/A
50%	19.5	HFO	50%	44%	17.8	N/A	N/A	N/A	0.97	N/A	N/A	N/A
75%	23.0	HFO	75%	69%	40.1	N/A	N/A	N/A	0.64	N/A	N/A	N/A
85%	24.0	HFO	85%	83%	47.3	N/A	N/A	N/A	1.65	N/A	N/A	N/A

Table 3-10 PM2.5 Emission Factors (g/kW-hr)

Test Set	Actual Speed (Knots)	Fuel	Target ISO Load	Actual Load	Particulate Emissions				Standard Deviation			
					$PM_{2.5}$	EC	OC	$SO_4^{2-}6H_2O$	$PM_{2.5}$	EC	OC	$SO_4^{2-}6H_2O$
					g/kW-hr							
Voyage 1												
VSR 12	12.0	HFO		10%	2.59	0.014	0.28	1.99	0.03	0.00	0.003	0.02
VSR 12	11.0	MGO		11%	0.25	0.007	0.10	0.02	0.04	0.00	0.009	0.01
VSR 15	15.0	MGO		21%	0.16	0.009	0.08	0.03	0.00	0.001	0.008	0.00
25%	17.0	HFO	25%	29%	1.19	0.010	0.15	0.89	0.03	0.001	0.003	0.32
50%	19.5	HFO	50%	52%	1.44	0.010	0.20	1.14	0.03	0.001	0.002	0.08
75%	23.0	HFO	75%	73%	2.14	0.008	0.23	1.64	0.37	0.001	0.010	0.06
85%	24.0	HFO	85%	81%	2.19	0.008	0.24	2.07	0.04	0.001	0.010	0.10
Overall Weighted Emission Factor					2.00	0.0	0.22	1.63				
Voyage 2												
VSR 12	13.0	MGO		9%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
VSR 15	14.0	MGO		17%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
VSR 15	14.0	MGO		19%	0.18	N/A	N/A	N/A	0.00	N/A	N/A	N/A
25%	16.0	HFO	25%	28%	0.91	N/A	N/A	N/A	0.03	N/A	N/A	N/A
50%	19.5	HFO	50%	44%	1.07	N/A	N/A	N/A	0.06	N/A	N/A	N/A
75%	23.0	HFO	75%	69%	1.60	N/A	N/A	N/A	0.03	N/A	N/A	N/A
85%	24.0	HFO	85%	83%	1.56	N/A	N/A	N/A	0.05	N/A	N/A	N/A
Overall Weighted Emission Factor					1.49	N/A	N/A	N/A				

4 Results for the Second Vessel

This section presents results and analysis of measured criteria pollutants and greenhouse gasses such as CO_2 emitted from the modern vessel launched in May 2010. The vessel was equipped with newest engine technologies meeting IMO Tier 1 NOx standards. Two different fuels, vessel speed and engine loads were the parameters varied during this testing. Measurements were made while the main engine operations approximated the modes in the ISO 8178-E3 certification test cycles and continuous measurements were made to evaluate the effect of fuel and VSR on emissions.

4.1 Test Schedule

The primary goal of this project was to determine the actual in-use emission of gases (CO_2, NO_x, CO, and THC) and particulate matter ($PM_{2.5}$) mass from the main engine of a Panamax Class container vessel following the ISO certification cycle and to determine emission reductions by reducing the vessel speed under the VSR program. Two measurement voyages between the Ports of Los Angeles and Oakland were undertaken for this purpose, one in July 2009 and the other in August 2009, each of which lasted for 3 days. Details of the test schedule for the measurement voyage is given in Table 4-1

Table 4-1 Actual Test Schedule

Voyage	Date	Fuels	Planned Test Points; Fuel & Load
Voyage 3 (Second Vessel)	09/01/2010	HFO & MGO	HFO: RT & ISO: 100%, 75%, 50% & 25% MGO : VSR 12 & 15 knots

Notes:

- RT: Real Time Monitoring and Recording of Gaseous Emission Samples;
- ISO: Filter samples taken in accordance with ISO 8178-4 E3.

4.2 Second Test Vessel and Engine for Testing

The last vessel to be tested in the program was a very modern Post-Panamax container ship that was placed in service in May of 2010. Some properties of the vessel are shown in Table 4-2.

Table 4-2 Selected Parameters for the Second Vessel

Vessel Type	Post-Panamax Class Container Ship
Shipyard	Hyundai, Korea
Year Built	2010
Length (m)	350.56
Beam (m)	42.8
Dead weight (ton)	106,491
Gross tonnage (ton)	91,051
Maximum TEU capacity	8,501
Maximum speed (knots)	25.4
Maximum draught (m)	14.5

The main propulsion engine for the vessel was an electronically controlled, camshaft-less low speed diesel engines two-stroke engine rated at 68,530kW. The engine included the latest technology to meet the Tier 1 specifications. According to MAN, this engine ushers in an era where the full potential of the electronic fuel injection with “rate shaping” (or “injection profiling”) is utilized to give a very attractive NOx/SFOC relationship.

Figure 4-1 MAN Picture showing Model MAN B&W 11K98ME7

Some properties of the engine are shown in Table 4-3 and in Appendix L.

Table 4-3 Selected Technical Parameters of the Second Test Engine

Manufacturer/Model	Hyundai MAN B&W 11K98ME7
Technology	2-stroke
Number of Cylinders	11
Speed (MCR)	97 rpm
Maximum Power Rating	68,530 kW
Bore	980 mm
Stroke	2660 mm
Displacement	22,060 liters

4.3 Test Fuels for Ship Tests

The main engine burned Heavy Fuel Oil (HFO) and Marine Distillate Oil (MGO) meeting ISO 8217 specifications (ISO 8217.2005). Fuels were typical of normal supply and two different fuel analyses were available. One analysis was performed by the fuel supplier and presented to the ship owner in the format of a Certificate of Analysis (C of A). The C of A provided by the fuel supplier is presented in Appendix C. For another analysis, fuel sample was obtained during the course of emissions testing. A 1 liter fuel samples were drawn from the main engine final filter drain, immediately upstream of the injector rail. These samples were subsequently analyzed by a different lab. Selected properties of the fuel from both the analyses are presented in Table 4-4.

Table 4-4 Selected Fuel Properties

Fuel Properties	Units	Certificate of Analysis (CoA)		UCR Samples	
		HFO	MGO	HFO	MGO
Density @15C	kg/m^3	988.8	845.5	-	-
Viscosity @40C	mm^2/s	368.6	3.3	-	-
Sulfur	% m/m	2.40	0.17	2.51	0.17
Ash	% m/m	0.07	<0.01	-	-
Vanadium	mg/kg	262	<1	-	-
Density @15.5C	kg/m^3	-	-	988.2	845.2

4.4 Operating Conditions for Vessel during Emissions Testing

The emissions testing were conducted approximately at engine loads specified in ISO certification cycles and at 12% and 23% of full load during reduced vessel speed. 100% load point was not achieved due to practical limitations. UCR members went to the engine control room to manually read the engine operating conditions from the instrument panel and recorded then on data sheets. Some of the operating conditions included the load, RPM, boost pressure and temperature. The operating conditions are presented in Table 4-5.

Table 4-5 Operating Conditions of Engine

Fuel	HFO	HFO	HFO	HFO	MGO	MGO
Load (%)	90	75	47	24	23	12
Load (kW)	61,944	51,703	31,902	16,707	15,481	8,275
Engine Speed (rpm)	97	91	78	61	59	49

4.5 Determining the Exhaust Flow Rate

For this vessel exhaust flow rate was calculated from the fuel consumption of engine. It was assumed that the all the carbon in the fuel got converted into carbon dioxide which was measured in the exhaust. A carbon mass balance was performed to calculate exhaust flow rate. Figure 4-2 shows the calculated exhaust flow rate against engine loads.

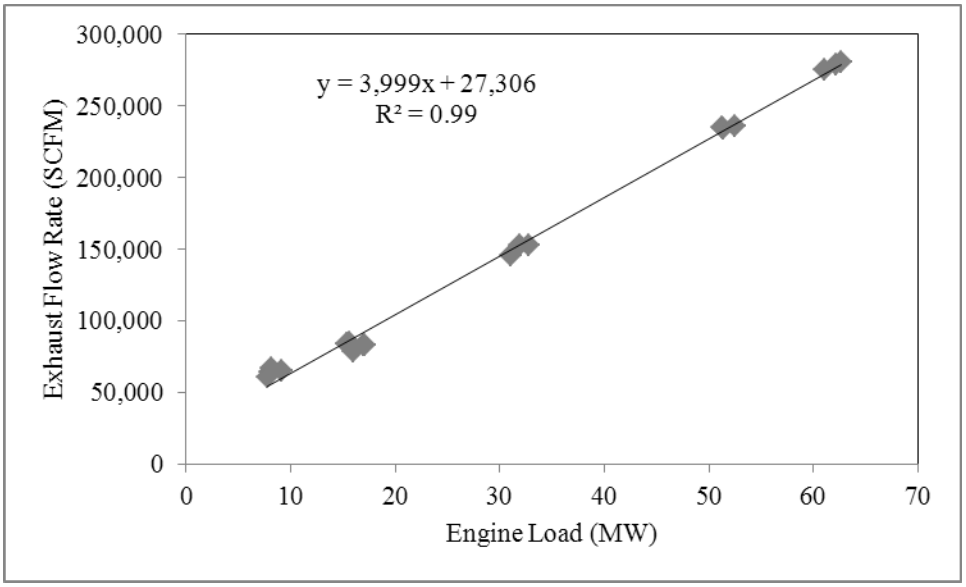

Figure 4-2 Calculated Exhaust Flow Rate vs. Engine Loads

4.6 Sampling Ports

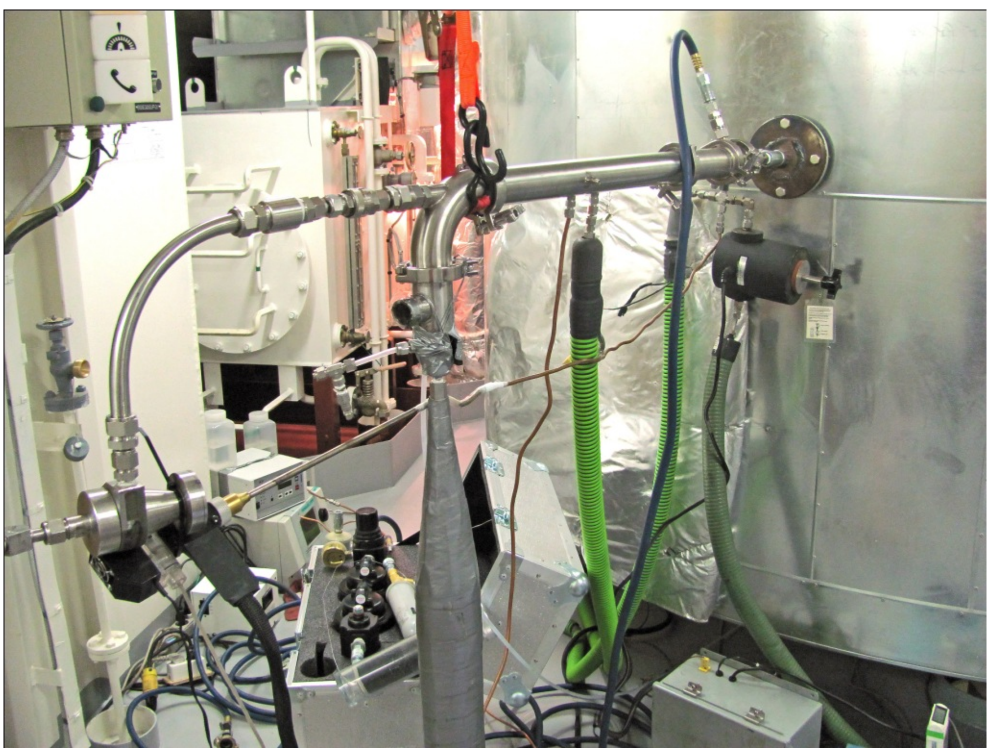

Figure 4-3 Installed Sampling System on the Stack of the Vessel

The raw exhaust was measured at the upstream of the dilution tunnel. Dilution up to the ratio of 6:1 was created by a compressed air stream that was treated to be free of moisture, hydrocarbons and particulates. Teflon and Quartz filters were used to collect

PM downstream of the dilution tunnel. Two sets of Semtech-DS and Horiba PG-250 were continuously measuring raw and diluted exhaust concentrations. A continuous PM monitoring instrument was sampling downstream of the dilution tunnel. Figure 4-3 shows the installed sampling system where the main exhaust is directly connected to the partial dilution system.

4.7 Gaseous Emissions-IMO Methods

The gaseous emissions of interest in this study were CO_2, NO_x, CO and THC similar to the first vessel. All the gaseous emissions were measured by instruments in compliance with the IMO standard specification and a detailed list of the gaseous emissions from both the measurement voyages are presented in kg/hr and g/kW-hr in this section. Three sets of consecutive readings were measured for every test condition, where each reading by itself was a five to seven minute average of one hertz data obtained from the instrument. The error bars in the figures represent the confidence limit of the analyzed data. Data were taken while operating on either heavy fuel oil or marine distillate oil.

4.7.1 Carbon Dioxide Emissions

The gaseous emissions for CO_2 in kg/hr are presented in Figure 4-4. The results in Figure 4-4 show the CO_2 emission increase as the load increases due to higher fuel consumption, as expected. The error bars in the figure represent the confidence limits of the data gathered and analyzed.

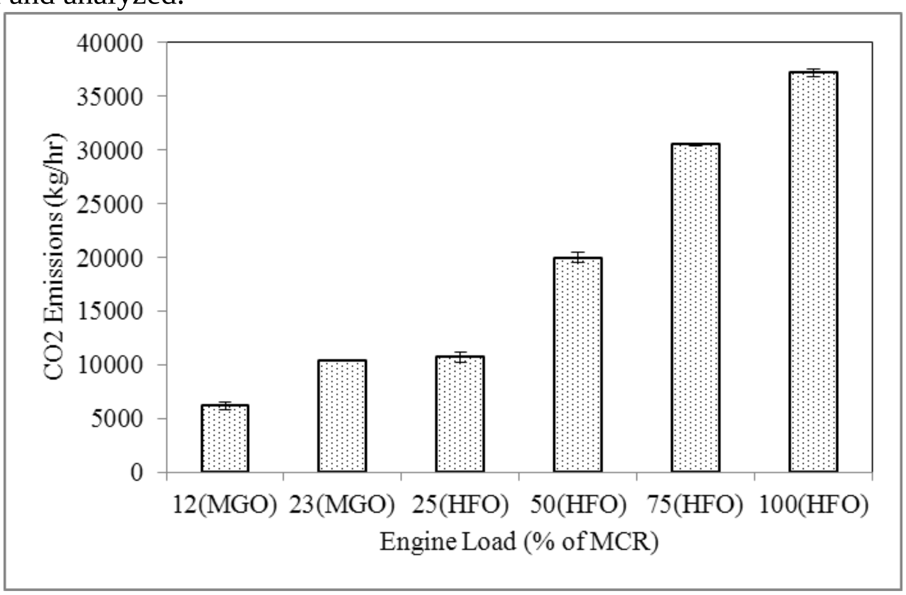

Figure 4-4 Modal Emission Rates for CO_2 in kg/hr

Another graphical representation for fuel consumption data as a function of engine load is presented in Figure 4-5. The coefficient of determination (R^2) is quite linear as expected.

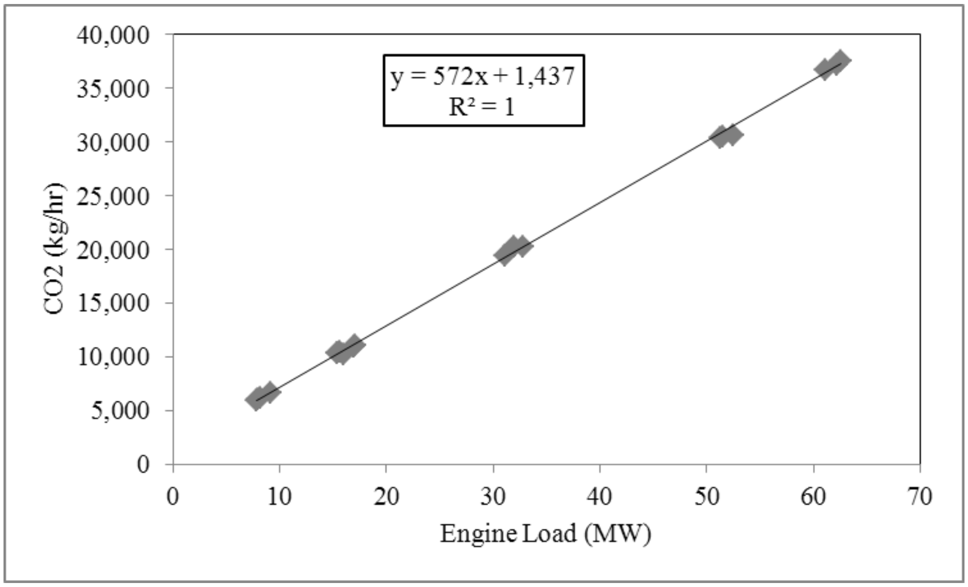

Figure 4-5 Engine Load vs. CO_2 Emissions (kg/hr)

CO_2 emissions were reviewed as they indicate the accuracy of the collected data. The emissions factors are presented in g/kW-hr for CO_2 in figure 4.5. The overall weighted emission factor of 600 g/kW-hr obtained is typical of a two-stroke, slow speed marine diesel engine. One would expect to have a higher emission factor at lower loads.

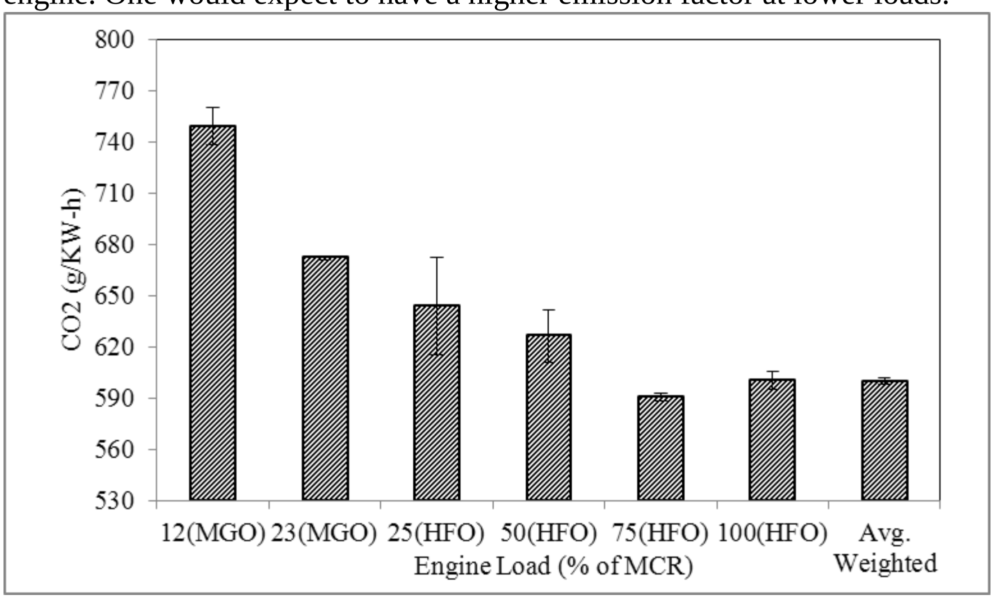

Figure 4-6 Modal Emission Factors for CO_2 in g/kW-hr

4.7.2 Quality Check: Carbon Mass Balance: Fuel vs. Exhaust

As part of the UCR's QA/QC, the carbon mass balance was checked between the fuel and the measured carbon in the exhaust. During the emission testing, the fuel flow rate was directly measured. The net fuel consumed was obtained from the control panel display in the engine room. Based on the typical carbon content of HFO and MGO fuels which are 86 and 87 wt% respectively, the carbon content of the fuel in kg/hr was estimated by using the fuel flow rate and density of the fuel obtained from the fuel analysis. The amount of carbon in the exhaust was calculated from the CO_2 and CO emissions and Figure 4-7hows the carbon mass balance between the fuel and the exhaust for the second voyage. The R^2 value is excellent.

