

Measurement of Criteria and Greenhouse Gas Emissions from Auxiliary Engines on Ocean-Going Vessels Operating on Heavy Fuel Oil and Marine Diesel Oil

Final Report (April, 2009)

Prepared for:

California Air Resources Board
1001 I Street
Sacramento, CA 95814

Contract 03-345



Authors:

Ms. Varalakshmi Jayaram

Dr. J. Wayne Miller

Dr. Abhilash Nigam

Mr. William A Welch

Dr. David R Cocker

University of California, Riverside

College of Engineering-Center for Environmental Research and Technology

Riverside, CA 92521

Disclaimer

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

Acknowledgements

The authors would like to thank California Air Resources Board for their financial support without which this project would not have been possible. A special thanks to the ship crew and administrative staff aboard the Post-Panamax vessels for their logistical support during testing of the auxiliary engine. The authors would like to acknowledge Mr. Charles Bufalino's invaluable efforts in the test preparation. We are deeply grateful of the support offered by Virgilio Afan, Harshit Agrawal, Ajay Chaudhary, Kathalena Cocker, Heather Donnelly, Cristina Hall, Karel Jansen, Irina Malkina, Anthony Turgman and Mary Sheppy of the analytical laboratory at CE-CERT in the preparation and analysis of the sample media.

Table of Contents

Disclaimer	ii
Acknowledgements	iii
Table of Contents	iv
List of Figures	vi
List of Tables	vii
Executive Summary	viii
1. Introduction	1
1.1. Project Objectives	2
2. Test Plan	3
2.1. Overview	3
2.2. Test Engine	3
2.3. Test Fuels	4
2.4. Test Cycle and Condition.....	4
2.5. Schedule and Test Plan	5
2.6. Emissions Testing Procedure	7
2.6.1. Sampling Ports	7
2.6.2. Transfer Line.....	7
2.6.3. Measuring Gases and PM _{2.5} emissions	7
2.6.4. Calculating Exhaust Flow Rates from Intake Air	7
2.6.5. Calculation of Emission Factors	8
3. Results	9
3.1. Fuel Properties	9
3.2. Primary Gaseous Emissions.....	9
3.2.1. Gaseous Emission from AE#1	10
3.2.2. Gaseous Emissions from AE#2	12
3.2.3. Gaseous Emissions from AE#3	14
3.3. Particulate Matter Emissions	17
3.3.1. Effect of Transfer Line on PM Emissions	17
3.3.2. Total PM Mass Emissions	18
3.3.3. Speciated PM Mass Emissions	19
3.3.4. Internal Quality Check for Conservation of Mass Emissions.....	20
3.3.5. Real Time PM Emissions.....	20
4. Discussion	22
4.1. Fuels Effects on Gaseous and PM Emissions	22
4.2. Effect of Low-NO _x Mode on Gaseous and PM Emissions.....	23
5. Summary and Recommendations	25
6. References	27
7. Glossary of Symbols and Abbreviations	28
8. Appendix A	30
8.1. Certification Emission Test Protocol for Marine Auxiliary Engines.....	30
8.2. Portable Laboratory for Sampling and Measuring Gaseous and Particulate Matter Emissions from Auxiliary Engines	30
8.2.1. Measuring Gaseous Emissions	33

8.2.2.	Measuring the Particulate Matter (PM) Emissions	35
8.2.3.	Measuring Size Segregated PM Emissions.....	36
8.2.4.	Measuring Real-Time Particulate Matter Emissions	36
8.3.	Quality Control/Quality Assurance (QC/QA)	37
9.	Appendix B	38
9.1.1.	PM Emissions from AE#1	38
9.1.2.	PM Emissions from AE#2	38
9.1.3.	Speciated PM from AE#1	39
9.1.4.	Speciated PM from AE#2	40
9.1.5.	PM _{2.5} Mass Closure for AE#1 and AE#2	41
10.	Appendix C.....	43
10.1.	PM Emissions for October 2005 Test.....	43
10.2.	PM Emissions for the July 2005 Test	44
10.3.	Real Time PM Emissions for AE#2.....	45
10.4.	Size Segregated PM Emissions.....	46

List of Figures

Figure 2-1: MAN B&W 7L32-40	4
Figure 2-2 HFO.....	4
Figure 2-3 MDO	4
Figure 3-1 CO ₂ Emission Factors for AE#1	11
Figure 3-2 NO _x Emission Factors for AE#1	11
Figure 3-3 CO Emission Factors for AE#1.....	12
Figure 3-4 CO ₂ Emission Factor for AE#2.....	13
Figure 3-5 NO _x Emission Factors for AE#2.....	13
Figure 3-6 CO Emission Factors for AE#2.....	14
Figure 3-7 CO ₂ Emission Factors for AE#3	15
Figure 3-8 NO _x Emission Factors for AE#3	16
Figure 3-9 CO Emission Factors for AE#3.....	16
Figure 3-10: Effect of Transfer Line on PM Emissions from AE#1	18
Figure 3-11 PM _{2.5} Mass Closure for AE#3.....	20
Figure 3-12 Real Time PM Emissions for AE#3.....	21
Figure 3-13 Comparison of Teflon Filter Vs DMM.....	21
Figure 4-1 Comparison of NO _x Emissions across Fuel Types	22
Figure 4-2: Effect of low-NO _x Mode on PM Emissions for AE#3	24
Figure 6-1 Partial Flow Dilution System with Single Venturi, Concentration Measurement and Fractional Sampling	32
Figure 6-2 Field Processing Unit for Purifying Dilution Air in Carrying Case.....	33
Figure 6-3 In-Field Illustration of Continuous Gas Analyzer and Computer for Data Logging.....	34
Figure 8-4 Micro Orifice Uniform Deposit Impactor	36
Figure 8-5 Picture of the DMM-230.....	37
Figure 9-1 EC, OC, Hydrated Sulfate Emission Factors for AE#1	40
Figure 9-2 EC, OC, Hydrated Sulfate Emission Factors for AE#2	41
Figure 9-3 Speciated PM Emissions for AE#1	42
Figure 9-4 Speciated PM Emissions for AE#2	42
Figure 10-1 Picture of Sample Filter Contaminated with Urea	43
Figure 10-2 Reflective FTIR results	44
Figure 10-3 Real Time PM Emissions for AE#2 on HFO.....	45
Figure 10-4 Real Time PM Emissions for AE#2 on MDO	46

List of Tables

Table ES-1 Test Campaigns Dates, Fuel and Target Engine Load.....	viii
Table ES-2 Weighted Emission Factor (g/kW-hr) for Gases	ix
Table 1-1 IMO Fuel Sulfur Limits.....	1
Table 1-2 IMO NO _x Emission Standards.....	1
Table 2-1 Test Engine Specifications	4
Table 2-2 ISO 8178 D2 Cycle	5
Table 2-3 Test Schedule and Test Plan.....	6
Table 3-1 Selected Fuel Properties	9
Table 3-2 Gaseous Emission Factors for AE#1	10
Table 3-3 Gaseous Emission Factors for AE#2.....	12
Table 3-4 Gaseous Emission Factors for AE#3.....	15
Table 3-5: Effect of Transfer Line on Gaseous Emissions from AE#3 at 50% Load	17
Table 3-6 PM Emission Factors for AE#3.....	19
Table 3-7 Speciated PM Emission Factors for AE#3	19
Table 4-1 Fuel Effects on Total and Speciated PM _{2.5} Mass Emissions for AE#3	23
Table 4-2: Effect of Low-NO _x Mode on Gaseous Emissions.....	24
Table 8-1 Five Mode Test Cycle for Constant Speed Engines (ISO-8178-D-2 test cycle)	30
Table 8-2 Detector Method and Concentration Ranges for Monitor.....	34
Table 8-3 Quality Specifications for the Horiba PG-250	35
Table 9-1 PM Emissions Factors for AE#1, December 2005.....	38
Table 9-2 PM Emission Factors for AE#2.....	39
Table 9-3 Speciated PM Emission Factors for AE#1, December 2005.....	39
Table 9-4 Speciated PM Emission Factors for AE#2	40
Table 10-1 PM Emissions from AE#1, October 2005	43
Table 10-2 PM Emissions from AE#1, July 2005	45
Table 10-3 Size Segregated PM Emissions	47

Executive Summary

California Air Resources Board (CARB), a major shipping company and University of California, Riverside (UCR) worked together to determine the in-use emissions of some criteria and greenhouse gases for auxiliary engines (AE) aboard post-Panamax container ships. Since emissions data on AEs were sparse and these engines operate while entering the ports and at berth, there was a considerable interest in learning more about their emissions.

Three auxiliary engines were tested near the load points specified in the ISO 8178 D2 certification cycle with multiple fuels during six campaigns (Table ES-1). All three marine diesel engines, AE#1, AE#2 and AE#3, were the same make and model, MAN B&W 7L32/40 engine with a maximum power rating of 3,500kW. Emissions were measured following the ISO 8178-1 protocols.

Table ES-1 Test Campaigns Dates, Fuel and Target Engine Load

AE#1	July 2005	HFO; 40%, 50%, 75% Low NO _x MDO; 25%, 50% Low NO _x
	October 2005	HFO & MDO; 25%, 50%, 75%
	December 2005	HFO & MDO; 25%, 50%, 75%
AE#2	December 2005	HFO & MDO; 25%, 50%, 75%
AE#3	March 2006	HFO & MDO; 25%, 50% Effect of Transfer Line @ 50%
	May 2006	MDO; 25% Normal vs. Low NO _x

The primary objectives of this project were:

- To measure the emissions of gases (CO₂, CO, NO_x,) and particulate matter (PM_{2.5}) mass from auxiliary engines operating on Heavy Fuel Oil (HFO) and Marine Distillate Oil (MDO).
- To speciate the PM mass into its major constituents: elemental carbon (EC), organic carbon (OC) and hydrated sulfate as H₂SO₄.6.5H₂O.
- To determine the effect on the measured PM emissions when using a 3m long heated raw gas transfer line to connect the sampling probe to the dilution tunnel.
- To determine the effect of low-NO_x mode on the criteria emissions of a marine auxiliary engine.

Gaseous Emissions

Real-time gaseous emissions data (CO₂, NO_x and CO) were continuously logged at various engine load points for each of the engines running on HFO and MDO. Modal emission factors for each of the six measurement campaigns are presented in the report. Three of the campaigns provided enough data to estimate the overall weighted emission factor and those figures are presented in Table ES-2. AE#3 was not tested at sufficient number of engine load points to determine the weighted emission factors.

Table ES-2 Weighted Emission Factor (g/kW-hr) for Gases

Engine	Campaign	NO _x g/kW-hr		CO ₂ g/kW-hr		CO g/kW-hr	
		HFO	MDO	HFO	MDO	HFO	MDO
AE#1	Oct 2005	15.5±0.3	10.5±0.4	709±8	685±18	1.05±0.01	1.03±0.02
	Dec 2005	16.5±0.3	10.8±0.1	721±14	731±4	1.01±0.03	1.01±0.02
AE#2	Dec 2005	19.0±0.2	17.4±0.3	743±10	711±14	0.90±0.02	0.84±0.02

Note: kW-hr denotes generated power

The coefficient of variation for the CO₂ emission factors <3% when compared to the standard of <2% for laboratory tests gives us confidence in the data. AE#1 has significantly lower NO_x emissions and higher CO emission for both fuels and lower CO₂ emissions for HFO (Table ES-2). This indicates that AE#1 behaves differently from AE#2. Discussions with engine manufacturer suggest that this could be an indication of wear on the engine resulting in lower peak pressure of operation.

Switching from HFO to MDO, results in both NO_x and SO_x emission benefits. AE#1 showed an average NO_x reduction of around 30%; AE#2 had a 7% to 10% reduction in NO_x; AE#3 showed a 15% reduction at the 50% load point. There was no significant CO₂ or CO emission benefit with fuel switching.

Particulate Matter (PM_{2.5}) Emissions

Particulate matter samples were collected on Teflo[®] and quartz media for each of the six campaigns to determine both the total and speciated PM_{2.5} mass emission factors. In addition to this the effect of the 3m long heated raw gas transfer line used to connect the sampling probe to the dilution tunnel on PM emission factors was determined during the March 2005 campaign. The transfer line though allowed by the ISO method resulted in a PM loss of ~40% for HFO and ~30% for MDO at the 50% engine load point, it did not affect the gaseous emissions.

Hence, only those PM_{2.5} emission factors which were measured without the use of the transfer line are provided in the body of the report. PM_{2.5} emission factors from earlier campaigns, which are biased low due to the PM losses in the transfer line, are reported in Appendix B.

Speciation of PM_{2.5} emissions into its major constituents shows:

- PM_{2.5} from HFO has ~56% hydrated sulfate, ~24% OC and ~2% EC
- PM_{2.5} from MDO has ~9% hydrated sulfate, ~50% OC and ~8% EC.

Effect of Low-NO_x Mode

Operating the marine auxiliary engine in the low-NO_x mode reduced NO_x emission factor by ~31% for MDO. Though the elemental carbon of PM_{2.5} almost doubled there was no significant change in total PM_{2.5} emissions by switching to low-NO_x mode.

1. Introduction

Ocean going ships contribute significantly to the global anthropogenic emissions. They produce about 9.2 times more NO_x emissions and 1200 times more particulate matter than aviation (Eyring et al., 2005a). With the increasing international trade and lack of stringent emission standards as compared with other diesel engines, the contribution of criteria pollutants from these sources are growing relative to others.

The principal sources of emissions aboard a ship are the main propulsion and auxiliary engines. The main engines are 2-stroke low speed diesel engines. Auxiliary engines on the other hand are 4-stroke marine diesel engines, usually medium speed and occasionally high speed, with a power output in the range of 30-3000kW (Cooper et al., 2003). The main propulsion engines are used at sea and the auxiliary engines operate at the ports for transit, maneuvering, hotelling and cargo refrigeration. Hence, emissions from auxiliary engines have a significant effect on regional air quality in populated areas.

Currently the International Maritime Organization (IMO) regulates the sulfur content of fuels (Table 1-1) and the NO_x emissions for marine engines (Table 1-2). These standards are more stringent in areas designated as “emission control areas” (ECA). The NO_x emissions standards are a function of the engine speed (International Maritime Organization., 1998).

Table 1-1 IMO Fuel Sulfur Limits

Date	Sulfur Limit in Fuel (%m/m)	
	SO _x ECA	Global
2000	1.5%	4.5%
2010.07	1.0%	
2012	0.1%	3.5%
2015		0.5%
2020 [†]		

[†]alternative date is 2025, to be decided by a review in 2018

Table 1-2 IMO NO_x Emission Standards

Tier	Year	NO _x Limit (g/kW-hr)		
		n < 130	130 ≤ n < 2000	N ≥ 2000
Tier I	2000	17.0	45*n ^{-0.2}	9.8
Tier II	2011	14.4	44*n ^{-0.23}	7.7
Tier III	2016 [†]	3.4	9*n ^{-0.2}	1.96

[†] In NO_x Emission Control Areas (ECA). Tier II standards apply outside ECA
‘n’ engine speed in rpm

The two fuels that are widely used by marine diesel engines are Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO). HFO, also called as bunker fuel contains the unrefined fraction of petroleum and has a high sulfur content. MDO is distillate fuel with lower sulfur content; however, it costs almost twice as much as HFO. In spite of the disadvantage of the increased cost, fuel switching is one of the easiest ways of reducing PM emissions without the overhead of installing a control technology.

There is very little in-use data available on auxiliary marine diesel engines on either fuel, let alone a comparison of the two. Hence, CARB, UCR and a major shipping company came together to determine some criteria pollutants and greenhouse gas emissions from a set of auxiliary engines operating on both fuels HFO and MDO.

Among the NO_x emission reduction techniques like selective catalytic reduction, water in fuel injection, Injection Timing Retard (ITR) and exhaust gas recirculation, ITR (otherwise known as low-NO_x mode) is one of the easiest to implement on existing engines. Due to lack of in-use data on marine auxiliary engines operating in the low-NO_x mode, this project also involved determining the effect of low-NO_x mode on gaseous (NO_x, CO, CO₂) and particulate matter (PM_{2.5}) emissions from these engines.

1.1. Project Objectives

The primary objectives of this project were

- To measure the emissions of gases (CO₂, CO, NO_x) and particulate matter (PM_{2.5}) mass from marine auxiliary engines operating on Heavy Fuel Oil (HFO) and Marine Distillate Oil (MDO).
- To speciate the PM_{2.5} mass into its major constituents: elemental carbon (EC), organic carbon (OC) and hydrated sulfate as H₂SO₄.6.5H₂O.
- To determine the effect on the measured PM emissions when using a 3m long heated raw gas transfer line to connect the sampling probe to the dilution tunnel.
- To determine the effect of low-NO_x mode on the criteria emissions of a marine auxiliary engine.

