Measurement of Criteria Emissions from a Tier 1 Ocean Going Container Vessel

Final Report

Prepared for

United States Maritime Administration (MARAD)
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Acronyms and Abbreviations

σ	standard deviation
AE	auxiliary engine (diesel generator)
BC	black carbon
BSFC	brake specific fuel consumption
CARB	California Air Resources Board
CE-CERT	College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CFR	Code of Federal Regulations
cm/s	centimeters per second
CO	carbon monoxide
COV	coefficient of variation
CO_2	carbon dioxide
DF	dilution factor
eBC	equivalent black carbon
EC	elemental carbon by NIOSH thermal optical methods
EPA	United States Environmental Protection Agency
HSF	high sulfur fuel (denoted for ULSFO)
IMO	International Maritime Organization
IMPROVE	Interagency Monitoring of Protected Visual Environment
ISO	International Organization for Standardization
kPa	kilo Pascal
lpm	liters per minute
LSF	low sulfur fuel (denoted for MGO)
MCR	maximum continuous rating
MGO	marine gas oil
MDL	minimum detection limit
ME	main engine
MFC	mass flow controller
ms	milliseconds
MSS	Micro Soot Sensor
NCR	nominal continuous rating
NIOSH	National Institute of Occupational Safety and Health 5040 protocol
NIST	National Institute for Standards and Technology
NO_x	nitrogen oxides
OC	organic carbon by NIOSH thermal optical methods
o.d.	outer diameter
OEM	original equipment manufacturer
PM	particulate matter
$PM_{2.5}$	fine particles less than 2.5 µm (50% cut diameter)
PTFE	polytetrafluoroethylene
QC	quality control
RPM	revolutions per minute
scfm	standard cubic feet per minute
S	sulfur
SO_2	sulfur dioxide

SO_x	sulfur oxide
UCR	University of California at Riverside
ULSFO	Ultra-low sulfur heavy fuel oil
VLSFO	Very-low sulfur heavy fuel oil

Table of Contents

Table of Figures

List of Tables

Executive Summary

Introduction: Emissions from marine engines (container vessels, crude tankers, bulk cargo, auto carrier, cruise ships, and other ocean-going vessels (OGV)) represent a significant contribution of particulate matter (PM), sulfur oxide (SO_x) and nitrogen oxide (NO_x) emissions. Global shipping represents over 80% of the volume and 70% of the value of goods transported, thus shipping is a major contributor to our global emissions inventory. To control SO_x emissions from marine engines, International Maritime Organization's (IMO) Annex VI regulations include caps on the sulfur content of fuel oil to less than 0.5% which indirectly also reduces PM emissions. To minimize PM and NO_x emissions further, the California Air Resources Board (CARB) requires OGV to use distillate fuels (less than 0.1%) such as a marine gas oil (MGO) within 24 nautical miles of California coastline. The CARB fuel rule, thus, prevents OGV from operating with low sulfur residual fuels and high sulfur fuels combined with scrubbers.

Objectives: The objective of this research is to perform emission measurements on a container OGV while operating on two fuels. One fuel is denoted as a high sulfur fuel (HSF) at less than 0.5% sulfur fuel, and the other fuel is denoted as a low sulfur fuel (LSF) at less than 0.1% sulfur. These fuels were switched while operating at a single vessel speed of 15 knots. In addition, the emissions were collected during a cold start and slow speed (6-7 knots, ~3% MCR) for the LSF as well as during transitions for the fuel switches. For this project, the sponsor will be using the data collected by CE-CERT to evaluate a Tier 1 container vessel emissions factors and will allow data in this report to be utilized for the evaluation of various in-stack air emissions sampling technologies and on-line fuel sulfur technologies available for OGVs.

Methods: The test methods utilized the 25% load point (15 knot vessel speed) from the ISO 8178 E3 cycle to determine the emissions rate of gaseous and particulate pollutants for the ME. The emissions measured were regulated gaseous $PM_{2.5}$ mass emissions and PM composition which included both elemental carbon PM and organic carbon PM. Other methods and practices, such as dry to wet correction and NO_x humidity correction, followed ISO and CFR recommendations.

Results, Tier 1 vessel emissions: The PM emissions were collected over an interval which averaged between 15- and 20-minutes. The ME $PM_{2.5}$ emissions were highest for the cold start condition (1.25 g/kWhr) and the low load condition (0.89 g/kWhr). The $PM_{2.5}$ emission varied from 0.4 g/kWhr to 0.26 g/kWhr for the hot stabilized 22% load condition. The HSF emissions were lower for elemental and organic carbon PM compared to the LSF but showed more sulfate mass due to the higher sulfur in the fuel. The total $PM_{2.5}$ mass emission, however, were the same between the fuels.

The CO_2 emissions ranged from 698 g/kWhr to 704 g/kWhr. The CO_2 emissions did not show a statistically significant change between the LSF and HSFs. The CO_2 emission factor decreased slightly when the engine load was decreased from 22% load to 2.4% load. Lower CO_2 emissions at lower loads is uncommon for compression ignition engines. It is suspected that some type of low load combustion technology was employed during the engine derating in 2015 to reduce fuel consumption at this low of a load. The derating was designed to improve the fuel economy of the vessel at low steaming operation as tested during this testing.

The average NO_x emissions at 22% load were about the same as the 25% load certification value but were about 50% higher than the certification standard for a Tier 1 engine (17 g/kWhr). The

NO_x emissions were similar for the cold start and hot running NO_x emissions. The NO_x emission at the low load (2.4% load and 6-7 knots) was also surprisingly low and showed a similar emission factor at the 22% load. Typically, NO_x increases as load decreases for compression ignition engines. It is speculated that the improved engine efficiency also reduced the low load NO_x emissions.

Results, comparison to other methods:
SO_2 concentration varied from 7 ppm prior to the fuel switch and increased to 34 ppm at the end of the fuel switch to the HSF (< 0.5 % Sulfur fuel). The CO_2 concentration increased from 7:00 am to about 9:30 am and ranged from 2.5% to 3.5%. It then dropped back down after 10 am to around 3%. NO_x concentration also increased from 7:00 am to about 9:30 am and ranged from 900 ppm to 1200 ppm. It also reduced back down to around 1100 ppm following the CO_2 trend. The fuel sulfur content, based on SO_2 mass emissions, was estimated to be 0.09 % for the LSF and up to 0.46 % for the HSF. This agrees well with the fuel bunker report from the vessel. See the other report for comparisons to the different technologies evaluated.

Summary: The Tier 1 vessel equipped with an upgraded engine for slow steaming operation resulted in improved low load fuel consumption and reduced NO_x emissions. However, when estimating NOx emissions inventories in a port area, one should use the 25% load point emission factor for non-SCR vessels. In addition, the derated engine emitted less organic and elemental carbon PM on HSF compared to the LSF (MGO compliant fuel). Although there is an anticipated total PM mass benefit for the use of low sulfur MGO fuels, their use near ports will increase organic and elemental carbon PM emissions compared to low sulfur residual fuel oils with <0.5% sulfur. The calculated sulfur fuel percent from the stack measurements agrees well with the bunker report, suggesting the results in this report can be used for the other measurement technology comparisons in the other study.

1 Background

1.1 Marine emissions

Global shipping represents over 80% of the volume and 70% of the value of goods (UNCTAD, 2015 and 2017) transported showing the impact this industry has on the environment. The major pollutants in ship exhaust are particulate matter with an aerodynamic diameter less than 2.5 µm ($PM_{2.5}$), sulfur oxides (SO_x), and nitrogen oxides (NO_x) (Dalsøren et al 2009, Endresen et al 2007, and Endresen et al 2005). NO_x emissions cause photochemical smog, and marine engines are one of the highest emitters of NO_x emissions. Ships typically burn residual high sulfur heavy fuel oil (HFO) containing polycyclic aromatic hydrocarbons and transition metals, and thus emissions of PM are of particular concern. International shipping has been linked with increased mortality in coastal regions, with an estimated 60,000 deaths from cardiopulmonary and lung cancer per annum attributed to $PM_{2.5}$ emissions from ship exhaust (Corbett et al., 2007); more recently these estimates have increased up to 250,000 deaths (Sofiev et al 2018). $PM_{2.5}$ is composed of sulfate particles, organic carbon (OC), elemental carbon (EC), and trace metals. The PM composition varies widely with the fuel sulfur, fuel quality, engine type (two vs four stroke), engine load, engine age, and engine size. Large slow speed diesel (SSD) engines operating on high sulfur fuels emit mostly hydrated sulfate particles and for low sulfur fuels SSD emit mostly OC and EC PM fractions where the split depends on the fuel quality (Johnson et al 2015).

To control SO_x emissions from marine engines, the IMO MARPOL Annex VI regulations include caps on the sulfur (S) content of fuel oil in emission control areas (ECA) and in global waters, see Figure 1-1 and Figure 1-2. From 2020 and beyond, the global sulfur fuel limit is required to be < 0.5% S. The SO_x regulation indirectly reduces PM emissions although the IMO does not have any explicit PM emission limits. Providing the vessel meets the applicable sulfur limit, HFO is allowed even with the ECA fuel sulfur rule if alternative technology is used to limit SO_x emissions to a fuel equivalent 0.1% S. Scrubbers, or other exhaust gas cleaning systems, are alternatives to using 0.1% S fuel.

Sulfur emissions have a relatively short atmospheric lifetime: 1.0-2.5 days for gaseous SO_2 and 4-6 days for particle sulfate (Berglen et al., 2004 and Endresen et al. 2007). This implies that the highest and strongest deposition of sulfur is found close to the sources. Emissions of SO_x are a major contributor to acid deposition, which has harmful effects to the natural environment as well as building structures. Unlike land based mobile sources, marine shipping can burn low-cost high sulfur fuels which has been reported to cause high SO_x and $PM_{2.5}$ emissions (Fridell and Salo, 2014; Winnes and Fridell, 2009). For comparison, a switch from high sulfur HFO to a low sulfur MGO resulted in a 75% $PM_{2.5}$ and 98% SO_x mass reduction where most of the $PM_{2.5}$ reduction was sulfur bound species (Winners et al 2009 and Kahn et al 2012). Thus, reducing the sulfur in the fuel can greatly reduce the SO_x and $PM_{2.5}$ emissions, but at a higher cost for the fuel.

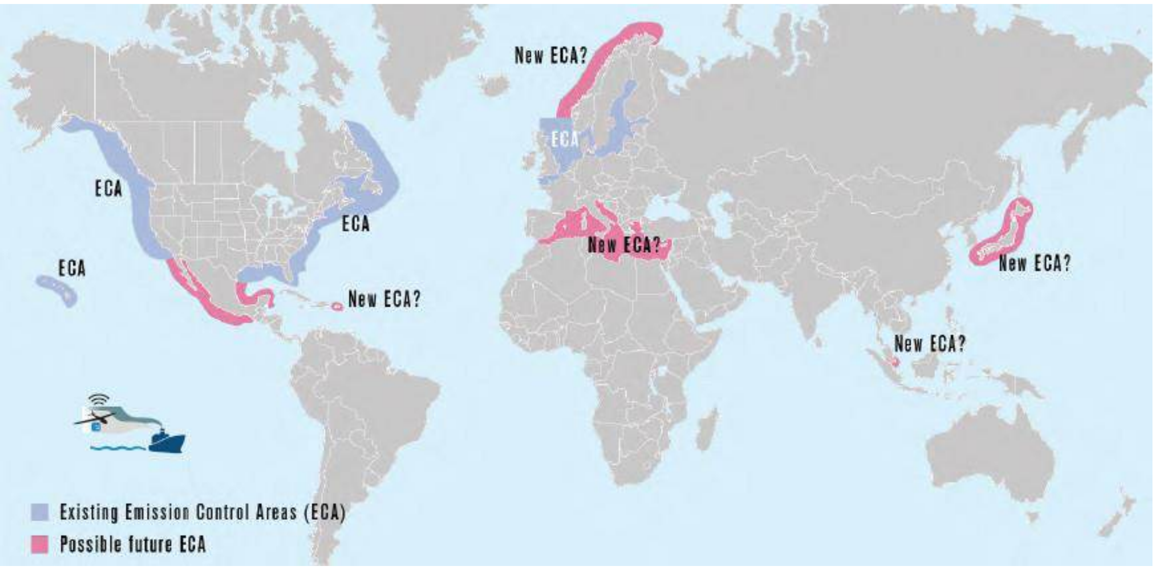

Figure 1-1 Emission control areas (adapted from CLS 2015)

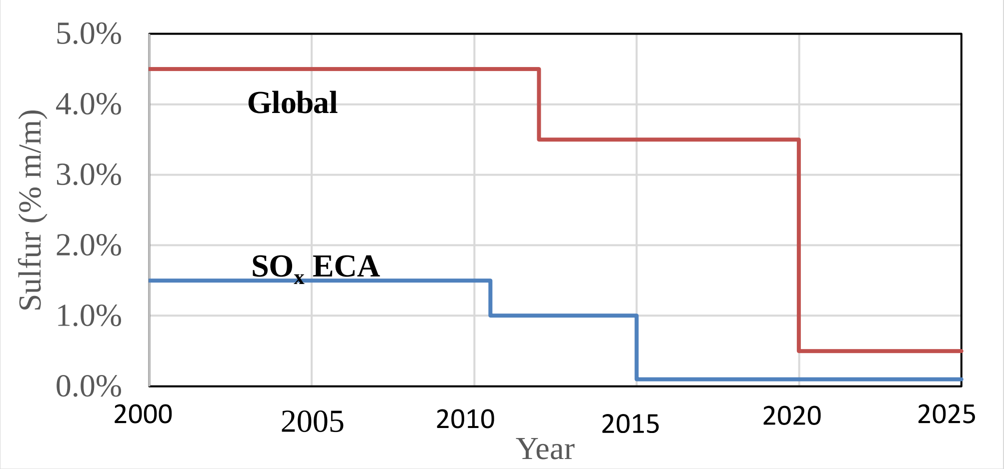

Figure 1-2 Global and ECA fuel sulfur limits

Due to the high cost for the ECA and CARB compliant fuels, marine vessels have been equipped with several technologies to meet the global fuel rule, such as an exhaust gas treatment system, also known as a scrubber, switching to liquefied natural gas (LNG) dual fuel systems, and other residual low sulfur fuels meeting the different regulatory specifications. Although LNG may be cost competitive to other ECA fuels, there are several additional expenses associated with the use of LNG, such as developing the necessary fueling infrastructure and converting existing engines to be able to operate on the fuel. In California waters there is an added requirement to utilize a non-residual fuel called a marine gas oil which is lighter and cleaner burning (CARB 2009). Given the wide range of options and cost associated with complying with the fuel sulfur regulations, verifying compliance is difficult due to the nature of the compliance enforcement approach especially in California waters where additional fuel rules are in place.

The current compliance enforcement methods are slow and limited to a small fraction of vessel visits to California ports. The current compliance approach in California is to board a vessel, take a fuel sample, take the fuel back to the laboratory, and then obtain that fuel sulfur compliance result in a day’s time. This approach limits the number of vessels that can be screened to less than 5% of the fleet, and it limits that to specific days when enforcement can be performed. Also, it limits those vessels that are at-berth and not those in transit and at anchor.

There are many new approaches being considered as enforcement tools for sulfur compliance, and these tools could be operated more widely such as enforcement through the coast guard. These new methods include drones, stack plume measurements, and some real time fuel sample analysis methods. The work presented in this report will be used to characterize the emissions from a Tier 1 ocean-going vessel (OGV) using IMO approved stack sampling methods. These results will also support a second research effort to investigate the effectiveness of different measurement techniques such as drone and vessel-based plume systems and new online analytical fuel sample methos. The results of the different sampling methods will be presented in a separate report as a compliment to this report. This report will only cover the results for the stack sampling method.

1.2 Objective

The objective of this research is to perform emission measurements on a container OGV while operating on two fuels for the evaluation of real time sulfur fuel enforcement technologies. One fuel is a compliant IMO fuel with a sulfur percent less than 0.5% denoted as a high sulfur fuel (HSF), and the other is an ECA compliant fuel with a sulfur content less than 0.1% denoted as a low sulfur fuel (LSF). These fuels were switched while operating at a single vessel speed of 15 knots (engine load of 22%). In addition to the single load point that was tested, samples were collected during the engine warming up, denoted as a cold start result, and at a very low load representative of a port maneuver (6-7 knots and 2.4% engine load).

This report covers the testing performed by CE-CERT’s stack source sampling measurement tool. This report provides the regulated emissions at the stack and estimates of the plume using the IMO 8178 direct stack reference method.

2 Approach

This section outlines the in-use emissions testing approach for the Tier 1 engine. This section describes the test article (vessel, engine, fuels, and load points), emissions systems (sample location, gaseous and PM measurement methods, and exhaust flow determination), and the calculations. The test article sections cover details on the specifics of the vessel and any details of importance to the stability of the emissions and the validity of the testing. The sampling approach describes the vessel operation, where the samples were collected from the exhaust, the test matrix, and the test protocol. The measurements section describes the measurement methods for the gaseous, PM (including its components), exhaust flow, and engine load. The calculations section provides details on the engine load and emission factors calculations.

2.1 Test article

2.1.1 Vessel details

The tested article is a container vessel with a deadweight tonnage of 115,993 tons and a gross tonnage of 99,002 tons, and an overall length of 367 m and a breadth of 43 m, see Table 2-1. The vessel's keel was laid in 2008, see Appendix D and was built after Tier 1 regulations but before Tier 2 regulations. The vessel's service speed is 18 knots and is equipped with one main engine (ME), five diesel auxiliary engines (AE), and one auxiliary boiler.

Table 2-1 Tier 1 test vessel specifications

MY	*Class*	*TEUs*	*Draught*	*Length*	*Breadth*	*Service Speed*
2008	Container	-	15.5	370	43	18.0
ULSFO m^3	***MGO Capc. m^3***	***Ballast Water***	***Fresh Water***	***ME***	***AE***	***Aux Boiler***
-	-	-	-	1	5	1

[1] MY is the delivery model year of the vessel, ME is the main engine, and AE is the auxiliary diesel engine/generator. ULSFO is the ultra-low sulfur fuel oil, MGO is marine gas oil. There are also two other fuel tanks on this vessel, they are a heavy fuel oil tank (8,380 m^3) and a diesel oil tank (121 m^3).

2.1.2 Combustion sources

Only the ME was sampled with the UCR measurement system during this project. The ME is a Tier 1 Wartsila 12RT-flex96C 61.776 MW slow speed diesel (SSD) 2-stroke engine. The ME was derated in 2015 and is planned to be derated again in 2022/23. During derating, the engine was tested for emissions, and the NO_x emissions at 25% load was 23.4 g/kWhr, see Appendix D, which is in good agreement with the results presented in this report. Testing the engine was performed in the derated state from 2015 and may produce different results if tested after the second scheduled derating.

Table 2-2 Main engine specifications [1]

Mfg	*Model*	*Rating kW*	NO_x *25%*	*BSFC 25%*	*Engine Hr*
Wartsila	12RT-flex96C	61,776	23.4	0.254	88,535

PM emissions are known to vary with the condition and age of diesel engines. OGVs accumulate some of the highest engine hours where PM emissions may be significantly impacted by the status of the engine age and maintenance. After an overhaul, some 2-stroke SSD engines utilize increased lubrication during the running-in period where it is expected PM emissions will be elevated. During testing, the ME was found to be well maintained and in good condition for PM emissions testing.

2.1.3 Test fuels

A standard low sulfur (< 0.1%S) distillate MGO fuel compliant to CARBs marine fuel sulfur regulation (CARB 2009) and a commercially available 0.5% globally compliant sulfur fuel described as a very-low heavy fuel oil (VLSFO) were used for this project. An exemption was provided by CARB to allow the ME to be operated in Regulated California Waters (a zone approximately 24 nautical miles seaward of the California baseline) on the VLSFO fuel instead of the compliant low sulfur MGO fuel required by the California Fuel Rule (CARB 2009). The MGO fuel had a sulfur level of 0.093% with a viscosity of 20 mm^2/s and the VLSFO fuel had a reported sulfur level of 0.48% and a viscosity of 118 mm^2/s, see Appendix D Table D-1 and D-2. The VLSFO also showed a higher density and higher carbon residual compared to the MGO fuel. The VLSFO fuel is denoted as HSF and the MGO fuel is denoted as LSF throughout this report for consistency. Fuel samples were collected every 15 minutes throughout the day. That data was analyzed by the other research group and will be presented in a separate report as a compliment to this report.