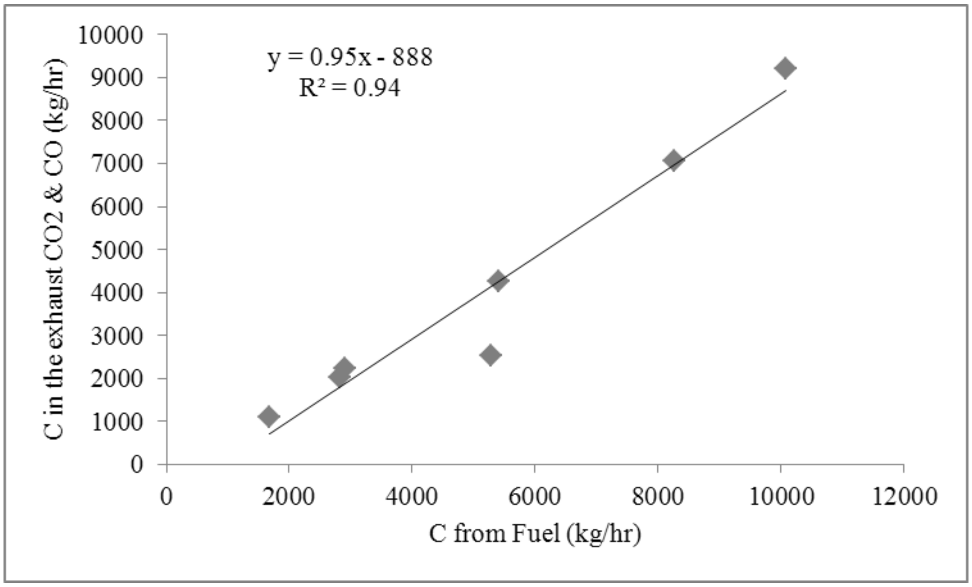

Figure 4-7 Carbon Mass Balance between Fuel and Exhaust

4.7.3 Quality Check: CO_2 Emissions vs. Engine and Vessel Speed

Another check of the data is the plot of fuel consumed or power versus the propeller/engine speed. As described in Section 2.81 *Analysis Relating Emissions, Fuel Consumption and Vessel Speed* one would expect the data to fit an equation where the power would vary with the cube of the speed. Basically more and more fuel is required as the vessel speeds up. The data in Figure 4-8 fall on a cubic line with an R^2 ~1 thus indicating a good fit for the engine data for this voyage. A plot of engine and vessel speed is shown in Figure 4-9 and is linear, as expected.

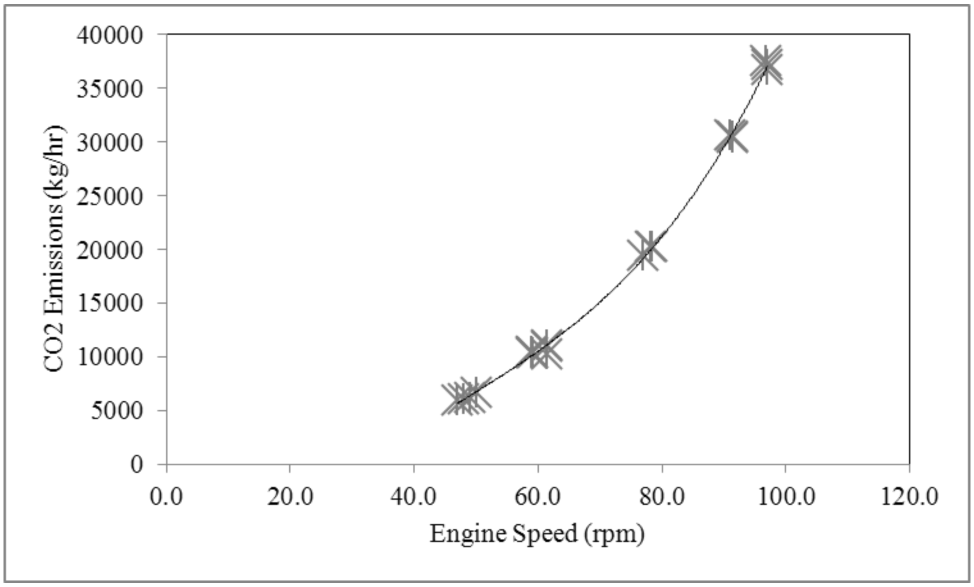

Figure 4-8 Emissions of CO_2 vs. Engine Speed

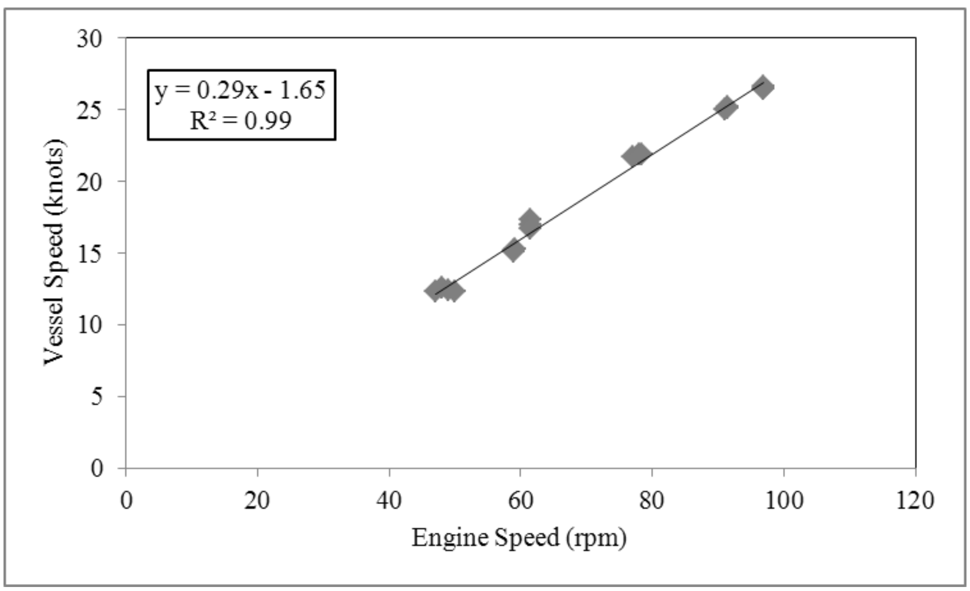

Figure 4-9 Engine Speed (rpm) vs. Vessel Speed (knots)

4.7.4 NOx Emissions

Ocean going vessels are huge emitter of NOx emissions. NOx emission rates and factors are of special interest as it is one of the criteria pollutants which contribute in the formation of ground level ozone and fine particle pollution. The gaseous emissions of NOx are presented in kg/hr and g/kW-hr in Figure 4-10 and Figure 4-11 respectively.

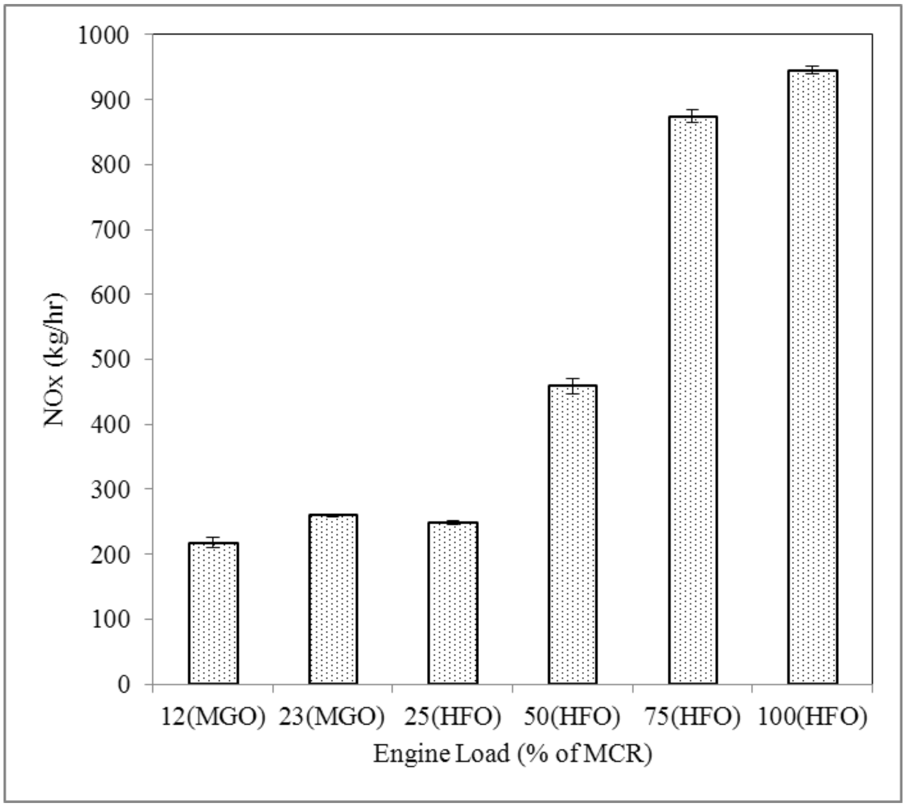

Figure 4-10 Modal Emission Rates for NOx in kg/hr

NOx emissions presented in g/kW-hr are fairly consistent across all loads for HFO similar to engines in this class. Overall averaged weighted emission factor for NOx is 16.1 g/kW-hr; lower than first vessel which indicates the proficiency of newest engine technology in reducing emissions.

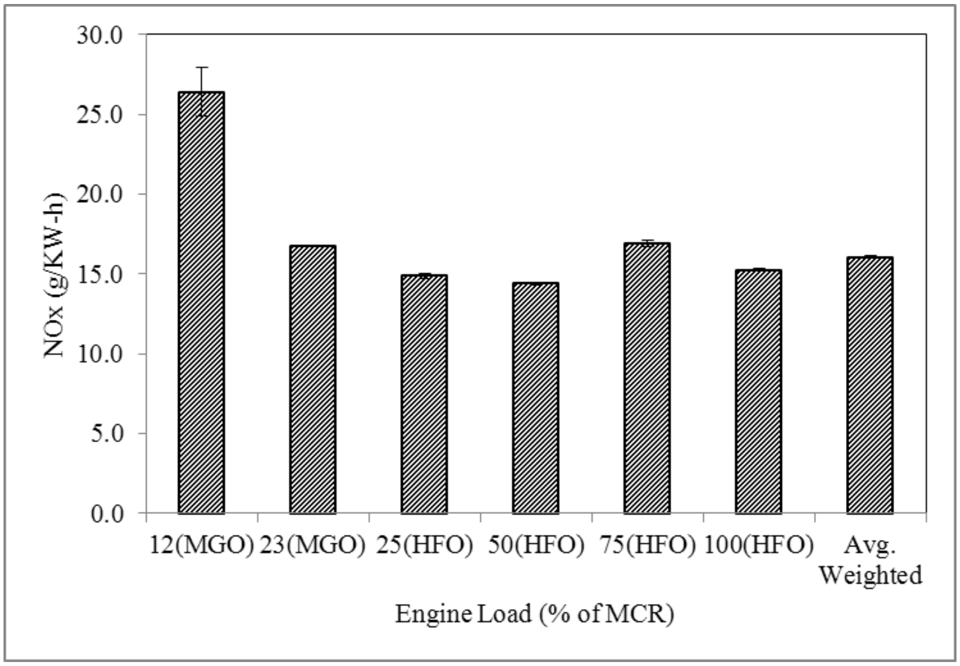

Figure 4-11 Modal Emission Factors for NOx in g/kW-hr

4.7.5 CO Emissions

The gaseous emissions for CO in kg/hr are shown in figure 4.11. Carbon monoxide forms under fuel-rich combustion conditions due to insufficient oxygen to complete the reaction to CO_2.

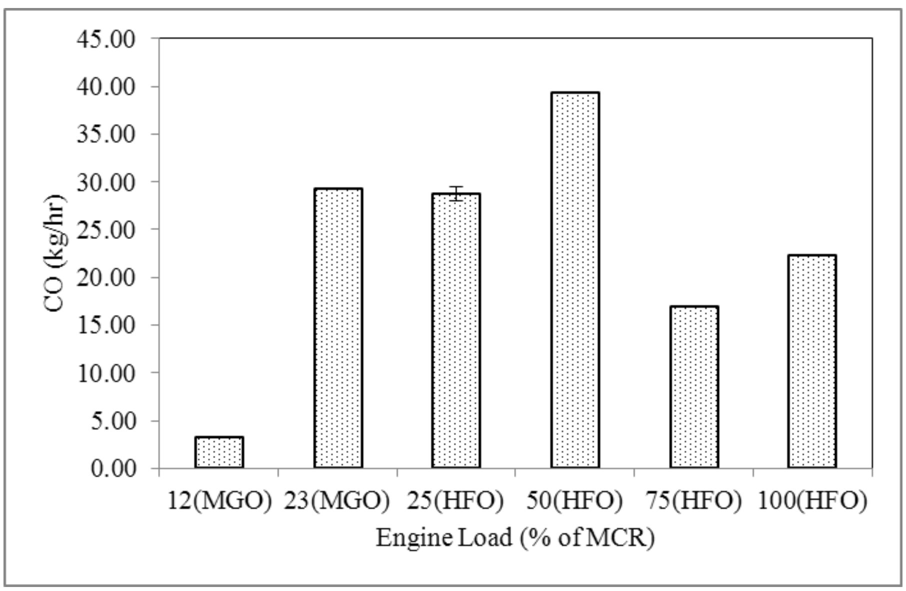

Figure 4-12 Modal Emission Rates for CO in kg/hr

The CO modal emission factors in g/kW-hr in figure 4.12 are found to be the highest at low power conditions, where burning rates and peak temperatures are relatively low. Overall CO is quite low as compared to the standards.

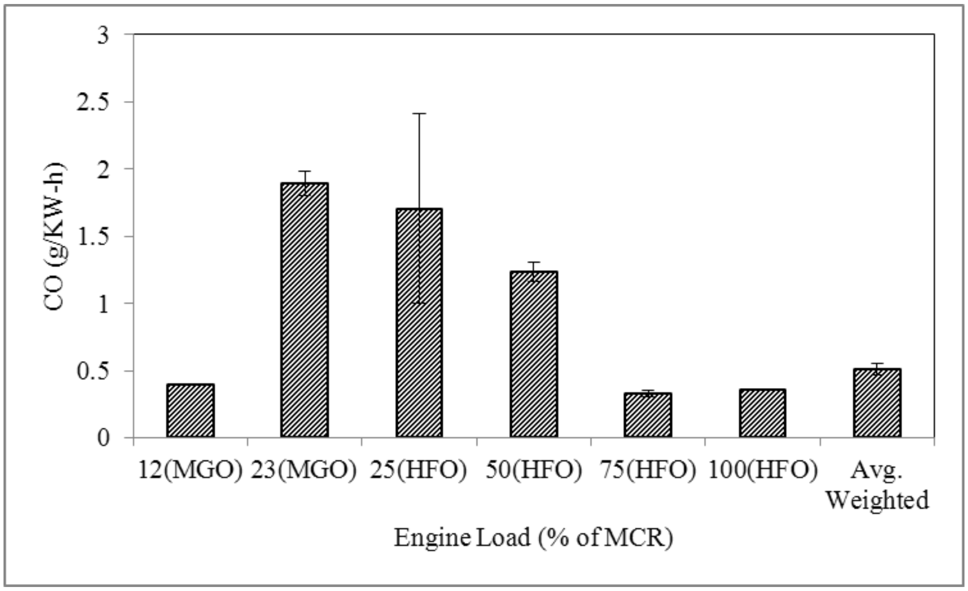

Figure 4-13 Modal Emission Factors for CO in g/kW-hr

4.7.6 Total Hydrocarbon (THC) Emissions

THC emissions are presented in kg/hr and g/kW-hr in Figure 4-14 and Figure 4-15, respectively. THC emission factors increases with decrease in engine load.

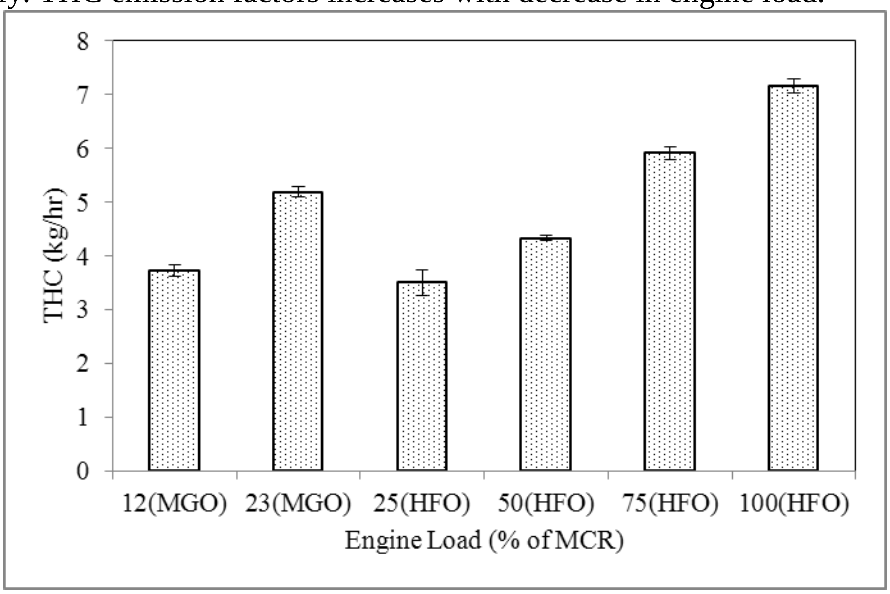

Figure 4-14 Modal Emission Rates for THC in kg/hr

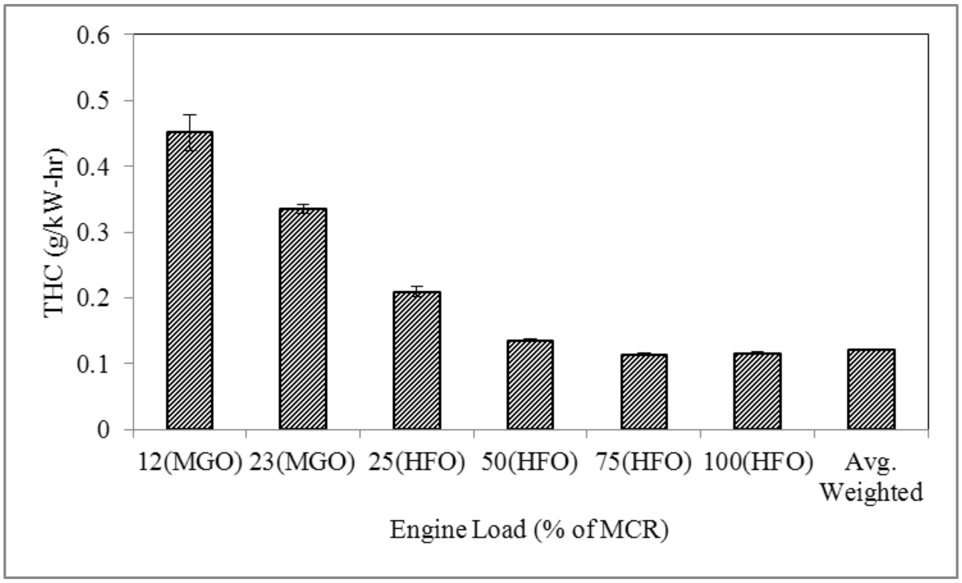

Figure 4-15 Modal Emission Factors for THC in g/kW-hr

4.7.7 SO_2 Emissions

As stated earlier, per ISO 8178-1 sulfur oxides concentrations are calculated based on the sulfur content in the fuel. The reported sulfur content in HFO and MGO were 2.51% and 0.17%, respectively. SO2 emission factors in g/kW-hr are presented in Table 4-6.