For this purpose, in-use emissions of some criteria pollutants and carbon dioxide (CO₂) were measured from a set of auxiliary engines on post-Panamax container vessels. Criteria pollutants include oxides of nitrogen (NO_x), carbon monoxide (CO), sulfur dioxide (SO₂) and Particulate Matter (PM_{2.5}). Measurements were made following ISO 8178-1 while the engine operated following the ISO 8178-D2 engine certification cycle.

2. Test Plan

2.1. Overview

Normally, the emissions from diesel engines are measured while the engine is in a test cell and mounted on an engine dynamometer. These conditions are necessary for the purpose of certification. For this project, emissions testing were performed on operating engines on ocean going vessels following the load points in the ISO 8178 D2 cycle. This approach added complexity to the project.

The first test survey on a vessel was carried out in May 2005. From that survey party we learned what was required to successfully be ready to set up an emissions test laboratory on a vessel and to test with their sampling port locations, electrical supply and compressed air fittings. The survey allowed us to gauge the available working space so as to not interfere with the crew on the vessels. In addition, discussions with the Chief Engineer on the vessel provided us with the safety rules and operating constraints, especially time, that would be essential in our planning process. We also learned the need to design special cases for our test equipment to prevent harm to the sensitive instruments and computers when they are lifted with a crane from the roadway and dropped in the vessel hold.

A series of plans were developed to measure emissions of criteria and greenhouse gas emissions from a set of auxiliary engines operating on both fuels HFO and MDO. A total of six campaigns over a time frame of 11 months were undertaken to perform the emissions tests on three auxiliary engines AE#1, AE#2 and AE#3. Pre-test inspections prior to each campaign were conducted aboard the vessels. UCR worked with the ship's engineering crew to install sample ports and locate utilities necessary for operating the sampling systems. During these inspections, a detailed plan and schedule for testing was developed along with the Chief Engineer.

This section provides: (a) information on the test engine, test fuels, test cycle and test schedule; (b) a brief description of the emissions testing procedures. Additional details on the testing procedures can be found in Appendix A.

2.2. Test Engine

Three auxiliary engines aboard two post-Panamax class container vessels were tested. AE#1 and AE#3 were on Ship A and AE#2 was aboard Ship B. All three engines were 4-stroke medium speed marine diesel engines manufactured in the year 1999. They were the same make and model, MAN B&W 7L32-40. Further details are provided in Table 2-1.



Figure 2-1: MAN B&W 7L32-40

Table 2-1 Test Engine Specifications

Manufacturer /Model	MAN B&W /7L32-40
Manufacture Year	1999
Technology	4-Stroke
Max. Power Rating	3500 kW
Max. Generated Power	3125 kW
Rated Speed	720 rpm
# of Cylinders	7
Displacement	225.2 lit

2.3. Test Fuels

Each of the auxiliary engines were tested on two fuels the Heavy Fuel Oil (HFO) and the Marine Distillate Oil (MDO). Both fuels used during the test were typical of normal supply and a certificate of analysis (C of A) was requested for each fuel from the Chief Engineer. Selected properties of the fuels used during each campaign are shown in Table 3-1.

HFO commonly known as bunker fuel or residual oil is the residual fraction of crude refining. It has very high viscosity and sulfur content.

MDO is a refined fraction of the crude which has lower sulfur content; however it is almost twice as expensive as HFO.



Figure 2-2 HFO



Figure 2-3 MDO

2.4. Test Cycle and Condition

The emissions from the auxiliary engines were measured following the load points in ISO 8178 D2 certification cycle. Table 8-1 details the load points and protocol specified by the ISO for certification of auxiliary engines. Due to practical and operational considerations, the actual engine load could differ from the ISO target load. Also, not all load points specified in the ISO cycle could be tested. For example, the auxiliary engines were never operated at loads higher than 75% because a safety feature onboard the vessel would automatically turn on another auxiliary engine and distribute the load whenever the load on the engine increased beyond that point.

Table 2-2 ISO 8178 D2 Cycle

Mode number	Engine Speed¹	Observed Torque²	Minimum time in mode, min.	Weighting factors
1	Rated	100	5.0	0.05
2	Rated	75	5.0	0.25
3	Rated	50	5.0	0.30
4	Rated	25	5.0	0.30
5	Rated	10	5.0	0.10

¹Engine Speed: $\pm 2\%$ of point; ²Torque: Throttle fully open at 100% point. Other points $\pm 2\%$

An abbreviated protocol shows:

- Allow the gaseous emissions to stabilize
- Measure gaseous and PM concentrations for a time long enough to get measurable filter mass
- Record engine RPM, displacement, boost pressure and intake manifold temperature in order to calculate the mass flow rate of the exhaust.
- Calculate emission factors from the measured concentration data and calculated mass flow rates.

2.5. Schedule and Test Plan

The primary goal of these campaigns was to establish emission factors for a greenhouse gas CO₂ and the criteria pollutants NO_x, CO and total PM_{2.5} mass emissions from these auxiliary engines while operation on the high sulfur HFO and lower sulfur MDO. For this purpose three MAN B&W 7L32/40 marine auxiliary engines: AE#1, AE#2 and AE#3 were tested while operating on board post-Panamax ocean going vessels. A total of six campaigns over a time period of eleven months were undertaken. Each engine was tested on both HFO and MDO to evaluate the emissions benefit from fuel switching. A detailed list of the test schedule for each of the campaigns is provided in Table 2-3.

The first four campaigns: AE#1 July 2005, AE#1 October 2005, AE#2 December 2005, AE#1 December 2005 were performed using 3m long heated raw gas transfer line to connect the sampling probe to the dilution tunnel. During the March 2005 campaign the effect of this transfer line on the PM_{2.5} mass emissions was investigated. It was established that the transfer line, though allowed by the certification method, caused significant losses in PM_{2.5} emission factors due. Hence, use of the transfer line was eliminated in subsequent campaigns.

AE#1 and AE#3 were tested while operating at Low NO_x modes to evaluate in-use reduction in NO_x emissions as well as determine the effect of the low NO_x mode on CO, CO₂ and total and speciated PM_{2.5} emission factors. Operating the engine in the low-NO_x mode is an effective way of reducing NO_x emissions without spending on the installation of an after-treatment device.

Table 2-3 Test Schedule and Test Plan

Test Campaign	Auxiliary Engine	Date	Fuel	Transfer Line	Controls	Test
July 2005	AE#1	07/24/2005	HFO	Yes	Low-NO _x Mode	RT & ISO: 75%, 50%, 40% MOUDI: 50%
		07/25/2005	MDO	Yes	Low-NO _x Mode	RT & ISO: 50%, 25%, MOUDI: 50%
October 2005	AE#1	10/08/2005	HFO	Yes	-	RT & ISO; 75%, 50%, 25%
			MDO	Yes	-	RT & ISO: 75%, 50%, 25%
December 2005	AE#2	12/3/2007	HFO	Yes	-	RT & ISO & DMM: 75%, 50%, 25%
			MDO	Yes	-	RT & ISO & DMM: 75%, 50%, 25%
December 2005	AE#1	12/23/2005	MDO	Yes	-	RT & ISO: 75%, 50%, 25%
		12/24/2005	HFO	Yes	-	RT & ISO: 75%, 50%, 25%
March 2006	AE#3	3/11/2006	HFO	Yes	-	RT & ISO: 50%
				No	-	RT & ISO: 50%, 25% MOUDI: 50%
			MDO	Yes	-	RT & ISO: 50%
				No	-	RT & ISO: 50%, 25% MOUDI: 50%
May 2006	AE#3	5/23/2006	MDO	No	-	RT & ISO & MOUDI & DMM: 25%
					Low-NO _x Mode	RT & ISO & MOUDI & DMM: 25%

RT Real Time Monitoring and Recording of Emission Gaseous Samples; **ISO** Filter Samples taken in accordance with ISO 8178-4 D2

MOUDI Size Segregated PM Emissions; **DMM** Real Time PM Emissions

2.6. Emissions Testing Procedure

The emissions testing of the auxiliary engines were performed using a partial dilution system that was developed based on the ISO-8178-1 protocol. This section gives a brief description of this testing procedure. Refer to Appendix A for further details.

2.6.1. Sampling Ports

Sample probe access into the exhaust stream was gained by using sampling ports installed during pre-test inspection. Two sampling ports were installed next to each other in the exhaust stack: one to sample the raw exhaust and the other for the dilution tunnel. The sample probes, ¼” diameter schedule 40 stainless steel tubes, extended about 6” into the raw exhaust stack (18” diameter). This distance is sufficiently away from any conditions found near the stack wall boundary.

2.6.2. Transfer Line

During the initial campaigns (July 2005 to December 2005), a 3m long heated transfer line was used to connect the sampling probe to the dilution tunnel. The ISO-8178 protocol is effective for testing fuels with sulfur content less than 0.8% sulfur; the fuels we tested had fuel sulfur contents in the range of 0.05 to 3.8% sulfur (Table 3-1). The protocol allows the use of a heated transfer line not more than 5m in length. Further it states that “If the tube is longer than 1 m, it shall be insulated and heated to a minimum wall temperature of 523 K (250 °C)”. The transfer line we used was unable to achieve this temperature; it was maintained at a temperature >120 °C. Subsequent testing showed in March 2005 showed that this transfer line resulted in significant losses of PM_{2.5}.

2.6.3. Measuring Gases and PM_{2.5} emissions

The concentrations of carbon dioxide (CO₂), nitrogen oxide (NO_x) and carbon monoxide (CO) were measured both in the raw exhaust and the dilution tunnel with a Horiba PG-250 portable multi-gas analyzer (Appendix A, Section 8.2.1).

Particulate matter (PM_{2.5}) was sampled from the dilution tunnel on Teflo® and quartz filters. These filters were analyzed to determine the total and speciated PM_{2.5} mass emissions (Appendix A, Section 8.2.2).

2.6.4. Calculating Exhaust Flow Rates from Intake Air

An accurate calculation of the exhaust gas flow rate is essential for calculating emission factors. For this project the exhaust gas flow rate was calculated as equal to the flow of intake air. This method is widely used for calculating exhaust flow rates in diesel engines similar to marine auxiliary engines. This method assumes the engine is an air pump, so the flow of air into the engine will be equal to the exhaust flow out of the engine. The flow rate of intake air is determined from the cylinder volume, recorded rpm, and the temperature and pressure of the inlet air. 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. The auxiliary engines we tested were a 4-stroke marine diesel engines.

2.6.5. Calculation of Emission Factors

The emission factor at each mode is calculated from the measured gaseous and PM_{2.5} concentration, the reported engine load in kilowatts (kW) and the calculated mass flow in the exhaust.

An overall single emission factor representing the engine is determined by weighting the modal data according to the ISO 8178 D2 requirements and summing them. The equation used for the overall emission factor is as follows:

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

Where:

A_{WM} = Weighted mass emission level (HC, CO, CO₂, PM_{2.5}, or NO_x) in g/kW-hr

g_i = Mass flow in grams per hour,

P_i = Power measured during each mode, including auxiliary loads, and

WF_i = Effective weighing factor.

3. Results

3.1. Fuel Properties

The auxiliary engines were tested on two fuels HFO and MDO. Both fuels are typical of the normal supply meeting the ISO 8217 requirements. Selected properties of the fuels from the C of A provided by the Chief Engineer are shown in the Table 3-1.

Table 3-1 Selected Fuel Properties

Auxiliary Engine	Date	Fuel	Density @ 15°C (kg/m ³)	Viscosity @ 50°C mm ² /s	Sulfur Content (%m/m)	Ash Content (%m/m)
AE#1	July 2005	HFO	983.6	376	3.4	0.04
		MDO	847.4	n/a	0.16	n/a
AE#1	Oct 2005	HFO	966.5	449	3.8	0.03
		MDO	855.1	n/a	0.263	n/a
AE#2	December 2005	HFO	989.5	400	2.7	0.05
		MDO	830.1	2.5 ¹	0.05	0.01
AE#1	December 2005	HFO	989.5	389	3.8	0.02
		MDO	846.9	n/a	0.160	n/a
AE#3	March 2006	HFO	988.8	n/a	3.30	n/a
		MDO	847.3	n/a	0.159	n/a
AE#3	May 2006	MDO	845.9	2.9 ¹	0.11	<0.005

¹Viscosity @ 40°C, n/a: Not Available

3.2. Primary Gaseous Emissions

The major gaseous emissions of interest in the exhaust gas were: carbon dioxide (CO₂), carbon monoxide (CO), sulfur dioxide (SO₂) and nitrogen oxides (NO_x). All of the gaseous emissions were measured using ISO instruments, except for SO₂. The ISO recommendation is to calculate the concentration of SO₂ from fuel sulfur levels as most (>95%) of the fuel sulfur is converted to SO₂ in the combustion process. Section 7.4.3.7 in ISO 8178 states “The SO₂ concentration shall be calculated from the sulfur content of the fuel used, since experience has shown that using the direct measurement method for SO₂ does not give more precise results.”

Due to practical considerations we were unable to measure the fuel consumption during the testing procedure. Hence, the fuel flow rate was estimated based on the assumption that 100% of the fuel C (fuel C content: 86% wt/wt for HFO; 87% wt/wt for MDO) is converted to CO₂. This in turn was used along with the sulfur (S) content of the fuel to calculate the SO₂ emissions. Since 2 to 4% of the fuel sulfur gets converted to PM, the SO₂ emissions are biased low. This bias is within our experimental error of 5%.

3.2.1. Gaseous Emission from AE#1

As seen in Table 2-3 AE#1 was tested three times in July, October and December 2005. A detailed list of the gaseous emission factors for this engine running on both HFO and MDO is presented in Table 3-2. The error bars in Figures 3-1, 3-2 and 3-3 represent the standard deviation in the triplicate measurements made at each test mode.

Table 3-2 Gaseous Emission Factors for AE#1

Target Load ISO	Actual Load		CO ₂ (g/kW-hr)		CO (g/kW-hr)		NO _x (g/kW-hr)		SO ₂ EPA Calculated (g/kW-hr)	
	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO
July 2005, Low NO_x Mode										
25%	-	23%	-	733	-	2.98	-	8.78	-	0.20
40%	40%	-	655	-	1.98	-	11.16	-	7.06	-
50%	54%	52%	632	649	1.33	1.60	11.16	8.31	6.82	0.23
75%	68%	-	618	-	0.67	-	9.66	-	6.67	-
October 2005										
25%	26%	26%	873	829	1.82	1.96	17.85	13.27	10.52	0.42
50%	49%	48%	684	656	1.01	1.03	15.31	11.19	8.24	0.33
75%	71%	72%	651	647	0.73	0.62	14.29	8.84	7.84	0.32
December 2005										
25%	30%	22%	814	955	1.61	1.99	17.33	14.68	9.81	0.48
50%	52%	52%	708	697	0.94	0.98	16.44	11.27	8.53	0.35
75%	67%	69%	684	676	0.75	0.64	16.01	8.87	8.24	0.34

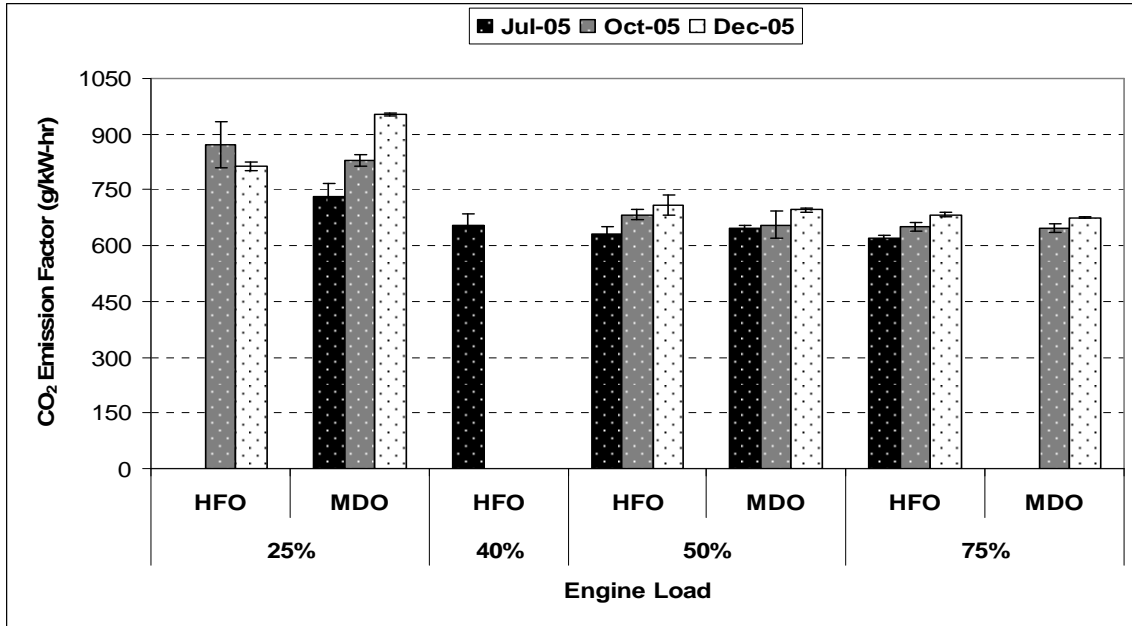
Note: kW-hr denotes generated power

A comparison of the CO₂ emission factors in g/kW-hr across loads and fuel types is presented in Figure 3-1. The variability of the CO₂ emission factor from one campaign to the next is reasonable and can be attributed to the change in the batch of fuel and load on the engine. Average weighted CO₂ emission factors for AE#1 based on the October 2005 and December 2005 campaigns is 715±11g/kW-hr for HFO and 705±26g/kW-hr for MDO.