2.2 Sampling approach

This section provides a discussion of the sample locations (PM representativeness and accessibility), the load points (achievable and practical), the test matrix (proposed load points), and the test protocol (methods of sampling).

2.2.1 Sample locations

The sampling approach for the ME are often determined by space constraints and desired measurement practices (e.g. the potential to sample from straight sections of exhaust). On this vessel, access to the exhaust after the economizer was not possible due to the many tight bends, short distances, and hard to reach areas. As such, the ME sample was performed just before the waste heat economizer, see Figure 2-1. UCR has tested several OGV from this sampling location and have found it to be representative and accurate for OGV emissions testing.

Sampling around an ME economizer is confounded because PM adsorption and desorption processes occur on the heat exchanger surfaces. During waste heat recovery (heating water to make steam for the ship's needs), the heat exchanger surfaces cool the exhaust gas constituents and PM (predominantly EC and BC) adsorbs on the cool surfaces. The adsorption of PM on a cool surface can be described by thermophoretic loss models. When PM is adsorbed onto the surface, stack PM emission factors can be underestimated (by about 10%) over short periods of time (measured in hours). To maintain economizer efficiency and performance, ships employ a periodic (at best daily) cleaning process of the heat exchanger surfaces. During cleaning, large amounts of PM (>20%) can be expected to be released that, if sampled, would overestimate the PM emissions factors of the ship. During this testing, the

Economizer was cleaned prior to testing based on discussions with the Chief Engineer thus making the in-stack sampling system a good sample location for this research project.

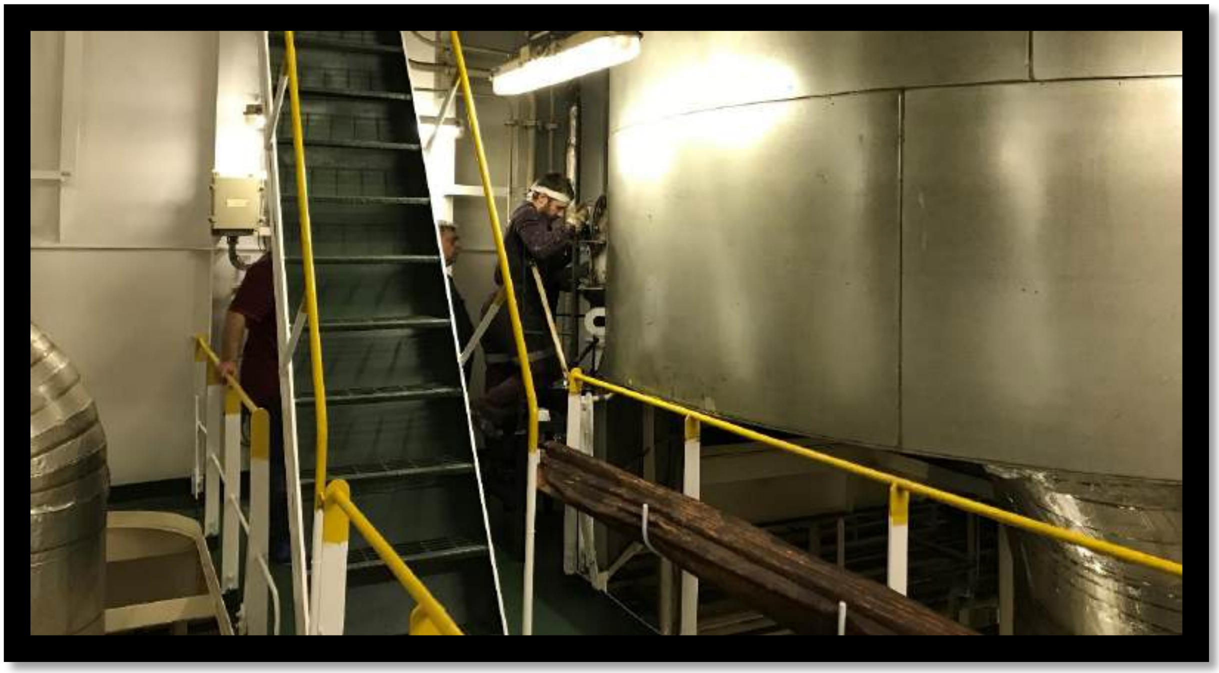

Figure 2-1 Setup on the ME, before the economizer (two decks above the ME)

Figure 2-2 Emissions testing setup on the ME

2.2.2 Test matrix

The test matrix subsection covers typical engine certification cycles, proposed test cycles for on-sea and in-use testing, and the impact these load points may have on the analysis.

Engine certification: The ME is directly connected to the propeller where vessel speed is follows the propeller curve. Direct drive engines are certified per the ISO 8178-4 E3 marine test cycle, see Appendix C for typical certification test points. The maximum achievable ME load is less than 100% and depends on several factors including constraints by navigational details, engine configurations, currents, wave patterns, wind speed and direction, and loads allowed by the Chief Engineer or ship Master. For this testing the targeted ME load was 22% of maximum continuous rate (MCR) and was dictated by a desired vessel speed of 15 knots.

Table 2-3 provides the test matrix of the fuel used on the vessel. Vessel speed, fuel usage rate and distance traveled on a specific fuel are given.

Table 2-3 Test matrix and fuel switching plan and timing table

Activity	Event Start Distance	Speed	Duration	Fuel	Start Time	Comment	Fuel Rate	Switch Over Delay	Distance	Accum Distance	End Time
	NM	NM/hr	hr	S%	HH:MM		Ton/hr	hr	NM	NM	HH:MM
Berth to Pilot	0.0	5	2.5	<0.1	5:00		0.2	28	12.5	12.5	7:30
drone testing	12.5	15	2.0	<0.1	7:30		2.4	2.3	30.0	42.5	9:30
drone testing	42.5	15	0.0	<0.1	9:30		2.4	2.3	0.0	42.5	9:30
drone testing	42.5	15	2.3	Switching	9:30		2.4	2.3	34.5	77.0	11:48
drone testing	77.0	15	0.0	<0.5	11:48	exemption	2.4	2.3	0.0	77.0	11:48
drone testing	77.0	15	2.0	<0.5	11:48	exemption	2.4	2.3	30.0	107.0	13:48
drone testing	107.0	15	2.8	switching	13:48		2.4	2.3	42.0	149.0	16:36
drone testing	149.0	15	0.0	<0.1	16:36		2.4	2.3	0.0	149.0	16:36
Pilot to Anchor	179.0	5	0.5	<0.1	18:36		0.2	28	2.5	181.5	19:06

1 Testing time takes into account sunrise of 6:10 and sunset of 19:47 and the fact one can see 0.5-1 hr prior to the event. Total distance Berth to Berth 344 NM, VSR blue whale 147 NM and open water 187 NM

Figure 2-2-3 provides the route taken by vessel during the test period. The route is displayed as the continuous black line. The photo in the figure was taken from a navigational console on the bridge mid-route, approximately 3pm. The remainder of the route has been added to the figure in red. The route shows the vessel leaving POLB, heading west, and crossing the major shipping lane that is designated by the two purple dashed lines that run parallel with the coast. The vessel then continued west passing Santa Barbara Island. The vessel then turned around and headed back east. The vessel made some meandering maneuvers to increase the distance of the route before returning to the shipping lane. After returning to the shipping lane, the vessel travelled north to Port Hueneme to end the testing period.

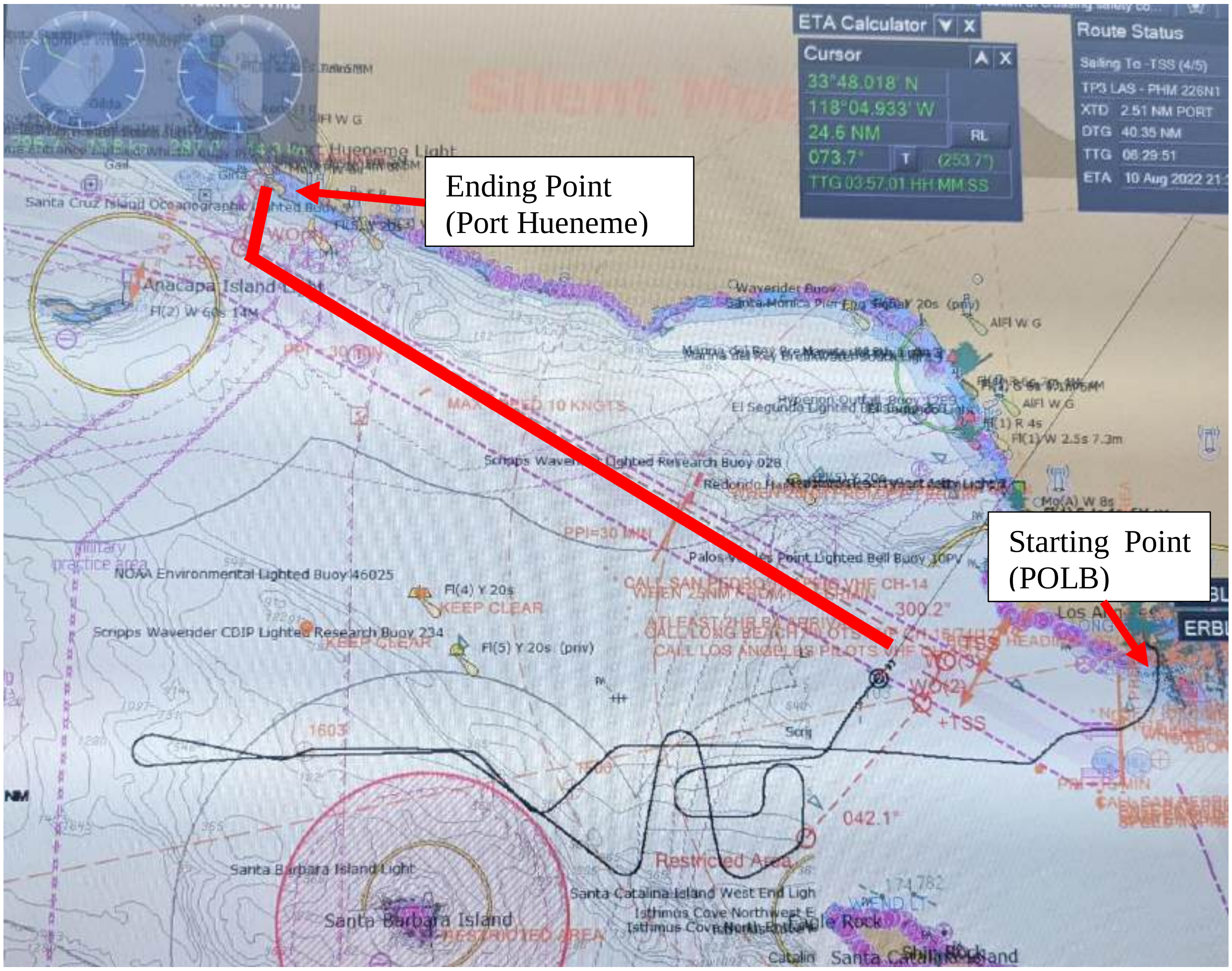

Figure 2-2-3 Route of Vessel. Photo taken at 3 PM while the route was still underway.

2.2.3 Test protocol

When following the ISO cycles, the engine was operated for more than 30 minutes at the highest power possible to warm the engine and stabilize emissions. Repeats of the same load are performed prior to changing loads (i.e. mode 1, 1, 1 load change, mode 2, 2, 2 load change…). Based on experience testing OGVs, repeating test points with this approach is needed to manage the time it takes between different load points and to prevent issues when navigating in areas with speed restriction. At each steady state test mode, the protocol requires the following:

- Allow the gaseous emissions to stabilize before measurement at each test mode (minimum 10 minutes as per ISO).
- Measure gaseous and PM concentrations for at least 3 minutes but no longer than 30 minutes (such that approximately 500 µg of filter mass is collected at a minimum dilution ratio of 4:1). For this testing, filter weights were expected to be high for a Tier 1 vessel on 0.1 % and 0.5 % sulfur fuel and ranged from 1000 µg to 3000 µg.
- Record engine RPM, boost pressure, and intake manifold temperature in order to calculate the mass flow rate of the exhaust via the air pump methods. Additionally, UCR records engine fuel consumption or brake specific fuel consumption (BSFC),

where available to calculate exhaust flow by an alternate method for the verification of both exhaust flow methods.

- Record engine load and, if available, BSFC. BSFC will be used for validation of the measurement systems. BSFC was not available on this vessel, thus shop trial BSFC was utilized.
- Calculate emission factors from the measured pollutant concentration data and calculated mass flow rates.

2.3 Measurements

The sampling approach includes selecting sample locations (PM representativeness and accessibility), load points (achievable and practical), test matrix (proposed load points to meet EPA desires), and test protocol (methods to use for sampling). Best recommended practices for OGV exhaust gas measurements follow ISO 8178-1 with additionally following 40 CFR Part 1065 specifically for dilution and filter conditioning. The measurement approach is summarized here with more details available in Appendix A.

2.3.1 Gaseous emissions

The gaseous emissions were measured in the raw exhaust with a Horiba PG-350. Nitrogen Oxides (NO_x) utilize a heated chemiluminescence detector (HCLD), carbon monoxide (CO), carbon dioxide (CO_2), and sulfur dioxide (SO_2) utilize non-dispersive infrared absorption (NDIR) with cross flow modulation, and oxygen (O_2) utilize a zirconium oxide sensor, see Table 2-4. Major features of the PG-350 include a built-in sample conditioning system with sample pumps, data storage on a flash drive, integrated mist and particle filters, and a thermoelectric cooler. The performance of the PG-350 was tested and verified under the U.S. EPA and ETV programs. The signal output of the instrument was interfaced directly with a data acquisition system to view measurement trends and for data recording backup continuously.

Gaseous concentrations were measured directly from the raw exhaust. Dry-to-wet corrections were performed using calculated water concentration from the exhaust. Intake air humidity was measured in order to correct for humidity effects on NO_x emissions as per ISO and CFR.

$PM_{2.5}$ mass: UCR's PM measurements uses a partial flow dilution system that was developed based on the ISO 8178-1 protocol, detailed information is provided in Appendix A. Total PM mass ($PM_{2.5}$) is measured from the diluted exhaust gas as per 40 CFR Part 1065 recommended practices which utilizes 47 mm 2 µm pore Teflon filters (Whatman Teflon) weighed offline with UCR's UPX2 Mettler Toledo micro balance in a temperature, humidity, and particle-controlled environment. The microbalance is operated following the weighing procedures of the Code of Federal Regulations (CFR). Before and after collection, the filters are conditioned for a minimum of 24 hours in an environmentally controlled room (RH = 40%, T = 25 °C) and weighed daily until two consecutive weight measurements are within 3µg.

Dilution ratio: Previous ship testing has utilized high dilution ratios (~20:1) as allowed by ISO 8178 methods. EPA 1065 recommendations are to target 6:1 at maximum load point. Previous testing by UCR evaluated the impacts of dilution factors between 20:1 and 6:1. No statistical findings were observed for an OGV and varying dilution ratio with-in these DR conditions. The testing performed in this project was at the targeted 6:1 following the EPA recommendations as specified in Appendix A.

PM Composition: The project measured PM composition which comprises elemental carbon (EC), organic carbon (OC) and sulfate PM fractions. The EC/OC were sampled with a quartz filter and analyzed using thermal optical reflectance NIOSH method and the sulfate PM was analyzed using an ion-chromatography method during off-site analysis. The PM composition filters were sampled from a UCR dilution tunnel.

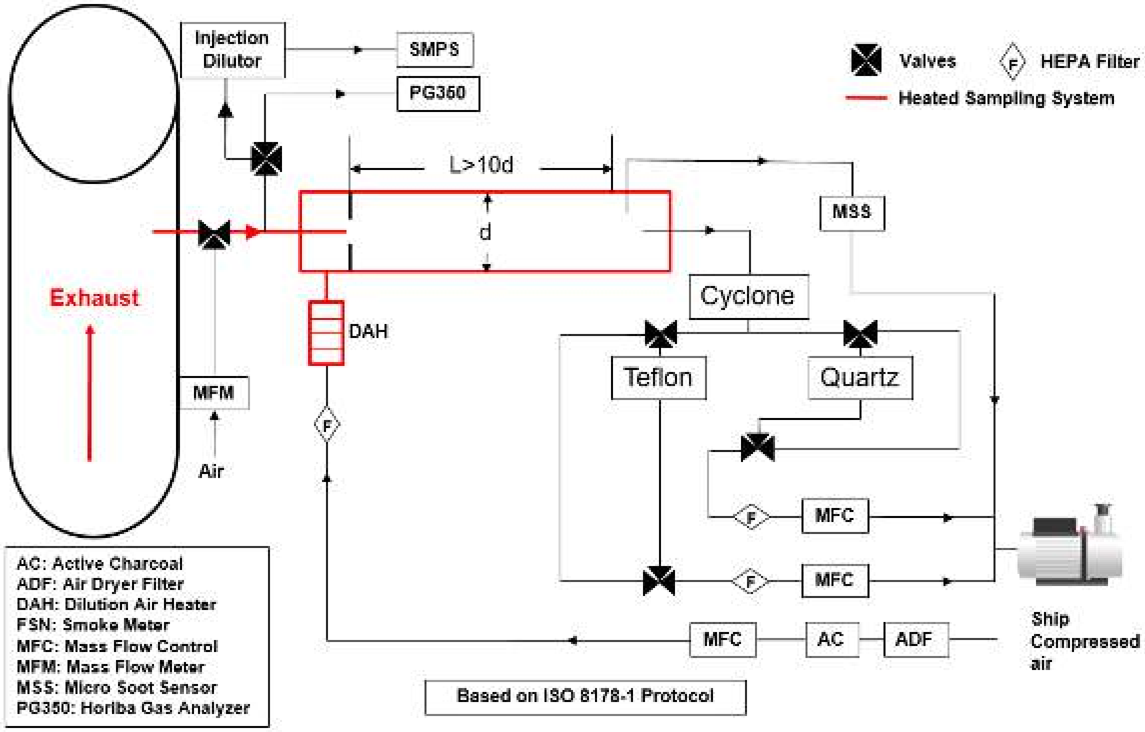

Figure 2-4 Schematic of the dilution sampling system

Table 2-4 Summary of emissions measured by UCR

Species Sampled			
NDIR CO	NDIR CO_2	CLD NO_x	Zirconium oxide O_2
NDIR SO_2	Total **$PM_{2.5}$** Gravimetric method	PM EC/OC NIOSH method	

2.3.2 *Exhaust flow*

The calculated emission factor requires the measurement of the engines exhaust flow rate. The exhaust gas flow can be determined by the following methods (and discussed below):

1. Direct measurement method (not available due to pipe bends and access)
2. Carbon balance method (**utilized** with shop trial vessel brake specific fuel consumption for the ME).
3. Intake air and fuel measurement Method (not available)

4. Air pump method (**utilized** and compared to carbon balance for scavenging fractions).

Direct exhaust flow measurement is complex and requires long straight exhaust stack sections without bends, which is not typically available on OGVs. Thus, direct measurement has not been a preferred method at UCR. Fuel flow measurement is the next best method for inferred exhaust flow measurements but was not available on this OGV. When measured fuel flow is not available, then reported BSFC[1] is utilized in conjunction engine load to calculate engine fuel consumption. Engine load was collected from torque and RPM measurements in the engine room by a vessel technician. This data was reported every 15 minutes throughout the day of testing.

The air pump method, which is based on scavenging air temperature, pressure, and RPM, is also typically available on all vessels. For the work presented in this study the exhaust flow was determined by the **Carbon Balance Method** and the **Air Pump Method.** For specific calculation details see Appendix A and Appendix E for details on exhaust flow values and assumptions.

For the data presented in this report, the Air Pump method was not of high quality compared to the carbon balance method. Thus, all the data presented is based on the carbon balance method with fuel rate calculated from load and BSFC.