Table 4-6 SO_2 emission factors (g/kW-hr)

VSR 12	VSR 15	25%	50%	75%	100%	Overall Weighted
MGO	MGO	HFO	HFO	HFO	HFO	HFO
0.76	0.68	10.14	9.86	9.29	9.44	9.44

4.7.8 Tabulated Gaseous Emissions Data

The gaseous emissions of interest in this study are CO_2, NO_x, CO and THC. All the gaseous emissions were measured by instruments in compliance with the IMO standard specification (Appendix A.2.1). A detailed list of the gaseous emissions from both measurement voyages is presented in kg/hr and g/kW-hr for all the test conditions and is provided in table 4-7 and 4-8, respectively. Three sets of consecutive readings were measured for every test condition, where each reading by itself was a five to seven minute average of one hertz data obtained from the instrument and the average of these is shown in Table 4-7 and Table 4-8.

Table 4-7 Gaseous Emissions (kg/hr)

Test Set	Speed (Knots)	Fuel	Target ISO Load	Actual Load	Gaseous Emissions				Standard Deviation			
					CO_2	NO_x	CO	THC	CO_2	NO_x	CO	THC
					kg/hr							
VSR 12	12.0	MGO		12%	6,194	218	3.3	3.7	335	7.1	0.2	0.10
VSR 15	15.0	MGO		23%	10,406	260	29.3	5.2	102	2.3	1.4	0.09
25%	17.0	HFO	25%	24%	10,766	248	28.8	3.5	476	2.6	11.8	0.24
50%	21.8	HFO	50%	47%	19,980	459	39.3	4.3	490	11.6	2.4	0.05
75%	25.0	HFO	75%	75%	30,524	874	17.0	5.9	117	9.9	1.0	0.11
100%	26.5	HFO	100%	90%	37,222	945	22.3	7.2	340	6.0	0.3	0.13

Table 4-8 Gaseous Emission Factors (g/kW-hr)

Test Set	Speed (Knots)	Fuel	Target ISO Load	Actual Load	Gaseous Emissions				$PM_{2.5}$ and Speciated $PM_{2.5}$			
					CO_2	NO_x	CO	THC	$PM_{2.5}$	EC	OC	SO_4^{2-}
					g/kW-hr							
VSR 12	12.0	MGO		12%	749	26.4	0.40	0.45	0.3	0.003	0.18	0.05
VSR 15	15.0	MGO		23%	672	16.8	1.89	0.34	0.3	0.003	0.17	0.09
25%	17.0	HFO	25%	24%	644	14.9	1.71	0.21	1.2	0.009	0.22	0.83
50%	21.8	HFO	50%	47%	626	14.4	1.23	0.14	1.2	0.006	0.19	0.94
75%	25.0	HFO	75%	75%	590	16.9	0.33	0.11	1.4	0.004	0.17	1.18
100%	26.5	HFO	100%	90%	600	15.2	0.36	0.12	1.5	0.004	0.16	1.34
Overall weighted emission factor					600	16.1	0.51	0.12	1.4	0.005	0.17	1.18

4.8 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 sulfate, elemental and organic carbon while the engine operated at the ISO and VSR modes. As described in Appendix B: *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 DustTrak. The total and speciated $PM_{2.5}$ mass emissions from both measurement voyages are presented in kg/hr and g/kW-hr for the specified test modes. Triplicate measurements were made as in the case of gaseous emissions and the error bars presented in the following figures are at one-sigma to provide an indication of confidence limits.

4.8.1 Total $PM_{2.5}$ Mass Emissions

Total $PM_{2.5}$ mass emissions are presented in kg/hr and g/kW-hr for all the test modes in Figure 4-16 and Figure 4-17. The $PM_{2.5}$ mass emissions in kg/hr increased with engine load due to increase in fuel consumption. The difference in the amount of PM between distillate fuel and heavy fuel is primarily due to the differences in the sulfur content of the heavy fuel oil.

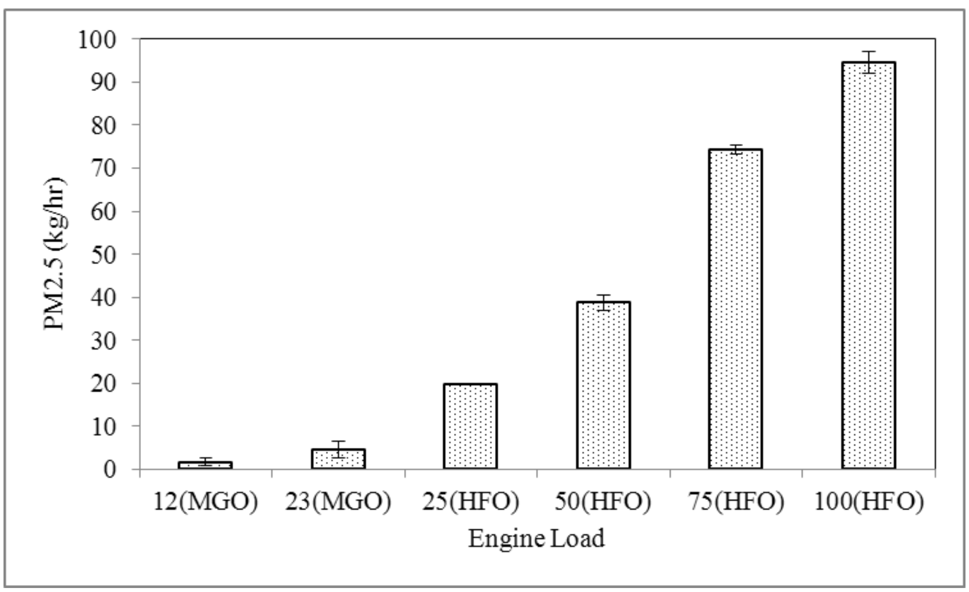

Figure 4-16 Modal Emission Rates for Total PM2.5 in kg/hr

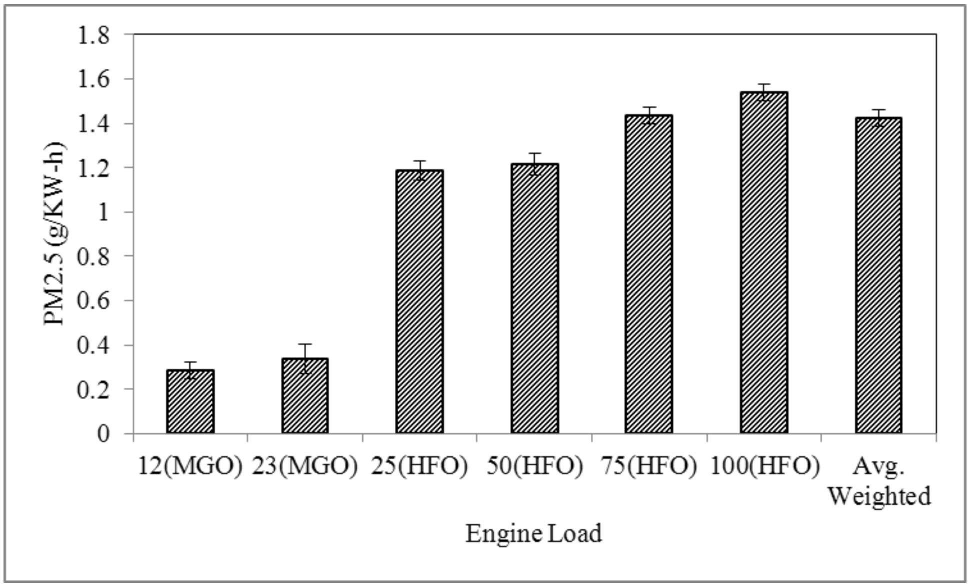

Figure 4-17 Modal Emission Rates for Total PM2.5 in g/kW-hr

4.8.2 Elemental Carbon (EC) Emissions

The elemental carbon (EC) fraction of the $PM_{2.5}$ mass emissions in kg/hr and g/kW-hr are shown in Figure 4-18 and Figure 4-19.

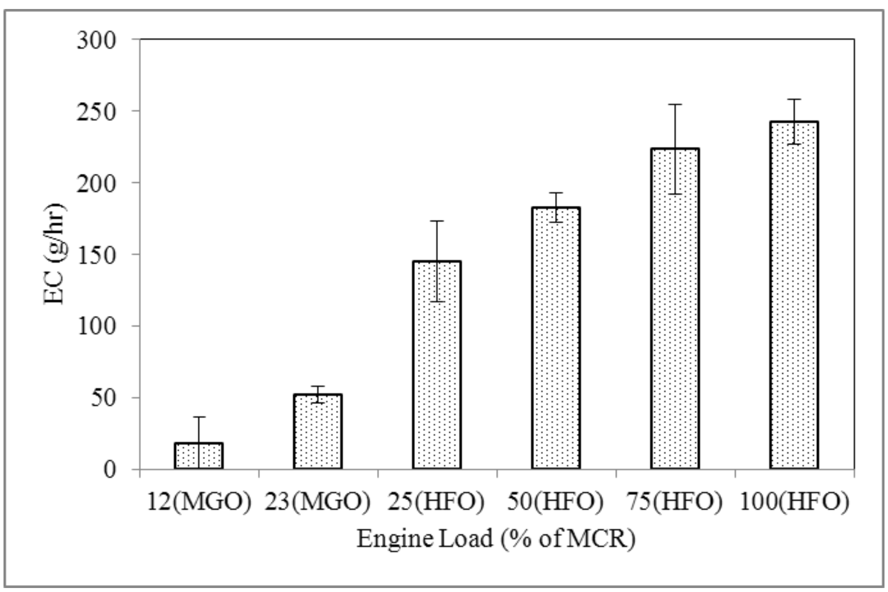

Figure 4-18 Modal Emission Rates for EC in g/hr

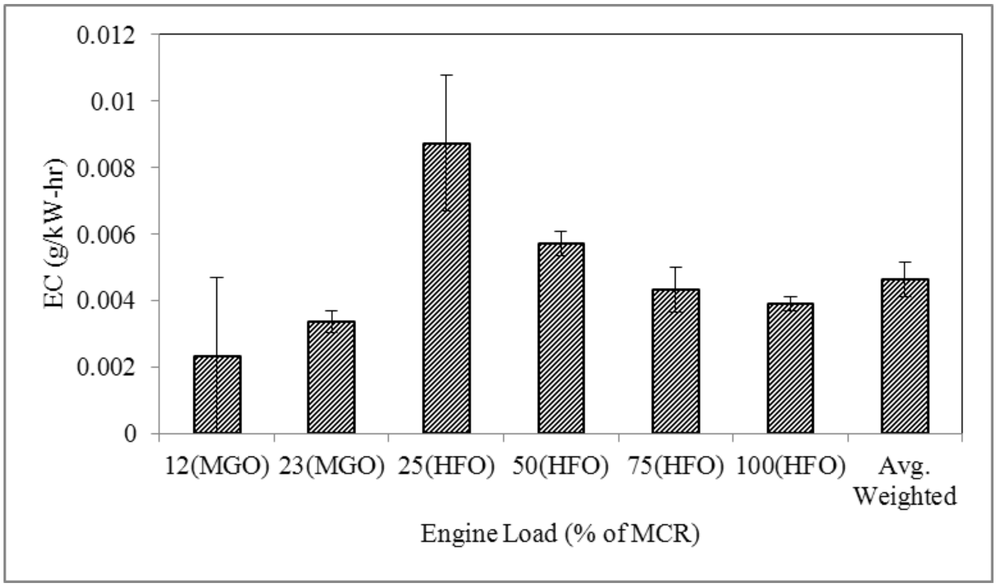

Figure 4-19 Modal Emission Rates for EC in g/kW-hr

4.8.3 Organic Carbon (OC) Emissions

The organic carbon fraction of the $PM_{2.5}$ mass emissions in kg/hr and g/kW-hr are shown in Figure 4-20 and Figure 4-21.

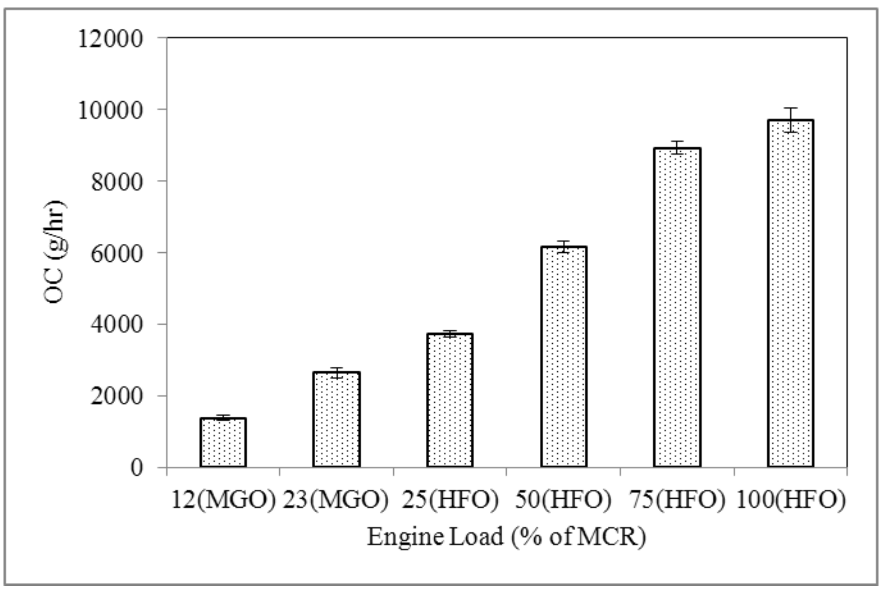

Figure 4-20 Modal Emission Rates for OC in g/hr

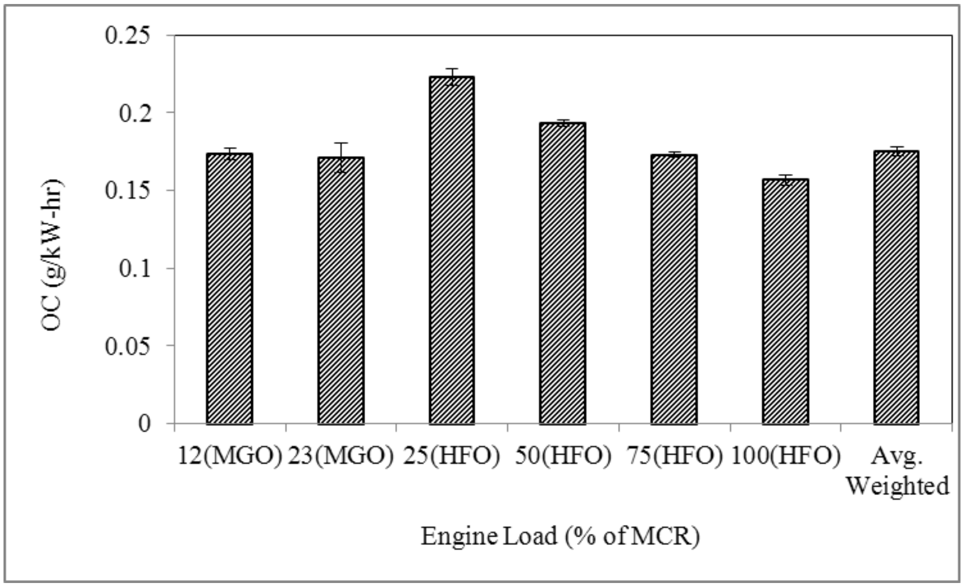

Figure 4-21 Modal Emission Rates for OC in g/kW-hr

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

An important element of UCR'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 with the sum of the carbon masses independently measured as elemental, organic carbon and hydrated sulfate measured by ion-exchange chromatography. The highest portion of PM mass emissions from large marine diesels operating on HFO is the sulfate contribution. Figure 4-22 below shows the balance when the sulfate mass, expressed as H_2SO_4 $6H_2O$, is added to the elemental and organic carbon masses.

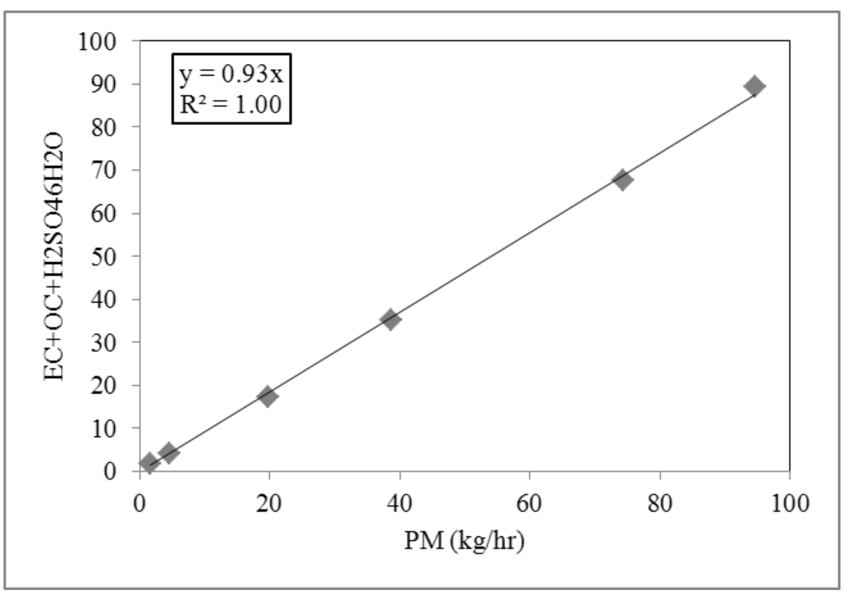

Figure 4-22 $PM_{2.5}$ Mass Balance

Speciation of $PM_{2.5}$ gives an insight into its characterization. Figure 4-23 shows that the $PM_{2.5}$ mass was comprised of 69-82% hydrated sulfate; 10-19% OC; <5% EC; and ash. EC and OC emissions decreased with increasing load (reflecting the engine efficiency tuning at 75% load) while sulfate emissions increased with increasing load. Fuel sulfur conversion sulfate increased from 2.4% to 4.2% as engine load increased from 24% to 90%, consistent with previous studies.