A plot of the NO_x emission factors for AE#1 is presented in Figure 3-2. The NO_x emission factor from the July 2005 test is lower than the other two campaigns because the engine was operating on low-NO_x Mode.

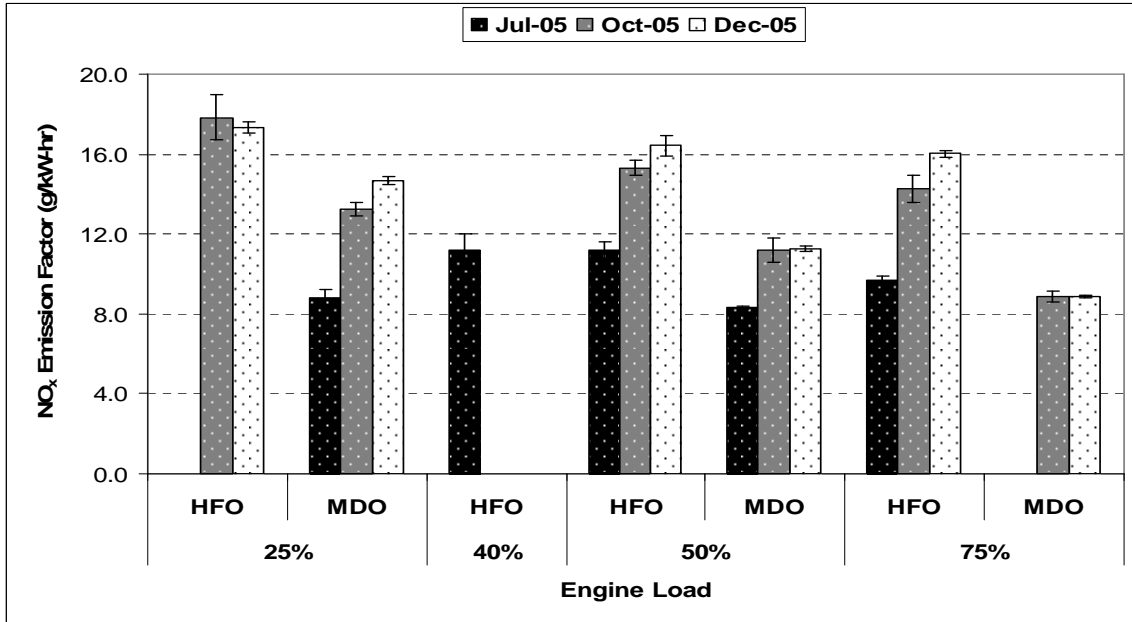
We notice a reduction in NO_x emission factor from of 15% to 45%, with an average of 30% by switching from HFO to MDO. The percentage reduction increases with increase in engine load. This NO_x emission benefit from fuel switching occurs even in the July 2005 campaign where the engine was operating in low-NO_x mode.

Figure 3-1 CO₂ Emission Factors for AE#1



Note: kW-hr denotes generated power, July 2005 engine was in low-NO_x mode

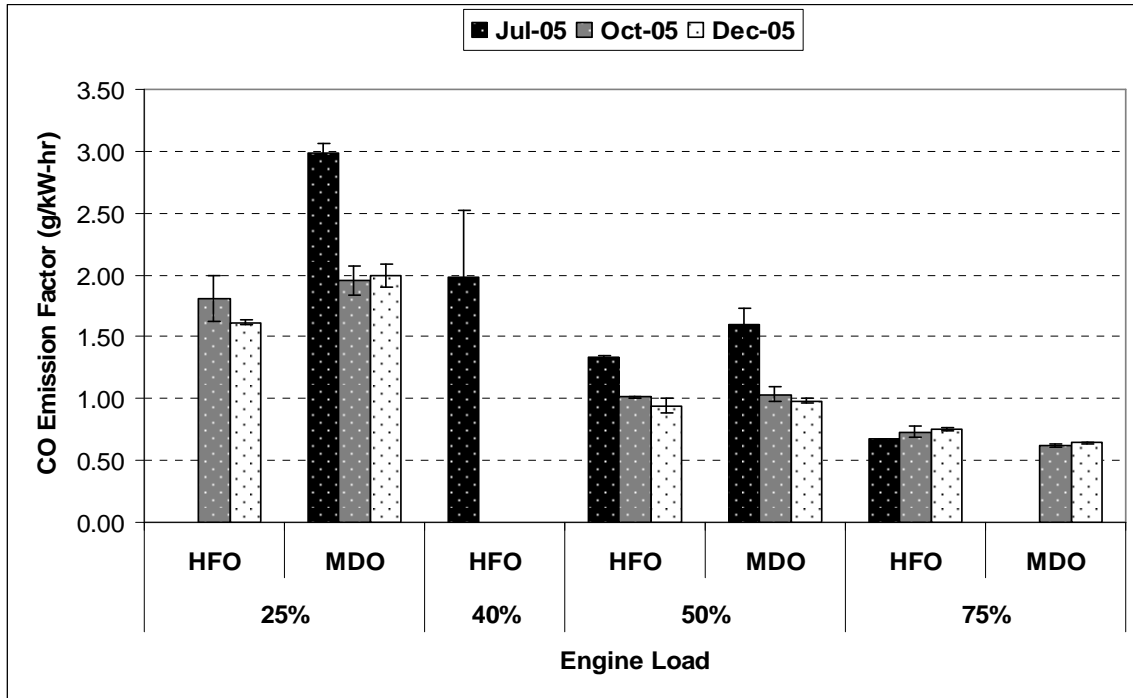
Figure 3-2 NO_x Emission Factors for AE#1



Note: kW-hr denotes generated power, July 2005 engine was in low-NO_x mode

Since diesel engines are highly efficient, the CO emission factor is expected to be low. This is clearly proved by the emission factors measured on AE#1 (Figure 3-3) which range from 0.50 to 2.00 g/kW-hr. As expected, the CO emissions are higher in the July 2005 campaign where the engine was operating in the low-NO_x mode. No significant emission benefit from fuel switching was observed for CO emissions.

Figure 3-3 CO Emission Factors for AE#1



Note: kW-hr denotes generated power, July 2005 engine was in low-NO_x mode

3.2.2. Gaseous Emissions from AE#2

AE#2 aboard Ship B was tested in early December of 2005. The gaseous emission factors across three loads and two fuels were tested and are reported in Table 3-3. Four readings were taken at each test mode. The standard deviation of the readings is presented in the form of error bars in Figures 3-4, 3-5 and 3-6.

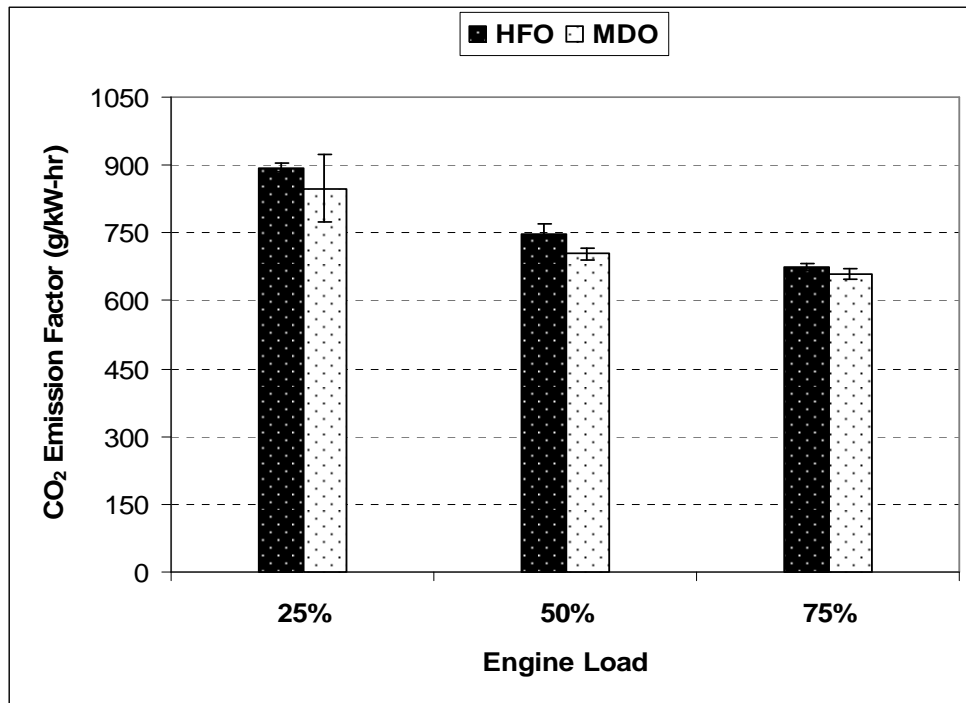
Table 3-3 Gaseous Emission Factors for AE#2

Target Load ISO	Actual Load		CO ₂ (g/kW-hr)		CO (g/kW-hr)		NO _x (g/kW-hr)		SO ₂ EPA Calculated (g/kW-hr)	
	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO
25%	27%	26%	894	848	1.59	1.37	21.05	19.57	7.66	0.70
50%	46%	47%	748	703	0.89	0.80	19.21	17.33	6.40	0.58
75%	73%	68%	673	659	0.61	0.63	17.99	16.47	5.76	0.54

Note: kW-hr denotes generated power

The CO₂ emission factors for AE#2 are shown in Figure 3-4. The weighted emission factor was found to be 743±10g/kW-hr for HFO and 711±14g/kW-hr for MDO.

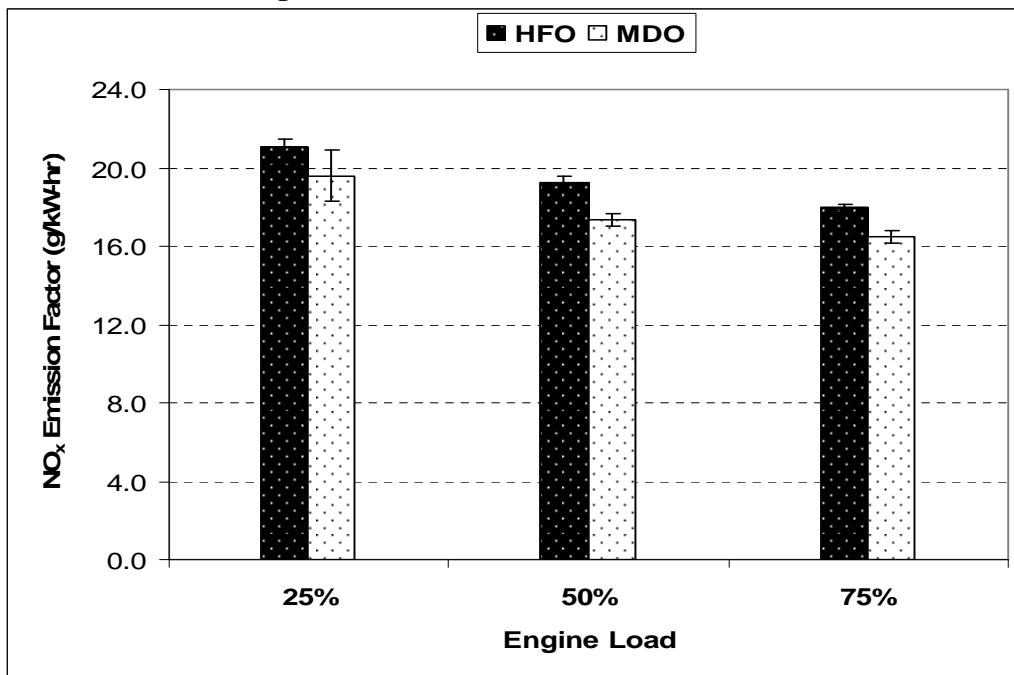
Figure 3-4 CO₂ Emission Factor for AE#2



Note: kW-hr denotes generated power

The NO_x emission factors are in the range of 16 to 22g/kW-hr which is greater than that observed for AE#1. The reduction of NO_x with fuel switching is pretty flat across the loads varying from 7 to 10%.

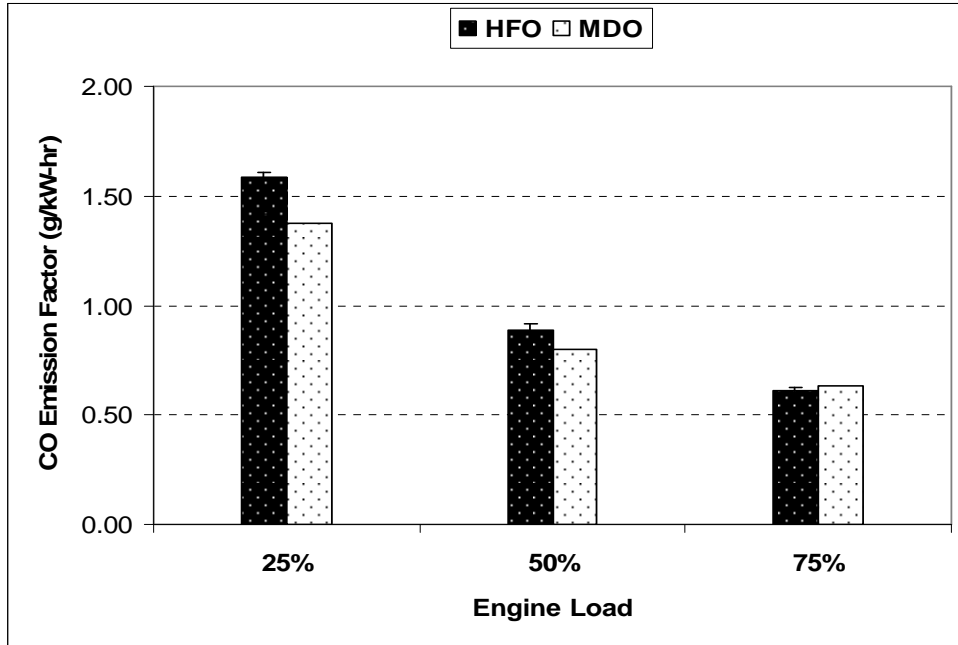
Figure 3-5 NO_x Emission Factors for AE#2



Note: kW-hr denotes generated power

The CO emission factor was found to be low, in the range of 0.05 to 2.00g/kW-hr as in the case of AE#1. The CO emission factors show a decreasing trend with the increase in engine load which seems to be the pattern followed by this engine model.

Figure 3-6 CO Emission Factors for AE#2



Note: kW-hr denotes generated power

3.2.3. Gaseous Emissions from AE#3

AE#3 was tested twice in March and May 2006. Not all ISO load points were tested during these campaigns because the primary goal of these tests was not to get detailed emission data.

The March 2006 test was undertaken to determine if the use of a 3m long transfer line to connect the probe to the dilution tunnel was resulting in lower PM emission factors hence the test was done with and without a transfer line. The May 2006 test was done to determine the effect of low-NO_x mode.

Though the data obtained from these tests are limited they add to our knowledge of emissions factors from auxiliary engines as well as give us an idea of problems we encounter during testing such as the use of a transfer line.

Detailed emission factors obtained during each measurement campaign are provided in Table 3-4. The error bars in Figures 3-7, 3-8 and 3-9 represent the standard deviation of the triplicate measurements taken at each test mode AE#3.