2.3.3 Engine

Chapter 6 of the NO_x Technical Code "Procedures for demonstrating compliance with NO_x emission limits on board" provides detailed instructions for the required measurements for on-board testing. Some of the engine performance parameters measured or calculated for each mode during the emissions testing are shown in Table 2-5. The records vary depending on available information for the ME.

Table 2-5: Engine Parameters Measured and Recorded [1]

Parameter	Units
Engine load, speed, and fuel cons.	kW, RPM, and kg/kWhr
Vessel speed	Knots
Generator output	amps, volts, kW, PF (where avail.)
Fuel consumption (shop trial)	kg/hr
Brake specific fuel consumption BSFC (shop trial)	g-fuel/kWhr
Air intake pressure, temperature	Psi, °C
Exhaust stack pressure, temperature	inH20, °C
Ambient pressure, temperature	kPa, °C

[1] Engine and vessel measurements are reported where available and estimated if not available using good engineering judgment.

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[1] Shop trial reports were available for the ME. The reports include BSFC at each load point from which fuel flow can be estimated. The estimated fuel flow and the carbon balance method is then used for the reporting of exhaust flow.

2.4 Calculations

The testing results include details of the engine loads utilized, the measured emissions, the calculated flow rates, and emission factors for the individual loads and the weighted emissions factors. Brake specific and time specific emission factors are also provided.

2.4.1 Engine load

Engine load was recorded in the engine room on a percent basis for each test. In addition, a technician from the OGV was collecting drive shaft torque measurement and RPM for power calculations every 15 minutes, see Table 2-6. These are recorded, summarized, and detailed in Appendix E. The engine room percent load only displaced two significant figures where the drive shaft data was around 4-5 significant figures. UCR utilized the higher quality torque data collected by the technician for the basis of the analysis in this report. The power and RPM were collected and reported, then fuel consumption was calculated by multiplying the relevant power BSCF by the measured power to get fuel consumption. The fuel consumption shown in Table 2-6 is based on this calculation.

Table 2-6 Summary of load data recorded every 15 minutes

Time	Power	RPM	bsfc	FuelRate	Time	Power	RPM	bsfc	FuelRate	Time	Power	RPM	bsfc	FuelRate
hh:mm	kW		kg/kWhr	kg/hr	hh:mm	kW		kg/kWhr	kg/hr	hh:mm	kW		kg/kWhr	kg/hr
6:00	7528	48.00	0.30	2237	9:52	13928	59.66	0.26	3661	13:37	15538	59.66	0.26	3963
6:20	11759	54.82	0.27	3220	10:07	13175	59.51	0.27	3512	13:52	15089	59.45	0.26	3881
6:32	14382	60.61	0.26	3748	10:22	13096	59.45	0.27	3497	14:07	13700	59.82	0.26	3616
6:47	13161	59.32	0.27	3509	10:37	12961	59.53	0.27	3469	14:22	12787	59.45	0.27	3434
7:00	13390	59.51	0.27	3555	10:52	14671	59.70	0.26	3803	14:37	9058	51.60	0.29	2612
7:15	13263	59.46	0.27	3530	11:07	12888	59.49	0.27	3454	14:52	1410	24.99	0.33	472
7:29	13260	59.53	0.27	3529	11:22	12578	59.50	0.27	3391	15:07	1603	25.34	0.33	535
7:50	13185	59.45	0.27	3514	11:37	13149	59.40	0.27	3507	15:22	4168	36.11	0.32	1323
8:10	15157	59.67	0.26	3894	11:52	13136	59.57	0.27	3505	15:37	6524	44.33	0.30	1977
8:22	13315	59.45	0.27	3540	12:07	15257	59.50	0.26	3912	15:52	2811	32.62	0.33	916
8:37	13492	59.54	0.27	3575	12:22	13492	59.74	0.27	3575	16:07	3423	34.80	0.32	1102
8:50	13276	59.56	0.27	3533	12:37	13012	59.51	0.27	3480	16:22	3422	34.82	0.32	1102
9:07	15541	59.67	0.26	3964	12:52	13941	59.12	0.26	3663	16:37	6093	43.90	0.31	1862
9:22	13586	59.50	0.26	3594	13:07	14090	59.71	0.26	3692	16:52	5979	43.84	0.31	1831
9:37	12732	59.38	0.27	3423	13:22	12866	59.73	0.27	3450	17:03	5993	43.81	0.31	1835

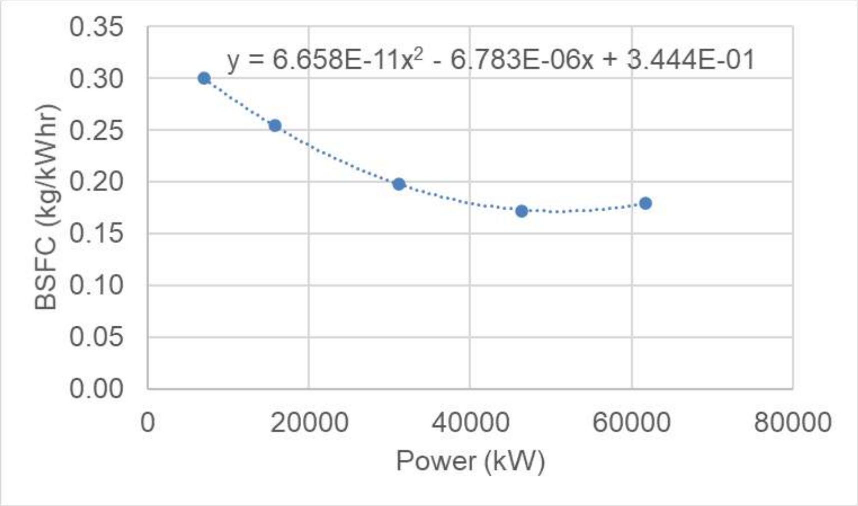

Figure 2-5 ME BSCF Curve

2.4.2 Emission factors

The emissions were collected at each mode in replicate to allow for the determination of confidence intervals for the reported means. The replicate measurements were performed by collecting numerous samples at test point for all the species of interest (gaseous continuous and integrated PM samples).

3 Results

The results for the Tier 1 ME are described in this section. The results compare the difference in emissions resulting from switching from MGO to VLSFO and then back to MGO fuel while performing moderate to low load operation near the port of Long Beach and Los Angeles. The MGO fuel is denoted as LSF and the VLSFO fuel is denoted HSF. The LSF is estimated to be around 0.098 % and the HSF is estimated to be 0.48 % sulfur.

The sections are divided into gaseous and PM emissions based on batched interval sampling and an addition section to correspond with the other plume and fuel sample measurement systems. These other measurement systems collected samples at different time intervals compared to the batched sampling, so the additional section was needed to make more direct comparisons to this other data.

In summary, the characterization of the vessel is best represented by Section 3.1 and 3.2, and Section 3.3 is best utilized to compare between the different measurement systems.

3.1 Gaseous emissions: Interval

This section includes gaseous emissions of NO_x, CO, CO_2, and SO_2 in g/kWhr. In each figure the testing period has been split into seven testing events including cold start, hot low-sulfur fuel (LSF), transition 1 to high-sulfur fuel (HSF), hot HSF, transition 2 to LSF, Hot LSF 2, and low load. The average engine load for each testing event in MCR (%) is also provided in each figure. These sections characterize the testing period as the vessel started from the POLB from a cold start, traveled out sea a few nautical miles, began the switch to the HSF, operated with the HSF, then switched back to the LSF as the vessel began the journey to Port Hueneme, and then finally slowed as it neared the port.

3.1.1 NO_x

The NO_x emissions for the ME are shown in Figure 3-1 and Figure 3-2 in units of g/kWhr and kg/hr, respectively. The ME Tier 1 engine NO_x emissions ranged from about 25.2 to 27.7 g/kWhr over the test period. The NO_x emissions were relatively unchanged from the transition to the HSF and back to LSF. The NO_x emissions also did not change drastically for the cold start and when the engine load was decreased during the low load section at the end of the test period. However, the NO_x emission rate in g/hr significantly changed between the 20-22% load and the low 2.4% load and dropped from 348 kg/hr to 40 kg/hr, see Figure 3-2. The relatively flat brake specific NO_x emissions demonstrates that the change in fuel did not affect the combustion temperature, as NO_x formation is primarily temperature dependent. The low load derating may have improved the sub 10% NO_x emissions to be similar to the 20% load condition, this is discussed further in the CO_2 emissions section. UCR's previous experience is that NO_x will continue to increase on a brake specific basis comparted to other vessels tested. This suggests the derating may have some strong emissions benefits for loads below 20% common for port logistics and navigation.

The average NO_x emissions may appear higher than the standard, but due to lower weighting factors at low loads and higher weighting factors at high loads, one cannot compare to the standard with a single measurement. However, the NO_x results at low loads, typical of operating at and around ports, is of interest for understanding the exposure from OGVs on port communities. The average measured NO_x emissions are about 50% higher than the certification standard for a Tier 1 engine (17 g/kWhr see Table 3-1). The measured emissions factors were measured from 6 knots to 15 knots where the emission rate was relatively flat on a brake specific basis but much lower at 6 knots on a kg/hr basis. This suggests that emission inventories for Tier 1 engines may be as much as 50% higher than the certification and will vary from 348 kg/hr to 40 kg/hr in and around port communities. It is expected the emission rate will follow the propeller load curve where between 15 and 6 knots given the relatively flat brake specific. During derating, the engine was tested for emissions and the NO_x emissions at 25% load was 23.4 g/kWhr which is similar to those measured in this study.

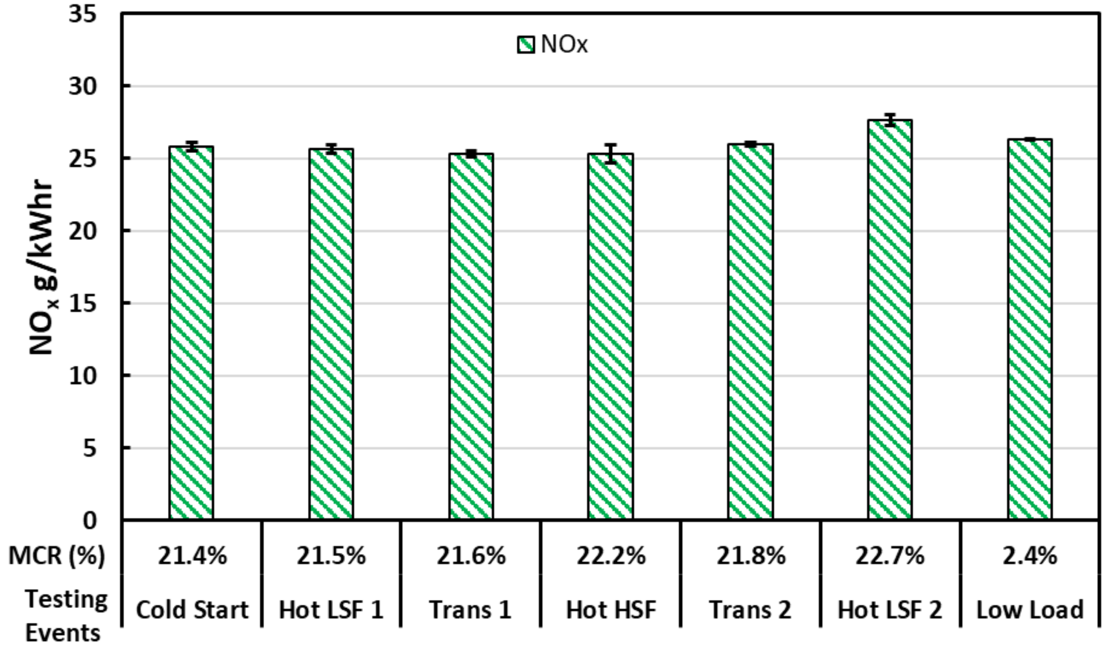

Figure 3-1 NO_x Emissions for the ME, g/kWhr [1]

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[1] The load percent is based on the percent of the vessels maximum continuous rating where the maximum rating of the engine was 61.8 MW at the time of testing. The engine is scheduled to be de-rated later in the next few years so this percent may be different with future testing.

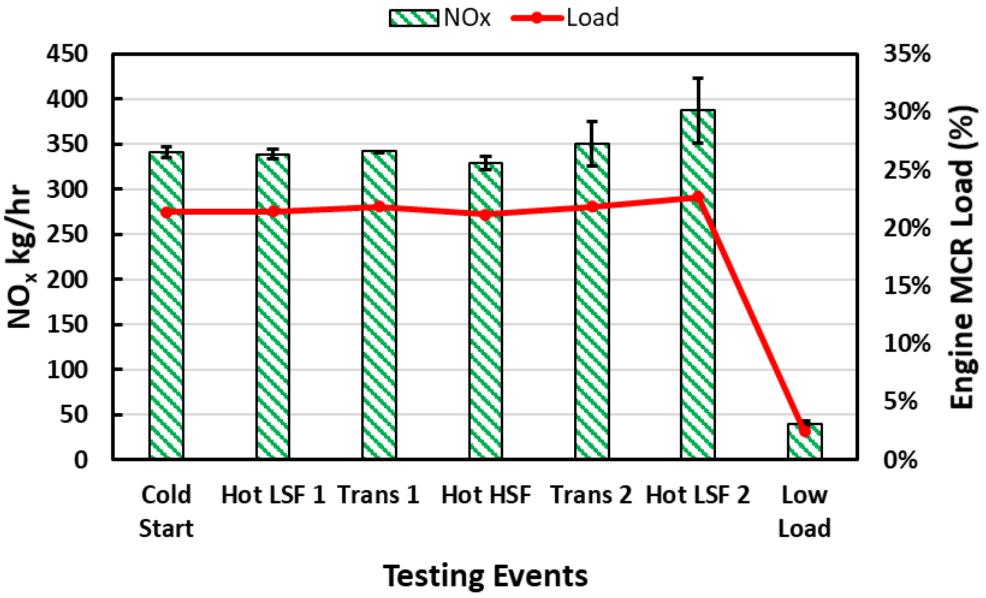

Figure 3-2 NO_x Emissions for the ME, kg/hr

Table 3-1: Category 1 OGV Emissions Standards Set by IMO [1]

Tier	Date	NOx Limit, g/kWhr
I	2000	17
II	2011	14.4
III	2016†	3.4

[1] In NO_x Emission Control Areas (Tier II standards apply outside ECAs).

3.1.2 CO

The CO emissions results are shown in Figure 3-3. CO emissions ranged from 0.9 to 4.3 g/kWhr. The CO emissions decreased during the switch to the HSF and reached their minimum at this time. They then increased after the switch back to the LSF and continued to increase to their maximum as the engine load decreased. It is interesting that CO emissions reduced with increase sulfur weight fraction in the fuel. CO emissions have been shown to correlate with PM emissions and, as discussed below, as the CO reduced with higher sulfur content, the PM emissions also reduced. This suggests the engine is more ideally tuned for higher sulfur fuel (0.5%) than it is for the MGO fuel (LSF). More discussion is provided in the PM section, but this is an important point to consider for characterizing health impact from OGV PM emissions.

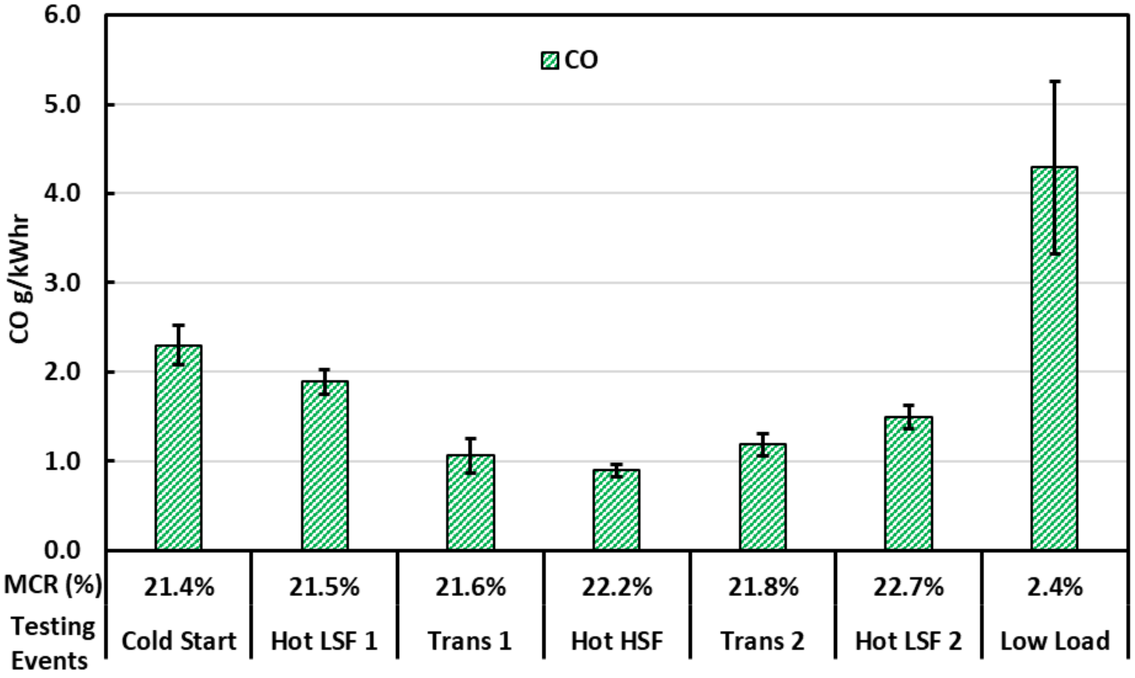

Figure 3-3 CO Emissions for the ME g/kWhr

3.1.3 CO_2

The CO_2 emission results are shown in Figure 3-4. The y-axis in the figure ranges from 650 to 750 g/kWhr to show the slight changes in the mass emission. The CO_2 emissions ranged from 698 g/kWhr to 704 g/kWhr. The CO_2 emissions were relatively constant throughout the testing period with almost no change during the transition to and from the HSF. In addition, the CO_2 emissions decreased slightly when the engine load was decreased from the roughly 22% load to 2% load. Lower CO_2 emissions at lower loads is uncommon for internal combustion engines. It is suspected that some type of cylinder cut out or other low load (low speed) combustion technology was employed to reduce fuel consumption on a brake specific basis at this low of a load. As discussed in Section 2.1.2, the engine was derated for improved low speed low load operation. This derating involved changing of fuel injectors, turbocharger nozzle ring, revised engine control software, and remote-control operations by MAN for continuous engine optimization. The results show good repeatability at each test event, indicating testing consistency and the low load and low CO_2 emissions suggest improved performance at low load operation which may have also reduced the NO_x emission at loads below 10% MCR (speeds less than 10 knots).