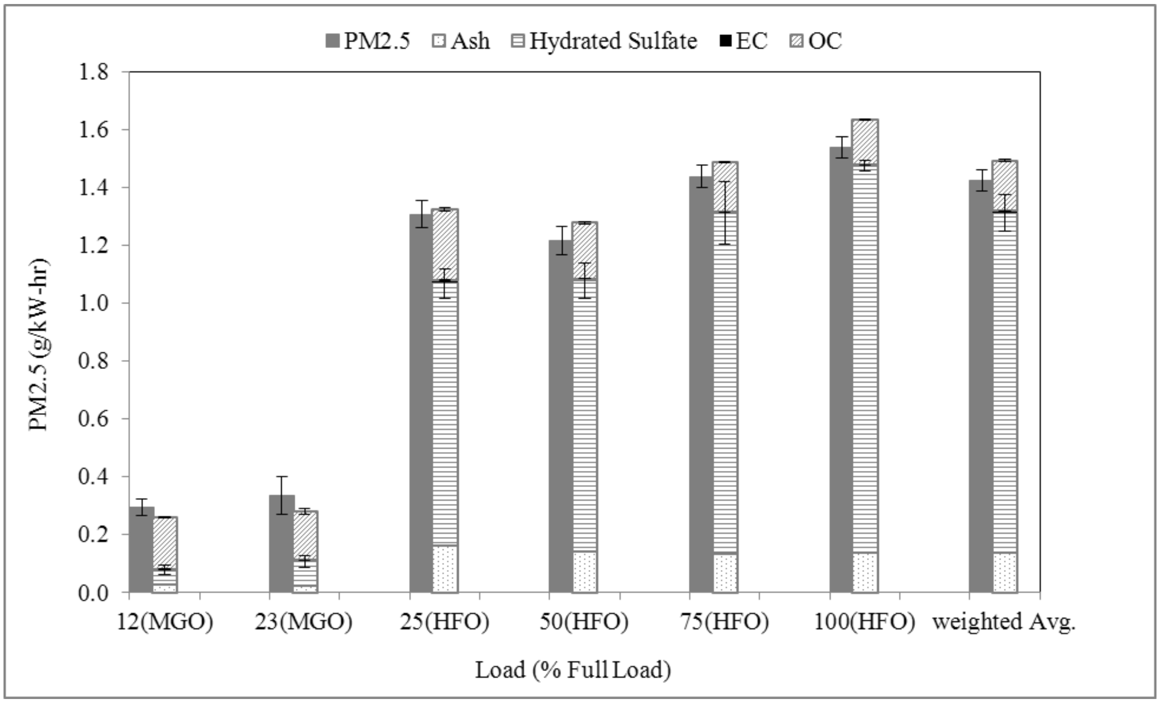

Figure 4-23 Mass Balance: Total & Speciated $PM_{2.5}$ Mass

4.8.5 Tabulated Particulate Matter Emission Data

The total and speciated $PM_{2.5}$ mass emissions are presented in kg/hr and g/kW-hr for the test modes and given in Table 4-9 and Table 4-10, respectively. Triplicate measurements were made for PM as in the case of gaseous emissions and the error bars presented in the following tables are at one-sigma and provide an indication of confidence limits.

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[b] Agrawal, H., et al., In-use gaseous and particulate matter emissions from a modern ocean going container vessel. *Atmospheric Environment*, **2008**. 42(21): p. 5504-5510

[c] Agrawal, H., Welch, W.A., Henningsen, S., Miller, J.W., Cocker, D.R. Emissions from Main Propulsion Engine on Container Ship at Sea. *Journal of Geophysical Research*, vol 115, D23205, 7 PP., **2010**

Table 4-9 Particulate Matter Emissions in kg/hr

Test Set	Speed (Knots)	Fuel	Target ISO Load	Actual Load	$PM_{2.5}$ and Speciated $PM_{2.5}$ (kg/hr)				Standard Deviation			
					$PM_{2.5}$	EC	OC	SO_4^{2-}	$PM_{2.5}$	EC	OC	SO_4^{2-}
VSR 12	12.0	MGO		12%	1.6	0.02	1.4	0.4	0.9	0.02	0.06	0.09
VSR 15	15.0	MGO		23%	4.6	0.05	2.6	1.3	1.9	0.01	0.14	0.30
25%	17.0	HFO	25%	24%	19.8	0.15	3.7	13.2	0.2	0.03	0.10	0.56
50%	21.8	HFO	50%	47%	38.8	0.18	6.2	28.7	1.8	0.01	0.15	2.18
75%	25.0	HFO	75%	75%	74.3	0.22	8.9	58.3	1.1	0.03	0.17	5.58
100%	26.5	HFO	100%	90%	94.7	0.24	9.7	79.5	2.6	0.02	0.33	1.61

Table 4-10 Particulate Matter Emissions in g/kW-hr

Test Set	Speed (Knots)	Fuel	Target ISO Load	Actual Load	$PM_{2.5}$ and Speciated $PM_{2.5}$ (g/kW-hr)				Standard Deviation			
					$PM_{2.5}$	EC	OC	SO_4^{2-}	$PM_{2.5}$	EC	OC	SO_4^{2-}
VSR 12	12.0	MGO		12%	0.3	0.002	0.17	0.05	0.04	0.002	-0.003	0.01
VSR 15	15.0	MGO		23%	0.3	0.003	0.17	0.08	0.07	0.000	0.010	0.02
25%	17.0	HFO	25%	24%	1.19	0.009	0.22	0.79	0.04	0.002	0.006	0.04
50%	21.8	HFO	50%	47%	1.22	0.006	0.19	0.90	0.05	0.000	0.002	0.06
75%	25.0	HFO	75%	75%	1.4	0.004	0.17	1.13	0.04	0.001	0.001	0.10
100%	26.5	HFO	100%	90%	1.5	0.004	0.16	1.28	0.04	0.000	0.003	0.02
Overall weighted emission factor					1.4	0.005	0.17	1.18	0.04	0.001	0.003	0.06

5 Results - Emission Reduction Strategy: Switching From HFO to MGO/MDO

There are few options that ship owners/operators can use to simultaneously reduce emissions from existing main propulsion and auxiliary engines. One is vessel speed reduction and another is switching the vessel from burning bunker fuel to distillate fuel, a lower-sulfur and cleaner burning fuel.

5.1.1 Background

As discussed in the introduction, CARB regulations require distillate fuels with a maximum of 0.2wt% sulfur for both main and auxiliary engines within 40 nautical miles (nm) of Point Fermin. With this fuel change, people living near the ports benefit as the emissions of sulfur oxide (SOx), particulate matter (PM), and nitrogen oxide (NO_x) are all reduced.

5.1.2 Real Time Emissions Monitoring of Gases and $PM_{2.5}$ Mass during Fuel Switching – First Vessel

The vessel operated its main propulsion engine on MDO fuel within the 40nautical mile limit of Point Fermin before it switched to HFO and increased its power from 19% to 81% of full load during the first voyage and from 18% to 69% during the second voyage. Figure 5-1 shows the continuous readings for the concentration of gaseous emissions during the fuel switching period for the first voyage. Note the change in emissions for gases NO_x, CO_2 and CO was instantaneous and small, as expected. For example, a NO_x change is estimated to be about 5-10%, within the error of measurement and calculable from the fuel-nitrogen content. However for SO_2, it took an hour to reach a steady value. Since up to 70% of the PM is sulfur related, these data suggest that the PM is increasing during the changeover time and emissions are lower for a longer period of time. The reason for the time delay is hypothesized to reflect the time that it takes for the fuel system to be completely changed over to HFO.

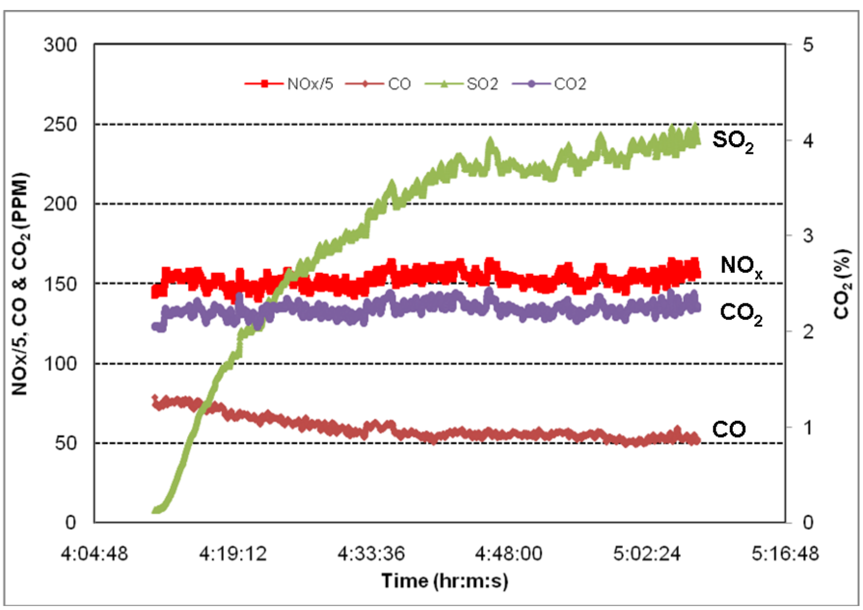

Figure 5-1 Continuous Monitoring of Emissions during Switch from MGO to HFO

In this project, the vessel left the Port of Los Angeles on distillate fuel, switched to HFO at sea in order to achieve higher operating speeds and loads that are not possible with the distillate fuel and finally changed back to MDO while entering the San Francisco Bay. Thus near San Francisco, the heavy fuel oil is replaced with a lighter, distillate fuel, or the opposite change of when leaving the port of Los Angeles. Figure 5-2 shows the continuous recording of the gases as the vessel switched from HFO to MGO on entering the San Francisco Bay area for the Port of Oakland. Again using the SO_2 as a surrogate for PM, the data show that it takes over 90 minutes for the system to come to steady state as the heavy fuel oil is replaced with distillate fuel in the fuel system. In fact, it never really comes to equilibrium. Be aware that SO_2 levels decline for two reasons: 1) much lower sulfur in the distillate fuel and 2) less fuel being burned. Separating these two effects in the streaming data is difficult. One would have to analyze a portion of data where one parameter is fixed; for example, where CO_2 levels (reflecting fuel consumption) are constant.

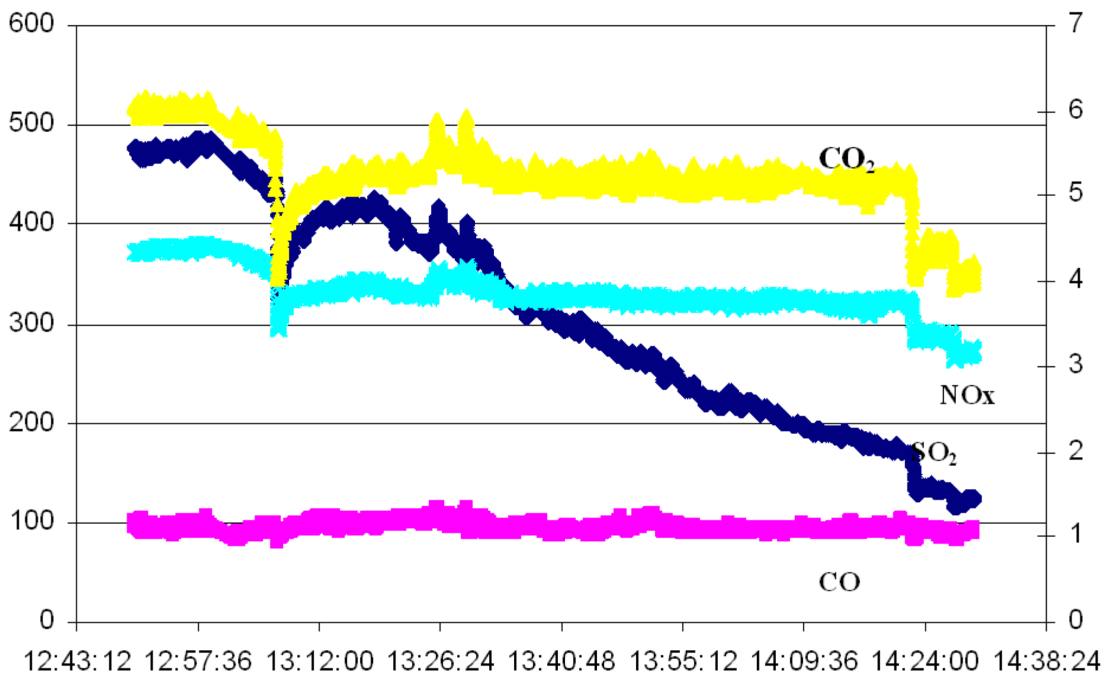

Figure 5-2 Continuous Emissions Monitoring during Switch from HFO to MDO

One of the most effective strategies to reduce $PM_{2.5}$ and SOx emissions is switching to a cleaner burning fuel with a lower sulfur content. In a recent regulation by CARB, main and auxiliary engines are required to burn distillate fuels with sulfur content equal or less than 0.2 wt% within 24nm of California coastline.

5.1.3 Real Time Emissions Monitoring of Gases and $PM_{2.5}$ Mass during Fuel Switching – Second Vessel

Real time monitoring of emissions during fuel switching gives an insight on the effect of fuel on emissions. Figure 5-1 and Figure 5-2 shows fuel switching plots of MGO to HFO and HFO to MGO respectively. It can be inferred from both figures that the time taken for complete the fuel switch was around 70 and 90 minutes for this engine as SOx took a similar amount of time to get stable. The $PM_{2.5}$concentration increased simultaneously with SOx when switched from MGO to HFO due to the increasing sulfur content in fuel as MGO was being replaced by HFO in the fuel tank. Oxidation of SO_2 leads to the formation of sulfate which adds up to the total particulate matter. All other gaseous emissions didn't change significantly throughout the fuel change except at two different times where a jump in emissions due to the rise in load was observed.

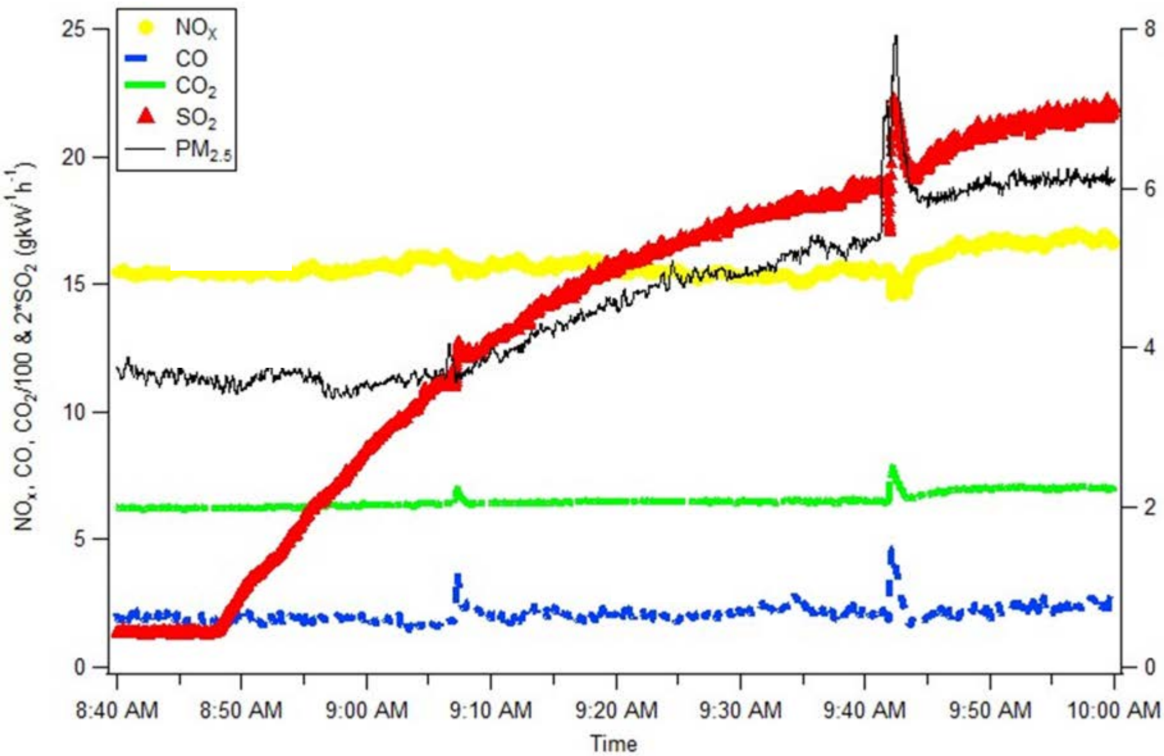

Figure 5-3 Fuel Switching from MGO to HFO

Similar to the first vessel, when fuel was switched back to MGO from HFO, a decreasing trend was observed for SOx, $PM_{2.5}$ and small changes for other gaseous emissions until the fuel switch was complete. One should note that different vessels will take different times to completely perform the fuel switch because it depends on the volume of fuel in the tank and the fuel usage rate when the fuel switch is performed.

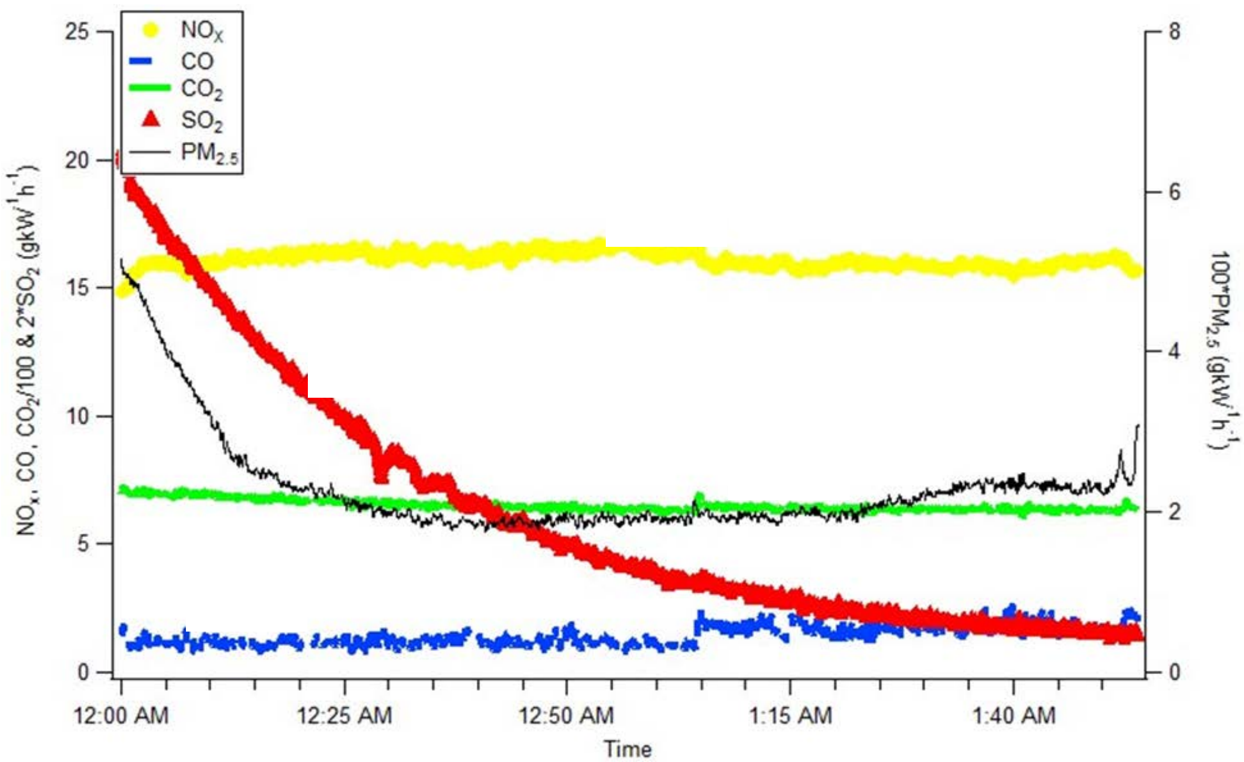

Figure 5-4 Fuel Switching from HFO to MGO

6 Discussion

The primary objective for the project was to measure emission benefits due to VSR.