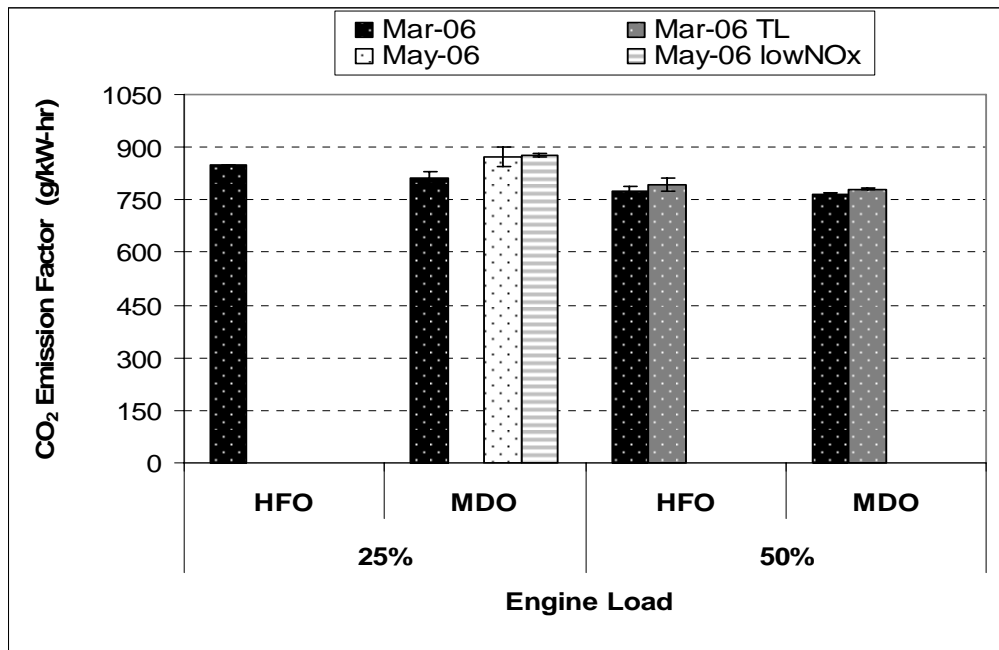
Table 3-4 Gaseous Emission Factors for AE#3

Target Load ISO	Actual Load		CO ₂ (g/kW-hr)		CO (g/kW-hr)		NO _x (g/kW-hr)		SO ₂ EPA Calculated (g/kW-hr)	
	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO
March 2006 with Transfer Line										
50%	47%	41%	794	781	0.88	0.66	18.80	15.63	8.60	0.40
March 2006, No Transfer Line										
25%	32%	30%	847	814	1.54	0.81	14.98	15.19	9.18	0.42
50%	45%	43%	776	766	0.78	0.61	16.62	14.38	8.41	0.39
May 2006, No Transfer Line										
25%	-	27%	-	872	-	0.77	-	16.99	-	0.31
May 2006, No Transfer Line, Low NO_x Mode										
25%	-	27%	-	877	-	0.89	-	11.52	-	0.31

Note: kW-hr denotes generated power

The CO₂ emission factor at a particular load (Figure 3-7) did not vary much across campaigns; this gives our confidence in our testing procedure.

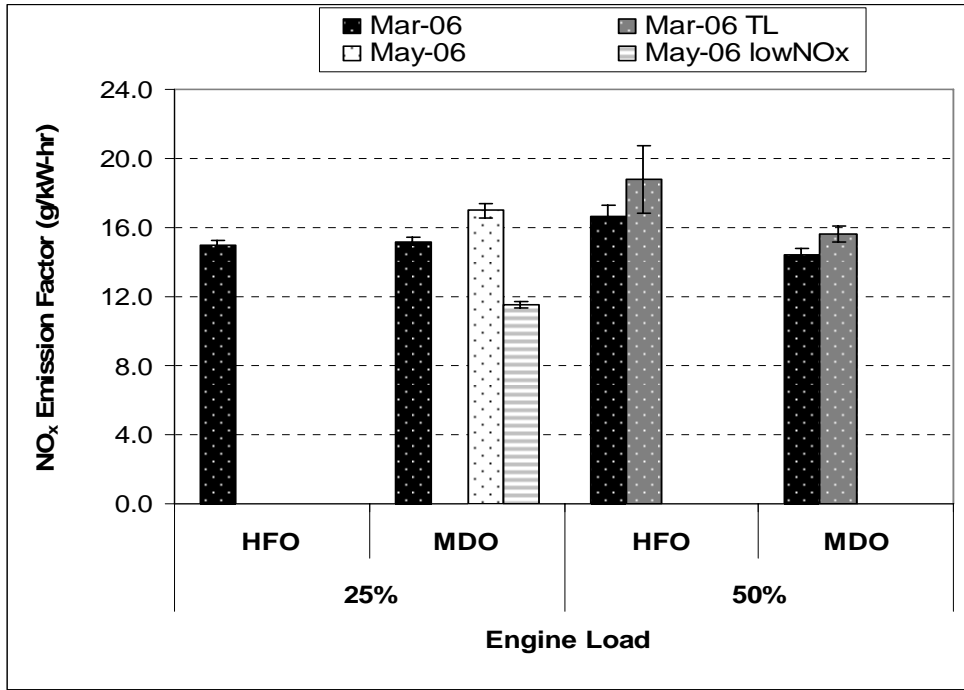
Figure 3-7 CO₂ Emission Factors for AE#3



Note: kW-hr denotes generated power, TL: Transfer Line

The NO_x emission factors (Figure 3-8) were also reasonably consistent across testing campaigns. Interesting to note that at the 25% load there is no emission benefit from fuel switching, while at the 50% load there is a NO_x reduction of ~15% by switching to MDO from HFO. There is a 32% reduction in NO_x by switching to low-NO_x mode.

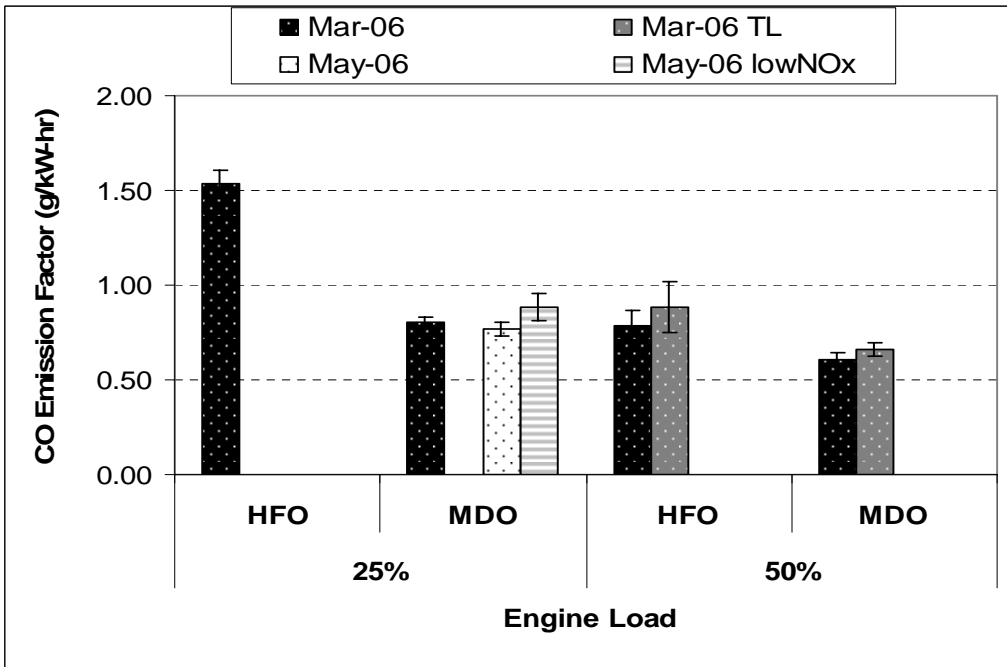
Figure 3-8 NO_x Emission Factors for AE#3



Note: kW-hr denotes generated power, TL: Transfer Line

As expected the CO emission factor (Figure 3-9) was low in the range of 0.50 to 2.00g/kW-hr, similar to that seen on AE#1 and AE#2.

Figure 3-9 CO Emission Factors for AE#3



Note: kW-hr denotes generated power, TL: Transfer Line

3.3. Particulate Matter Emissions

In addition to the gaseous emissions, this project measured the Particulate Matter (PM) mass emission rates. Particulate emissions mainly originate due to the incomplete combustion of fuel and lubricating oil and from the condensation of sulfuric acid and hydrocarbon aerosols. Secondary sources of PM include the trace elements in the fuel and lubricating oil; for example, vanadium in bunker fuel and calcium on the lube oil.

The PM_{2.5} mass was sampled from the main stream with a partial dilution method and collected on filter media. Subsequent analyses allowed us to report the PM mass as well as the mass fractions such as hydrated sulfate as H₂SO₄.6.5H₂O, Organic Carbon (OC) and Elemental Carbon (EC). Some real time PM measurements using the Dekati Mass Monitor (DMM) were also done.

The ISO protocol for PM measurement was followed for testing these engines; however since the sulfur content of the fuels was extremely high, not typical of fuels tested using ISO, some issues that were encountered.

- High loading of PM_{2.5} mass on the filters. This was overcome by reducing the sample flow rate through the filters
- PM losses in the 3m long transfer line (allowed by the ISO protocol) used to connect the sample probe to the dilution tunnel. This line was eliminated during later campaigns. This is discussed further in Section 3.3.1

3.3.1. Effect of Transfer Line on PM Emissions

During the initial test campaigns July 2005 to December 2005 a 3m long heated transfer line was used to connect the sampling probe to the dilution tunnel. The use of this transfer line is allowed by the ISO 8178-1 protocol. In the March 2005 campaign on AE#3 a set of tests were performed at the 50% engine load point with and without the transfer line to see if there were any significant losses of PM_{2.5} in the transfer line.

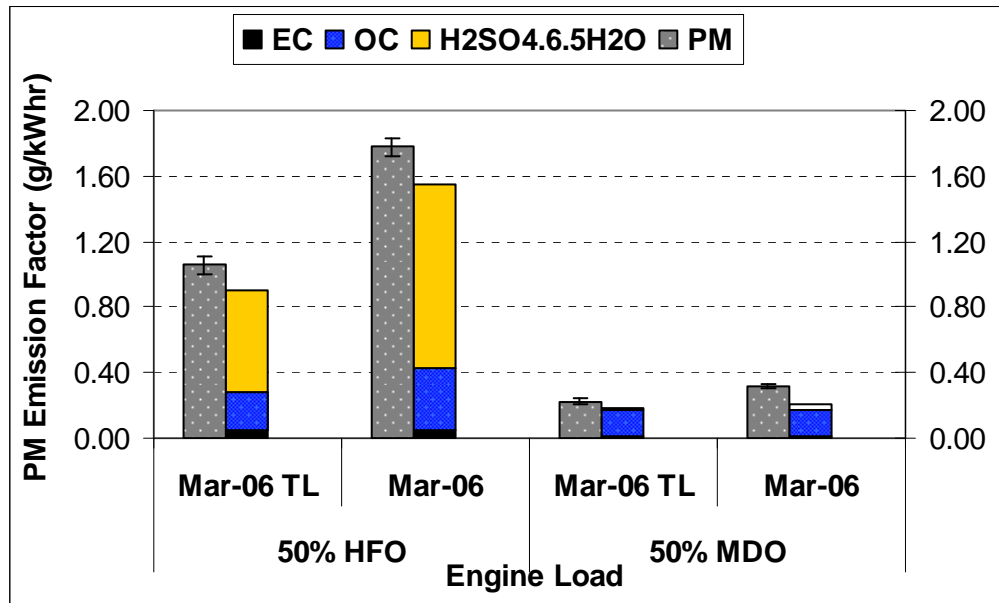
Table 3-5 shows the NO_x, CO and CO₂ emission factors that were measured with and without the transfer line. Each of these reading was taken in triplicate and the error bars are shown in the table. These emission factors as expected did not vary much with the use of the transfer line.

Table 3-5: Effect of Transfer Line on Gaseous Emissions from AE#3 at 50% Load

Fuel	Transfer Line	NO _x g/kW-hr	CO g/kW-hr	CO ₂ g/kW-hr
HFO	Yes	18.80 ± 1.98	0.78 ± 0.08	776 ± 12
	No	16.62 ± 0.65	0.88 ± 0.13	794 ± 20
MDO	Yes	15.63 ± 0.46	0.61 ± 0.03	781 ± 12
	No	14.38 ± 0.40	0.66 ± 0.04	766 ± 3

Note: kW-hr denotes generated power

Figure 3-10: Effect of Transfer Line on PM Emissions from AE#1



Note: TL: Transfer Line, kW-hr denotes generated power

A comparison of the speciated PM emissions factors with and without the use of a transfer line at the 50% engine load point for both fuels HFO and MDO is shown in Figure 3-10. The error bars give an indication of the confidence limits. There is a 40% reduction of PM mass in the case of HFO and a 30% reduction for MDO. In the case of HFO there is a 40% reduction in OC and a 44% reduction of hydrated sulfate with the use of the transfer line. For MDO we find a 70% reduction of hydrated sulfate while the change in the OC fraction was not significant. The EC fraction is also not affected significantly. Clearly a lot of the hydrated sulfate and some of the OC fraction of PM mass are lost in the transfer line probably due to deposition on the walls.

Hence for all of the campaigns before March 2006 the PM emission factors are biased low particularly for the high sulfur HFO fuel. Though the numbers would probably be good for a comparative study of the fuels of engines, the absolute values of the emissions are lower than the actual value. The results from these tests are presented in Appendix B.

3.3.2. Total PM Mass Emissions

As mentioned earlier AE#3 was not tested on all loads. The effect on the PM emission factors with the use of a transfer line was tested during the March 2006 test and the May 2006 test was conducted to test the effect of the low-NO_x mode.

A detailed list of the PM emission factors for AE#3 is presented in Table 3-6. There is extremely good agreement between the PM emission factors measured at 25% engine load point when the engine was operating on MDO in the two campaigns March 2006 and May 2006. Also we find that there is 82% reduction in PM emissions by switching from HFO to MDO at both the 25% and 50% engine loads. No significant change in the PM emission was observed by switching to the low-NO_x mode.

Table 3-6 PM Emission Factors for AE#3

Target Load ISO	Actual Load		PM (g/kW-hr)	
	HFO	MDO	HFO	MDO
March 2006				
25%	32%	30%	1.891±0.031	0.333±0.008
50%	45%	43%	1.774±0.053	0.32±0.01
May 2006				
25%	-	27%	-	0.333±0.001
May 2006 Low NO_x Mode				
25%	-	27%	-	0.34±0.02

Note: kW-hr denotes generated power

3.3.3. Speciated PM Mass Emissions

There is very little in-use data of speciated PM from marine diesel engines available in literature. The chief constituents of PM from marine diesel engines are hydrated sulfate, organic carbon and elemental carbon with the hydrated sulfate fraction being the dominant one for HFO. This section compares the emission factors of each of these species from all three engines operating on HFO and MDO fuels.

As mentioned earlier AE#3 was tested at a limited number of loads during the March 2006 and May 2006 campaigns. A detailed list of the EC, OC and hydrated sulfate emission factors are presented in Table 3-7.

Table 3-7 Speciated PM Emission Factors for AE#3

Target Load ISO	Actual Load		EC (g/kW-hr)		OC (g/kW-hr)		H ₂ SO ₄ ·6.5H ₂ O (g/kW-hr)	
	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO
March 2006								
25%	32%	30%	0.041	0.033	0.490	0.167	0.928	0.025
50%	45%	43%	0.023	0.021	0.375	0.162	1.117	0.033
May 2006								
25%	-	27%	-	0.036	-	0.144	-	0.039
May 2006 Low NO_x Mode								
25%	-	27%	-	0.072	-	0.125	-	0.037

Note: kW-hr denotes generated power

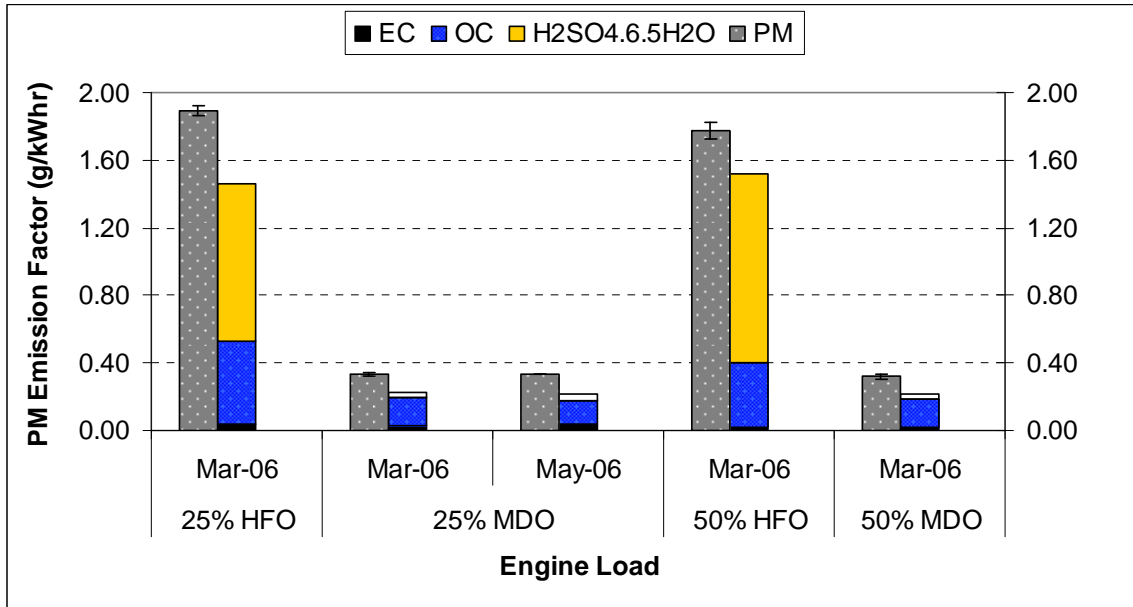
For HFO, hydrated sulfate is the most dominate species accounting for ~56% of the PM mass followed by OC ~24% and EC ~2%. In the case of MDO, OC is accounts for ~50% of the PM_{2.5} mass, while EC and hydrated sulfate are ~9% and ~8% of total mass respectively.