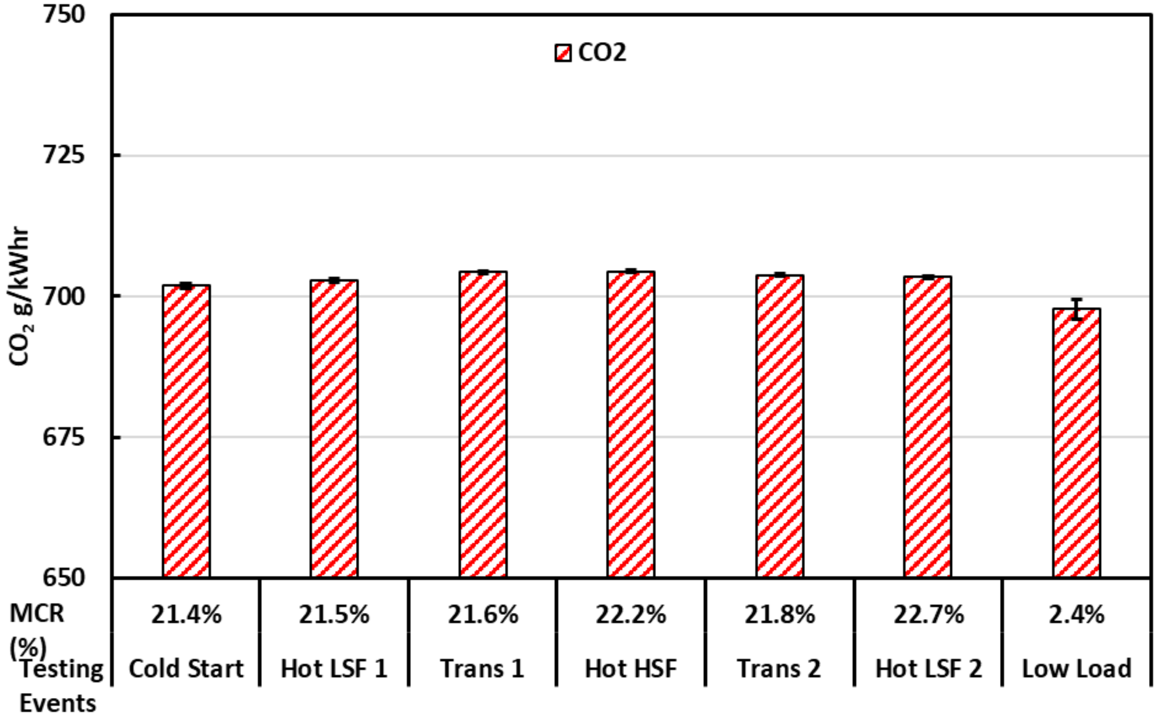

Figure 3-4 CO_2 Emissions for the ME in g/kWhr

3.1.4 SO_2

The SO_2 emission results are provided in Figure 3-5 in g/kWhr. The SO_2 emissions increased from 0.21 g/kWhr during the first hot LSF section to 0.90 g/kWhr after the fuel was switched to the HSF. It was observed that the SO_2 amount did not decline very quickly after the fuel was switched back to the LSF. This is shown by comparing the two hot LSF sections which increased from 0.21 g/kWhr (Hot LSF 1) compared to 0.34 g/kWhr (Hot LSF 2). The SO_2 also during the low load section was 0.33 g/kWhr.

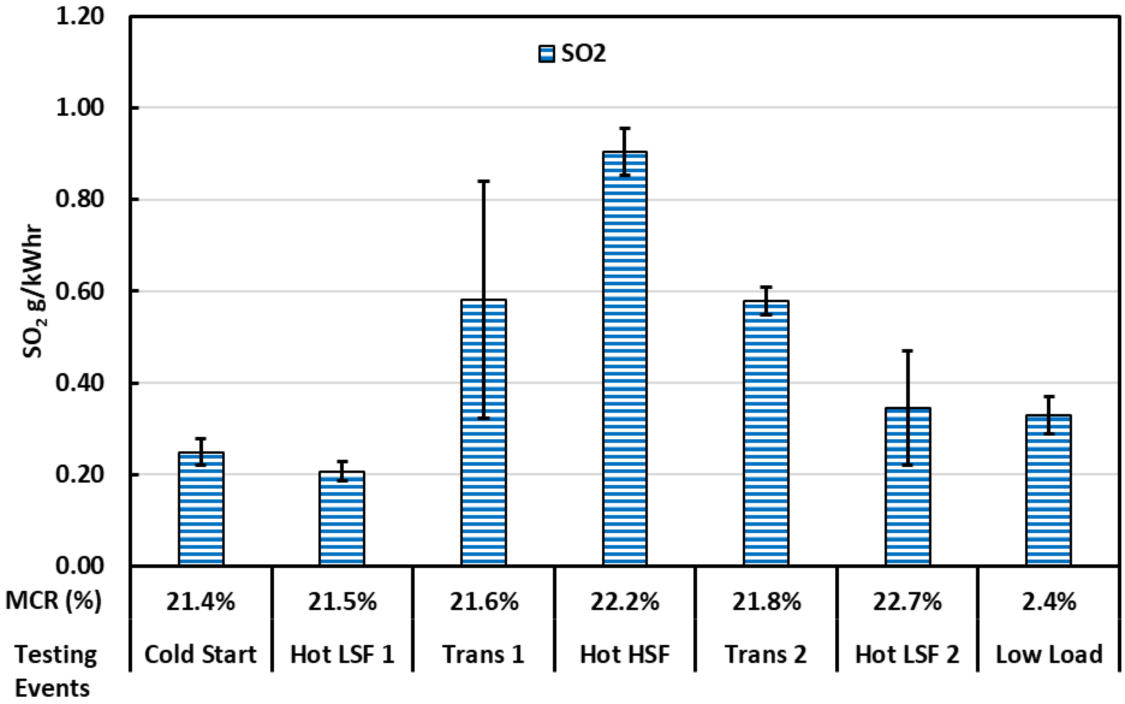

Figure 3-5 SO_2 Emissions for ME in g/kWhr

3.2 PM: Interval

The PM emissions are organized by PM mass ($PM_{2.5}$ diameter less than 2.5 µm) and PM composition (EC, OC), see Section 2.3 for more details on sampling methodology. The PM mass measurement includes all of the PM formed during combustion and dilution cooling (such as elemental, organic, sulfur, and metals) and the composition separates out the elemental carbon (or equivalent black carbon) and organic carbon to look at changes is composition as the engine transitions from the two fuels studied in this project. PM sulfur was not measured as part of this project but will be estimated based on previous testing.

3.2.1 PM Mass

During startup in the morning, as the vessel was transitioning away from the dock, PM emission flakes were depositing on the deck of the vessel. To qualitatively capture the magnitude of the emissions, we took a photo to compliment the measurements we performed in the exhaust stack. Figure 3-6 shows a photograph of the PM plume as we slow steamed (5-6 knots) away from the port. It was a unique experience to get the photograph at the same time the stack emissions as the engine were warming up and transiting. This transitioning data is usually not collected since most test plans target stabilized emission factors and not startup and transitioning emissions. The photo correlates to our first sample point denoted “cold start” in Figure 3-7 and Figure 3-8. Figure 3-7 and Figure 3-8 show the $PM_{2.5}$ mass emissions for the ME in units of g/kg-fuel, respectively. Once the vessel was under way and had transitioned to cruise conditions, the plume was no longer visible as shown in Figure 3-6.

The ME $PM_{2.5}$ emissions were highest for the cold start condition (1.25 g/kWhr) and the low load condition (0.89 g/kWhr) which is very representative for normal port maneuvers. Once the vessel had reached its operating conditions and stabilized speeds of 15 knots, the $PM_{2.5}$ emission factors varied from 0.4 g/kWhr to 0.26 g/kWhr and appear slightly lower on the HSF than with the LSF, but due to the large error bars, the differences are not statistically significant. However, a deeper evaluation of the PM composition suggests there a statistically significant change in the PM composition which is of interest. This will be discussed in the next section. The PM mass trend was similar for the fuel specific emissions as shown in Figure 3-8.

Figure 3-6 PM emissions resulting from the vessel during port maneuvering.

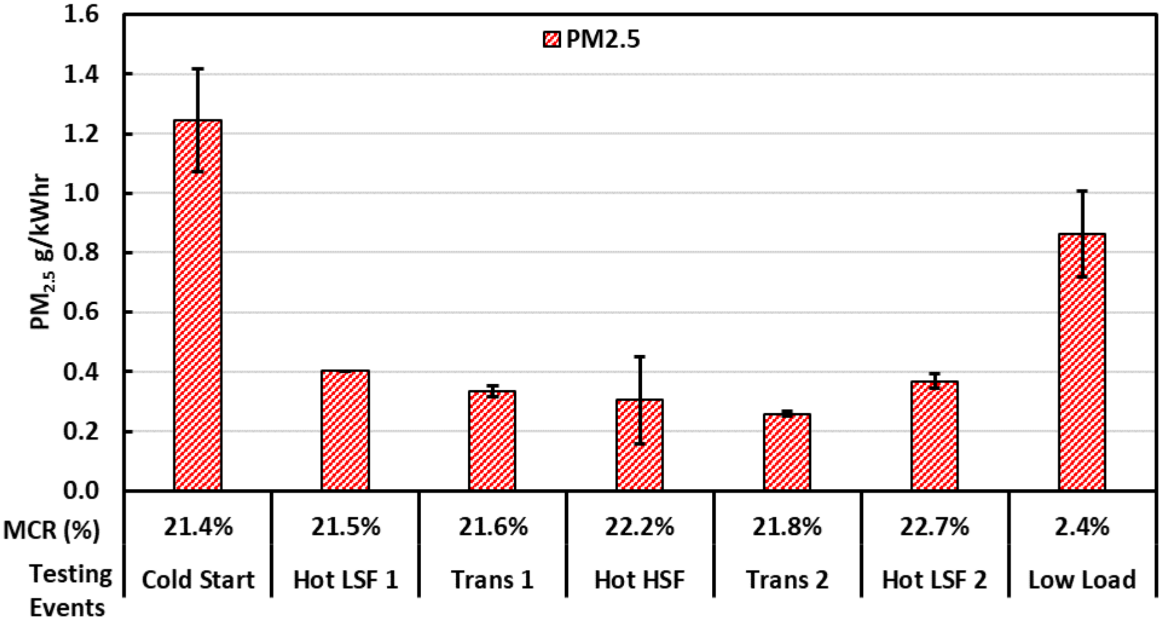

Figure 3-7 $PM_{2.5}$ Emissions for the ME in g/kWhr

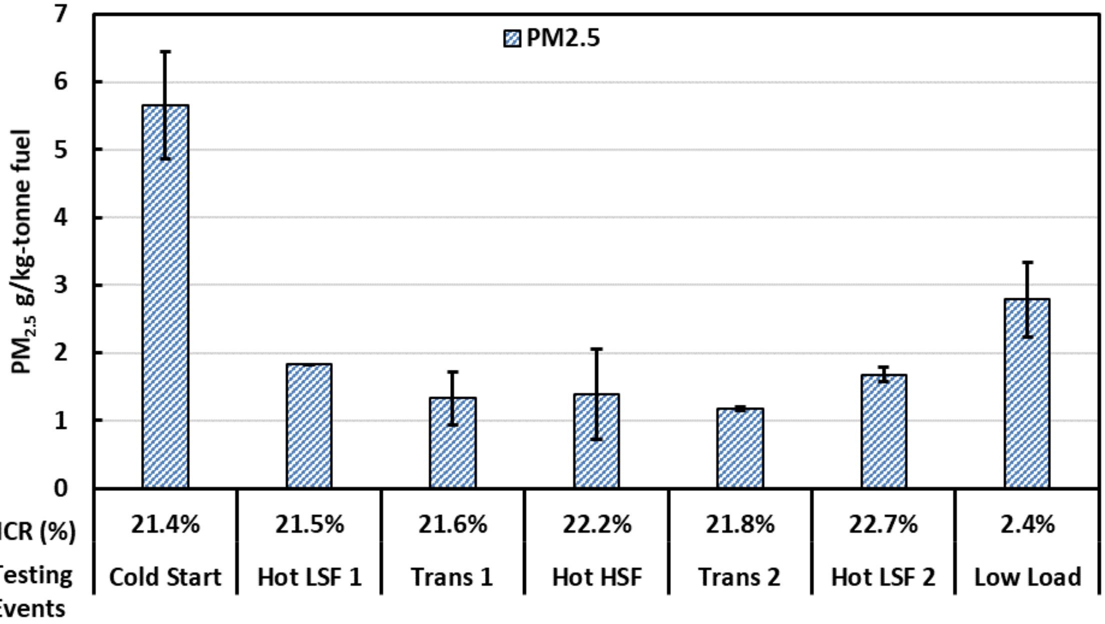

Figure 3-8 $PM_{2.5}$ Emissions for the ME in g/kg-fuel

3.2.2 PM composition

The PM composition for the MEs shown in Figure 3-9 (units of g/kWhr) and Figure 3-10 (g/kg-fuel). The ME PM emissions for the LSF are predominantly composed of OC (69% in total) and a smaller contribution from EC (30% in total) and less than 1% for sulfur and metals (the sulfur and metals are estimated based on previous testing of OGVs). The EC fraction of the PM composition was greater during the cold start and the low load sections, similar to the total PM.

In comparing the second Hot LSF section and the Hot HSF section, the low-sulfur fuel showed a higher total PM emission compared to high sulfur fuel where the increase in total PM resulted from an increase in both elemental and organic PM emissions

Elemental carbon (or combustion soot or equivalent black carbon) is typically a product of combustion efficiency and organic carbon is typically a product of fuel quality. It is interesting to see that as the fuel transition from LSF to HSF, the elemental and organic carbon decrease then increase back as the fuel transition switches back to LSF, but total PM mass is relatively constant, see Figure 3-11 and Figure 3-12. The reason for the flat PM emission factor is a result of added sulfur in the fuel which adds to the total PM mass. This suggests the HSF burns better and produces less elemental and organic carbon PM compared to the LSF but with more sulfate mass due to the higher sulfur in the fuel where the total PM mass is the same.

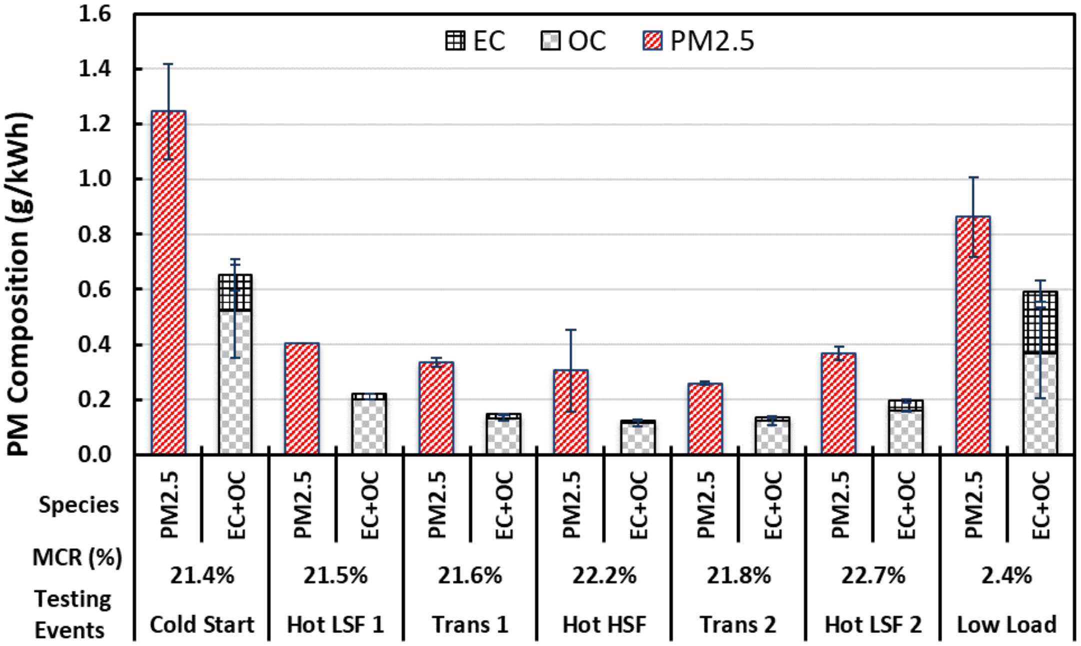

Figure 3-9 PM composition Emissions for the ME in g/kWhr

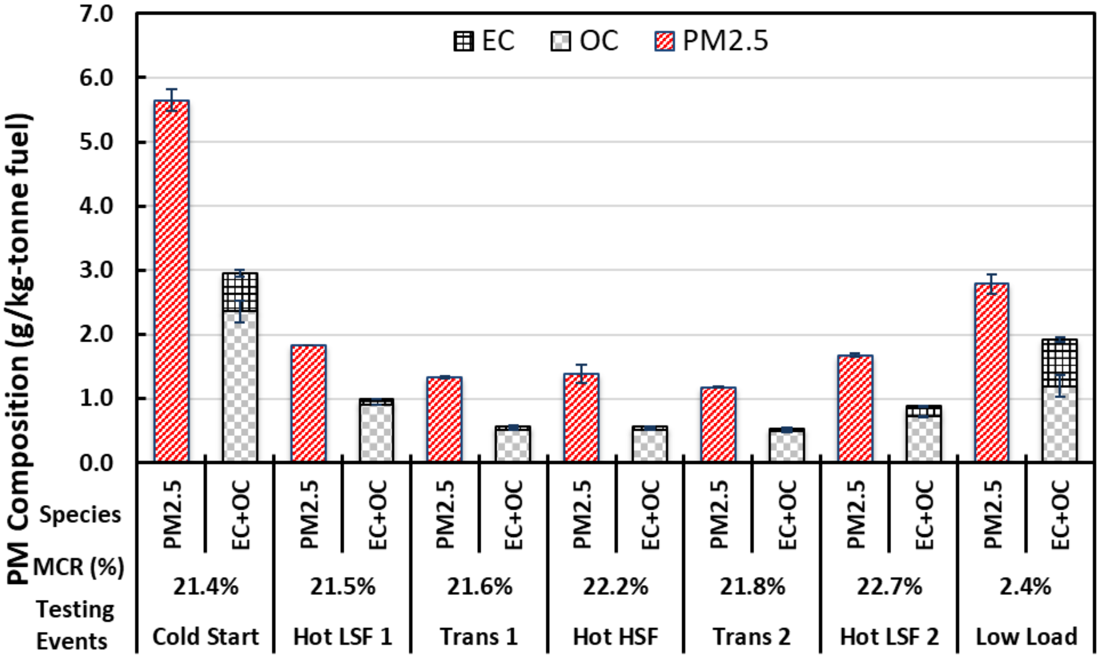

Figure 3-10 PM composition Emission for the ME in g/kg-fuel

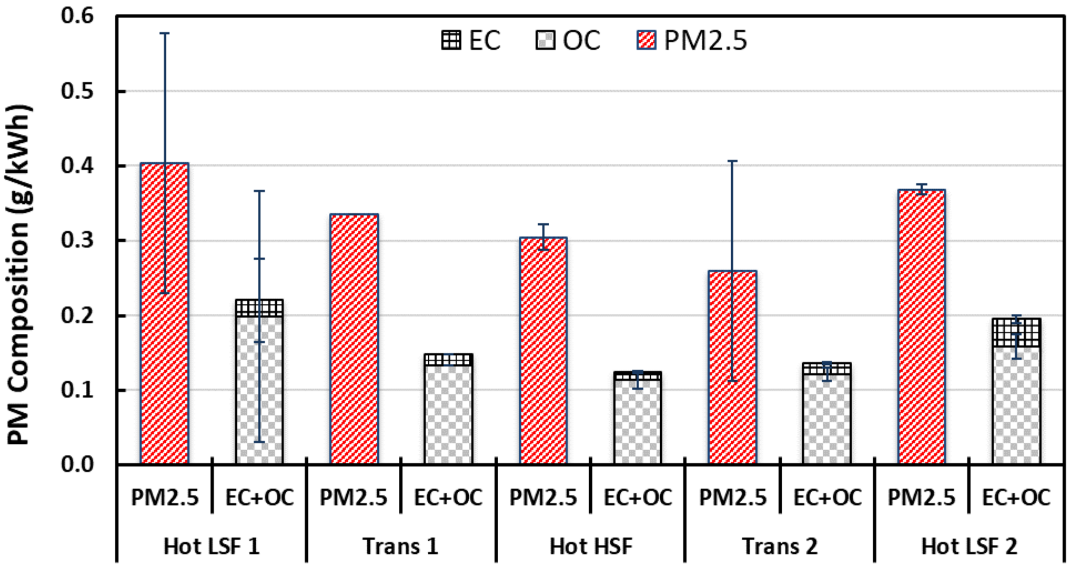

Figure 3-11 PM composition for the 22% load points, g/kWhr

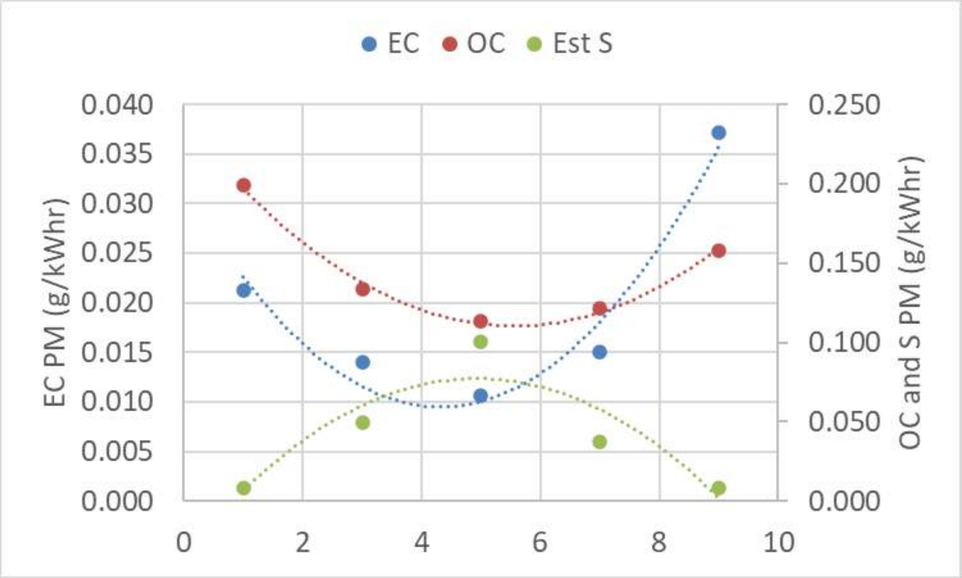

Figure 3-12 EC, OC, and estimated S (Est S) for the 22% load points, g/kWhr

[1] Sulfate PM was not measured but calculated based on the measured SO_2 concentration and previous sulfate contribution to the total PM mass from previous testing on SSD engines.