6.1 Higher Vessel Speeds and Power Required

The relationship between the vessel speed and power is non-linear as discussed in earlier sections and Appendix E. In general, measurements show the greater the fuel consumption, the greater the emissions. An earlier figure showed power represented as CO_2 emissions data varies as the cube of velocity (see Figure 6-). Figure 6.2 shows the 'wave effect' discussed in Appendix E. Note the similarity with data from this study. Basically at the higher speeds, more and more power is required per knot increase in speed for an OGV vessel, until the power requirement is so steep that there is limiting speed, the so called "wave wall".

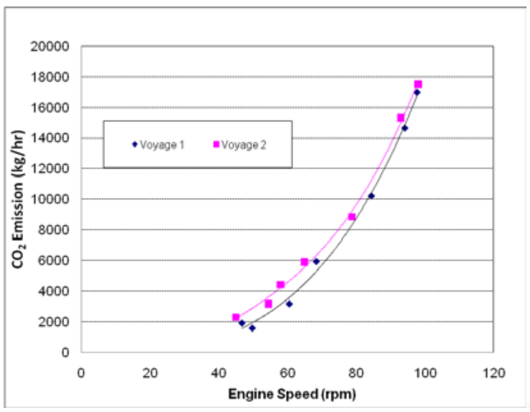

Figure 6-1 Power vs. Speed

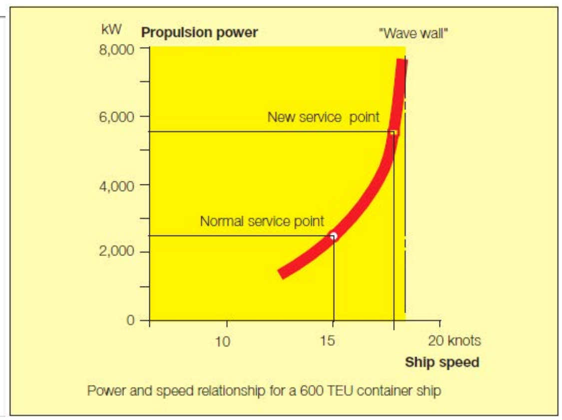

Figure 6-2 Ship Speed Barrier

The figure shows that reducing the engine speed from about 100 to 50 RPM in half reduced fuel consumption from 18,000 to 2,000 or by a factor of nine. From the earlier plot, vessel speed is directly proportional to engine speed. Even at lower engine and vessel speed, for example from 60 to 40 RPM, the data show fuel and emissions savings.

6.2 Emissions at VSR Speeds

6.2.1 Background Discussion

As described earlier, the Ports of Long Beach and Los Angeles have a voluntary vessel speed reduction (VSR) program wherein OGVs are asked to reduce their speed to 12 knots on arrival to and departure from the ports. In the present study, two VSR test opportunities were available per voyage; first as the vessel departed from the port starting at 12 knots and then as the vessel increased speed to 15 knots. The vessel burned MDO/MGO during this period.

It is important to understand that operating at a slow speed does not always mean operating at low power. For example, in UCR's study[4] of a Suez-max tanker with one million barrels of crude, the vessel had a 37MW main propulsion engine and that engine operated at about 50% power for 12 knots speed when entering the harbor. In another study[5] a Post Panamax container ship with a 55MW main propulsion engine operated at about 8% load at 12 knots. Other measurements on a ferry showed the sea current was important. At constant speed, a ferry used ~15% load with the current and ~65% load when operating into the current. Thus simply specifying a vessel is operating at a slow speed of 12 knots is insufficient to understand the relationship of vessel speed, emissions and the impact on inventory. More parameters are needed to understand the impact of emissions at VSR speeds.

Emission rates expressed in grams per hour and emission factors expressed as grams per kW-hour will change as the vessel speed changes. The tanker operating at 12 knots and 50% load is operating in an efficient portion of the design engine map. Within that operating space, the emissions per kW-hour are nearly constant from about 25 to 75% load. However, the container ship at ~10% load is operating outside the section of the engine map where the engine is operating efficiently. As a result of the inefficient operation, the emissions per kW-hour will increase significantly. Our experience indicates >10% higher. Furthermore, operation at such low power will necessitate the operation of the auxiliary blower in order to provide sufficient air for the combustion process. The point where the blower is turned on depends on the main engine design and can range from about 20 to 30%. An example is provided in Figure 6-.

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[4] Agrawal, H., Welch, W. A., Miller, J. W., Cocker, D. R., Emission Measurements from a Crude Oil Tanker at Sea, *Environmental Science & Technology, 42* (19), pp 7098–7103 **2008**

[5] Agrawal H., Malloy Q. G. J., Welch W. A., Miller J. W., Cocker III D. R. In-Use Gaseous and Particulate Matter Emissions from a Modern Ocean Going Container Vessel, *Atmospheric Environment*, 4 March **2008**

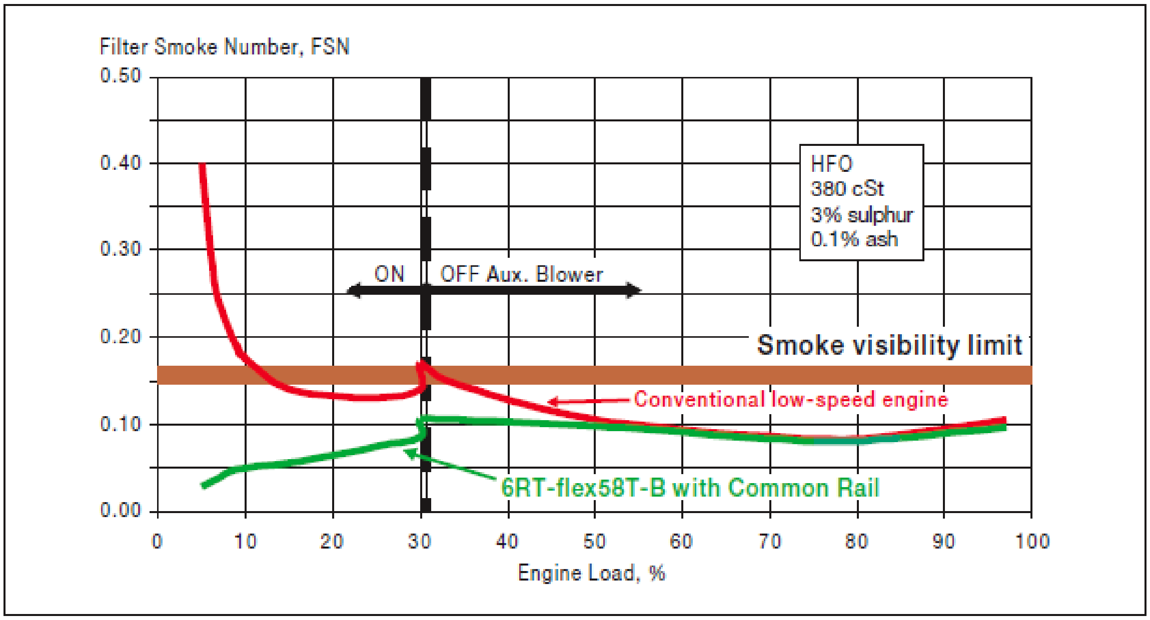

Figure 6-3 Example of Engine Design with Auxiliary Blower

6.3 Vessels Speed

The speed of every vessel in the speed reduction zone is measured and recorded by the Marine Exchange of Southern California. Data for the two voyages reported in this project are shown below in Table 6-1. Vessel speed data for the third voyage is only based on the engine computer in the engine control room.

Table 6-1 Vessel Speed Data from the Marine Exchange of SoCal

Call		Vessel	Distance from Point Fermin (nautical miles) and Speed (knots)							
Date	Activity	Type	10	15	20	25	30	35	40	Avg
8/4/2009 18:30	Departure	UCC	13	14	14	14	14	14	14	13.4
8/3/2009 4:35	Arrival	UCC	11	11	11	15	15	14	13	11
7/1/2009 1:00	Departure	UCC	11	11	11	14	15	15	13	11
6/30/2009 17:45	Shift	UCC								
6/29/2009 5:05	Arrival	UCC	11	11	11	12	13	13	13	11

6.3.1 Gaseous Benefits due to VSR

The speed of the vessel (V), at ~80% of engine load is considered to be cruise speed.[a] Therefore, the engine load considered for cruise speed in Voyage 1 (24 knots), Voyage 2 (24 knots) and Voyage 3 (25 knots) were 81%, 83% and 75% respectively. Identical engine loads were not obtained due to practical constraints. Comparisons of greenhouse gas and criteria pollutant emissions were made when the vessels were running at cruise and at VSR speeds.

Table 6-2, 6-3 and 6-4 represent emissions measured in kg/hr, kg/nautical mile (kg/nmi) and g/kW-hr at cruise and reduced speeds from three different voyages, respectively. However, to compare emissions emitted for a given distance at different vessel speeds, emissions represented in kg/nmi (Table 6-3) should be referred. Based on data from three voyages, reducing vessel speeds from cruise to 15 knots or less resulted in a 43-72% reduction in CO_2 and a 50-74% reduction in NOx. CO emissions were low across all loads as stated earlier, and engines were inefficient at low loads (≤20%). Therefore, at most of the reduced speeds CO emissions were higher than at cruise speeds.

[a] California Air Resources Board. Emissions Estimation Methodology for Ocean-Going Vessels. October **2005** http://www.arb.ca.gov/regact/marine2005/appd.pdf

Table 6-2 Comparison of emissions measured (kg/hr) at cruise and reduced speeds in three voyages

Voyage 1 (Out of Long Beach Port)					
Gases	Emissions (kg/hr)			% Reduction with Reduced Speed	
	Cruise speed (24 Knots)	15 Knots	11 Knots	15 Knots	11 Knots
CO_2	17102	4855	3067	72	82
NO_x	567	150	98	74	83
CO	10	16	8	-57	20
Voyage 2 (Out of Long Beach Port)					
Gases	Emissions (kg/hr)			% Reduction with Reduced Speed	
	Cruise speed (24 Knots)	14 Knots	13 Knots	14 Knots	13 Knots
CO_2	17513	4752	2733	73	84
NO_x	575	147	84	74	85
CO	10.6	10.0	6.9	5	35
Voyage 3 (Into Oakland Port)					
Gases	Emissions (kg/hr)			% Reduction with Reduced Speed	
	Cruise speed (25 Knots)	15 Knots	12 Knots	15 Knots	12 Knots
CO_2	30524	10406	6194	66	80
NO_x	874	260	218	70	75
CO	17.0	29.3	3.3	-72	81

Table 6-3 Comparison of emissions measured (kg/nmi) at cruise and reduced speeds in three voyages

Voyage 1 (Out of Long Beach Port)					
Gases	Emissions (kg/nmi)			% Reduction with Reduced Speed	
	Cruise speed (24 Knots)	15 Knots	11 Knots	15 Knots	11 Knots
CO_2	744	324	279	56	63
NO_x	24.7	10.0	8.9	59	64
CO	0.45	1.08	0.75	-141	-66
Voyage 2 (Out of Long Beach Port)					
Gases	Emissions (kg/nmi)			% Reduction with Reduced Speed	
	Cruise speed (24 Knots)	14 Knots	13 Knots	14 Knots	13 Knots
CO_2	761	339	210	55	72
NO_x	25.0	10.5	6.5	58	74
CO	0.46	0.72	0.53	-56	-16
Voyage 3 (Into Oakland Port)					
Gases	Emissions (kg/nmi)			% Reduction with Reduced Speed	
	Cruise speed (25 Knots)	15 Knots	12 Knots	15 Knots	12 Knots
CO_2	1221	694	516	43	58
NO_x	35.0	17.3	18.2	50	48
CO	0.7	2.0	0.3	-187	60

Table 6-4 Comparison of emissions measured (g/kW-hr) at cruise and reduced speeds in three voyages

Voyage 1 (Out of Long Beach Port)					
Gases	Emissions (g/kW-hr)			% Reduction with Reduced Speed	
	Cruise speed (24 Knots)	15 Knots	11 Knots	15 Knots	11 Knots
CO_2	574	704	777	-23	-35
NO_x	19.0	21.7	24.9	-14	-31
CO	0.3	2.3	2.1	-579	-501
Voyage 2 (Out of Long Beach Port)					
Gases	Emissions (g/kW-hr)			% Reduction with Reduced Speed	
	Cruise speed (24 Knots)	14 Knots	13 Knots	14 Knots	13 Knots
CO_2	579	709	828	-23	-43
NO_x	19.0	21.9	25.5	-15	-34
CO	0.4	1.5	2.1	-328	-500
Voyage 3 (Into Oakland Port)					
Gases	Emissions (g/kW-hr)			% Reduction with Reduced Speed	
	Cruise speed (25 Knots)	15 Knots	12 Knots	15 Knots	12 Knots
CO_2	590	672	749	-14	-27
NO_x	16.9	16.8	26.4	1	-56
CO	0.3	1.9	0.4	-476	-20

The average percent reductions in gaseous emissions (CO_2 and NO_x) are presented in Figure 1 for $V \leq 12$ (Case 1) and $12 < V \leq 15$ (Case 2). The reductions in emissions are attributed to both lower sulfur fuel and reduced power/speed for both cases. Using lower sulfur fuel (MGO) does not affect CO_2 emissions significantly and therefore the CO_2 reductions observed are attributed to VSR; use of MGO compared with HFO is expected to decrease NO_x emissions by ~6-10% due to the lower nitrogen content in the MGO. On average, emissions (kg/nmi) reductions in CO_2 and NO_x for V > 12 and ≤ 15 knots were 57% and 60% respectively. Moreover, vessels operated at 12 knots or below showed a similar reduction (61% and 56%) in CO_2 and NO_x. In this instance, it appears that a vessel speed of ≤15 knots is almost equally effective in reducing gaseous emissions within the VSR zone for container ships. However, it is important to note that vessels speeding up to make up for the slower speeds in the VSR zone could have an overall increase in CO_2 and other emissions.

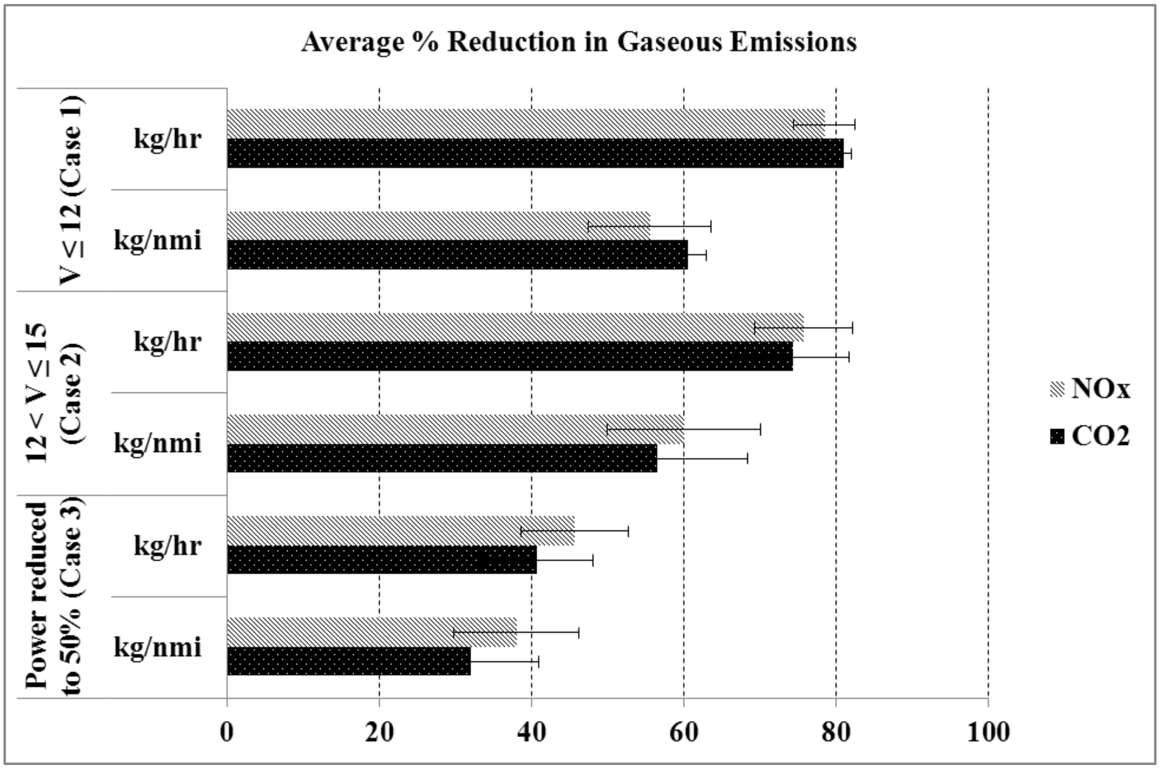

Figure 6-4 Average reduction in gaseous (NO_x and CO_2) emissions from all Voyages for vessel speed (V) equal to 12 knots or less (Case 1), 12< V ≤ 15 (Case 2) and at 50% engine load (Case 3). **Reductions in NO_x and CO_2 for Case 1 and 2 are due to change in speed and fuel (HFO to MGO) whereas for Case 3 reductions are due to change in speed only.**

OGVs are mostly operated in international waters and can be subject to local, national, and international requirements. Currently, the IMO has only capped fuel sulfur content (≤3.5%) in international boundaries. These vessels typically run at cruising speed consuming tonnes of fuel with high sulfur content and consequently emit large quantities of greenhouse gas and other criteria pollutants. However, when fuel prices are high and time is secondary, vessels sail at a speed closer to 50% engine load to save fuel. Therefore, emission measurements were also conducted at 50% engine load and were compared with loads at cruising speed. Vessel speeds at ~50% engine load for Voyage 1, 2 and 3 were 19.5, 19.5 and 21.8 knots, respectively. Case 3 in Figure 1 represents the CO_2 and NO_x benefits by reducing speed by between 13 and 19% (engine load ~50%) in international waters. On average, 31% and 37% reduction in CO_2 and NO_x emissions (kg/nmi) were observed. Hence on a global perspective, CO_2 and NO_x mitigation reduction may be possible by reducing the vessel speed by mere 3-6 knots from cruise speed.