Fuel switching resulted in ~97% of hydrate sulfate, ~61% of organic carbon. Operating the engine on the low-NO_x mode almost doubled the elemental carbon fraction of PM_{2.5}.

3.3.4. Internal Quality Check for Conservation of Mass Emissions

An important element in the analysis of the PM_{2.5} mass emissions is to compare the total mass collected on the Teflon filter with the sum of the masses independently measured as hydrated sulfate (H₂SO₄.6.5H₂O), organic and elemental carbon. Figure 3-11 shows the mass closure at different test modes for AE#3. The sum of the speciated PM_{2.5} is a little less than the total PM_{2.5} mass because the OC has to be multiplied by a factor of about 1.2 to 1.4 to get the organic mass. Also ash content of the PM has not been account for.

Figure 3-11 PM_{2.5} Mass Closure for AE#3



Note: kW-hr denotes generated power

3.3.5. Real Time PM Emissions

Real time PM emissions were measured using the DMM on AE#2 and AE#3. The data obtained on AE#2 seems suspect as it was extremely variable in spite of the load on the engine and gaseous emissions being stable. Hence, this is presented in Section 10.3.

For AE#3 the real time PM was measured at the ISO target load of 25% for the engine operating in the normal and low-NO_x modes during the May 2006 test (Figure 3-12). Results show that there was no significant change in the real time PM mass by switching to low-NO_x mode.

A comparison of the PM mass collected on the Teflo[®] versus the average real time PM mass measured by the DMM are shown in Figure 3-13. The DMM measured a much lower PM mass compared to the filter.

Figure 3-12 Real Time PM Emissions for AE#3

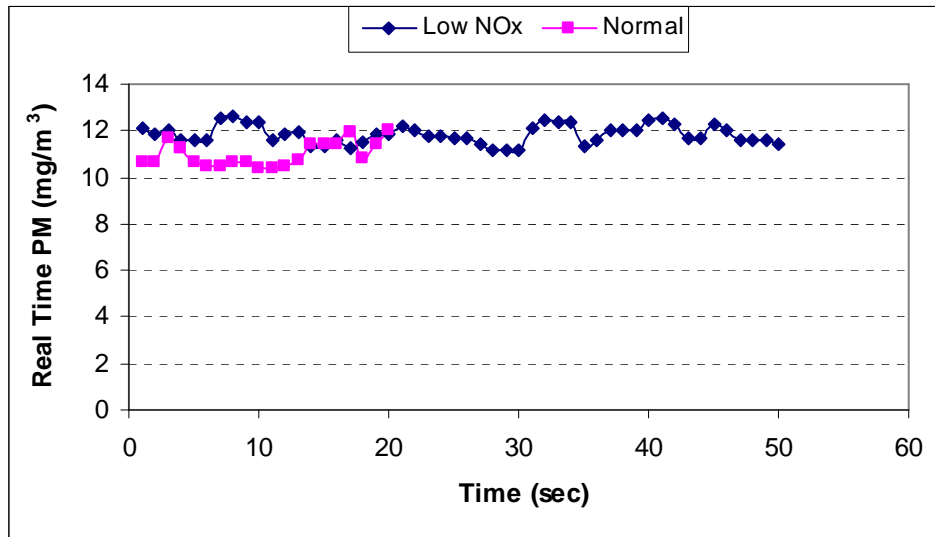
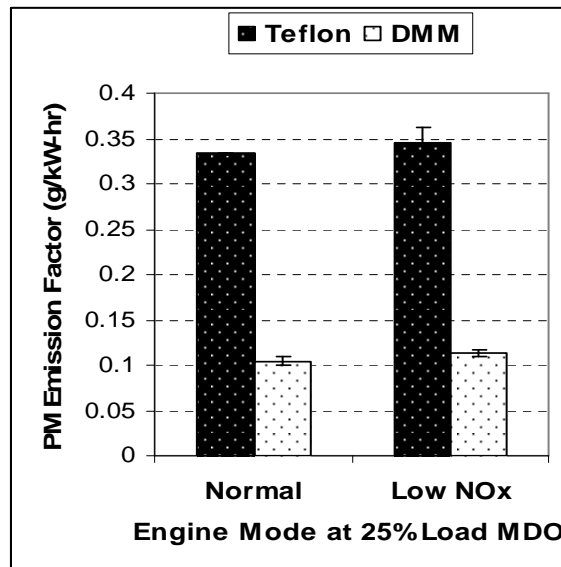


Figure 3-13 Comparison of Teflon Filter Vs DMM



Note: kW-hr denotes generated power

4. Discussion

4.1. Fuels Effects on Gaseous and PM Emissions

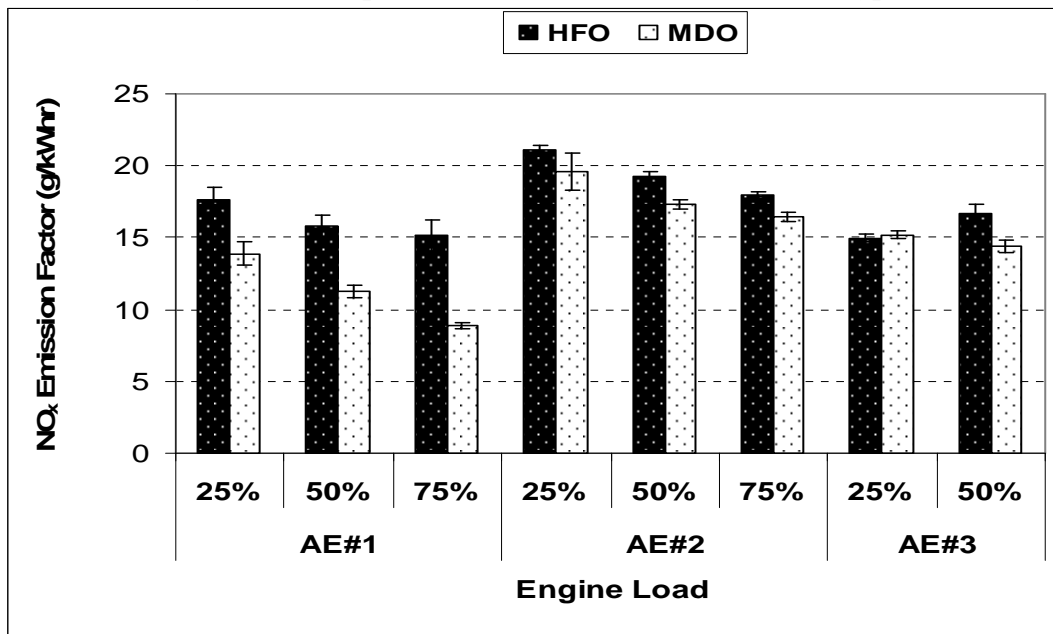
One of the goals of this research was to determine emission reductions due to switching from the high sulfur HFO fuel to lower sulfur MDO fuel. A discussion about the fuel effects on gaseous and PM_{2.5} emissions is presented in this section.

Gaseous Emissions

The results of the gaseous emissions factors shown in Sections 3.2 indicate no significant reduction in CO and CO₂ emissions from fuel switching. However, NO_x and SO₂ are reduced considerably.

Figures 4-1 provides summary comparison of the NO_x emission factors between HFO and MDO from all three auxiliary engines at various engine load points. Note here that the emission factors presented for AE#1 are an average across the October 2005 and December 2005 campaigns.

Figure 4-1 Comparison of NO_x Emissions across Fuel Types



Note: kW-hr denotes generated power

AE#1 shows a NO_x reduction of 21% to 42% with an average reduction of about 30%. AE#2 shows a NO_x reduction of about 7% to 10% across the loads. AE#3 does not show any reduction at the 25% load but a reduction of about 13% at the 50% load. Based on the nitrogen content of the fuels we would expect HFO to generate about 1g/kW-hr NO_x more than MDO which is consistent with the results seen on AE#2 and AE#3.

AE#1 seems to be behaving quite differently with MDO, showing a much greater NO_x reduction. The engine manufacturer suggested that this increased NO_x reduction could be

indicative of engine wear leading to lower cylinder compression ratio which becomes more evident while the engine is operating on the light MDO. This is corroborated by the slightly higher CO emissions (Section 3.2) and higher OC emissions seen on AE#1 (Appendix B).

Total and Speciated PM_{2.5} Mass Emissions

A comparison of the PM Mass, Elemental Carbon, Organic Carbon and hydrated Sulfate emission factors between HFO and MDO AE#3 is presented in Table 4-1.

Table 4-1 Fuel Effects on Total and Speciated PM_{2.5} Mass Emissions for AE#3

Target Load ISO	PM Mass (g/kW-hr)		EC (g/kW-hr)		OC (g/kW-hr)		H ₂ SO ₄ .6.5H ₂ O (g/kW-hr)	
	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO
25%	1.89	0.33	0.041	0.033	0.490	0.167	0.928	0.025
50%	1.77	0.32	0.023	0.021	0.375	0.162	1.117	0.033

Note: kW-hr denotes generated power

Switching from HFO to MDO, results in an average PM_{2.5} reduction of 82% which can be attributed to the ~97% reduction in hydrated sulfate fraction and ~61% reduction in OC. As mentioned earlier in Section 3.3.3 there is a shift in the proportions of the constituents of PM_{2.5} with a change in the fuel. PM_{2.5} for HFO has ~56% hydrated sulfate, ~24% OC and ~2% EC, while PM_{2.5} from MDO has ~9% hydrated sulfate, ~50% OC and ~8% EC.

4.2. Effect of Low-NO_x Mode on Gaseous and PM Emissions

Two auxiliary engines AE#1 and AE#3 were tested in the low-NO_x mode. AE#1 was tested in the low-NO_x mode in July 2005, baseline emissions were determined in two subsequent campaigns October and December 2005. AE#3 was tested in the normal and low-NO_x mode on MDO during the May 2005 campaign.

A summary of the gaseous and PM_{2.5} emissions are presented in Table 4-2 and Figure 4-2.

Gaseous Emissions

As expected operating the engine in the low-NO_x mode reduced the NO_x emission factor by ~31%. We also saw slight reduction in CO₂ emissions factors for AE#1 and increase in CO emission factors for both AE#1 and AE#3 when the engine operated in the low-NO_x mode.

Table 4-2: Effect of Low-NO_x Mode on Gaseous Emissions

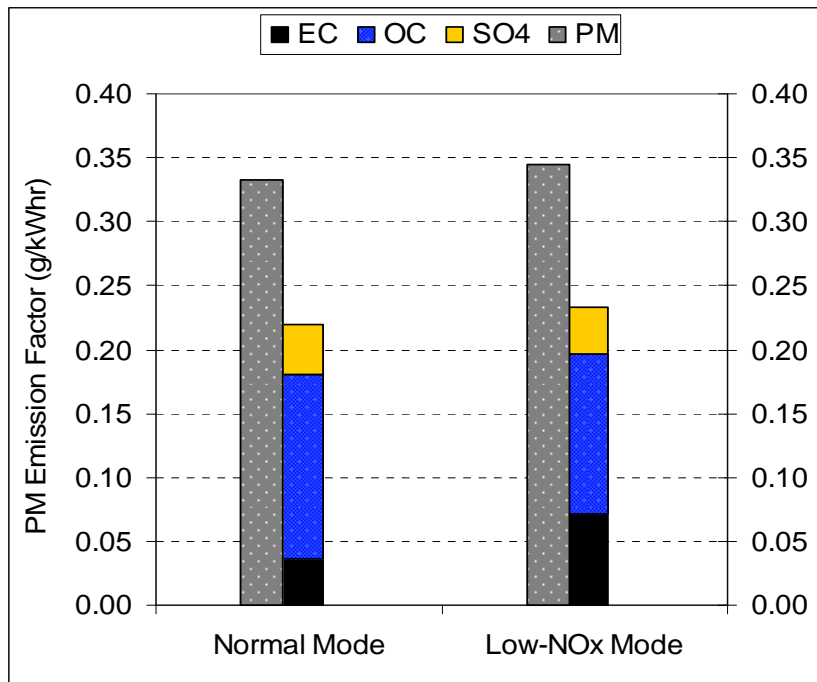
Engine/ Fuel	Target Load ISO	CO ₂ (g/kW-hr)		CO (g/kW-hr)		NO _x (g/kW-hr)	
		Baseline	low-NO _x	Baseline	Low- NO _x	Baseline	low-NO _x
AE#1 HFO	25%	848*	-	1.73*	-	17.6*	-
	40%	-	655	-	1.98	-	11.16
	50%	694*	632	0.98*	1.33	15.8*	11.16
	75%	667*	618	0.74*	0.67	15.1*	9.66
AE#1 MDO	25%	883*	733	1.97*	2.98	13.9*	8.78
	50%	673*	649	1.01*	1.60	11.2*	8.31
AE#3	25%	872	877	0.77	0.89	17.0	11.52

*Average of October and December 2005 Campaigns, Note: kW-hr denotes generated power

PM Emission Factors

Emissions of elemental carbon species of PM_{2.5} almost doubled from 0.036 to 0.072 when the engine was operated on the low-NO_x mode. There is however no significant change in the overall PM_{2.5} mass emissions because EC is such a small fraction of the total PM_{2.5} mass.

Figure 4-2: Effect of low-NO_x Mode on PM Emissions for AE#3



Note: kW-hr denotes generated power

5. Summary and Recommendations

Working with the California Air Resources Board and a major shipping company, the University of California, Riverside (UCR) measured the in-use emissions of criteria pollutants and some greenhouse gases from a number of auxiliary engines aboard post Panamax Class container ships while operating at the load points specified in the ISO 8178 D2 certification cycle. The engines were 4-stroke; MAN 7L32/40 diesel engines rated at 3500kW and were typical of the size used on modern container ships. Three different auxiliary engines of the same engine model were tested on two different vessels during a total of six campaigns.

Detailed emissions factors for CO₂, CO, NO_x, total PM_{2.5} mass and speciated PM_{2.5} mass (EC, OC and hydrated sulfate) at various engine load points for two different fuels HFO and MDO are presented in the report. A comparison of the auxiliary engines that were tested and the effect of fuel switching on emissions from these engines are also provided. A discussion of the effect of using a transfer line allowed by the ISO protocol on PM emissions is also presented. The report also presents a comparison of the emissions factors of the engine running in the low-NO_x mode versus the normal operating mode.

Overall the measurements campaigns represented the first extensive series of tests aimed at learning the repeatability and reproducibility of emissions factors for the same engine family. Further, the study showed:

- The range of emission factors for these three auxiliary engines and generators varied more than seen in previous studies of backup generators.
- Changing from HFO to MDO reduced the NO_x emissions by about 5 to 10% and this reduction can be explained by the reduction in the fuel-NO_x in the HFO. Reductions larger than 10% were explained by maintenance problems and the resultant reduced cylinder pressure in the engine.
- PM_{2.5} for HFO has ~56% hydrated sulfate, ~24% OC and ~2% EC, while PM_{2.5} from MDO has ~9% hydrated sulfate, ~50% OC and ~8% EC.
- Operating in the low-NO_x mode reduced NO_x emissions by ~31% for MDO fuel. Though the elemental carbon of PM_{2.5} almost doubled there was no significant change in total PM_{2.5} emissions by switching to low-NO_x mode.
- The mass of PM measured is significantly reduced when a transfer line is used, even if the length is within that allowed by the ISO standards.

Recommendations for further study:

- The use of the heated transfer line allowed by the ISO protocol results in loss of PM thereby leading to an underestimation of the PM emission factor. A detailed study is required to characterize this loss.

- Actual fuel measurement would allow the actual fuel flow rate in subsequent tests as it will help in another internal quality control check by comparing the estimated fuel flow rate from the CO₂ numbers to the actual fuel flow rate.
- Actual SO₂ emissions should be measured and a mass balance between the fuel sulfur content and the sulfate in the PM mass and the SO₂ emissions could be done.
- The high OC to EC ratio in the PM mass indicates that there could be a high concentration of volatile hydrocarbons. Sampling these during subsequent tests would be good idea.