3.3 Gaseous: Comparison to other instruments

This section was provided to compare the direct stack sampling ISO 8178 methods with the other measurement methods demonstrated as part of the broader scope of this work. The other methods included drone sampling, continuous direct plume sampling, 15-minute fuel samples, and other off-line analysis methods. As such, UCR analyzed the data from the continuous analyzers over different time segments (see Section 3.3.1 Sample averaging) and then calculated the concentrations expected in the raw plume during 15 minutes intervals (see Section 3.3.2 Gaseous concentration), then those were calculated into a mass emission rate (see Section 3.3.3 Gaseous mass emissions), then finally a sulfur calculated result was provided during the specific intervals (see Section 3.3.4 Fuel sulfur). The gaseous emissions include NO_x, CO, CO_2, and SO_2. In the figures below, fuel switching is marked by a vertical black dashed line.

3.3.1 *Sample averaging*

Figure 3-13 shows the comparison between a thirty-second average for SO_2, a two-minute average, and the integrated batch sampling average for SO_2. The close comparison between the thirty-second and two-minute averaging methods suggests the data is stabilized and comparable to other measurement methods utilized by the drone, fuel samples, and other real time devices demonstrated as part of a different element of this research project. The slight delay and lower value for the integrated sampling, representative of the data from Section 3.1 suggest the integrated data is slightly low and delayed.

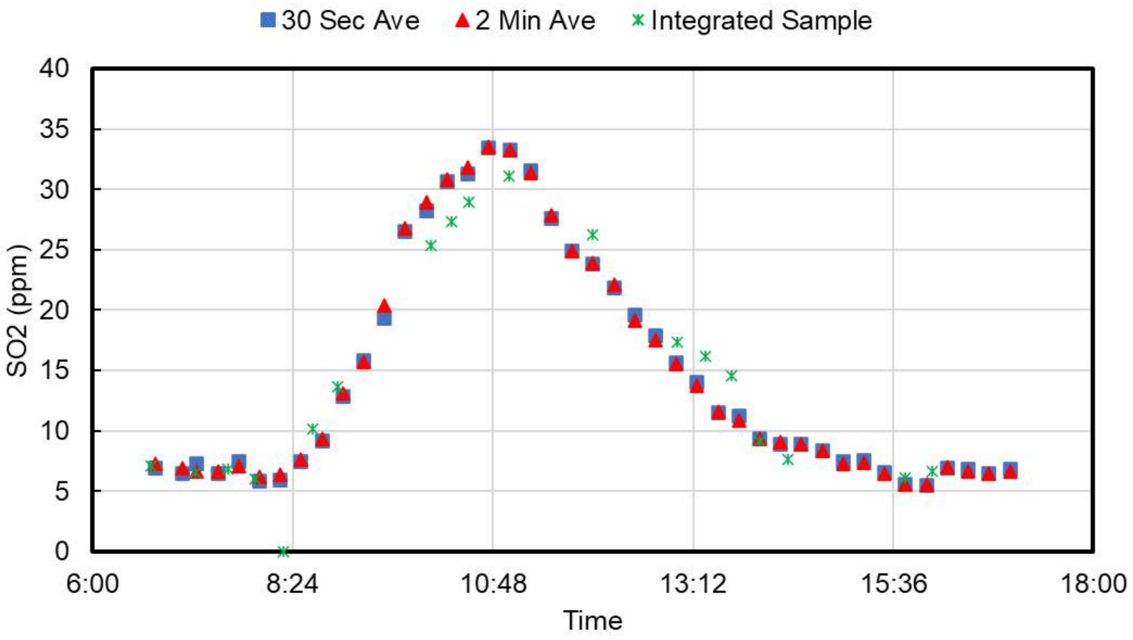

Figure 3-13. Continuous Gaseous Emissions of SO_2 and CO.

3.3.2 *Gaseous concentration*

In this section, gaseous measurements were averaged in two-minute intervals centered at the time the fuel samples were taken. In the figures below, the time at which fuel samples were pulled is marked as Fuel Flag. Fuel switching is marked by a vertical black dashed line. A vertical solid black line marks when the fuel switch was assumed to be completed.

The CO_2 and NO_x emissions are shown in Figure 3-14 in units of PPM, with CO_2 in %. The CO and SO_2 emissions are shown in Figure 3-15 in PPM. CO_2 and NO_x largely follow the same trend. Neither display a significant change during the fuel switching to and from the high sulfur fuel. The increase in NO_x concentration at the beginning of the test day, before the fuel switch, may be attributed to engine combustion temperatures, as NO_x formation is largely temperature dependent, and the engine started cold. The CO and SO_2 emissions followed opposite trends. SO_2 followed a sharp incline where it started at 7 PPM before the fuel switch and reached a maximum of 34 PPM at the switch back to the low sulfur fuel in about two hours. SO_2 then declined at a slower rate relative to the incline, where it took approximately four hours to reach 7 PPM.

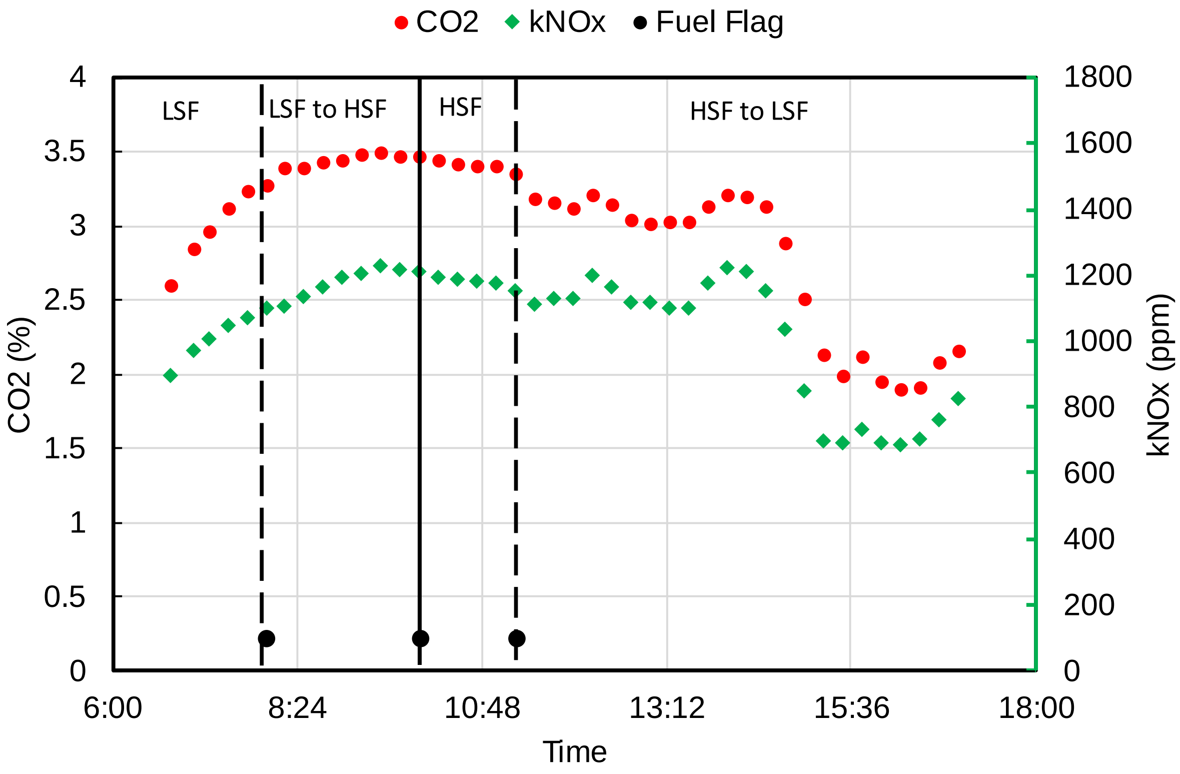

Figure 3-14. Continuous Gaseous Emissions of CO_2 and NO_x.

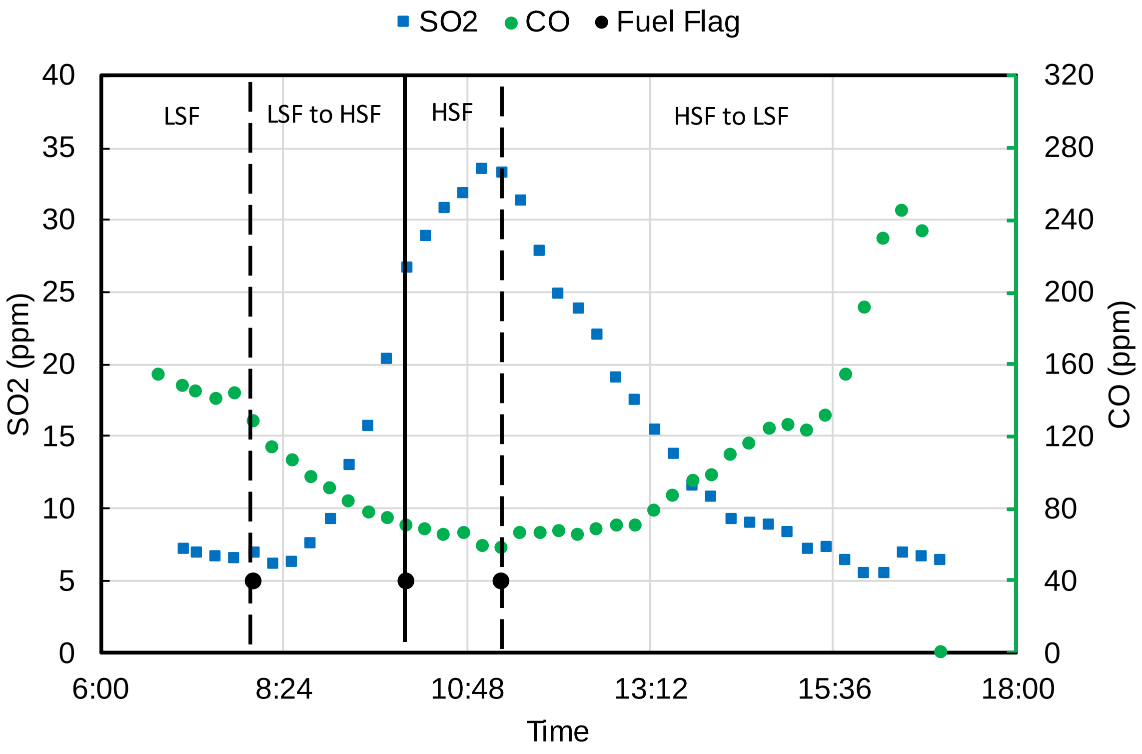

Figure 3-15. Continuous Gaseous Emissions of SO_2 and CO.

3.3.3 Gaseous mass emissions

In this section, gaseous mass measurements were averaged in two-minute intervals centered at the time the fuel samples were taken. In the figures below, the time at which fuel samples were pulled is marked as Fuel Flag. Fuel switching is marked by a vertical black dashed line. A vertical solid black line marks when the fuel switch was completed.

The exhaust flow, fuel rate, and engine power/10 are shown in Figure 3-16 in m^3/hr, kg/hr, and kW. This figure shows that there was some variability in the engine power once it reached ~13,000 kW (21 % MCR) from approximately 7:00 to 14:00. During this time there is large variability in the fuel rate and exhaust flow. This has a large impact on mass emissions which are displayed in Figure 3-17 and Figure 3-18, showing large variations in the mass emissions, in comparison to the previous gaseous emission figures in Section 3.3.2 plotted in concentration. The figures are presented in concentrations displayed a smoother line but when multiplied by the exhaust flow, the variation is greatly increased. UCR believes the variability in exhaust flow is not real, but demonstrates the difficulty in making these measurements on OGV.

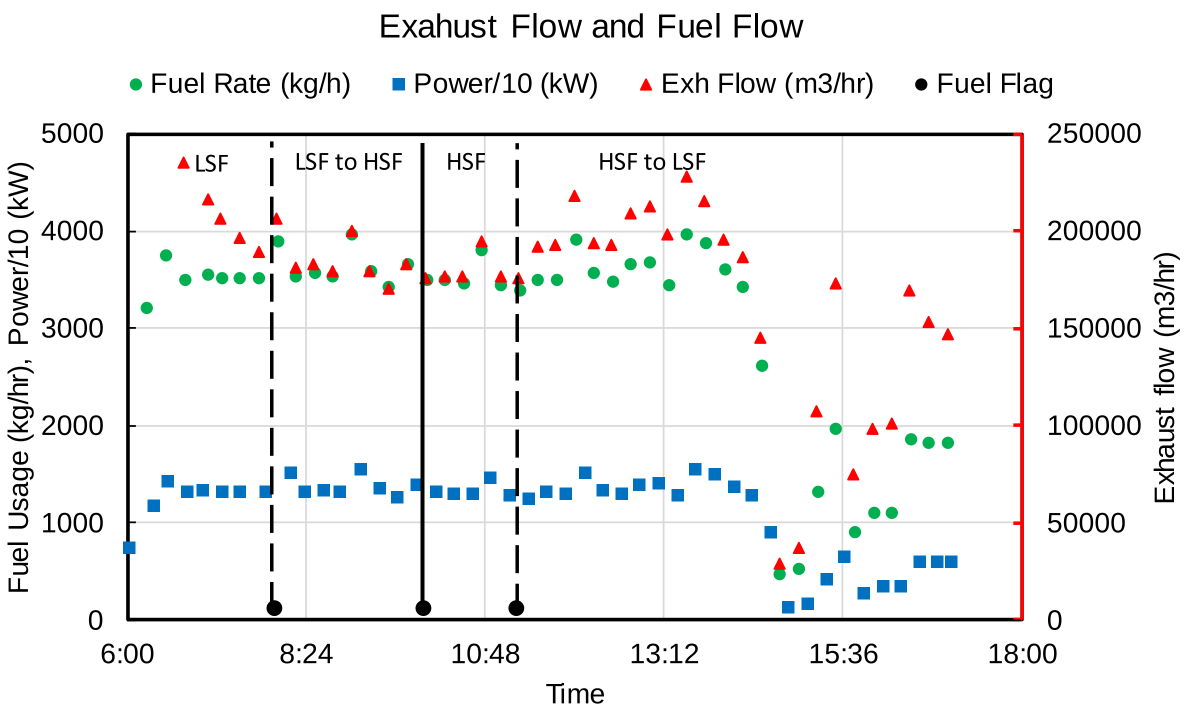

Figure 3-16. Exhaust flow (m^3/hr), fuel rate (kg/hr), and engine power/10 (kW)).

[1] plotted with the fuel switches (dashed black line) and fuel switch completion (solid black line

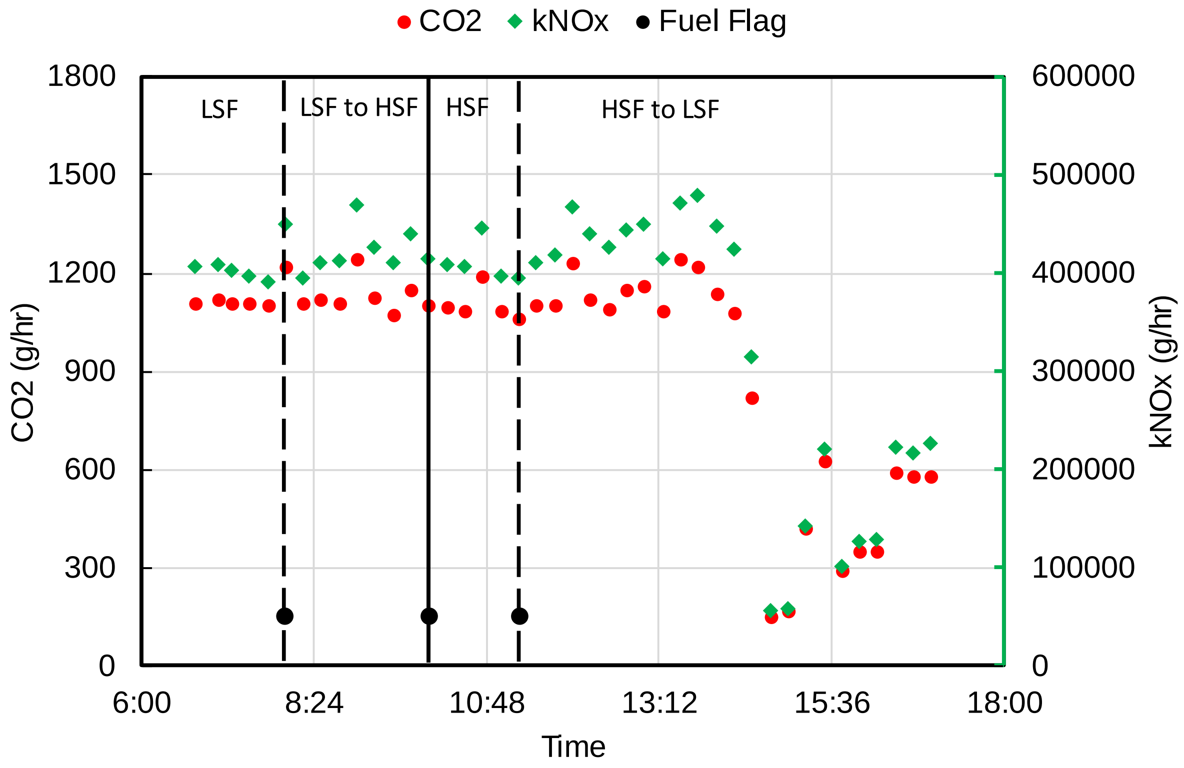

Figure 3-17. Continuous Gaseous Mass Emissions of CO_2 and NO_x.