6.3.2 Particulate Emissions Benefit due to VSR

Particulate measurements were also conducted at lower speeds with vessel operating on HFO and MGO during Voyage 1. Total particulate matter measured was observed to be primarily composed of hydrated sulfate, with moderate amounts of OC and small amounts of EC and ash, similar to previous studies[b, c]. Figure 2 shows the emissions reduction in kg/hr and kg/nmi occurring due to vessel speed reduction and fuel consumed. When vessel was operated on HFO and its speed was reduced to 12 knots, an approximately 69% reduction in $PM_{2.5}$ (g/nmi) was obtained. These reductions improved to a total of ~97%, when fuel was switched to MGO and operated at the reduced speed of 11 knots. Almost the entire hydrated sulfate was removed after switching to MGO, consistent with the low sulfur content in MGO (0.00065%) in comparison to HFO (3.14%). EC and OC emissions were reduced by 53% and 70% on reducing the vessel speed to 12 knots. Similar to $PM_{2.5}$, higher reductions (77% in EC and 85% in OC) were observed on switching to MGO. $PM_{2.5}$ emission benefits by reducing engine load from ~80% to ~50% in international waters where vessels consumed HFO led to reductions of 48%, 54% and 40% in $PM_{2.5}$ (kg/nmi) for Voyage 1, 2 and 3, respectively. Particulate emissions for trip 1 in kg/hr, g/nmi and g/kW-hr are provided in Table 6-4.

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[b] Agrawal, H., et al., In-use gaseous and particulate matter emissions from a modern ocean going container vessel. *Atmospheric Environment*, **2008**. 42(21): p. 5504-5510

[c] Agrawal, H., Welch, W.A., Henningsen, S., Miller, J.W., Cocker, D.R. Emissions from Main Propulsion Engine on Container Ship at Sea. *Journal of Geophysical Research,* vol 115, D23205, 7 PP., **2010**

Table 6-5 Reduction in $PM_{2.5}$ mass due to change in speed and fuel

Trip 1 : Particulate emissions (kg/hr) reduction due to change in speed and fuel					
Units	(kg/hr)			% reduction	
Fuel	HFO	HFO	MGO	HFO	MGO
Speed	24 knots	12 knots	11 knots	12 knots	11 knots
$PM_{2.5}$	64.8	10.00	0.99	84.6	98.5
$H_2SO_4.6H_2O$	61.3	7.67	0.07	87.5	99.9
EC	0.23	0.05	0.03	76.6	87.9
OC	7.06	1.07	0.41	84.8	94.2
Trip 1 : Particulate emissions (g/nmi) reduction due to change in speed and fuel					
Units	(g/nmi)			% reduction	
Fuel	HFO	HFO	MGO	HFO	MGO
Speed	24 knots	12 knots	11 knots	12 knots	11 knots
$PM_{2.5}$	2700	833	90	69.1	96.7
$H_2SO_4.6H_2O$	2554	639	6.4	75.0	99.8
EC	9.6	4.5	2.5	53.2	73.5
OC	294	89	37	69.7	87.3
Trip 1 : Particulate emissions (g/kW-hr) reduction due to change in speed and fuel					
Units	(g/kW-hr)			% reduction	
Fuel	HFO	HFO	MGO	HFO	MGO
Speed	24 knots	12 knots	11 knots	12 knots	11 knots
$PM_{2.5}$	2.19	2.59	0.25	-18.3	88.7
$H_2SO_4.6H_2O$	2.07	1.99	0.02	3.8	99.2
EC	0.01	0.01	0.01	-80.3	10.3
OC	0.24	0.28	0.10	-16.9	57.1

6.4 Emission Changes on Switching from HFO to MDO/MGO

Data in the earlier section show the transient nature of a fuel switch and that it takes over an hour after the fuel switch before the system returns to steady-state. The reason for the time delay can be understood by viewing the layout of a typical fuel system as shown in Figure 6-. Notice that fuel moves from the main storage tanks, either MDO or bunker, through a settling tank and centrifuge before reaching the service tank, the last stop before heading to the main propulsion or auxiliary engines. Not shown here is that many fuel systems have a return line where fuel not consumed in the engines is returned to the service tank. Thus the reason for the 1+ hour delay to return to steady state is system has to be flushed of all the old fuel before steady state can be restored.

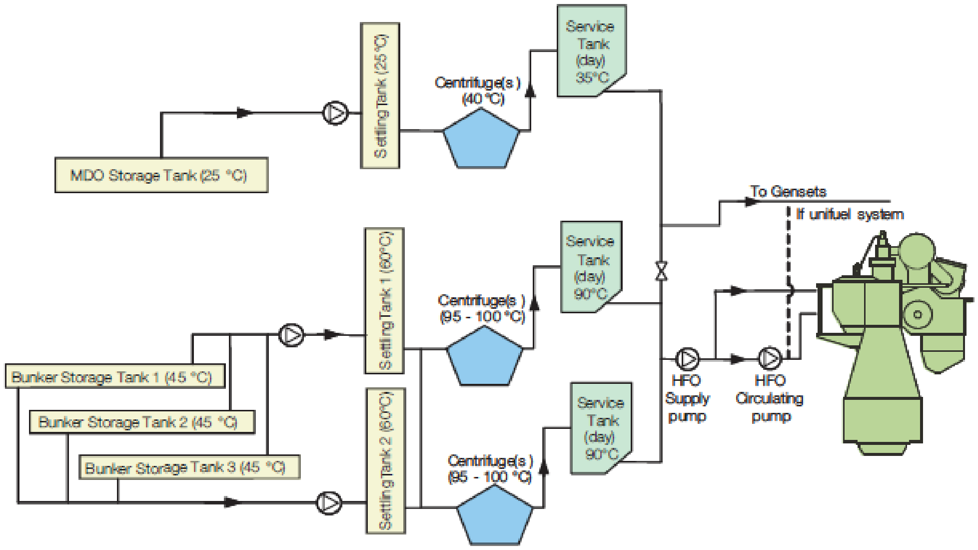

Figure 6-5 One MDO Settling Tank and Two Sets of HFO Settling and Service Tanks[6]

UCR has attempted to model the mixing that occurs during the fuel switch by assuming ideal behavior and an exponential fit as predicted by theory. Because the time required for the fuel switch was about an hour, rather than minutes, a simple kinetic equation was independently developed with the goal of identifying the primary parameters that control the length of time required for 95% switchover of the fuel, t_{95}. Developing an equation required a schematic of the fuel flow system model for a marine engine (Figure 6-3) and some assumptions of: 1) ideal mixing in the day tank, 2) the rate of fuel to the engine, E >> R, the fuel rate in the return line, 3) perturbations in load due to variations in the sea state are insignificant, and 4) t_{95} is not affected by changes in fuel-viscosity. With these assumptions, t_{95} can be parameterized as a function of net fuel consumption rate, f (L min^{-1}), and volume of the fuel in the day tank, V_{DT} (L), Eqn. (1).

$$t_{95} = \frac{V_{DT}}{f} \ln 20 \qquad (1)$$

The output of this equation is compared with the observed time needed for fuel switch in Voyage 3. Comparisons are presented here as *Case I* (MGO to HFO, f = 77 L min^{-1}, see Figure 5-3) and *Case II* (HFO to MGO, f = 65 L min^{-1}, see Figure 5-4). V_{DT} reported for this study was 1500 L in both cases. The t_{95} calculated by the equation is equal to 59 and 69 minutes, for *Case I* and *Case II*, respectively. With 95% change in fuel for *Case I*, the expected SO_2 concentration would be 435 ppm after 65 minutes of fuel switching and agrees with calculated values from Eq. 1. Similarly, in *Case II*, expected SO_2 concentration is 50 ppm after 84 minutes of fuel switching. The comparison of measured and calculated SO_2 concentrations with time are shown in Figure 6-4. Additional

[6] MAN, *Operation on Low-Sulphur Fuels MAN B&W Two-stroke Engines*, Technical bulletin # 5510-0075-00ppr_low.pdf

measurements are required to account for uncertainties associated with Eq. 1. A detailed derivation for the equation is provided elsewhere[d].

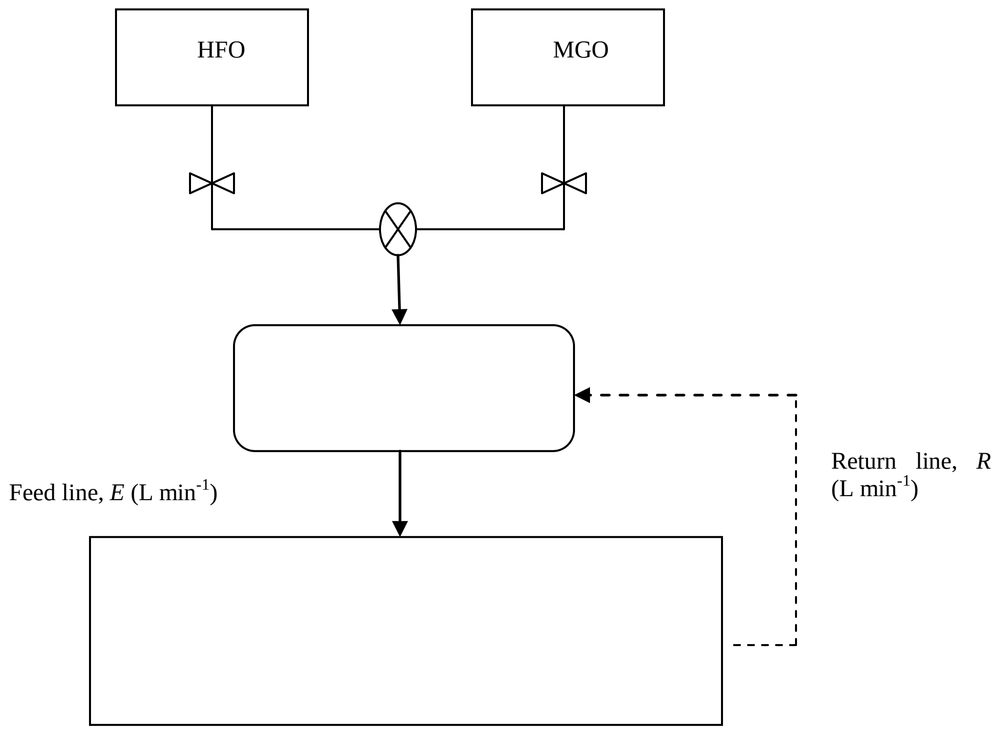

Figure 6-6 Fuel flow system for marine diesel engine

Note the Eq. 1 predicts the longer time to switch for *Case II* since the load and corresponding fuel rate were lower. The key parameters driving the length of time for the fuel switch are the volume fuel in day tank and the rate of fuel consumption. Eqn. 1 predicts that the time required for fuel switching for a OGV can be reduced by either decreasing the volume of fuel in the day tank or by increasing the rate of fuel consumption or both.

[d] Khan, M.Y. et al.; Benefits of Two Mitigation Strategies for Container Vessels: Cleaner Engines and Cleaner Fuels. Environmental Science and Technology, , **2012**, *46* (9), pp 5049–5056

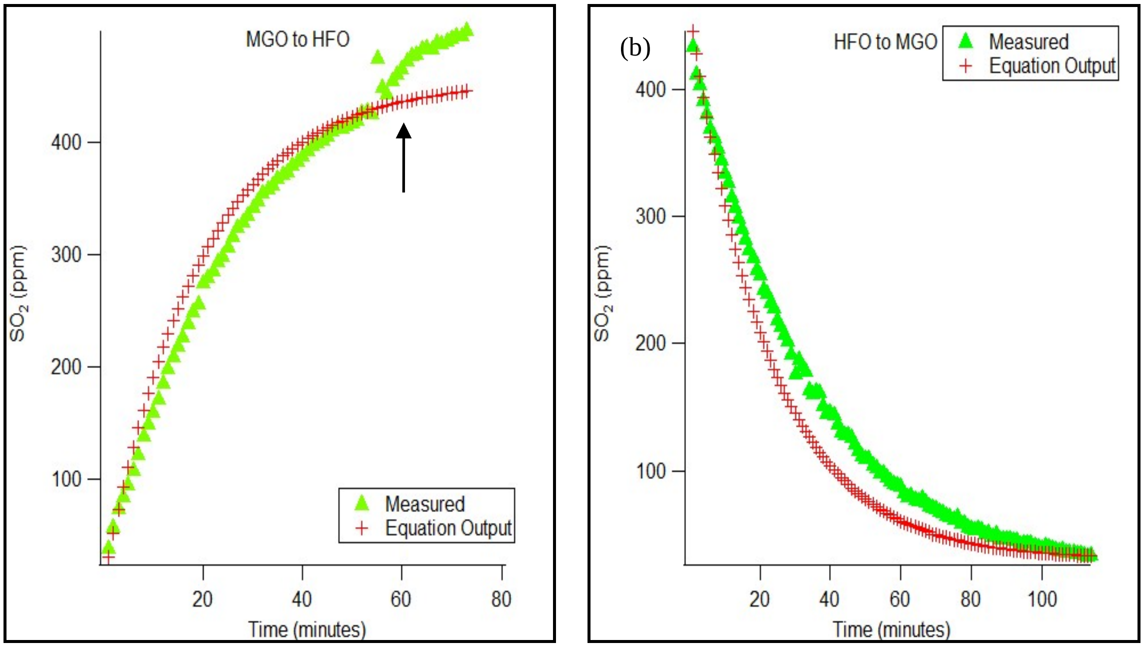

Figure 6-7 Comparison of measured and calculated SO_2 concentrations based on the equation output for (a) MGO to HFO and (b) HFO to MGO.

7 Conclusions

Emission measurements were made from two different types of vessels for three voyages. The first vessel was a Panamax class container vessel and its main engine was tested twice in 2009. The emission factors from two different voyages for the same vessel were reproducible. The emission factors for CO_2, NOx and CO were within ~10% across ISO load points. The modal emission factor for CO_2 suggested that the engine was operating most efficiently around 50% load in both voyages. The second vessel was a Post-Panamax class container vessel with a modern electronically controlled engine and low NOx slide valve designed to meet Tier 1 certification. It was launched in May 2010 and tested in September 2010. The overall in-use NOx emission factor was 16.1±0.1 g/kWhr, lower than the Tier 1 certification (17 g/kWhr) and significantly lower than the benchmark value of 18.7 g/kWhr commonly used for estimating emission inventories. Hydrated sulfate dominated the composition of PM in all voyages. Variation among SO_2 emission factors was attributed to variable sulfur content in all voyages.

The main objective of this research was to measure emission benefits on reducing vessel speed from cruise to 15 knots or less. VSR to 12 knots or less resulted in approximately 61% and 56% reduction in CO_2 and NOx emissions (kg/nmi), respectively. Note that the reductions in emissions are attributed to change in both speed and fuel. However, switching from HFO to MGO would not change CO_2 emissions significantly whereas NOx emissions are expected to reduce by ~6-10% due to the lower nitrogen content in MGO. The mass emission rate (kg/nmi) of $PM_{2.5}$ was reduced by 69% with VSR at 12 knots alone and by ~ 97% when coupled with the use of MGO. Approximately 75%, 70% and 53% reduction in hydrated sulfate, organic carbon and elemental carbon was observed when reducing vessel speed from cruise to 12 knots, respectively. These reductions increased to 99.8%, 87% and 74%, when fuel was switched to MGO and vessel speed was reduced to 11 knots in VSR zone. Therefore, based on three measurements from two ships, reducing vessel speed in VSR zone would result in significant reduction of criteria pollutants (NOx and $PM_{2.5}$) and greenhouse gas emissions (CO_2).

8 References

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9 Appendix A Test Cycles and Fuels for Different Engine Applications

9.1 Introduction

Engines for off-road use are made in a much wider range of power output and used in a more applications than engines for on-road use. The objective of IS0 8178-4[7] is 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 (RIG) engines coupled to a dynamometer or at the site. The tests are carried out under steady-state operation using test cycles which are representative of given applications.

Table 9-1 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 measurement 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.

9.1.1 Intermediate speed

For engines designed to operate over a speed range on a full-load torque curve, the intermediate speed shall be the maximum torque speed if it occurs between 60% and 75% of rated speed. If the maximum torque speed is less than 60% of rated speed, then the intermediate speed shall be 60 % of the rated speed. If the maximum torque speed is greater than 75 % of the rated speed then the intermediate speed shall be 75% of rated speed. The intermediate speed will typically be between 60% and 70 % of the maximum rated speed for engines not designed to operate over a speed range on the full-load torque curve at steady state conditions. Intermediate speeds for engines used to propel vessels with a fixed propeller are defined based on that application.

[7] 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)

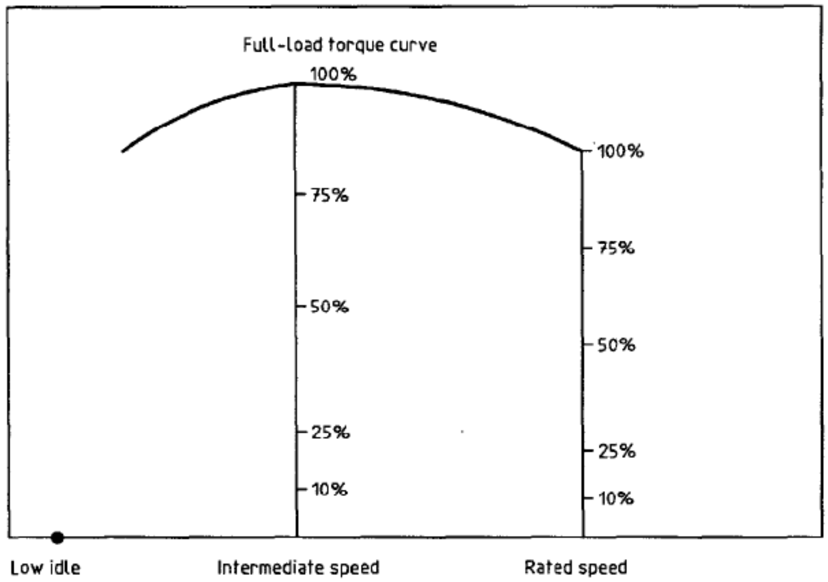

Figure 9-1 Torque as a Function of Engine Speed

9.2 Engine Torque Curves and Test Cycles

The percentage of torque figures given in the test cycles and Figure 9-1 represent the ratio of the required torque to the maximum possible torque at the test speed. For marine test cycle E3, the power figures are percentage values of the maximum rated power at the rated speed as this cycle is based on a theoretical propeller characteristic curve for vessels driven by heavy duty engines. For marine test cycle E4 the torque figures are percentage values of the torque at rated power based on the theoretical propeller characteristic curve representing typical pleasure craft spark ignited engine operation. For marine cycle E5 the power figures are percentage values of the maximum rated power at the rated speed based on a theoretical propeller curve for vessels of less than 24 m in length driven by diesel engines. Figure 9-2 shows the two representative curves.