6. References

Cooper D.A. (2003). Exhaust Emissions from Ships at Berth. *Atmospheric Environment*, 37:3817-3830.

Eyring V, Köhler H.W, van Aardenne J, and Lauer A. (2005a). Emissions from International Shipping: 1. The Last 50 Years. *Journal of Geophysical Research*, Vol. 110, D17305, doi: 10.1029/2004JD005619

Eyring V, Kohler H.W, Lauer A, and Lemper B.(2005b). Emissions from International Shipping: 2. Impact of Future Technologies on Scenarios until 2050. *Journal of Geophysical Research*, Vol 110, D17306, doi:10.1029/2004JD005620.

International Maritime Organization. (1998). Regulations for the Prevention of Air Pollution from Ships and NO_x Technical Code. ANNEX VI of MARPOL 73/78, London.

ISO 8178, 'Reciprocating Internal Combustion Engines – Exhaust Emission Measurement', Parts 1 to 9.

MAN B&W Diesel A/S, R&D Basic Research & Emission Dept. (2004). Emission Measurement Results A.P.Moeller – Sine Maersk.

MAN B&W Diesel. Emission Control Two-Stroke Low-Speed Diesel Engines. http://www.mandiesel.com/files/news/files_of1417/19993701.pdf access date 01/03/2008.

7. Glossary of Symbols and Abbreviations

Al	Aluminum
°C	degree centigrade
C	Carbon
C of A	Certificate of Analysis
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
HFO	Heavy Fuel Oil
Hz	Hertz
HCLD	heated chemiluminescence detector
HEPA	High Efficiency Particulate Air
H ₂ O	Water
H ₂ SO ₄ .6.5H ₂ O	hydrated sulfate or hydrated sulfuric acid
IMO	International Maritime Organization
ISO	International Organization for Standardization
ITR	Injection Timing Retard
kg/m ³	kilograms per cubic-meter
kW	kilowatt
lit	liters
lit/hr	liters per hour
m	meter
MDO	Marine Distillate 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) ₂ CO	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 %

8. Appendix A

8.1. Certification Emission Test Protocol for Marine Auxiliary Engines

In general, the operating conditions during a certification test for internal combustion engines follows a prescribed sequence that is specified in the ISO 8178-Part 4, *Test cycles for different engine applications*. The ISO 8178 D-2 test cycle is used for engines operating at constant speed with intermittent load, such as backup generators or auxiliary engines. The standard test protocol consists of a series of preconditioning cycles to warm and stabilize the engine at full load followed by a sequence of stabilization and testing at the five specified modes, each with a defined speed, load and minimum test duration as shown in Table 8-1. The weighting factors used in the determination of the emission factor are listed as well.

Table 8-1 Five Mode Test Cycle for Constant Speed Engines (ISO-8178-D-2 test cycle)

Mode number	Engine Speed ¹	Observed Torque ²	Minimum time in mode, min.	Weighting factors
1	Rated	100	5.0	0.05
2	Rated	75	5.0	0.25
3	Rated	50	5.0	0.30
4	Rated	25	5.0	0.30
5	Rated	10	5.0	0.10

¹Engine Speed: $\pm 2\%$ of point; ²Torque: Throttle fully open at 100% point. Other points $\pm 2\%$

While the engine is operating at these load points, the gases and particulate matter in the exhaust are sampled and analyzed according to the ISO described procedures. Additionally, the environmental conditions, such as charge air pressure and temperature and the engine operating parameters were recorded at each test mode as these parameters are used to determine the mass flow rate of the exhaust. The test procedure was designed to determine the brake-specific emissions of regulated emissions: carbon monoxide, oxides of nitrogen, and particulate matter.

8.2. Portable Laboratory for Sampling and Measuring Gaseous and Particulate Matter Emissions from Auxiliary Engines

One of the problems of measuring diesel emissions in the field is the lack of suitable methods and standardized equipment. Furthermore, measuring emissions in the field rather than in a laboratory often presented specialized challenges that need to be solved at the site and time of testing. Added challenges were the laboratory grade equipment needed to be safely moved to the field site where a laboratory was built from scratch for each campaign and the testing carried out on a schedule that met the needs of the equipment owner. UCR opted to use the ISO 8178-1 as their guidance for the sampling

and analysis protocols and designed suitable test equipment. In the final UCR design, the laboratory grade equipment, meeting ISO and Annex VI, and computers fit into several metal cases with an interior of foam molding to allow the sensitive equipment to be easily transported or even be lifted and dropped into cargo areas on a vessel without harm to the contents. For practical purposes, the design included equipment that accommodated a range of electrical (120/240V, 50/60Hz) and fittings on the compressed air supply.

UCR needed to measure both gases and particulate matter in the field. The measurement of particulates required a dilution system with a high enough dilution air flow to eliminate water condensation in the sampling system while maintaining a temperature of at or below 52°C at the filter face. Many methods for sampling and analysis of gases and particulate matter (PM) from diesel engines are outlined in ISO 8178-1¹. UCR selected a partial flow dilution system with single venturi as shown in Figure 6-1. The partial flow dilution system split the exhaust stream into two fractions, the smaller one being diluted with air and subsequently used for particulate measurement.

Raw exhaust gas was transferred from the exhaust pipe (EP) to the dilution tunnel (DT) through the sampling probe (SP) and the transfer tube (TT) due to the negative pressure created by the venturi (VN) in DT. ISO provides guidance on the exhaust and transfer lines, the dilution tunnel and the sampling probe. For example, bends/elbows/sudden changes in diameter for the exhaust pipe are minimized to reduce inertial deposition. For systems without iso-kinetic probes – like UCR’s approach -- , the exhaust pipe should be straight 6 pipe diameters upstream and 3 pipe diameters downstream of the tip of the probe.

ISO provides the following guidance on the transfer tube:

- as short as possible, but not more than 5 meters long;
- equal to or greater than the probe diameter, but not more than 25 mm in diameter;
- exiting on the center line of the tunnel and pointing downstream;
- insulated and heated to a minimum wall temperature of 523 K (250°C).

ISO 8178-1 Section **7.5.3** provides additional specifications for particulate measurement and states all parts of the dilution system and the sampling system from the exhaust pipe up to the filter holder, which are in contact with raw and diluted exhaust gas, shall be designed to minimize deposition or alteration of the particulates. All parts shall be made of electrically conductive materials that do not react with exhaust gas components, and shall be electrically grounded to prevent electrostatic effects.

In operation, the gas flow rate through TT depends on the momentum exchange at the venturi zone and is therefore affected by the gas temperature 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. The tracer gas concentrations (CO₂ or NO_x) are measured in the raw exhaust gas, the diluted exhaust gas and the

¹ *International Standards Organization, ISO 8178-1, Reciprocating internal combustion engines - Exhaust emission measurement -Part 1: Test-bed measurement of gaseous particulate exhaust emissions, First edition 1996-08-15*

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

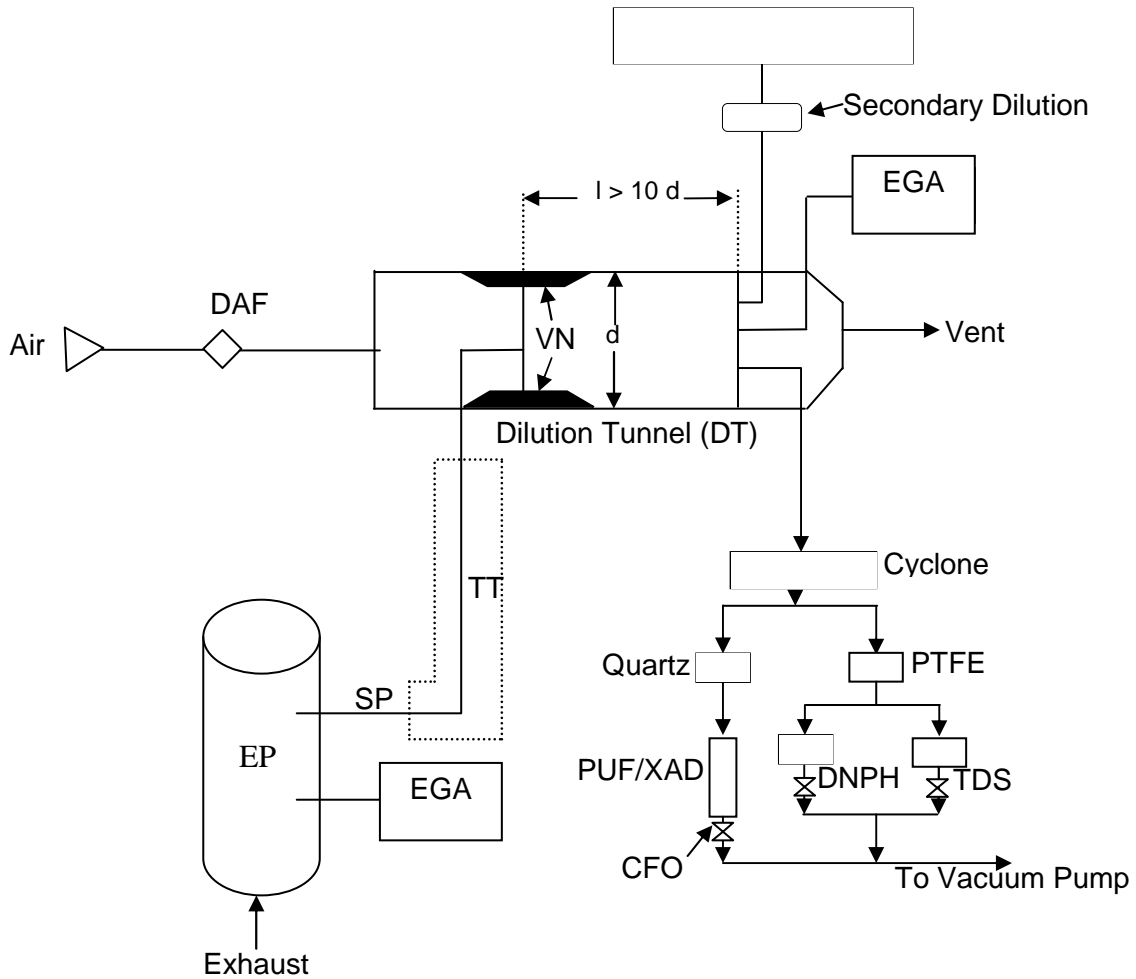


Figure 6-1 Partial Flow Dilution System with Single Venturi, Concentration Measurement and Fractional Sampling

ISO 8178-1 Section 9.3 *Checking the dilution ratio* offers guidance for determining the dilution ratio with the use of either the CO_2 , or NO_x concentration measurements in the raw and dilute exhaust. The measured dilution ratio shall be within $\pm 10\%$ of the dilution ratio calculated from CO_2 , or NO_x concentration measurements. ISO points out it is essential that the dilution ratio be determined very accurately, UCR measures and compares the dilution ratio based on both NO_x and CO_2 and most often finds them to agree within the 10% limit.

ISO provides some guidance on the design of the dilution tunnel design and dilution air. For example, the engine exhaust shall be directed downstream at the point where it is introduced into the dilution tunnel and thoroughly mixed. The dilution tunnel shall be small enough in diameter to cause turbulent flow (Reynolds Number greater than 4,000) and of sufficient length to cause complete mixing of the exhaust and dilution air.

Guidance for the dilution air included filtering to remove PM and charcoal scrubbing to eliminate background hydrocarbons. The UCR system accepts compressed air and reduces it to about 30psig after which it is processed through: 1) a liquid knock-out section, 2) a desiccant to remove moisture with silica gel containing an indicator, 3) a hydrocarbon removal section with activated charcoal and 4) a HEPA filter to remove any fine aerosols present in the supply air. The silica gel and activated carbon were changed for each field campaign. Figure 6-2 below shows the unit for processing the dilution air.



Figure 6-2 Field Processing Unit for Purifying Dilution Air in Carrying Case

8.2.1. Measuring Gaseous Emissions

The concentrations of gases in the raw exhaust and the dilution tunnel were measured with a Horiba PG-250 portable multi-gas analyzer. The PG-250 can simultaneously measure up to five separate gas components using the measurement methods recommended by the EPA, ISO and MARPOL Annex VI. The signal output of the instrument was interfaced directly with a laptop computer through an RS-232C interface to record measured values continuously. 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 6-3 In-Field Illustration of Continuous Gas Analyzer and Computer for Data Logging

Details of the gases and the ranges for the Horiba instrument are shown in Table 8-2. While the Horiba instrument measured sulfur oxides (SO₂); the values in this report are calculated from the sulfur content of the fuel. ISO 8178-1 Section 7.4.3.7 on Sulfur dioxide (SO₂) Analysis states that: “The SO₂, concentration shall be calculated from the sulfur content of the fuel used, since experience has shown that using the direct measurement method for SO₂, does not give more precise results.”

Table 8-2 Detector Method and Concentration Ranges for Monitor

Component	Detector	Ranges
Nitrogen Oxides (NO _x)	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 carried out analyzer checks with calibration gases both before and after each test to check for drift. Because the instrument measures the concentration of five gases, the calibration gases are a blend of several gases (super-blend) made to within 1% specifications by Praxair (Los Angeles, CA). Drift was determined to be within manufacturer specifications of $\pm 1\%$ full scale per day, except for SO₂ set at $\pm 2\%$ F.S./day. Other specifications of the instruments are provided in Table 8-3.

Table 8-3 Quality Specifications for the Horiba PG-250

Repeatability	$\pm 0.5\%$ F.S. (NO _x : ≤ 100 ppm range CO: ≤ 1000 ppm range) $\pm 1.0\%$ F.S.
Linearity	$\pm 2.0\%$ F.S.
Drift	$\pm 1.0\%$ F.S./day (SO ₂ : $\pm 2.0\%$ F.S./day)

8.2.2. Measuring the Particulate Matter (PM) Emissions

A raw particulate sampling probe was fitted close to and upstream of the raw gaseous sample probe in the exhaust. In order to measure PM, a sampling probe was inserted into the end of the dilution tunnel (>10 diameters downstream) and directed to a PM sample splitter that allowed up to three samples to be collected.

For this test, we used one of the PM lines and directed it to a cyclone separator, sized to remove particles $>2.5\mu\text{m}$. From the separator, we added two lines with 47 Gelman filter holders, one for collecting PM on a Teflo[®] filter and the other for collecting PM on a quartz filter. Thus the flow in the dilution tunnel was split into two fractions, a smaller flow for measuring PM mass and PM properties and a much larger flow that was vented outside the vessel. Note, with the partial dilution approach for measuring gases and PM, it is critical for the dilution ratio be determined very accurately.

UCR collected simultaneous Teflo[®] and quartz filters at each operating mode and analyzed them according to standard procedures. The simultaneous collection of quartz and Teflo[®] filters allows an internal quality check of the PM mass. Teflo[®] filters used to acquire

PM mass were weighted following the procedure of the Code of Federal Regulations (CFR) (40 CFR Part 86). Briefly, total PM were collected on Pall Gelman (Ann Arbor, MI) 47 mm Teflo[®] filters and weighed using a Cahn (Madison, WI) C-35 microbalance. Before and after collection, the filters were conditioned for 24 hours in an environmentally controlled room (RH = 40%, $T = 25^\circ\text{C}$) and weighed daily until two consecutive weight measurements were within $3\mu\text{g}$.

The PM mass on the Teflo[®] filter was then extracted in double distilled water and analyzed in a Dionex ICS 1000 using ion chromatography to determine the mass of sulfate on the filter.

PM samples were collected in parallel on a 2500 QAT-UP Tissuquartz Pall (Ann Arbor, MI) 47 mm filters that were preconditioned at 600°C for 5 h. A 1.5 cm² 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.

8.2.3. Measuring Size Segregated PM Emissions

In order to measure the size segregated PM emissions (aerodynamic diameter) the sample probe is inserted into the dilution tunnel (>10 diameters downstream of) and directed to the Micro Orifice Uniform Deposition Impactor (MOUDI). The MOUDI is a precision high performance cascade impactor that provides a high sampling flow rate, low inter-stage wall loss and sharp cut-point characteristics. The 10 stage non-rotating MOUDI Model 110 provides cut point diameters of 18, 10, 5.6, 3.2, 1.8, 1.0, 0.56, 0.32, 0.18, 0.1, and 0.056 μm.



Figure 8-4 Micro Orifice Uniform Deposit Impactor

47mm Al filter substrates are used for collecting the sample. These are weighed before and after collection using a Cahn (Madison, WI) C-35 microbalance. Before each weighing, the filters were conditioned for at least 24 hours in an environmentally controlled room (RH = 40%, $T = 25^{\circ}\text{C}$). Also they were weighed daily until two consecutive weight measurements were within 3 μg.