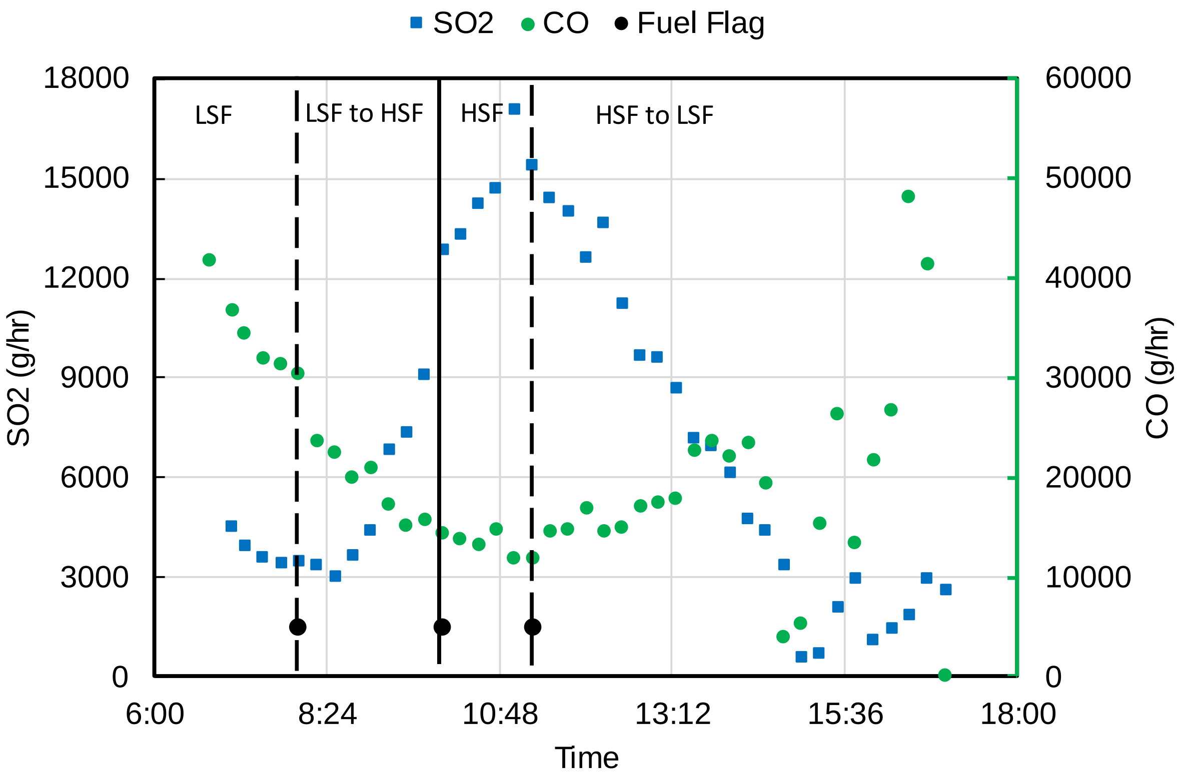

Figure 3-18. Continuous Gaseous Mass Emissions of SO_2 and CO.

3.3.4 Fuel sulfur

This section provides a comparison of two ways to report fuel sulfur. In the figures below, the time at which fuel samples were pulled is marked as Fuel Flag. Fuel switching is marked by a vertical black dashed line. A vertical solid black line marks when the fuel switch was completed. The fuel sulfur percentage is plotted with the exhaust flow in m^3/hr in Figure 3-19. The fuel sulfur percentage is determined by mass calculation of the fuel rate and the SO_2 mass emissions. The ratio of SO_2/CO_2, the exhaust flow in m^3/hr, are shown in Figure 3-20. The SO_2/CO_2 method of reporting fuel sulfur is used by OGVs that are equipped with scrubbers by their CEMS. A line at a ratio of 4.3 was added to the figure to show the 0.1% fuel sulfur compliance. Both methods show a similar representation of the fuel sulfur content.

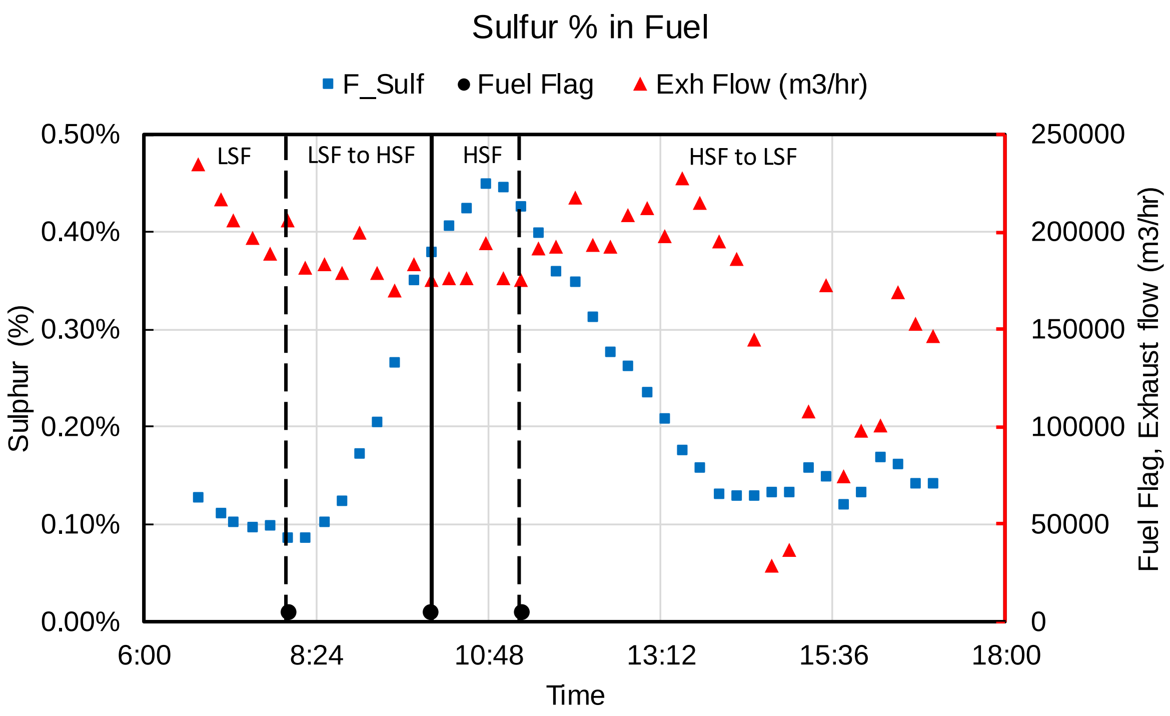

Figure 3-19. Fuel sulfur percentage and exhaust flow.

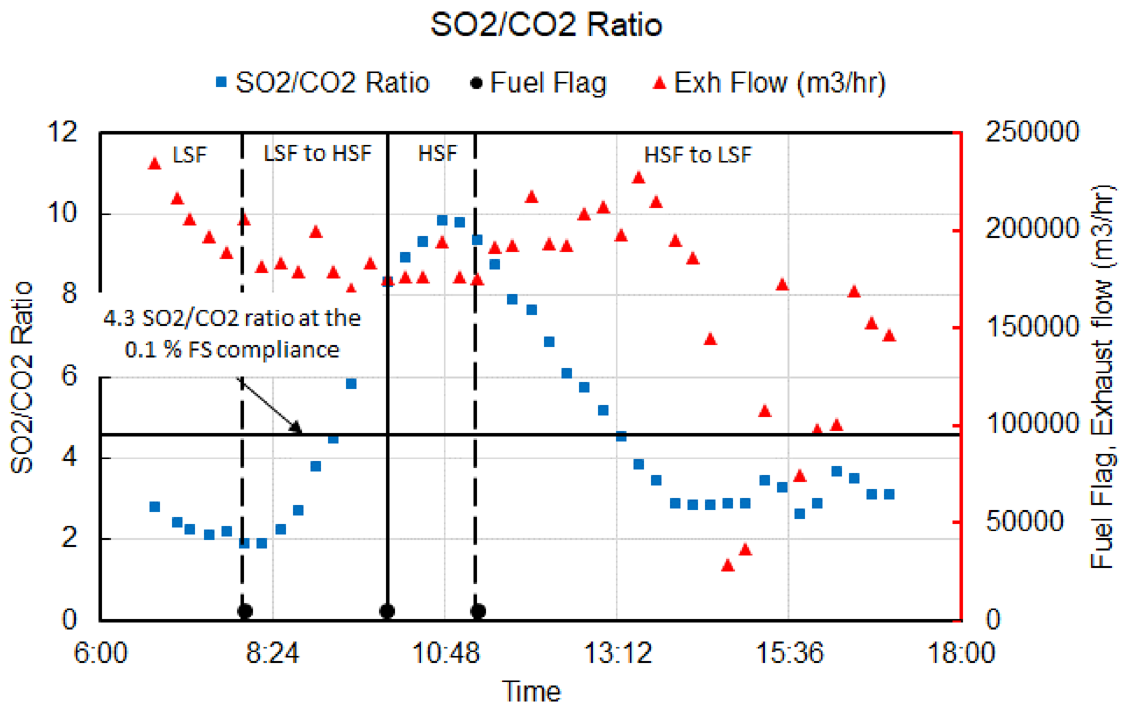

Figure 3-20. SO_2/CO_2 Ratio and exhaust flow for different 2 min sample intervals

[1] IMO compliance of scrubbers uses a ratio of SO_2/ CO_2 for compliance at the 0.1% fuel sulfur. The limit is a value of 4.3 which is representative of 0.1% sulfur limit. The data shows all the measurements are below 4.3.

Summary

Emissions measurements were made on a Tier 1 large container ocean-going container vessel on two fuels, a low sulfur MGO fuel and a low sulfur residual fuel oil (VLSFO). The two fuels were representative of fuel required for local port maneuvers and one utilized while cruising at sea. The low sulfur MGO fuel is denoted as the low sulfur fuel (LSF) and the VLSFO is denoted as the high sulfur fuel (HSF) in this summary.

Testing occurred at near the ports of Long Beach and Los Angeles. The ME testing included a cold start, fuel switching from 22% load (15 knots), and one low load condition at 2.4% of the engines maximum continuous rating (MCR) load (6-7 knots) which is representative of typical operation near and around ports. The emissions were measured following ISO and CFR methods for gaseous and PM emissions (PM total mass and its composition including elemental and organic carbon species). Gaseous and PM emission and calculations were performed following ISO 8178 and tighter specifications for PM dilution ratio and filter temperatures met 40 CFR 1065 specifications.

A summary of the results for the testing is as follows:

- The testing of this vessel’s ME was a success and included:
    - samples collected at specific intervals to characterize the vessel emission factor for non-continuous measurements such as PM mass and composition.
    - samples collected continuously to allow direct comparison to measurements made by other researchers. These other data are provided in a separate report but include the following measurements methods and species can be compared between the studies.
        - Drone plume measurements, Aeromon (SO_2, NO_x, CO_2, CO)
        - Vessel fixed point plume measurement, Telops (SO_2 and NO_x)
        - Fuel samples using traditional analytical methods, CARB (fuel Sulfur)
        - Fuel samples using experimental online method, Adept Group (fuel Sulfur)
- The results presented in this report represent the derated conditions of the engine which employed hardware and software changes targeted for improved efficiency at slower speeds.
- The bunker report for the two fuels were 0.48% sulfur for the HSF and 0.0928% sulfur for the LSF.
- The interval emission results were slightly shifted and lower compared to the two-minute continuous analyzer samples. Thus, the two-minute samples represent the better data for the comparisons between the plume and other fuel sampling methods and the characterization of the vessel is best represented by the 15-minute interval samples.
- The load varied several times in the middle of the day which may be a measurement error or a real load change during maneuvering. The load change did cause a small impact in both the interval results and the mass based continuous emissions results for sulfur fuel content since all the stack methods are dependent on engine load for mass determination. Further analysis is needed to understand if this is real since the vessel

was maintaining a constant speed but was making course corrections throughout the day.

- **Vessel emission factors, interval emissions results**
    - PM mass and composition
        - The PM emissions were collected over an interval which averaged between 15- to 20-minutes. During this interval the continuous gaseous concentrations were also measured.
        - The ME $PM_{2.5}$ emissions were highest for the cold start condition (1.25 g/kWhr) and the low load condition (0.89 g/kWhr).
        - The $PM_{2.5}$ emission factors varied from 0.4 g/kWhr to 0.26 g/kWhr for the hot stabilized 22% load condition.
        - The HSF elemental and organic carbon PM emissions were lower compared to the LSF but showed a higher sulfate mass emission. The higher sulfate mass emissions were a result of the higher sulfur fuel. The total $PM_{2.5}$ mass emissions, however, were the same between the two fuels.
    - CO_2
        - The CO_2 emissions ranged from 698 g/kWhr to 704 g/kWhr.
        - The CO_2 emissions did not show a statically significant change between the LSF and HSF.
        - The CO_2 emission factor decreased slightly when the engine load was decreased from 22% load to 2.4% load. The lower CO_2 emissions at lower loads is uncommon for compression ignition engines. It is suspected that some type of low load combustion technology was employed to reduce fuel consumption at this low of a load. The vessel was derated in 2015 to improve the fuel economy of the vessel at low steaming operation as tested during this testing which may be the reason for the improvement in fuel economy at the 2.4% load.
    - NO_x
        - The average NO_x emissions at 22% load were about the same as the 25% load certification value but were about 50% higher than the certification standard for a Tier 1 engine (17 g/kWhr).
        - The NO_x emissions were similar for the cold start and hot running NO_x emissions.
        - The 2.4% load (6-7 knot vessel speed) NO_x emission factor was also surprisingly low and showed a similar emission factor at the 22% load. Typically, NO_x increases as load decreases for compression ignition engines. It is speculated that the improved engine efficiency during the derating also reduced the low load NO_x emissions.
- **Method comparison, continuous sampling**
    - SO_2 varied from 7 ppm to 34 ppm at the peak of the measurements performed.
    - The CO_2 concentration varied from 7:00 am to about 9:30 am and ranged from 2.5% to 3.5%. It then dropped back off after 10 am to around 3%.
    - NO_x concentration varied from 7:00 am to about 9:30 am and ranged from 900 ppm to 1200 ppm. It then dropped back off after 10 am to around 1100 ppm.

    - The measured fuel sulfur content based on SO_2 mass emissions and fuel consumption rates varied from 0.09 % for the LSF up to 0.46 % for the HSF. This agrees well with the fuel bunker report from the vessel.
    - The SO_2/CO_2 ratio ranged from two to ten which agrees well with the IMO requirement for scrubbers to be less than 4.3 representative of a fuel sulfur level of 0.1 sulfur.
- **Summary of observations**
    - The Tier 1 vessel equipped with an upgraded engine for slow steaming operation resulted in improved low load fuel consumption and reduced NO_x emissions.
    - When estimating NO_x emissions inventories in a port area, a 25% load point emission factor for non-SCR vessels should be used.
    - The derated engine emitted less organic and elemental carbon PM on HSF compared to the LSF (MGO compliant fuel). Although there is an anticipated total PM mass benefit for the use of low sulfur MGO fuels, their use near ports will increase organic and elemental carbon PM emissions compared to low sulfur residual fuel oils with <0.5% sulfur.
    - The calculated sulfur fuel percent from the stack measurements agrees well with the bunker report, suggesting the results in this report can be used for the other measurement technologies comparisons in the other study.

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Appendix A – Sample Collection Methods

ISO 8178-1[2] and ISO 8178-2[3] specify the measurement and evaluation methods for gaseous and particulate exhaust emissions when combined with combinations of engine load and speed provided in ISO 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[4], 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.

Gaseous and Particulate Emissions

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

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[2] 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

[3] 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

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

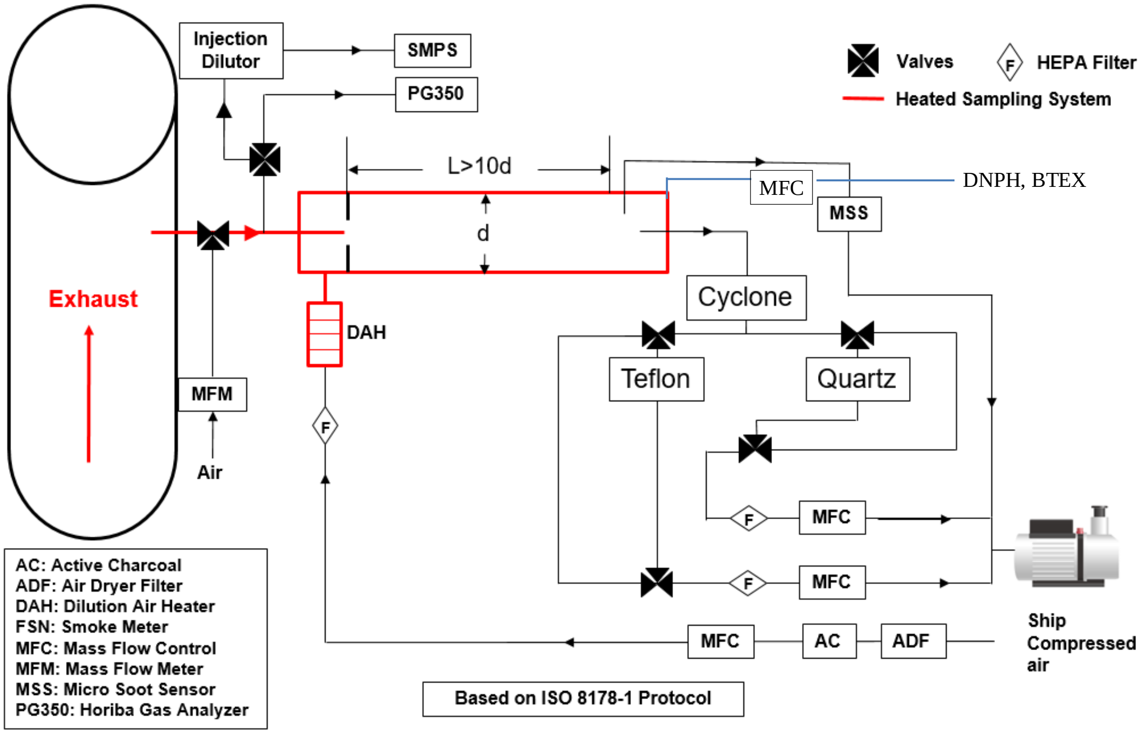


Figure A-1 Regulated and non-regulated emissions sampling system

The flow in the dilution system eliminates water condensation in the dilution tunnel and sampling systems and maintains the temperature of the diluted exhaust gas at <52°C before the filters. ISO cautions that 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 is shown in Figure A-1. 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 A-1.

In 2015 UCR upgraded its dilution tunnel to include dilution air heating and sample heating. These upgrades are implemented on all testing systems, but due to heat in the exhaust, they do not impact the sampling system for non-scrubber tests. During previous scrubber testing UCR dilution and filter temperature control was found to be inadequate. Scrubbers utilize cold sea water which reduces the exhaust temperature and impacts the PM formation mechanism (as part of the scrubber design). Due to low scrubber exhaust gas exit temperatures (<20˚C vs ~300˚C without a scrubber), sample heating was needed to maintain a filter face temperature near 47˚C above the saturation point of the supersaturated exhaust. Consistent filter face temperatures have been shown to improve PM sampling and are recommended by 40 CFR Part 1065 and are optional (but still better) as per ISO 8178.

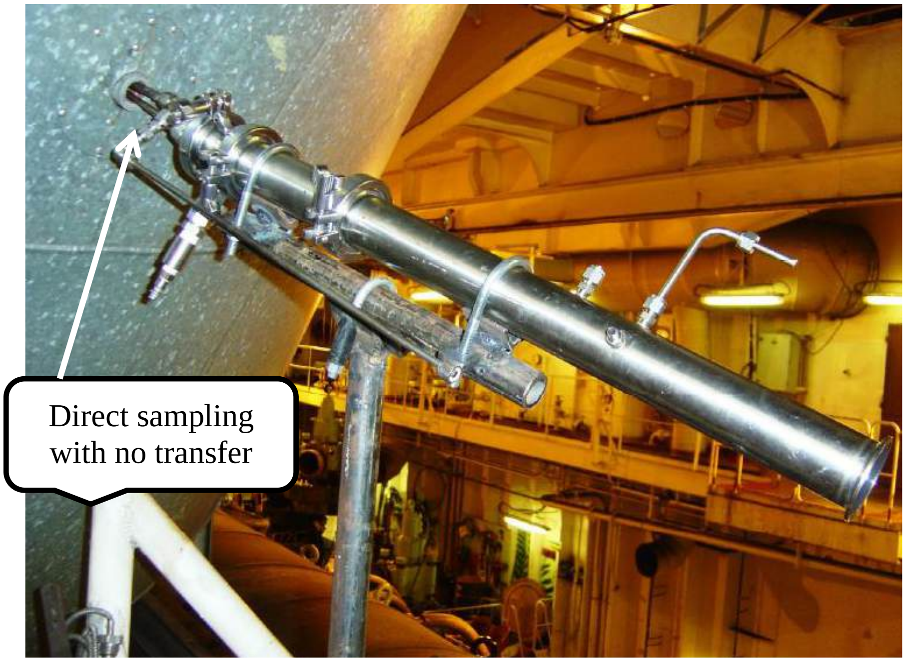


Figure A-2 measurement layout on an engine exhaust stack

UCR implemented active dilution air and sample heating for scrubber equipped vessels. The design of the system has a one second residence time (recommended) and has a heated sample line section followed by a heated dilution air system. Both heated systems were designed to target a 47˚C (±5˚C) filter face temperature for both pre and post-scrubber samples. Since this testing did not involve a scrubber, the heater was turned off due to high exhaust temperatures.