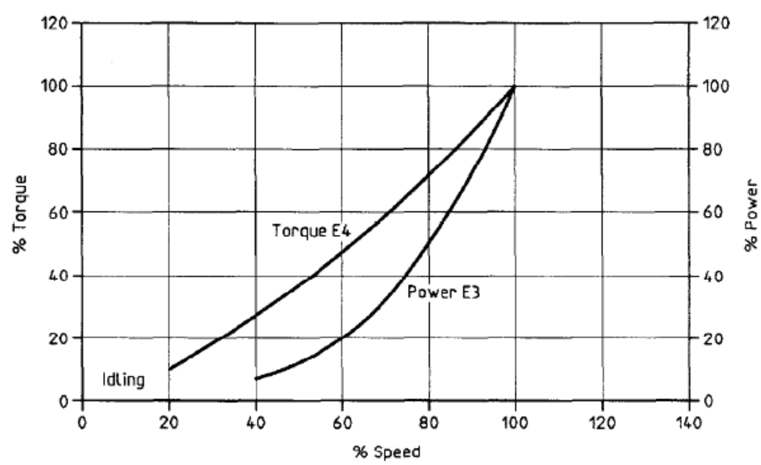

Figure 9-2 Examples of Power Scales

9.3 Modes and Weighting Factors for Test Cycles

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.

Table 9-2 Combined Table of Modes and Weighting Factors

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

9.4 Test Fuels

Fuel characteristics influence engine emissions so ISO 8178-1 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 9-3.

Table 9-3 Test Fuels

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.

10 Appendix B: Measuring Gaseous & Particulate Emissions

10.1 Scope

ISO 8178-1[8] and ISO 8178-2[9] 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[10], 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.

10.2 Sampling System for Measuring Gaseous and Particulate Emissions

A properly designed sampling system is essential to 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 UCR chose the partial flow dilution system with single venturi as shown in Figure 10-1.

[8] 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

[9] 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

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

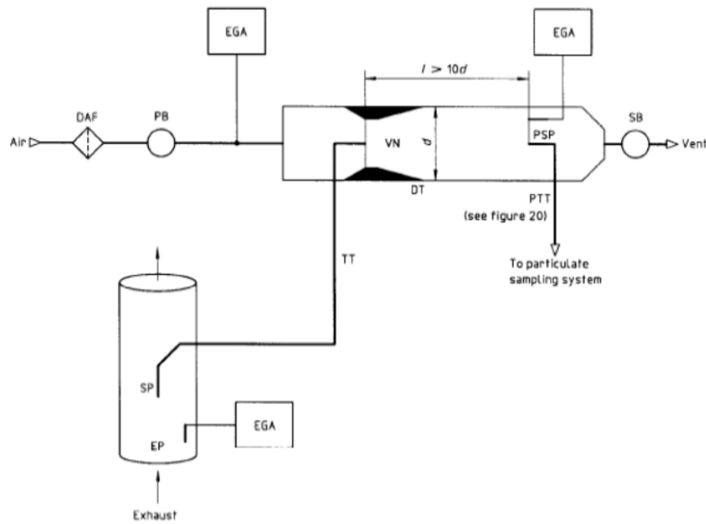

Figure 10-1 Partial Flow Dilution System with Single Venturi, Concentration Measurement and Fractional Sampling

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 UCR’s partial dilution system in Figure 10-1 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 10-1.

10.3 Dilution Air System

A partial flow dilution system requires dilution air and UCR 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 UCR processes any supplied air through a field processing unit that reduces the pressure to about 30psig 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 10-2 shows the field processing unit in its transport case. In the field the case is used as a framework for supporting the unit

Figure 10-2 Field Processing Unit for Purifying Dilution Air in Carrying Case

Table 10-1 Components of a Sampling System: ISO/IMO Criteria & UCR Design

Section	Selected ISO and IMO Criteria	UCR 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.	UCR 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.	UCR 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.	UCR 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.	UCR 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.	UCR uses a 5-gas analyzer meeting IMO/ISO specs

10.4 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 what UCR uses. The dilution ratio is simply calculated from measured gas concentrations of CO_2 and/or NO_x in the raw exhaust gas, the diluted exhaust gas and the dilution air. UCR 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%. UCR’s experience indicates the independently determined dilution ratios are usually within 5%. 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.

10.5 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. UCR 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 UCR that the flow rate selected should be the lowest rate in the system under test.

10.6 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 used by UCR. For SO_2, ISO recommends and UCR concurs that the concentration of SO_2 is calculated based on the fact that 95+% of the fuel sulfur is converted to SO_2.

10.6.1 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.

- 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 by < ±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.

10.6.2 Measuring Gaseous Emissions: UCR 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 ETV program.

Figure 10-3 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 10-2. Note that the Horiba instrument measured sulfur oxides (SO_2); however, the UCR 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.

Table 10-2 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 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%

For quality control, UCR 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 10-3. 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.

Table 10-3 Quality Specifications for the Horiba PG-250

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)

10.7 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 UCR 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 UCR practices for sampling PM is shown in Table 10-4.

Table 10-4 Measuring Particulate by ISO and UCR Methods

	ISO	UCR
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

Sulfur content. According to ISO, particulates measured using IS0 8178 are “conclusively proven” to be effective for fuel sulfur levels up to 0.8%. UCR 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.

10.7.1 Added Comments about UCR’s Measurement of PM

In the field, UCR 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 streams leaving the dilution tunnel; the major flow is vented outside the tunnel and the minor flow is 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 Gelman filter holder. One holder collects PM on a Teflon filter and the other collects PM on a quartz filter. UCR simultaneously collects PM on Teflon and quartz filters at each operating mode and analyzes them according to standard procedures.

Briefly, total PM was 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 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.

10.8 Measuring Non-Regulated Gaseous Emissions

Neither ISO nor IMO provide a protocol for sampling and analyzing non-regulated emissions. UCR 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.

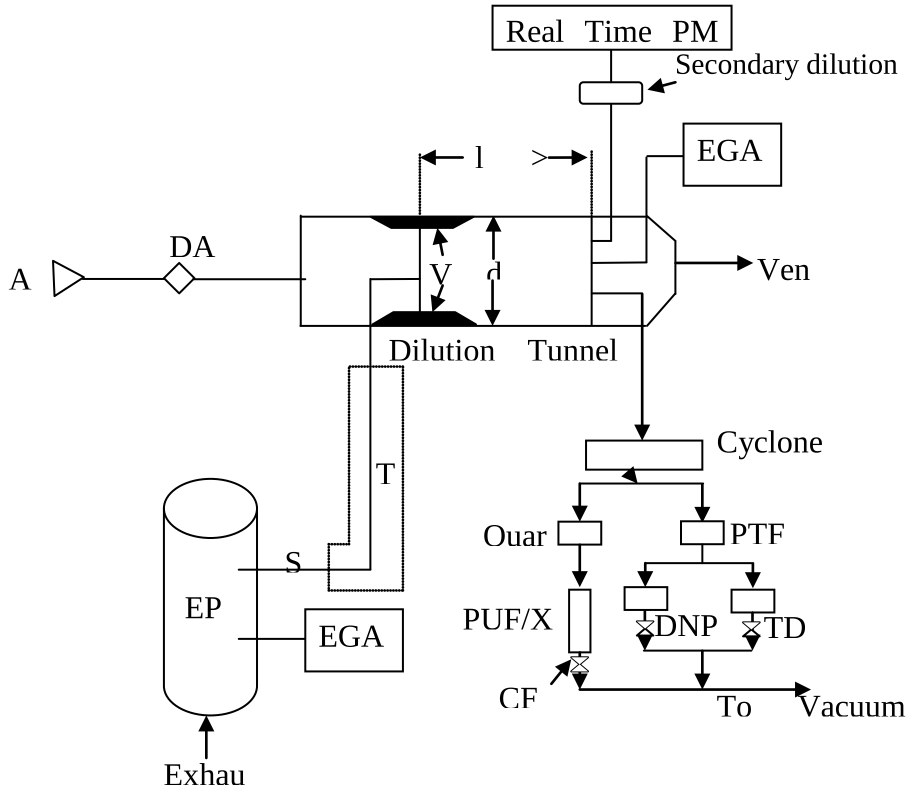

Figure 10-4 Partial Flow Dilution System with Added Separation Stages for Sampling both Regulated and Non-regulated Gaseous and PM Emissions

10.8.1 Flow Control System

Figure 10-4shows the sampling media and calibrated flow rates for the system. Critical orifices were used to control flow rates through all systems and all flows were 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 were also metered as differential pressure through a laminar flow element. Nominal flow rates are 20 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.

10.8.2 Speciation of C_1 to C_{30} Hydrocarbons

Often a comprehensive identification of the concentration of multiple hydrocarbon species is required. As there are hundreds of organic compounds in diesel exhaust, the sampling system needs to be tailored to match the desired deliverables. The hydrocarbon species of interest range from C_1 to C_{30} and Table 10-5 lists details of the analysis method and detection limits by carbon number or functional group.

Table 10-5 Hydrocarbon Speciation: Sampling and Analyses Methods

Chemical Group	Sampling Media	Instrument	Method	Detection Limit
C_1-C_8	SUMMA Canister	GC-MS	EPA	
C_4-C_{12}	Thermal desorption tubes	GC-FID	SAE 930142HP	10 ppbC
Aldehydes and ketones	DNPH	HPLC/UV-VIS	SAE 930142HP	0.02 µg/mL
C_{10}-$C_{30,}$ inc PAHs	Quartz/PUF/XAD denuder	GC-MS	EPA TO-13A	0.01 ng *
Polynuclear Aromatic Hydrocarbons	Quartz	GC-MS	EPA TO-13A	0.01 ng *

*depends on compound

10.8.3 C_1 to C_8 Hydrocarbons

Analyses of the very light hydrocarbons are carried out by sampling into a SUMMA® canister equipped with a flow controller. The samples are analyzed for TGNMO as methane per modified EPA method TO-3 using a gas chromatograph equipped with a flame ionization detector (FID). The samples are also analyzed for methane and TGNMO as methane according to modified EPA Method 25C. The analyses included a single injection (method modification) analyzed by gas chromatography using FID/ total combustion analysis. The samples can be further analyzed for carbon dioxide according to modified EPA method 3C (single injection) using a gas chromatograph equipped with a thermal conductivity detector (TCD).

10.8.4 C_4 to C_{12} Hydrocarbons, BTX & Light Hydrocarbons

Traditional air monitoring methods for direct measurement of very-volatile and volatile organic compounds (VVOC/VOC) are insensitive at the low levels that most trace compounds are found in exhaust from lean burn engines. Accordingly UCR uses selective adsorbents for concentrating the molecules of interest after the diluted exhaust gas pass through a Teflon filter. After collection, the adsorbents are returned to the laboratory where the adsorbed molecules are flashed into a concentrator/reservoir at low temperature and then controllably vaporized into a gas chromatograph with a field ionization detector (GC/FID). A mass spectrometer detector (GC/MS) can also be used.

Molecules starting about C_4 (butadiene) through C_{12} are effectively collected and concentrated on an adsorbent column composed with a multi-bed carbon bed including molecular sieve, activated charcoal, and carbotrap resin, each adsorbent with a specific selectivity towards certain boiling ranges or polarity. The absorbent material first contacted in the column adsorbs the most volatile compounds and the remaining compounds will adsorb sequentially in relation to their volatility. The GC sample injection, columns, and operating conditions are set up according to the specifications of SAE 930142HP Method-2 for C_4-C_{12} hydrocarbons.

10.8.5 C_1 to C_{12} Hydrocarbons, Carbonyls

Carbonyls are collected on 2,4-dinitrophenylhydrazine (DNPH) coated silica cartridges (Waters Corp., Milford, MA) after the Teflon filter. A critical flow orifice controls the flow to 1.0 LPM through the cartridge and the sample time is adjusted to draw a known volume of exhaust sample through the DNPH cartridge so that the amount of formaldehyde on the cartridge is at the mass level recommended by Waters. Sampled cartridges are extracted using 5 mL of acetonitrile and injected into Agilent 1100 series high performance liquid chromatograph (HPLC) equipped with a diode array detector. The column is a 5μm Deltabond AK resolution (200cm x 4.6mm ID) with upstream guard column. The HPLC sample injection and operating conditions are set up according to the specifications of the SAE 930142HP protocol Samples from the dilution air are collected for background correction.

10.8.6 C_{10} to C_{30} Hydrocarbons, including Naphthalene and PAHs

The flow diagram, Figure 10-4 indicates that a sample of exhaust flows through a quartz filter and into a column packed with polyurethane foam (PUF)/XAD-4 resin. A portion of the quartz filter is used to analyze for the elemental and organic carbon. Both the PUF/XAD-4 cartridge and the remainder of quartz filter are extracted with methylene chloride and analyzed using a modified method EPA TO13A protocol (GC-MS analysis) to determine total emission rates for naphthenes, PAHs, and other heavy hydrocarbons. The analysis method is found in Shah[11]. Note that only about 5-10% of the recovered OC mass is identified as the majority of the extract becomes the baseline in the chromatogram.

10.9 Measuring Non-Regulated Particulate Emissions

10.9.1 Measuring the Elemental and Organic Carbon Emissions

UCR 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 were sealed in containers immediately after sampling, and kept chilled until analyzed.

10.9.2 Measuring Emissions of Ions and Metal

At each operating mode a representative sample of the diluted exhaust gas flows through a Teflon filter. Subsequently, portions of the filters are analyzed for ions such as sulfate, chloride and nitrate and for metals. For ions, the Teflo™ filter is extracted with HPLC grade water after wetting the filter surface with a few drops of isopropyl alcohol using methods described by Sawant[12]. The solution is filtered and analyzed using a Dionex DX-120 ion

[11] Shah, S.D., Ogunyoku, T. A., Miller, J. W., and Cocker III, D. R. (2004), *On-Road Emission Rates of PAH and n-Alkane Compounds from Heavy-Duty Diesel Vehicles*, Environ. Sci. & Technology, **2005**, 39, 5276-5284

[12] Sawant, A.A., Na, K., Zhu, X., Cocker, K., Butt, S., Song, C., Cocker III, D.R., (2004) *Characterization of PM2.5 and Selected Gas-phase Compounds at Multiple Indoor and Outdoor Sites in Mira Loma, CA.*, Atmospheric Environment 38, 6269-6278.

chromatograph to determine the mass of sulfate and other ions on the filter. For metals Teflo™ filters are analyzed using XRF method as per EPA IO-3 at an outside laboratory using XRF methods.

10.9.3 Measuring Real-Time Particulate Matter (PM) Emissions-DustTrak

In addition to the filter-based PM mass measurements, UCR takes continuous readings with a Nephelometer (TSI DustTrak 8520) so as to capture both the steady-state and transient data. The Dust Trak 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/nephelometers 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 as 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, UCR 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 10-5 Picture of TSI Dust Trak

10.9.4 Measuring the Real-Time Particulate Matter (PM) Emissions-Dekati DMM

ISO or conventional PM measurements are based on particulate mass measurement with a gravimetric filter, resulting in a total, cumulative mass emission. A concern with the ISO approach is the PM mass emission rate is assumed to be constant during the collection period of 5 to 15 minutes. Thus for some projects, UCR takes data with a Dekati Mass Monitor (DMM-230)[13]. The DMM is a real-time PM instrument that provides second-by-second information not only about particle total mass but also median diameter of particles, which are two important parameters related to particle health effects. The sample for the DMM was taken from a second dilution tunnel as the dilution ratio needed to operate the DMM was ten-fold greater than in the primary dilution tunnel. Dilution was accomplished by adding another line and HEPA-filtered ambient air for dilution. The added dilution is needed as the DMM was designed with detection limit as low as >1 μg/m^3 allowing studies with diesel after-treatment controls.

Figure 10-6 Picture of the DMM-230

10.10 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

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, starting with rated speed. If UCR suspects the 100% load point at rated speed is unattainable, then we select the highest possible load on the engine as Mode 1. Emissions are measured while the engine operates according to the requirements of ISO-8178-E3. For a diesel engine the highest power mode is run first and then each mode was run in sequence. The minimum time for samples is 5 minutes and if necessary, the time was extended to collect sufficient particulate sample mass or to achieve stabilization with large engines.

[13] http://www.dekati.com/cms/dmm

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 blend relative to the baseline fuel.

11 Appendix C

11.1 Certificate of Analysis

DNV Petroleum Services - Fuel Quality Report dated : 24-APR-09

Vessel : SEA-LAND INTREPID (9143025)

Sample No	F709008264
Sample Type	(HFO)
Bunker Port	LOS ANGELES
Bunker Date	20-APR-09
Sampling Point	SHIP MANIFOLD
Sent From	SIGNAL HILL, CA
Date Sent	22-APR-09
Arrived at Lab	23-APR-09
Supplier	CHEM OIL
Loaded From	MAX 111
Quantity per C.Eng	3400

Seal Data	DNVPS	
	3767137	
	INTACT	Related Samples
Supplier	3767138	
Ship	3767139	
Ship (DNVPS MARPOL)	3767140	

Receipt Data*		C.ENG
Density @ 15C	kg/m3	989.6
Viscosity @ 50C	mm2/s	200
Sulfur	%m/m	3.10
Volume	m3	UNKNOWN
Quantity	MT	UNKNOWN

*Please include a copy of the Bunker Delivery Note (BDN).

Tested Results	Units		RMG380
Density @ 15C	kg/m3	990.3	991.0

1

ity @ 50C	mm2/s	262.3	380.0
	%V/V	LT 0.1	0.5
[illegible] Carbon Residue	%m/m	15	18
lfur	%m/m	3.44	4.50
tal Sediment Potential	%m/m	0.02	0.10
Ash	%m/m	0.07	0.15
anadium	mg/kg	276	300
Sodium	mg/kg	5	
Aluminium	mg/kg	21	
Silicon	mg/kg	23	
Iron	mg/kg	9	
Nickel	mg/kg	56	
Calcium	mg/kg	8	
Magnesium	mg/kg	LT 1	
Lead	mg/kg	LT 1	
Zinc	mg/kg	2	
Phosphorus	mg/kg	2	
Potassium	mg/kg	5	
Pour Point	Deg.C	LT 24	30
Flash Point	Deg.C	GT [illegible]	60

Calculated Values

Net Specific Energy	MJ/kg	40.09	
CCAI (Ignition Quality)	-	855	
Aluminium + Silicon	mg/kg	44	60

Note: LT means Less Than, GT means Greater Than.

Specification Comparison :

Based on this sample the tested results meet the ISO 8217:2005 specification RMG380, table 2 requirements.

Operational Advice :

Approximate fuel temperatures:
- injection: 135C for 10 mm2/s, 120C for 15 mm2/s
- transfer : [illegible]

Based on Density, centrifuge operation may be difficult with this fuel. Ensure that gravity ring size, fuel temperature and flow rate through centrifuge are optimum. Failing to operate as purifier, centrifuge(s) should be operated temporarily as clarifier(s). Preferably split the flow between two clarifier(s) in parallel. Shorten intervals between bowl discharges since this is the only way to remove water. Take samples to monitor fuel quality before/after centrifuges. Retain samples for future reference.