8.2.4. Measuring Real-Time Particulate Matter Emissions

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. For this project, UCR decided to take data with a Dekati Mass Monitor (DMM-230). 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. Also, mass measurement provides information that is comparable with existing data and with emission regulations.



Figure 8-5 Picture of the DMM-230

The sample for the DMM was taken from the dilution tunnel. However, further dilution was needed to operate the DMM as the dilution ratio needed to be ten-fold greater than in the 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 $>1 \mu\text{g}/\text{m}^3$ allowing studies with diesel after-treatment controls.

8.3. 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 when the standard is run. Additionally the data for the standards are plotted to ensure that the values fall within the upper and lower control limits for the method and that there is no obvious trends or bias in the results for the reference materials. As an additional quality check, results from independent methods are compared and values from this work are compared with previously published values, like the manufacturer data base.

- For the ISO cycles, run the engine at rated speed and the highest power possible to warm the engine and stabilize emissions for about 30 minutes.
- Determine a plot or map of the peak power at each engine RPM, starting with rated speed. UCR suspected the 100% load point at rated speed was unattainable with propeller torque so Mode 1 would represent the highest attainable RPM/load.
- Emissions were measured while the engine operates according to the requirements of ISO-8178-D2. For the auxiliary engine the highest power mode was run first and then each mode was run in sequence. The minimum time for auxiliary engine samples was 5 minutes and if necessary, the time was extended to collect sufficient particulate sample mass or to achieve stabilization with large engines.
- The gaseous exhaust emission concentration values were measured and recorded for the last 3 min of the mode.
- Engine speed, displacement, boost pressure, and intake manifold temperature were measured in order to calculate the gaseous flow rate.
- Emissions factors are calculated in terms of grams per kilowatt hour for each of the operating modes and fuels tested, allowing for emissions comparisons of each blend relative to the baseline fuel.

9. Appendix B

9.1.1. PM Emissions from AE#1

AE#1 was tested during three campaigns – July 2005, October 2005 and December 2005. This engine was equipped with an SCR and the sampling port selected upstream of the SCR for measuring these baseline emissions was unfortunately downstream of the point of urea injection. Hence the PM in the July 2005 and October 2005 were contaminated with urea. Refer to Sections 10.1 and 10.2 for details. During the December 2005 test the urea injection was turned off while testing thereby eliminating the possibility of any contamination.

The total PM_{2.5} mass emission factors across different engine loads and fuels measured in December 2005 are presented in Table 9-1. These samples were measured in triplicate, the standard deviation of which gives an idea of the confidence limits.

Table 9-1 PM Emissions Factors for AE#1, December 2005

Target Load ISO	Actual Load		PM Emission g/kW-hr	
	HFO	MDO	HFO	MDO
25%	30%	22%	0.675±0.007	0.702±0.036
50%	52%	52%	0.479±0.027	0.297±0.012
75%	67%	69%	0.293±0.009	0.192±0.013

Note: kW-hr denotes generated power, Transfer Line used.

Note here that all of the tests were done with the use of a 3m long heated stainless steel transfer line used to connect the probe to the dilution tunnel. Though the use of the transfer line is allowed by the ISO protocol it was found in subsequent tests that there was significant loss of PM in the transfer line especially for the high sulfur HFO fuel (Section 3.3.1). As a result, the emission factors presented in this section are biased low; however the trends in emission numbers are probably not affected.

Note here that there is a PM_{2.5} mass reduction of 34% to 48% by switching from HFO to MDO at higher engine loads (50% and 75%). The 25% load point there is a reverse trend probably because of the large difference in the actual engine load which was 30% for HFO and 22% for MDO.

9.1.2. PM Emissions from AE#2

AE#2 aboard the post-Panamax container vessel B was tested in December 2005 to determine the emissions while operating on both fuels HFO and MDO. The PM emission factors determined for this test are presented in Table 9-2. These measurements were taken in quadruples; the standard deviations are presented as the confidence limits. Note here that this test was performed with the use of a transfer line; hence the PM emission factors are biased low (Section 3.3.1).

Table 9-2 PM Emission Factors for AE#2

Target Load ISO	Actual Load		PM Emission g/kW-hr	
	HFO	MDO	HFO	MDO
25%	27%	26%	0.623±0.027	0.338±0.048
50%	46%	47%	0.519±0.041	0.167±0.003
75%	73%	68%	0.374±0.039	0.132±0.008

Note: kW-hr denotes generated power, Transfer Line used

As in the case of AE#1 we find a significant PM Emission benefit from fuel switching. A PM reduction of 46% to 68% is observed by switching from HFO to MDO. This reduction can chiefly be attributed to the sulfur content of the fuel.

9.1.3. Speciated PM from AE#1

Though AE#1 was tested for PM Emissions during all three campaigns July 2005, October 2005 and December 2005, we had issues with the PM data collected from the first two (Sections 10.1 and 10.2), hence only the December 2005 data is presented below. A detailed list of the EC, OC and hydrated Sulfate emission factors are presented in Table 9-3. The error bars in Figure 9-1 give an idea of the confidence limits for the test. Note here that a transfer line was used while testing hence the PM emission factors measured are lower than the actual values due to losses in the transfer line (Section 3.3.1).

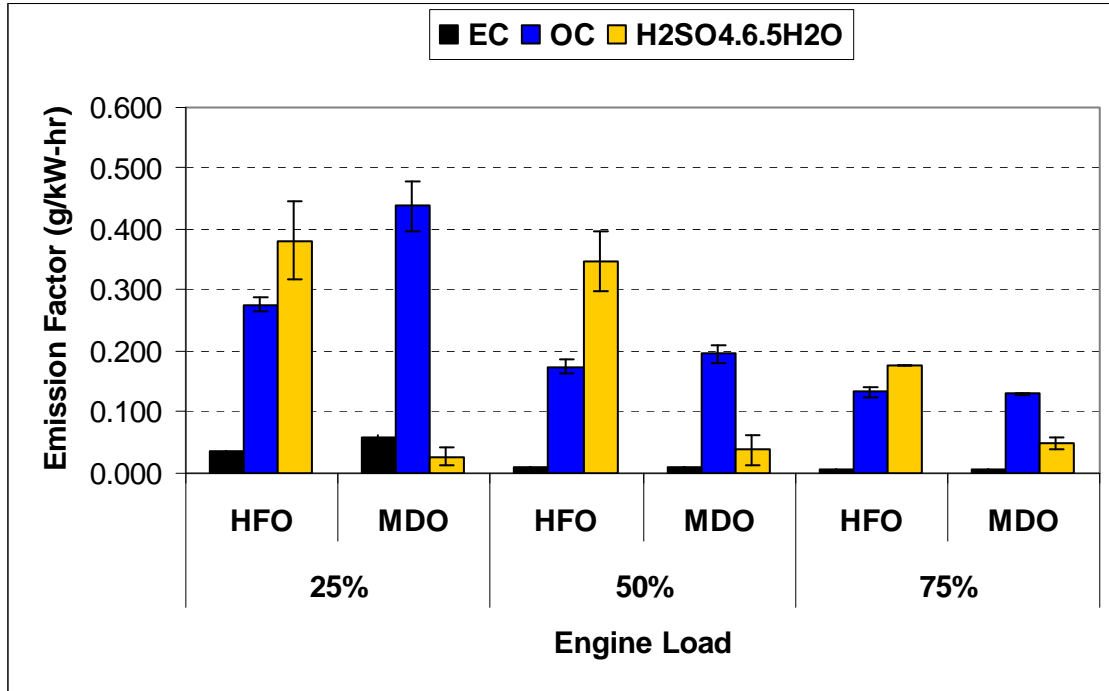
Table 9-3 Speciated PM Emission Factors for AE#1, December 2005

Target Load ISO	Actual Load		EC (g/kW-hr)		OC (g/kW-hr)		H ₂ SO ₄ .6.5H ₂ O (g/kW-hr)	
	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO
25%	30%	22%	0.035	0.060	0.276	0.438	0.382	0.027
50%	52%	52%	0.009	0.010	0.175	0.198	0.347	0.039
75%	67%	69%	0.006	0.006	0.134	0.132	0.178	0.049

Note: kW-hr denotes generated power, Transfer Line Used

In the case of HFO, clearly hydrated Sulfate is the most significant fraction of the PM, accounting for 57% to 73% of the PM mass. Organic carbon is the next most abundant species of the PM. The OC to EC ratio for this Engine operating on HFO was found to range from 8 to 22 increasing with the increase in engine load.

Figure 9-1 EC, OC, Hydrated Sulfate Emission Factors for AE#1



Note: kW-hr denotes generated power, Transfer Line Used

Since MDO is a lower Sulfur fuel than HFO, hydrated Sulfate fraction accounts for a lower percentage of the PM mass around 4% to 26%. The most dominant fraction of the PM emission for MDO is Organic Carbon which accounts for about 62% to 68% of the PM mass. The OC to EC ratio for AE#1 operating on MDO ranged from 7 to 22, the ratio increasing with an increase in the engine load as observed in the case of the HFO fuel.

9.1.4. Speciated PM from AE#2

AE#2 aboard Ship B was tested on both fuels HFO and MDO across three engine load points 25%, 50% and 75% during the December 2005 campaign. The EC, OC and hydrated sulfate emission factors determined by this test are shown in Table 9-4. The error bars in Figure 9-2 give an idea of the confidence limits of the test.

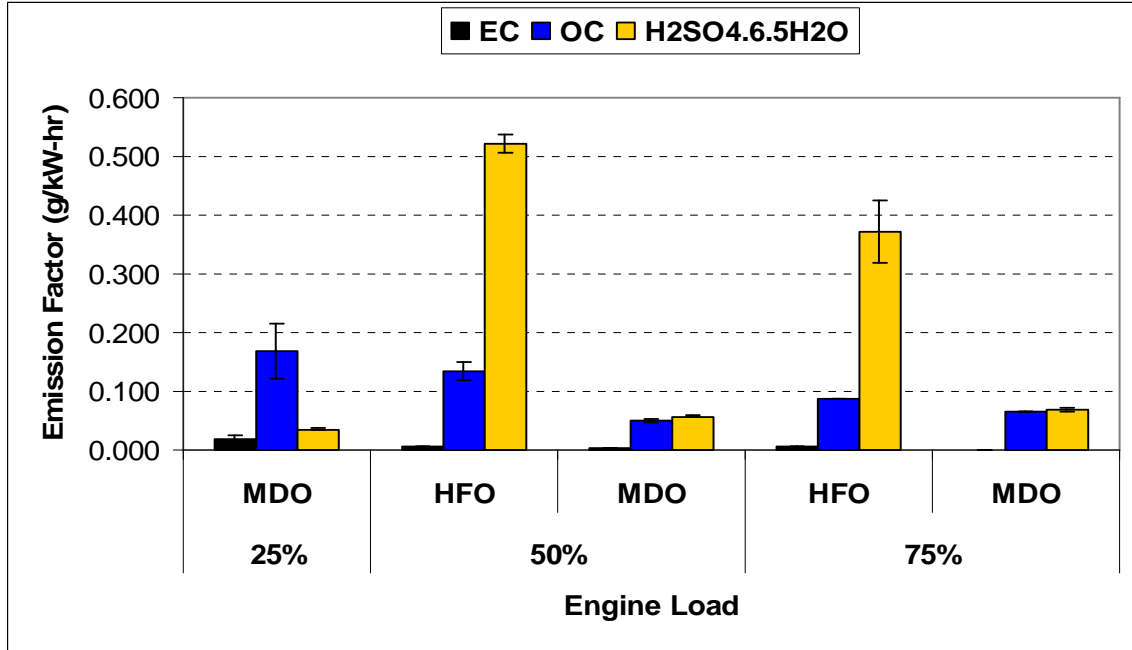
Table 9-4 Speciated PM Emission Factors for AE#2

Target Load ISO	Actual Load		EC (g/kW-hr)		OC (g/kW-hr)		H ₂ SO ₄ .6.5H ₂ O (g/kW-hr)	
	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO
25%	27%	26%	-	0.020	-	0.169	0.591	0.035
50%	46%	47%	0.005	0.003	0.135	0.051	0.522	0.058
75%	73%	68%	0.005	0.002	0.089	0.066	0.372	0.069

Note: kW-hr denotes generated power, Transfer Line Used

As in the case of AE#1 we find that sulfate was the most significant fraction of the PM emitted by the engine operation on HFO accounting for about 66% of the PM mass. In the case of MDO, OC accounted for 30% to 50% of the PM mass. The OC to EC ratio ranged from 8 to 17 for HFO and 27 to 43 for MDO both fuels showing an increasing trend with the increase in engine load.

Figure 9-2 EC, OC, Hydrated Sulfate Emission Factors for AE#2



Note: kW-hr denotes generated power, Transfer Line Used

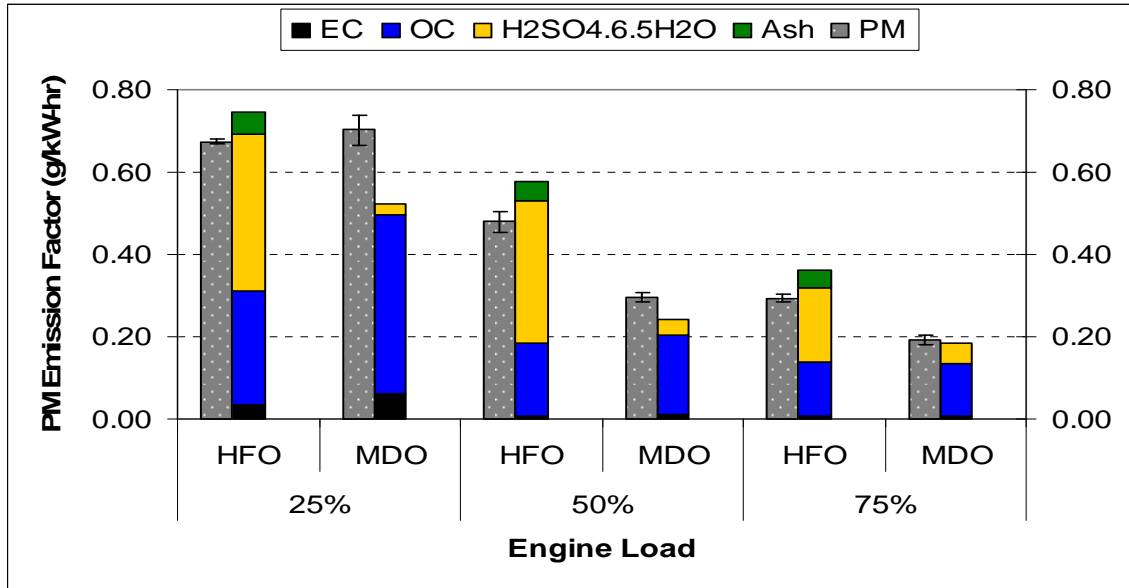
9.1.5. PM_{2.5} Mass Closure for AE#1 and AE#2

An important element in UCR’s analysis approach is the QA/QC check that total mass is conserved for the various PM methods. Specifically, we compare the total mass collected on the Teflon filter with the sum of the masses independently measured as sulfate, organic, elemental carbon and ash (calculated). This mass balance for some of the tests on AE#1 and AE#2 are shown in Figures 8-3 and 8-4.

The Ash content of the PM is calculated based on the assumption that all of the ash in the fuel goes to PM. We do not have the actual rate of fuel consumption so it is estimated from the CO₂ emission factor, as done for the calculation of SO₂. The fuel ash content was not available for MDO on the tests performed on AE#1; hence it is not shown in Figure 9-3.