Dilution Air System

40 CFR Part 1065 recommends dilution air to be 20 to 30°C and ISO recommends 25 ±5°C. Both also recommend using filtered and charcoal scrubbed air to eliminate background hydrocarbons. The dilution air may be dehumidified. The system can be described as follows: The pressure is reduced to around 40 psig, 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 campaign. Figure A-3 shows the field processing unit in its transport case. In the field the case is used as a framework for supporting the unit.

Table A-1 Components of a Sampling System: ISO 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 collection of 10 pipe diameters of straight pipe upstream is recommended and performed where possible. For some tight configurations use good engineering judgment.	UCR follows the ISO recommendation, when 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 uses a transfer tube of 0.15 m (6 inches). Additionally the sample tube insertion length varies with stack diameter, but typically penetrates at least 10%, but not more than 50% of the stack diameter.
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 the 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

Figure A-3 Field Processing Unit for Purifying Dilution Air in Carrying Case

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.

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.

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/CFR recommends that the concentration of SO_2 is calculated based on the fact that 97.75% of the fuel sulfur is converted to SO_2 (40 CFR Part 1065). UCR agrees with this recommendation and the enclosed SO_2 reported emissions are calculated from fuel sulfur levels.

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 dioxide;
- Heated chemiluminescent detector (HCLD) or equivalent for measurement of nitrogen oxides;
- Paramagnetic detector (PMD) or equivalent for measurement of oxygen.
- Cross-Flow Modulation Non-Dispersive Infrared Absorption Method for sulfur dioxide and carbon monoxide

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

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

ISO, IMO, and CFR 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. 40 CFR Part 1065 requires 95% and recommends 98%. The efficiency of the converter shall be >95 % and will be evaluated prior to testing.

ISO requires measurement of the effects of exhaust gases on the measured values of CO, CO_2, NO_x, and O_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.

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 USEPA.

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.

Cross-Flow Modulation advanced efficiency of NDIR analysis

In PG-300, Cross-Flow Modulation is newly applied to SO_2, CO, and new CH_4 analyzers. With Cross-Flow Modulation NDIR method, sample gas and reference gas flow into a single measurement cell switching one by one, and it brings about advantages that no optical adjustment is required, the zero point is kept stable, and the sample cell remains clean and it reduces span drift. The equipments will be kept safe for a long time as well. Cross-Flow Modulation Chemiluminescence detection method is already introduced for NOx analyzer in previous model and has the same effects as aforesaid analyzers.

Figure A-4 Gas analyzer setup with measurement cell description

Details of the gases and the ranges for the Horiba instrument are shown in Table A-2. Note that the Horiba instrument measures sulfur oxides (SO_2); however, UCR follows the protocol in ISO which recommends calculation of the SO_2 level from the sulfur content of the fuel as the direct measurement for SO_2 is less precise than calculation. When an exhaust gas scrubber is present, UCR recommends measuring the SO_2 concentration after the scrubber since the fuel calculation approach will not be accurate due to scrubber SO_2 removal performance expectations.

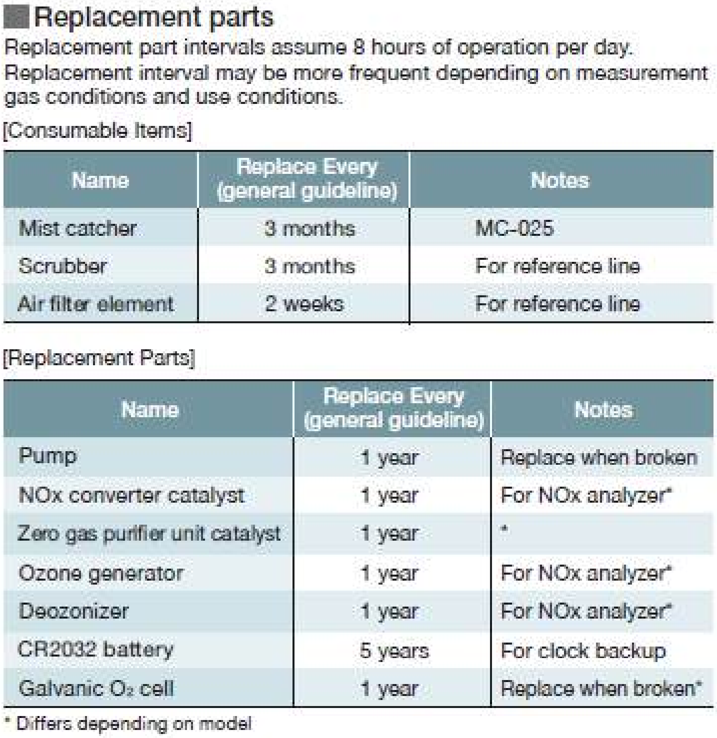
Table A-2 Detector Method and Concentration Ranges for Monitor

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). Cross flow modulation	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). Cross flow modulation	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 A-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 A-3 Quality Specifications for the Horiba PG-350

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)



Replacement parts

Replacement part intervals assume 8 hours of operation per day. Replacement interval may be more frequent depending on measurement gas conditions and use conditions.

[Consumable Items]

Name	Replace Every (general guideline)	Notes
Mist catcher	3 months	MC-025
Scrubber	3 months	For reference line
Air filter element	2 weeks	For reference line

[Replacement Parts]

Name	Replace Every (general guideline)	Notes
Pump	1 year	Replace when broken
NOx converter catalyst	1 year	For NOx analyzer*
Zero gas purifier unit catalyst	1 year	*
Ozone generator	1 year	For NOx analyzer*
Deozonizer	1 year	For NOx analyzer*
CR2032 battery	5 years	For clock backup
Galvanic O_2 cell	1 year	Replace when broken*

* Differs depending on model

Figure A-4b Gas analyzer replacement parts and maintenance

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 (40 CFR Part 1065 is 47±5 °C), as measured at a point immediately upstream of the PM filter. The particulate consists of primarily carbon, condensed hydrocarbons, sulfates, associated water, and ash. 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 (and is typically below 47°C also). IMO does not offer a protocol for measuring PM and thus a combination of ISO and CFR practices are adopted. A comparison of the ISO and UCR practices for sampling PM is shown in Table A-4.

Table A-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	PTFE coated glass fiber	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	Single is typical unless looking at artifacts
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, post PM control ~ 100
Weighing chamber	22±3°C & RH= 45%± 8	22±1 °C & dewpoint of 9.5 °C±1°C (typically < ±0.6°C)
Analytical balance, LDL µg	10	LDL = 3 and resolution 0.1
Flow measurement	Traceable method	Same
Flow calibration, months	< 3months	Every campaign

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 adopted the 40 CFR Part 1065 sampling methodologies as no other method is prescribed for fuels with a higher sulfur content.

Calculating Exhaust Flow Rates

The calculated emission factor requires the measurement of the engine’s exhaust flow rate. The exhaust gas flow can be determined by the following methods:

1. Direct Measurement Method
2. Carbon Balance Method
3. Air and Fuel Measurement Method
4. Air Pump method

Method 1: Direct Measurement of exhaust
Actual exhaust mass flow rate can be determined from the exhaust velocity, cross sectional area of the stack, and moisture and pressure measurements. The direct measurement method is a difficult technique, and precautions must be taken to minimize measurement errors. Details of the direct measurement method are provided in ISO 5167-1.

Method 2(a)-Carbon Balance
Carbon Balance is used to calculate the exhaust mass flow based on the measurement of fuel consumption and the exhaust gas concentrations with regard to the fuel characteristics. The method given is only valid for fuels without oxygen and nitrogen content, based on procedures used for EPA and ECE calculations. Detailed calculation steps of the Carbon Balance method are provided in annex A of ISO 8178-1. Basically: In…lbs fuel/time * wt% carbon * 44/12 → input of grams CO_2 per time Out… vol % CO_2 * (grams exhaust/time * 1/density exhaust) → exhaust CO_2 per time
Note that the density = (mole wt*P)/(R* Temp) where P, T are at the analyzer conditions. For highly diluted exhaust, M ~ of the atmosphere.

Method 2(b)-Universal Carbon/Oxygen balance
The Universal Carbon/Oxygen Balance is used for the calculation of the exhaust mass flow. This method can be used when the fuel consumption is measurable and the fuel composition and the concentration of the exhaust components are known. It is applicable for fuels containing H, C, S, 0, N in known proportions. Detailed calculation steps of Carbon/Oxygen Balance method is provided in annex A of ISO 8178-1.

Method 3-Air and Fuel Measurement Method
This involves measurement of the air flow and the fuel flow. The calculation of the exhaust gas flow is provided in Section 7.2 of ISO 8178-1.

Method 4-Air Pump Method
Exhaust flow rate is calculated by assuming the engine is an air pump, meaning that the exhaust flow is equal to the intake air flow. The flow rate is determined from the overall engine displacement, and rpm; corrected for temperature and pressure of the inlet air and pumping efficiency. In the case of turbocharged engines, this is the boost pressure and intake manifold temperature. This method should not be used for diesel engines equipped with additional air input for cylinder exhaust discharge, called purge or scavenger air, unless the additional flow rate is known or can be determined.

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 vented outside the tunnel and the minor flow directed

to a cyclone separator, sized to remove particles >2.5um. The line leaving the cyclone separator is split into two lines; each line has a 47 mm 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 the quartz filters utilizing the NIOSH or IMPROVE methods. UCR recommends the IMPROVE method over the NIOSH.

Briefly, total PM is collected on Pall Gelman (Ann Arbor, MI) 47 mm Teflon filters and weighed using a Mettler Toledo UMX2 microbalance with a 0.1 ug resolution. Before and after collection, the filters are conditioned for 24 hours in an environmentally controlled room (22±1 °C and dewpoint of 9.5 °C) and weighed daily until two consecutive weight measurements are within 3 µg or 2%. It is important to note that the simultaneous collection of PM on quartz and Teflo™ filters provides a comparative check of PM mass measured by two independent methods for measuring PM mass.

Sulfur in the fuel produces SO_2 in the combustion process and some of the SO_2 becomes SO_3 in the exhaust and subsequently produces $H_2SO4 \bullet 6H_2O$ which is collected on the Teflon filter paper. After the final weights for the particulate laden Teflon filters have been determined a portion of the filter is punched out, extracted with High Performance Liquid Chromatography grade water and isopropyl alcohol and analyzed for sulfate ions by ion chromatography.

Measuring Real-Time Particulate Matter (PM) Emissions-DustTrak 8520

In addition to the filter-based PM mass measurements, UCR uses a Nephelometer (TSI DustTrak 8520) for continuous measurements of steady-state and transient data. The DustTrak is a portable, battery-operated laser photometer that gives real-time digital readout and has a built-in data logger. It measures light scattered (90 degree light scattering at 780nm near-infrared) by aerosol introduced into a sample chamber and displays the measured mass density in units of mg/m^3. As scattering per unit mass is a strong function of particle size and refractive index of the particle size distributions and as refractive indices in diesel exhaust strongly depend on the particular engine and operating condition, some 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 $3m^2/g$.

Figure A-5 Picture of TSI DustTrak

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.

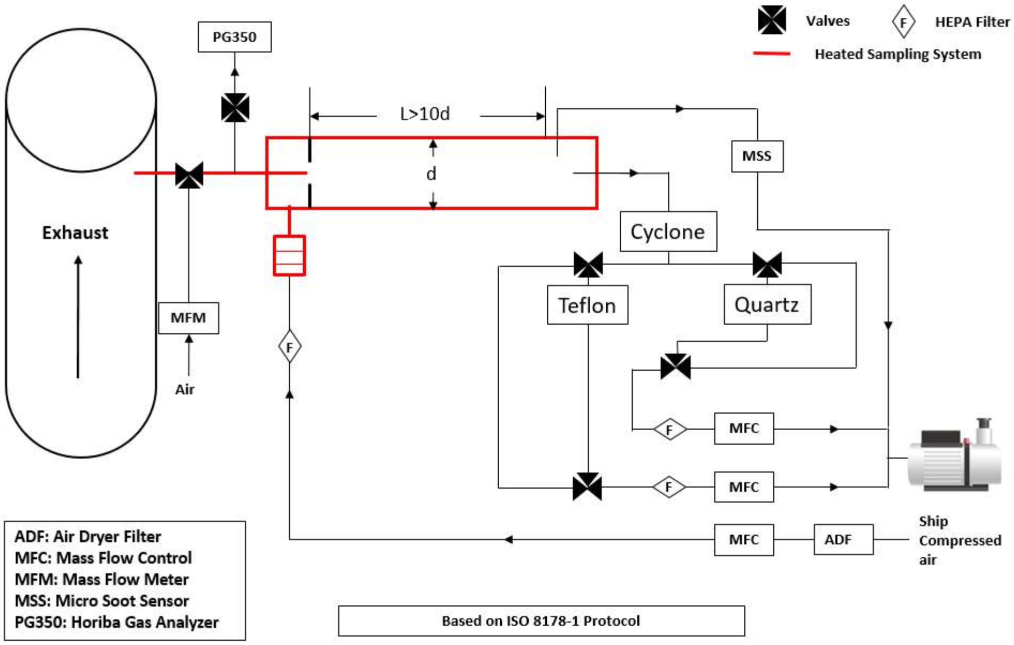


Figure A-5 Regulated emission sampling system

Appendix B – Quality Control

Pre-test calibrations

Prior to departing from UCR all systems will be verified and cleaned for the testing campaign. This included all instruments used during this testing project. Sample filters are checked and replaced if necessary.

On-site calibrations

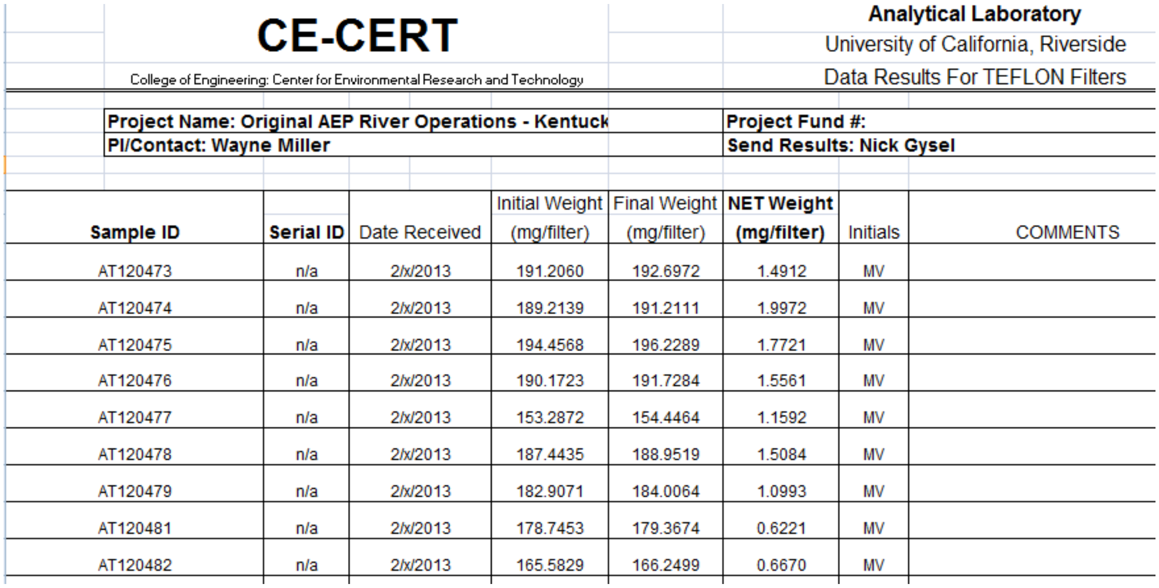
Pre- and post-test calibrations will be performed on the gaseous analyzer using NIST traceable calibration bottles. Dilution ratio was controlled and monitored with real time mass flow control. Zero checks were performed during selected times to coordinate with other testing that was occurring on the vessel. Leak checks were performed for the total $PM_{2.5}$ system prior testing for each setup.

Post-test and data validation

Post-test evaluation includes verifying consistent dilution ratios between points, and verifying brake specific fuel consumption with reported manufacturer numbers. Typically this involves corresponding with the engine manufacturer to discuss the results on an emissions basis of interest. If the brake specific fuel consumption results are within reason this suggests that the load and mass of emissions measured are reasonable and representative.

The figure below (Figure B-1) is an example of a chain of custody form. This is the form used to track filter weights from the test to the laboratory. One form for the filter weights, EC/OC, fuel sample, and sulfate analysis exists. This is just an example of media tracking that is used.

Figure B-2 is an example of UCR certified calibration bottles used for testing. Prior to using a new bottle the old one is verified with the new one as bottles can incorrect in their stated value. It is rare, but can happen.



CE-CERT

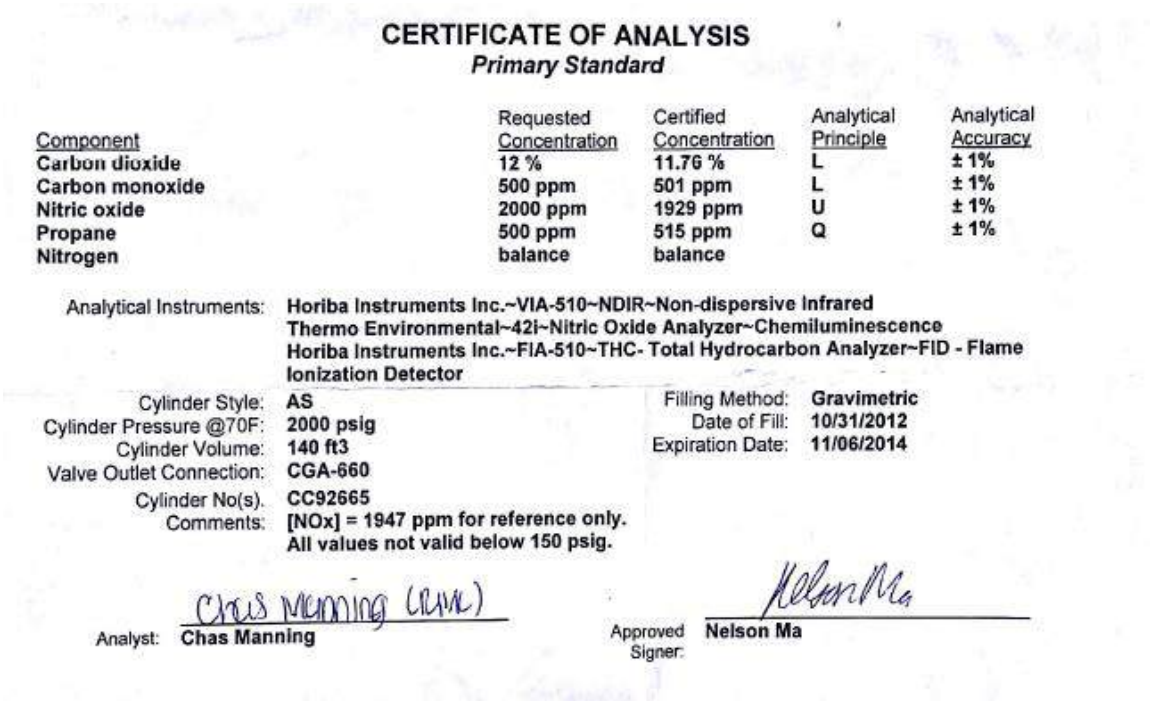
College of Engineering: Center for Environmental Research and Technology

Analytical Laboratory
University of California, Riverside
Data Results For TEFLON Filters

Project Name: Original AEP River Operations - Kentuck
Project Fund #:
PI/Contact: Wayne Miller
Send Results: Nick Gysel

Sample ID	**Serial ID**	Date Received	Initial Weight (mg/filter)	Final Weight (mg/filter)	**NET Weight (mg/filter)**	Initials	COMMENTS
AT120473	n/a	2/x/2013	191.2060	192.6972	1.4912	MV	
AT120474	n/a	2/x/2013	189.2139	191.2111	1.9972	MV	
AT120475	n/a	2/x/2013	194.4568	196.2289	1.7721	MV	
AT120476	n/a	2/x/2013	190.1723	191.7284	1.5561	MV	
AT120477	n/a	2/x/2013	153.2872	154.4464	1.1592	MV	
AT120478	n/a	2/x/2013	187.4435	188.9519	1.5084	MV	
AT120479	n/a	2/x/2013	182.9071	184.0064	1.0993	MV	
AT120481	n/a	2/x/2013	178.7453	179.3674	0.6221	MV	
AT120482	n/a	2/x/2013	165.5829	166.2499	0.6670	MV	

Figure B-1 Sample Chain of Custody Form



CERTIFICATE OF ANALYSIS

Primary Standard

Component	Requested Concentration	Certified Concentration	Analytical Principle	Analytical Accuracy
Carbon dioxide	**12 %**	**11.76 %**	**L**	**± 1%**
Carbon monoxide	**500 ppm**	**501 ppm**	**L**	**± 1%**
Nitric oxide	**2000 ppm**	**1929 ppm**	**U**	**± 1%**
Propane	**500 ppm**	**515 ppm**	**Q**	**± 1%**
Nitrogen	**balance**	**balance**		

Analytical Instruments: **Horiba Instruments Inc.~VIA-510~NDIR~Non-dispersive Infrared**
Thermo Environmental~42i~Nitric Oxide Analyzer~Chemiluminescence
Horiba Instruments Inc.~FIA-510~THC- Total Hydrocarbon Analyzer~FID - Flame Ionization Detector

Cylinder Style: **AS**
Cylinder Pressure @70F: **2000 psig**
Cylinder Volume: **140 ft3**
Valve Outlet Connection: **CGA-660**
Cylinder No(s). **CC92665**
Comments: **[NOx] = 1947 ppm for reference only.**
All values not valid below 150 psig.