Aluminium + Silicon indicates fuel contains abrasive contaminants. It is therefore important that the fuel is efficiently centrifuged. Use the lowest possible through put. Frequent bottom draining of all tanks and filters in use is advisable. Check purifier for optimum gravity disk. Operate conventional centrifuges in series as purifier/ clarifier. For high density separators recommend to operate two centrifuges in parallel.

Vanadium - Contributes to ash deposits on the turbocharger nozzle rings. Avoid high exhaust temps and clean the turbo chargers more frequently.

Fuel System Check (FSC) Samples:
Based on the Aluminium + Silicon levels, we recommend to send a set of FSC samples to assess the efficiency and confirm optimum operation of the fuel treatment plant. As a minimum, representative samples taken before and after the separators are required for this assessment. Red labels should be used for the FSC samples. Please refer to the Instruction Manual included in the sample kits for more detailed information.

DNV Petroleum Services - Fuel Quality Report dated : 29-MAY-09

Vessel : SEA-LAND INTREPID (9143025)

Sample No	FT09010690
Sample Type	(MGO)
Bunker Port	LOS ANGELES
Bunker Date	25-MAY-09
Sampling Point	SHIP MANIFOLD
Sent From	SIGNAL HILL, CA
Date Sent	27-MAY-09
Arrived at Lab	28-MAY-09
Supplier	CHEM OIL
[illegible] From	JAKE J
Quantity per C.Eng	200

Seal Data	DNVPS	
	494691	
	INTACT	Related Samples
Supplier	494692	
Ship	494693	
Ship (DNVPS MARPOL)	494694	

Receipt Data*		C.ENG
Density @ 15C	kg/m3	843.0
Viscosity @ 40C	mm2/s	2.9
Sulfur	%m/m	0.02
Volume	m3	UNKNOWN
Quantity	MT	UNKNOWN

*Please include a copy of the Bunker Delivery Note (BDN).

Tested Results	Units		DMA
Density @ 15C	kg/m3	842.8	890.0

1

sity @ 40C	mm2/s	2.7	1.5\6.0
r	%V/V	LT 0.1	
ro Carbon Residue 10%	%m/m	LT 0.10	0.30
lfur	%m/m	LT 0.05	1.50
sn	%m/m	LT 0.01	0.01
Vanadium	mg/kg	1	
Sodium	mg/kg	LT 1	
Aluminium	mg/kg	LT 1	
Silicon	mg/kg	1	
Iron	mg/kg	LT 1	
Nickel	mg/kg	LT 1	
Calcium	mg/kg	1	
Magnesium	mg/kg	LT 1	
Lead	mg/kg	LT 1	
Zinc	mg/kg	LT 1	
Phosphorus	mg/kg	LT 1	
Potassium	mg/kg	LT 1	
Pour Point	Deg.C	LT -6	-6\0
Flash Point	Deg.C	67	60
Visual Appearance	-	CLEAR	CLEAR
FTIR Analysis	-	NORMAL	

Calculated Values

Net Specific Energy	MJ/kg	42.81	
Aluminium + Silicon	mg/kg	LT 2	
Calculated Cetane Index	-	47	40

Note: LT means Less Than.

Specification Comparison :

Based on this sample the tested results meet the ISO 8217:2005 specification DMA, table 1 requirements.

Regards, Hussain, Qamar, Houston, USA
END OF REPORT FOR SEA-LAND INTREPID

Reference to part(s) of this report which may lead to misinterpretation is prohibited.

From 1 July 2009 onwards, SOLAS Regulation VI/5-1 requires that bunker suppliers, prior to delivery, provide your ship crew with a Material Safety Data Sheet (MSDS) for each type of marine fuel to be loaded to your vessel.
A copy of the MSDS must accompany the corresponding fuel sample(s) sent to DNV Petroleum Services for analysis.

DNV Petroleum Services - Fuel Quality Report dated : 04-JUL-09

Vessel : SEA-LAND INTREPID (9143025)

Sample No		F709012923	
Sample Type		(HFO)	
Bunker Port		LOS ANGELES	
Bunker Date		29-JUN-09	
Sampling Point		SHIP MANIFOLD	
Sent From		SIGNAL HILL, CA	
Date Sent		01-JUL-09	
Arrived at Lab		02-JUL-09	
Supplier		UNKNOWN	
Loaded From		FDH-35-4	
Quantity per C.Eng		1000	
Seal Data		DNVPS	
		3219531	
		INTACT	Related Samples
Supplier		3219532	
Ship		3219533	
Ship (DNVPS MARPOL)		3219534	
Receipt Data*		C.ENG	
Density @ 15C	kg/m3	990.3	
Viscosity @ 50C	mm2/s	355	
Sulfur	%m/m	2.40	
Volume	m3	UNKNOWN	
Quantity	MT	UNKNOWN	

*Please include a copy of the Bunker Delivery Note (BDN).

Tested Results	Units		RMG380
Density @ 15C	kg/m3	990.6	991.0

1

Viscosity @ 50C	mm2/s	367.0	380.0
Water	%V/V	0.3	0.5
Micro Carbon Residue	%m/m	13	18
Sulfur	%m/m	2.50	4.50
Total Sediment Potential	%m/m	0.01	0.10
Ash	%m/m	0.03	0.15
Vanadium	mg/kg	57	300
Sodium	mg/kg	9	
Aluminium	mg/kg	11	
Silicon	mg/kg	12	
Iron	mg/kg	32	
Nickel	mg/kg	21	
Calcium	mg/kg	4	
Magnesium	mg/kg	LT 1	
Lead	mg/kg	LT 1	
Zinc	mg/kg	1	
Phosphorus	mg/kg	LT 1	
Potassium	mg/kg	LT 1	
Pour Point	Deg.C	LT 24	30
Flash Point	Deg.C	GT 70	60

Calculated Values

Net Specific Energy	MJ/kg	40.26	
CCAI (Ignition Quality)	-	852	
Aluminium + Silicon	mg/kg	23	80

Note: LT means Less Than, GT means Greater Than.

Specification Comparison :

Based on this sample the tested results meet the ISO 8217:2005 specification RMG380, table 1 requirements.

Operational Advice :

Approximate fuel temperatures:
- Injection: 145C for 10 mm2/s, 125C for 15 mm2/s
- transfer : 45C

Based on Density, centrifuge operation may be difficult with this fuel. Ensure that gravity ring size, fuel temperature and flow rate through centrifuge are optimum. Failing to operate as purifier, centrifuge(s) should be operated temporarily as clarifier(s). Preferably split the flow between two clarifier(s) in parallel. Shorten intervals between bowl discharges since this is the only way to remove water. Take samples to monitor fuel quality before/after centrifuges. Retain samples for future reference.

Sample No		F709010690
---------		----------
Sample Type		(MGO)
Bunker Port		LOS ANGELES
Bunker Date		25-MAY-09
Sampling Point		SHIP MANIFOLD
Sent From		SIGNAL HILL, CA
Date Sent		27-MAY-09
Arrived at Lab		28-MAY-09
Supplier		CHEM OIL
Loaded From		JAKE J
Quantity per C.Eng		200

Seal Data	DNVPS	
	494691	
	INTACT	Related Samples
Supplier	494692	
Ship	494693	
Ship (DNVPS MARPOL)	494694	

Receipt Data*		C.ENG

Density @ 15C	kg/m3	843.0
Viscosity @ 40C	mm2/s	2.9
Sulfur	%m/m	0.02
Volume	m3	UNKNOWN
Quantity	MT	UNKNOWN

*Please include a copy of the Bunker Delivery Note (BDN).

Tested Results	Units		DMA
--------------	-----		---
Density @ 15C	kg/m3	842.8	890.0
			1

Viscosity @ 40C	mm2/s	2.7	1.5\6.0
Water	%V/V	LT 0.1	
Micro Carbon Residue 10%	%m/m	LT 0.10	0.30
Sulfur	%m/m	LT 0.05	1.50
Ash	%m/m	LT 0.01	0.01
Vanadium	mg/kg	1	
Sodium	mg/kg	LT 1	
Aluminium	mg/kg	LT 1	
Silicon	mg/kg	1	
Iron	mg/kg	LT 1	
Nickel	mg/kg	LT 1	
Calcium	mg/kg	1	
Magnesium	mg/kg	LT 1	
Lead	mg/kg	LT 1	
Zinc	mg/kg	LT 1	
Phosphorus	mg/kg	LT 1	
Potassium	mg/kg	LT 1	
Pour Point	Deg.C	LT -6	-6\0
Flash Point	Deg.C	67	60
Visual Appearance	-	CLEAR	CLEAR
FTIR Analysis	-	NORMAL	

Calculated Values

Net Specific Energy	MJ/kg	42.81	
Aluminium + Silicon	mg/kg	LT 2	
Calculated Cetane Index	-	47	40

Note: LT means Less Than.

Specification Comparison :

Based on this sample the tested results meet the ISO 8217:2005 specification **DMA,** requirements.

12 Appendix D

12.1 Analysis of UCR Fuel Sample

SOUTHWEST RESEARCH INSTITUTE®

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DATA SUMMARY FOR U.C. Riverside
SWRI WORKORDER #49269
PO # RT10246942

D 4052 Density (API by Meter) at 60°F

Sample ID	HFO I	HFO II	MDO I	MDO II
API @ 60 F (15.5C)	17.3	15.5	36.4	36.3
Specific Gravity @ 60 F	0.8356	0.9507	0.8428	0.8432
Density @ 15.5C	950.1	962.2	842.3	842.7

D 2622 Sulfur - Wavelength Dispersive X-Ray Florescence

Sample ID	HFO I	HFO II	MDO I	MDO II
Sulfur, Weight %	3.1443	2.1534	-	-
Sulfur, ppm	31442.7	21534.3	-	-

D 5453 Sulfur - UV (Antek)

Sample ID	HFO I	HFO II	MDO I	MDO II
Sulfur, ppm	-	-	6.5	94.2

No uncertainties have been determined for these results, but ASTM repeatability may be referenced.

OJPDBIX9(RT10246942)
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8

13 Appendix E

13.1 Ship Resistances[14]

To move a ship, it is necessary to overcome resistance, i.e. the force working against its propulsion. The calculation of this resistance *R* plays a significant role in the selection of the correct propeller and in the subsequent choice of main engine. A ship's resistance is particularly influenced by its speed, displacement, and hull form. The total resistance R_T, consists of many source resistances *R* which can be divided into three main groups, viz.:1) Frictional resistance; 2) Residual resistance = Wave plus Eddy Resistances and 3) Air resistance

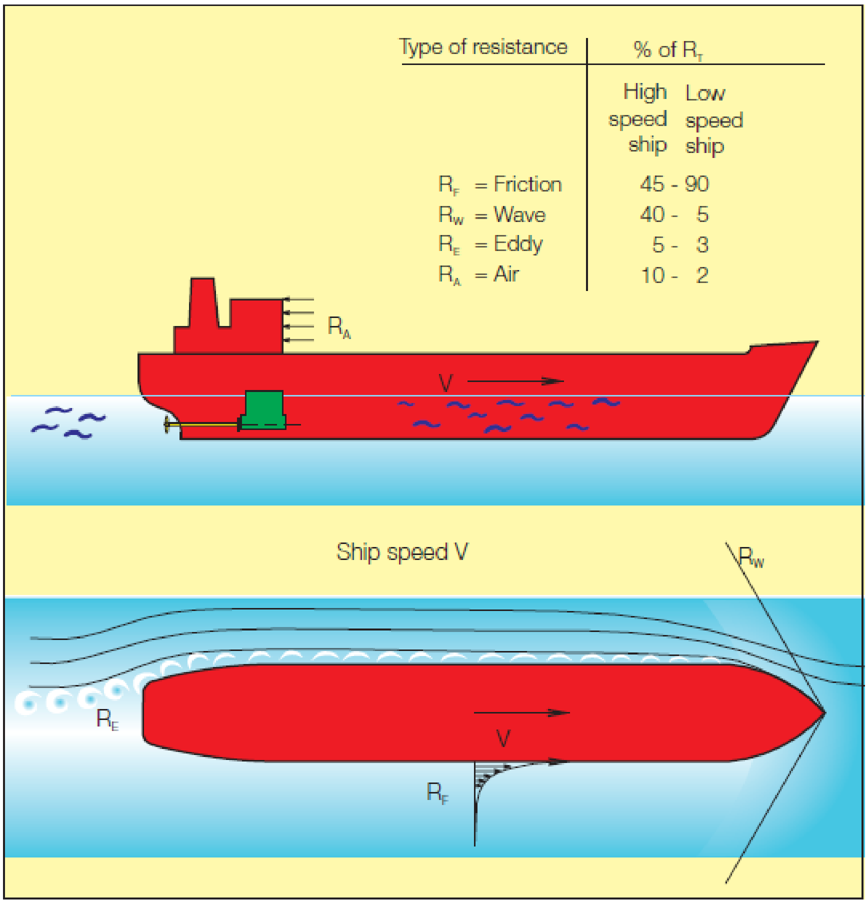

Figure 13-1 Total Ship Towing Resistance $R_T = R_F + R_W + R_E + R_A$

The influence of frictional and residual resistances depends on how much of the hull is below the waterline, while the influence of air resistance depends on how much of the ship is above the waterline. In view of this, air resistance will have a certain effect on container ships which carry a large number of containers on the deck.

Water with a speed of *V* and a density of ρ has a dynamic pressure of:

$\frac{1}{2} \times \rho \times V^2$ *(Bernoulli's law)*

Thus, if water is being completely stopped by a body, the water will react on the surface of the body with the dynamic pressure, resulting in a dynamic force on the body. This relationship is used as a basis when calculating or measuring the source resistances *R* of a

[14] Appendix E from MANN B&W Technical Report, *Basic Principles of Ship Propulsion*

ship's hull, by means of dimensionless resistance coefficients C. Thus, C is related to the reference force K, defined as the force which the dynamic pressure of water with the ship's speed V exerts on a surface which is equal to the hull's wetted area A_S. The rudder's surface is also included in the wetted area. The general data for resistance calculations is thus:

Reference force: $K = ½ \times \rho \times V^2 \times A_S$ and source resistances: $R = C \times K$

On the basis of many experimental tank tests, and with the help of pertaining dimensionless hull parameters, some of which have already been discussed, methods have been established for calculating all the necessary resistance coefficients C and, thus, the pertaining source resistances R. In practice, the calculation of a particular ship's resistance can be verified by testing a model of the relevant ship in a towing tank.

Frictional resistance R_F The frictional resistance R_F of the hull depends on the size of the hull's wetted area A_S, and on the specific frictional resistance coefficient C_F. When the ship is propelled through the water, the frictional resistance increases at a rate that is virtually equal to the square of the vessel's speed. Frictional resistance represents a considerable part of the ship's resistance, often some 70-90% of the ship's total resistance for low-speed ships (bulk carriers and tankers), and sometimes less than 40% for high-speed ships (cruise liners and passenger ships) [1]. The frictional resistance is found as follows: $R_F = C_F \times K$

Residual resistance R_R : Residual resistance R_R comprises wave resistance and eddy resistance. Wave resistance refers to the energy loss caused by waves created by the vessel during its propulsion through the water, while eddy resistance refers to the loss caused by flow separation which creates eddies, particularly at the aft end of the ship.

Wave resistance at low speeds is proportional to the square of the speed but increases much faster at higher speeds. In principle, this means that a speed barrier is imposed, so that a further increase of the ship's propulsion power will not result in a higher speed as all the power will be converted into wave energy. The residual resistance normally represents 8-25% of the total resistance for low-speed ships, and up to 40-60% for high-speed ships.

Air resistance R_A: In calm weather, air resistance is, in principle, proportional to the square of the ship's speed, and proportional to the cross-sectional area of the ship above the waterline. Air resistance normally represents about 2% of the total resistance. For container ships in head wind, the air resistance can be as much as 10%. The air resistance can, similar to the foregoing resistances, be expressed as $R_A = C_A \times K$, but is sometimes based on 90% of the dynamic pressure of air with a speed of V, i.e.:

$$R_A = 0.90 \times ½ \times \rho_{air} \times V^2 \times A_{air}$$

where ρ_{air} is the density of the air, and A_{air} is the cross-sectional area of the vessel above the water.

Towing resistance R_T and effective (towing) power P_E The ship's total towing resistance R_T is thus found as: $R_T = R_F + R_R + R_A$. The corresponding effective (towing) power, P_E, necessary to move the ship through the water, i.e. to tow the ship at the speed V, is then: $P_E = V \times R_T$

The power delivered to the propeller, P_D, in order to move the ship at speed V is, however, somewhat larger. This is due, in particular, to the flow conditions around the propeller and the propeller efficiency itself, the influences of which are discussed in the next chapter which deals with Propeller Propulsion.

Total ship resistance in general: When dividing the residual resistance into wave and eddy resistance, as earlier described, the distribution of the total ship towing resistance R_T could also, as a guideline, be stated as shown in Figure 13-1. The right column is valid for low-speed ships like bulk carriers and tankers, and the left column is valid for very high-speed ships like cruise liners and ferries. Container ships may be placed in between the two columns. The main reason for the difference between the two columns is, as earlier mentioned, the wave resistance. Thus, in general all the resistances are proportional to the square of the speed, but for higher speeds the wave resistance increases much faster, involving a higher part of the total resistance.

This tendency is also shown in Figure 13-2 for a 600 TEU container ship, originally designed for the ship speed of 15 knots. Without any change to the hull design, the ship speed for a sister ship was requested to be increased to about 17.6 knots. However, this would lead to a relatively high wave resistance, requiring a doubling of the necessary propulsion power. A further increase of the propulsion power may only result in a minor ship speed increase, as most of the extra power will be converted into wave energy, i.e. a ship speed barrier valid for the given hull design is imposed by what we could call a "wave wall", see Figure 13-2. A modification of the hull lines, suiting the higher ship speed, is necessary.

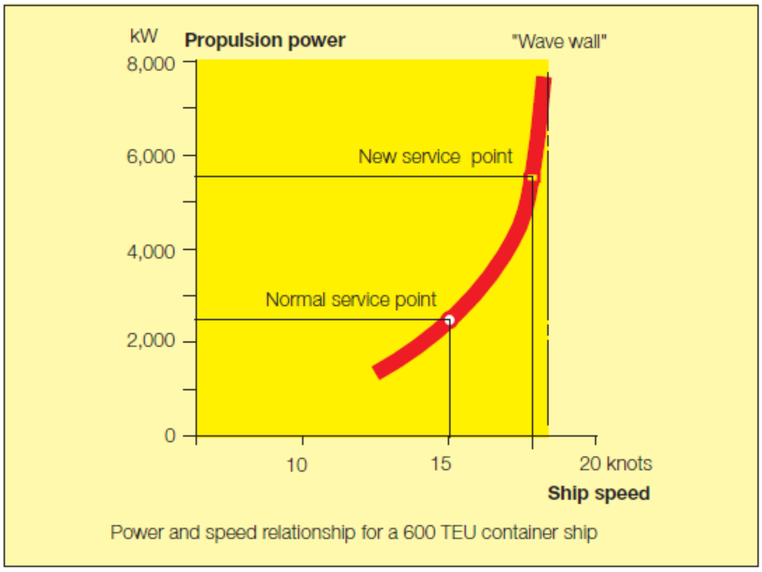

Figure 13-2 The "Wave Wall" Ship Speed Barrier