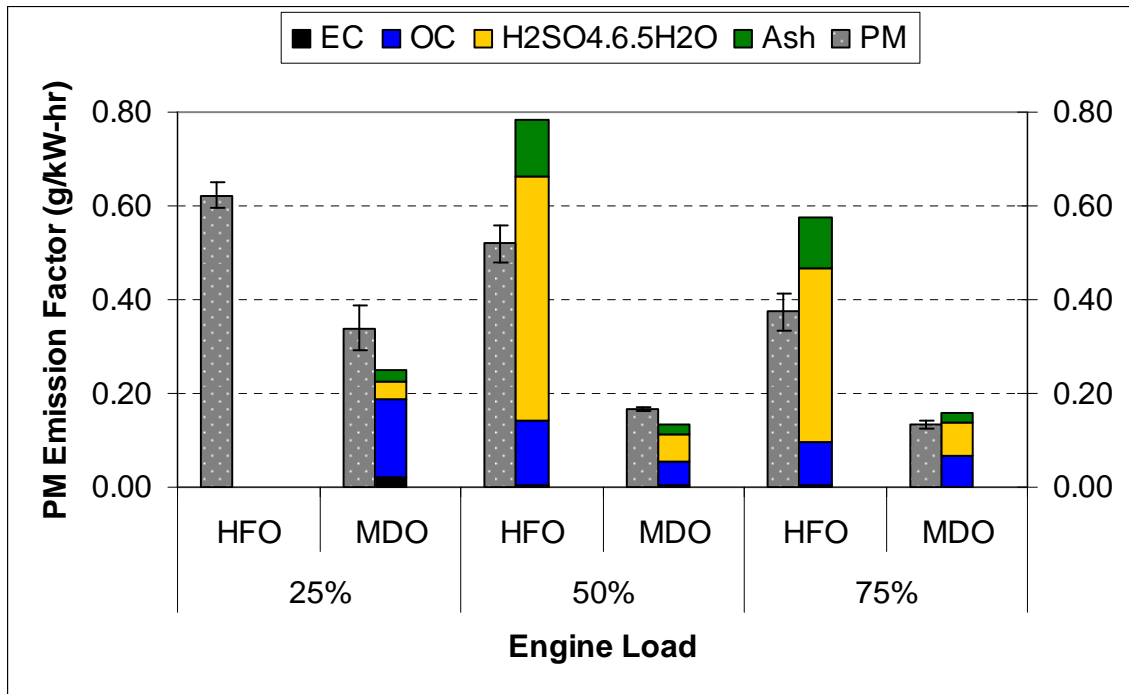
The mass balance is found to be reasonably good with the HFO fuel for both AE#1 and AE#2. For MDO however the sum of the speciated PM falls short of the total PM mass this is probably due to the fact that the OC needs to be multiplied by a factor of 1.2 to 1.4 to convert it to organic mass.

Figure 9-3 Speciated PM Emissions for AE#1



Note: kW-hr denotes generated power, Transfer Line Used

Figure 9-4 Speciated PM Emissions for AE#2



Note: kW-hr denotes generated power, Transfer Line Used

10. Appendix C

10.1. PM Emissions for October 2005 Test

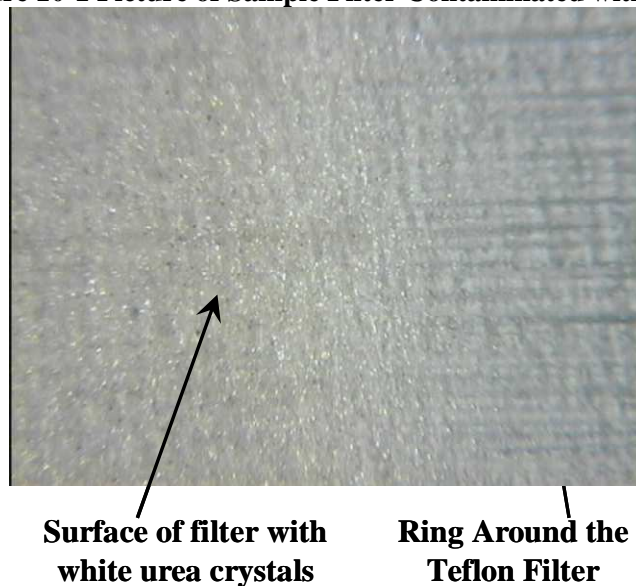
AE#1 was tested three times July 2005, October 2005 and December 2005. This engine was equipped with a selective catalytic reduction unit in the exhaust manifold. The sampling for baseline emissions was done upstream of this unit. Unfortunately the sampling port that was made available to us was located downstream of the point of urea injection. During the October 2005 test the urea injection was on and we found very high masses on the filters. These are reported in Table 10-1. Also the filters looked white in color (Figure 10-1). Hence, we suspected contamination of the PM mass with urea.

Table 10-1 PM Emissions from AE#1, October 2005

Fuel	Actual Load	PM Mass (g/kW-hr)	EC (g/kW-hr)	OC (g/kW-hr)
HFO	26%	0.873	0.011	0.300
	49%	1.160	0.005	0.252
	71%	1.011	0.003	0.179
MDO	26%	3.155	0.020	0.333
	48%	2.663	0.007	0.427
	72%	3.064	0.002	0.246

DO NOT USE DATA Urea Contamination

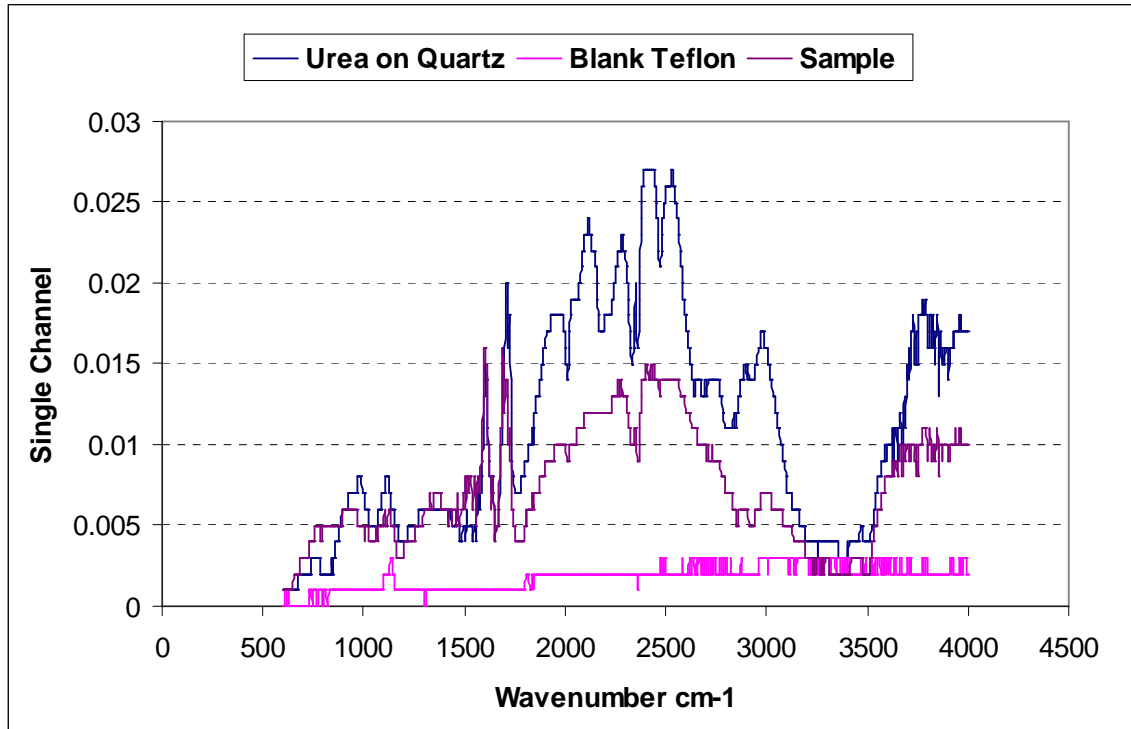
Figure 10-1 Picture of Sample Filter Contaminated with Urea



To confirm that the filters were indeed contaminated with urea, reflective Fourier Transform Infra Red (FTIR) spectroscopy was performed on the sample filters. Also a

blank Teflon filter and a Quartz filter with urea on it prepared specifically for this were analyzed by reflective FTIR. The spectrum obtained from the instrument is shown in Figure 10-2. Clearly the signal for urea is found in the wavelength range of 1500cm^{-1} to 3200cm^{-1} . The Sample filter had a strong urea signal. Hence it was confirmed that the samples were indeed contaminated with urea.

Figure 10-2 Reflective FTIR results



10.2. PM Emissions for the July 2005 Test

As mentioned in the previous section, AE#1 was equipped with a SCR unit. The sampling port upstream of the SCR used for testing the baseline emissions was unfortunately downstream of the point of urea injection. A total of three tests were performed on this engine – July 2005, October 2005 and December 2005. During the October 2005 test we found high PM Mass numbers and confirmed with further analysis that this was due to contamination of the filters with urea (Section 10.1). As a result special care was taken during the December 2005 test to turn urea injection off while sampling upstream of the SCR.

However, during the July 2005 test which was our first campaign testing the SCR, the urea injection was on while sampling before the catalyst. The PM mass numbers measured were higher than that in December 2005 test, though not as high as the October 2005 test. Note here that during this test the engine was probably running on the Low NO_x mode so these PM numbers are not directly comparable to that from the October 2005 or the December 2005 tests. Unfortunately, the filters had been destroyed by further analysis on them and were unavailable to test for urea by FTIR.

Another difference is that a heated Teflon transfer line was used here while a heated stainless steel transfer line was used for subsequent tests. The ISO method allows use of a heated stainless steel line. Tests conducted at CE-CERT on a back up generator running on ULSD show that there is no significant difference in PM mass by changing the transfer line from stainless steel to teflon, though the error bars are higher for the Teflon line (Welch, 2006). Subsequent tests on auxiliary engines showed that there is a loss of PM mass as high as 40% with the used of the stainless steel transfer line (Section 3.3.1). We have not quantified this number for the teflon transfer line.

Table 10-2 PM Emissions from AE#1, July 2005

Fuel	Actual Load	PM Mass (g/kW-hr)	EC (g/kW-hr)	OC (g/kW-hr)	H ₂ SO ₄ .6.5H ₂ O (g/kW-hr)
HFO	40%	0.703	0.033	0.226	0.297
	54%	0.789	0.009	0.279	0.282
	68%	0.841	0.004	0.225	0.388
MDO	23%	0.409	0.103	0.214	0.011
	52%	0.616	0.022	0.200	0.027

Considering all the variables involved and the possibility that the filters were indeed contaminated with urea this data is to be used with extreme caution. Note here that, urea would be detected as OC, hence the OC numbers may be larger than they actually are. The EC and hydrated Sulfate fractions of the PM mass however would not be affected by the urea injection. A detailed list of the emission factors is provided in Table 10-2.

10.3. Real Time PM Emissions for AE#2

This was our first experience using the DMM in the field. We found really high variability in the real time PM emissions (Figures 10-3 and 10-4) in spite of the fact that the gaseous data was quite stable. This is contrary to other tests that we have done on in-use marine engines; hence we suspect that there was some kind of error in the operation of the instrument. Nonetheless the data is presented in the graphs below.

Figure 10-3 Real Time PM Emissions for AE#2 on HFO

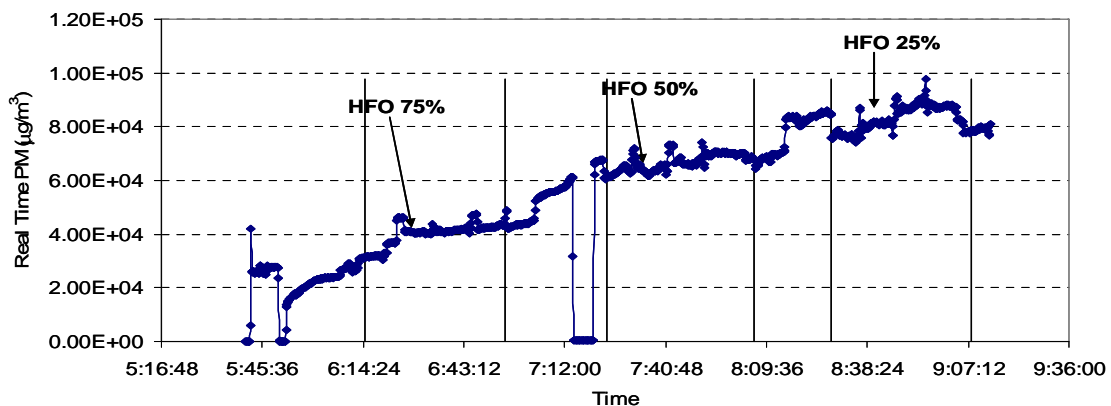
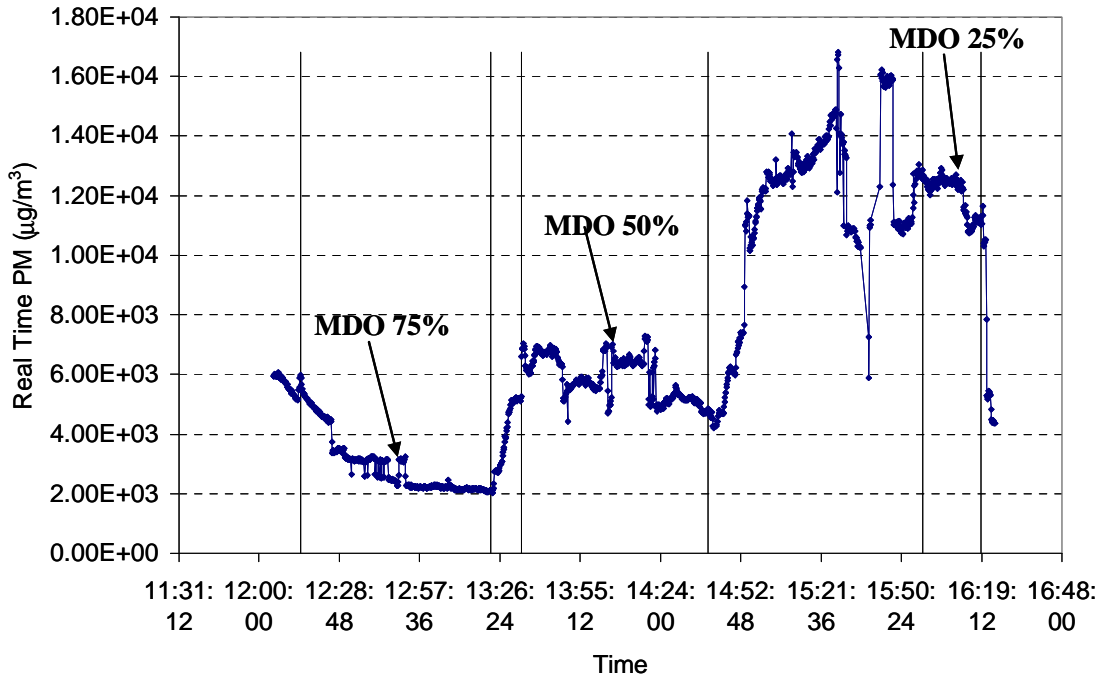


Figure 10-4 Real Time PM Emissions for AE#2 on MDO



10.4. Size Segregated PM Emissions

This was our first experience in testing size segregated PM emissions from an in-use marine auxiliary engine. The chief aim of this was to set up the protocol and gain experience in sampling on the Micro-Orifice Uniform Deposit Impactor (MOUDI). The PM mass numbers obtained here are not reliable for the following reasons.

- The pump used was unable to handle the pressure drop across the MOUDI and the flow through the MOUDI was only 18lit/min instead of 30lit/min hence cut size of each stage will be different from that of the instrument. We were unable to correct for this as the flow was too far from the target value to make a reasonable correction.
- For the July 2005 test a long Teflon raw gas transfer line was used which is known to cause significant loss of PM Mass (Section 3.3.1). Also we suspect that there was urea contamination of the filters while sampling upstream of the SCR. Refer to Section 10.2 for more details.

Hence the data presented below should be used with extreme caution. No definite conclusions can be made from these.

Table 10-3 Size Segregated PM Emissions

Size Range of Particle ¹ µg	Concentration in Exhaust (mg/m ³)					
	July 2005 Teflon Transfer Line		March 2006 No Transfer Line		May 2006 No Transfer Line	
	HFO 54%	MDO 52%	HFO 45%	MDO 43%	MDO 29%	MDO 29% Low NO _x
<0.056	n/a	n/a	n/a	n/a	4.73	1.60
0.056-0.1	5.03	1.14	16.15	2.66	0.09	0.04
0.1-0.18	0.11	4.45	19.84	2.32	0.09	0.09
0.18-0.32	0.05	3.57	68.79	1.97	1.06	1.73
0.32-0.56	0.13	1.69	12.04	1.04	1.60	1.94
0.56-1	0.32	0.53	10.76	0.74	0.65	1.10
1-1.8	0.21	0.28	4.98	0.40	0.42	0.51
1.8-3.2	0.28	0.00	1.93	0.32	0.20	0.18
3.2-5.6	0.15	0.15	1.07	0.09	0.20	0.13
5.6-10	0.32	0.13	0.61	0.13	0.06	0.17
10-18	0.32	0.00	0.30	0.08	0.02	0.03
>18	0.18	0.53	0.39	0.81	0.08	0.03
Time Sampled (min)	10	10	30	30	53	50

¹Actual Particle Size will be higher because the flow through the MOUDI was lower
n/a: not available

Our experience showed us that the MOUDI needs to be sampled for about one hour to get sufficient mass on the different stages. Notice the increase in sampling times from one campaign to the next. During the initial tests no after filter was used; the May 2006 test showed that a significant amount of mass was collected on the after filter.