Filling Method: **Gravimetric**
Date of Fill: **10/31/2012**
Expiration Date: **11/06/2014**

Chas Manning (RMK)
Analyst: **Chas Manning**

Nelson Ma
Approved Signer: **Nelson Ma**

Figure B-2 Sample Protocol Gas Analysis

Appendix C –Test Modes and Load Estimates

Test Cycles and Fuels for Different Engine Applications

Heavy duty engines for non-road use are made in a much wider range of power output and used in more applications than engines for on-road use. The objective of IS0 8178-4[5] is to provide the minimum number of test cycles by grouping applications with similar engine operating characteristics. ISO 8178-4 specifies the test cycles while measuring the gaseous and particulate exhaust emissions from reciprocating internal combustion 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 C-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.

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

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[1] 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)

conditions. Intermediate speeds for engines used to propel vessels with a fixed propeller are defined based on that application.

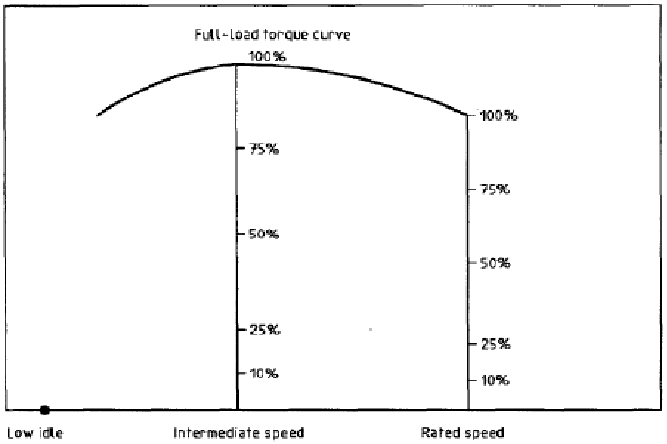


Figure C-1 Torque as a Function of Engine Speed

Engine Torque Curves and Test Cycles

The percentage of torque figures given in the test cycles and Figure C-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 C-2 shows the two representative curves.

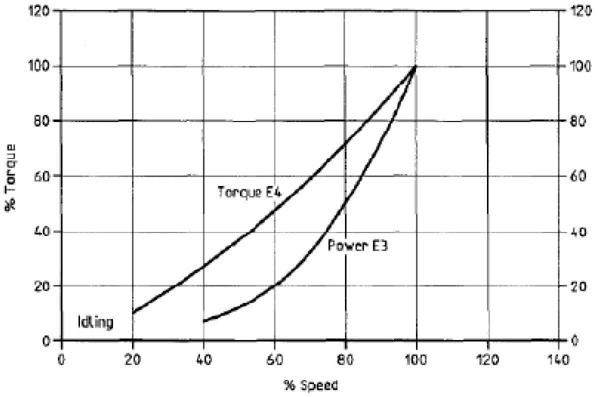
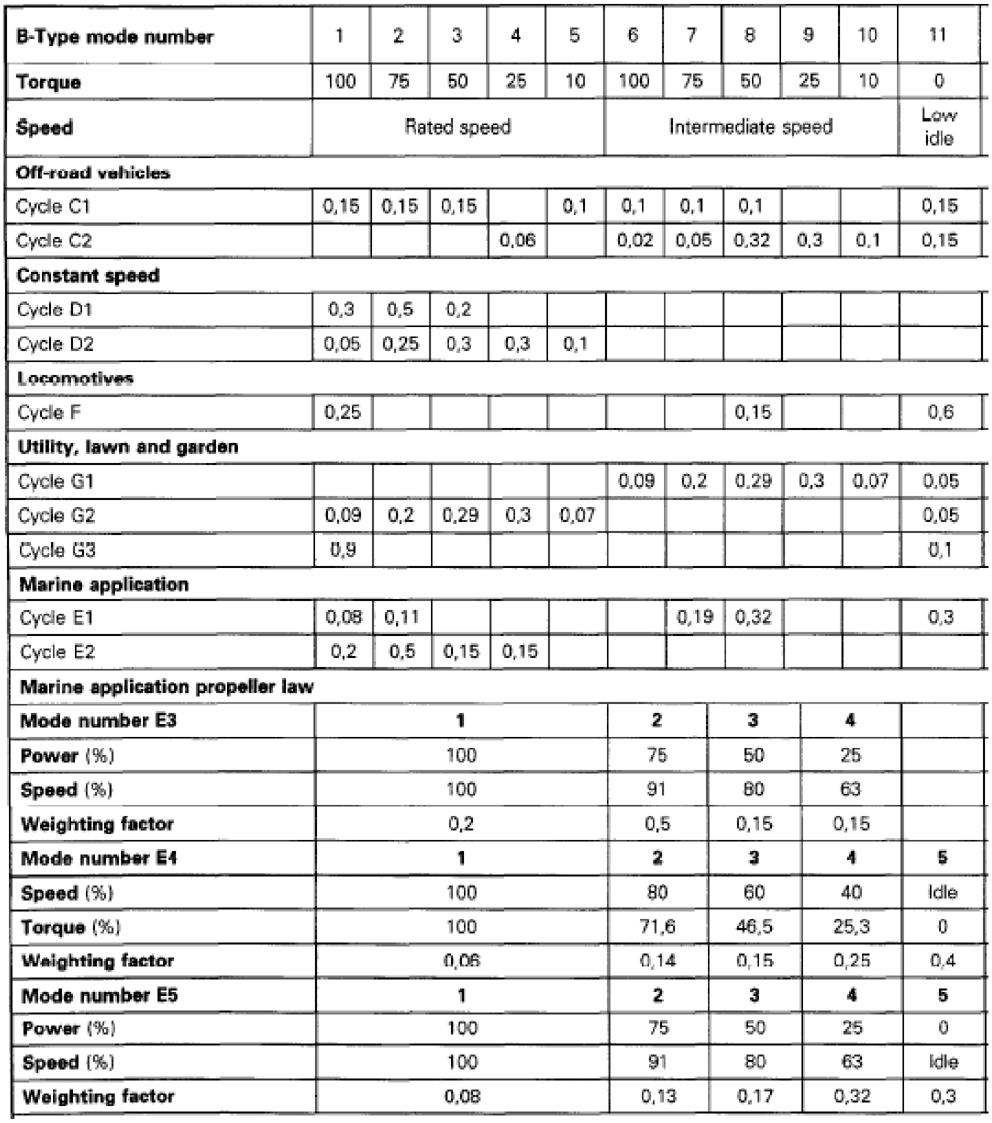


Figure C-2 Examples of Power Scales

Modes and Weighting Factors for Test Cycles

Most test cycles are 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 5 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.

Table C-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							

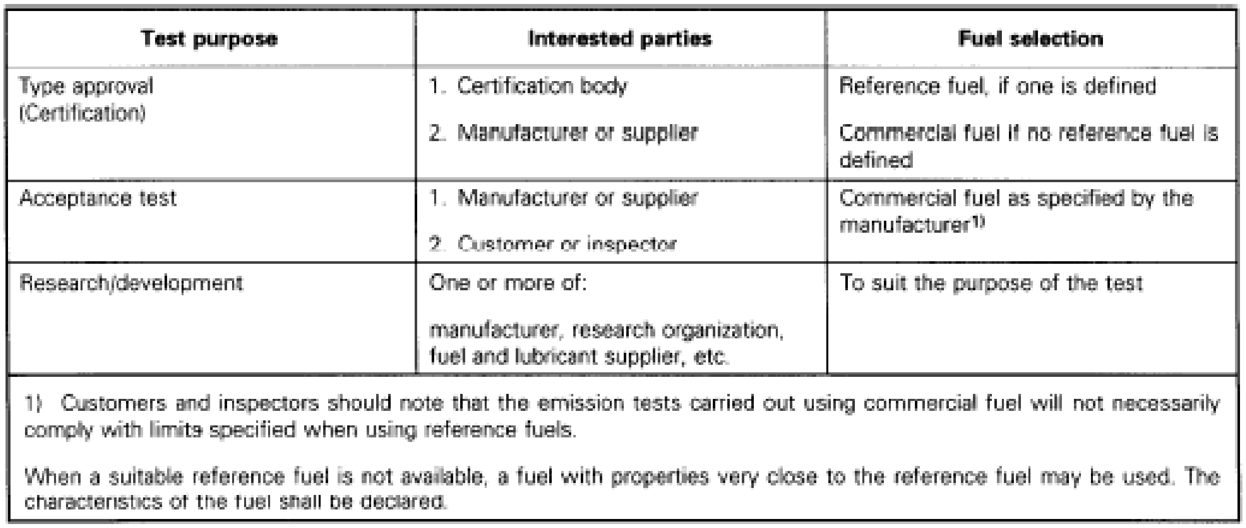
Marine application propeller law					
Mode number E3	**1**	**2**	**3**	**4**	
Power (%)	100	75	50	25	
Speed (%)	100	91	80	63	
Weighting factor	0,2	0,5	0,15	0,15	
Mode number E4	**1**	**2**	**3**	**4**	**5**
Speed (%)	100	80	60	40	Idle
Torque (%)	100	71,6	46,5	25,3	0
Weighting factor	0,06	0,14	0,15	0,25	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

Cycle C1 (also known as the Non-Road Steady Cycle NRSC) and C2 are typically used for off-road vehicles and industrial equipment such as yard tractors and air compressors (C1 for diesel and C2 for spark ignition). D1 and D2 are used for constant speed engines such as generators (marine or land based) and power plants. D1 is for power plants and irrigation pumps, but D2 is for generators and other. The D2 cycle is typically used for marine auxiliary electrical generation. The “E” cycles are for marine application. E1 and E5 are for diesel engines craft less than 24 meters, E2 is for constant speed propulsion (variable prop applications), E3 is for large marine direct drive engines.

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 C-3

Table C-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.

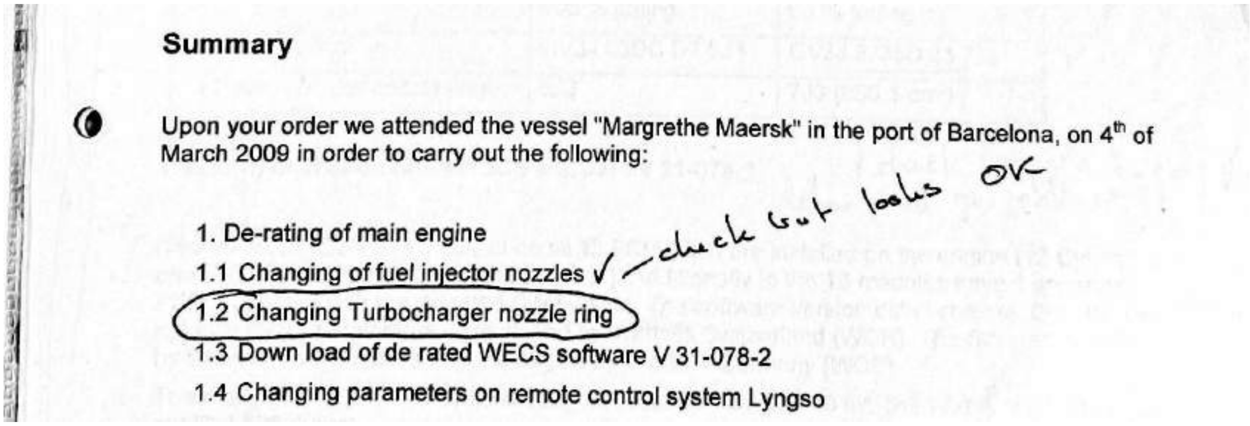
When a suitable reference fuel is not available, a fuel with properties very close to the reference fuel may be used. The characteristics of the fuel shall be declared.

Appendix D –Test Details and Data Records

This Appendix includes vessel and fuel records 1) Derating Records, 2) Fuel Analysis, and 3) Engine Screen Shots. These records were collected during testing.

1. Engine recertification information

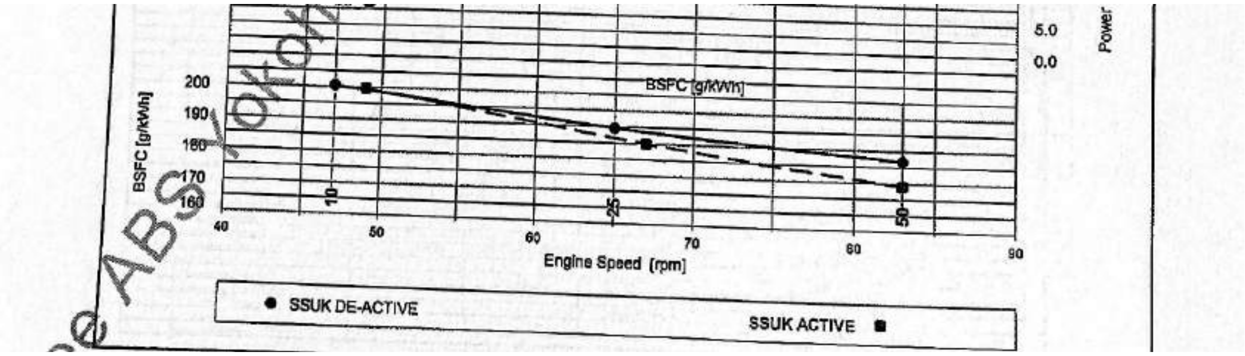
The engine derating included changes to the fuel injector nozzle, turbocharger nozzle ring, and software, see below taken from the summary report. Below the summary is a result of the de rated brake specific fuel consumption from 25% to 90% load as tested.



Summary

Upon your order we attended the vessel "Margrethe Maersk" in the port of Barcelona, on 4th of March 2009 in order to carry out the following:

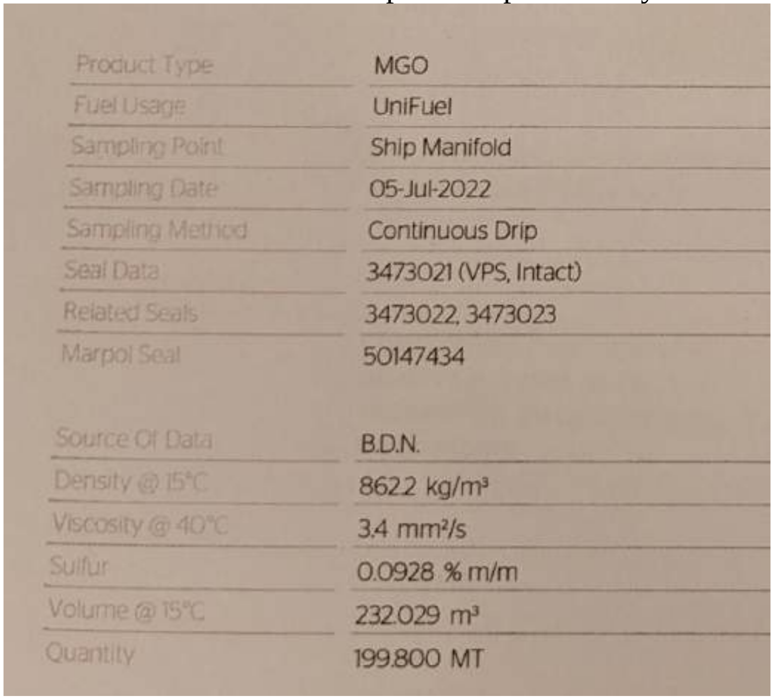
1. De-rating of main engine
1.1 Changing of fuel injector nozzles ✓ — check but looks OK
1.2 Changing Turbocharger nozzle ring
1.3 Down load of de rated WECS software V 31-078-2
1.4 Changing parameters on remote control system Lyngso



2. Fuel Certificates

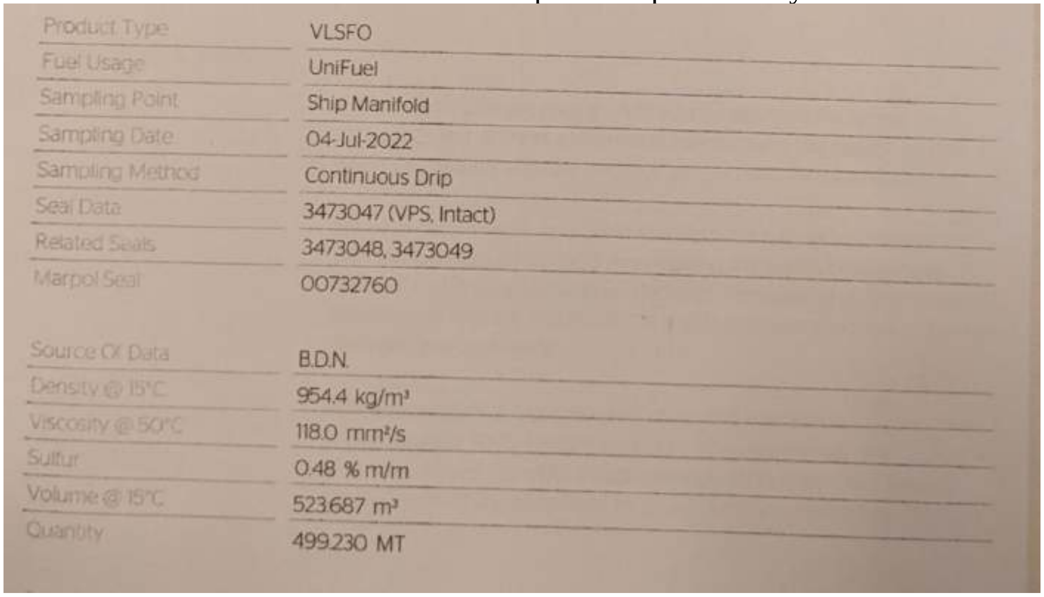
A fuel sample was collected during our testing and sent out for analysis. The results are shown in the table below. The fuel sulfur was 0.0893 % for the ULSFO fuel and 0.0382 % for the MGO fuel (fuel sample FS19001 and FS19002 respectively, see Figure D-1). The heating value utilized for the ULSFO fuel was 42.99 MJ/kg and for the MGO it was 44.0 MJ/kg. A vessel bunker report, from June 2018, listed the ULSFO sulfur at 0.05%, see Table D2, suggesting the fuel sulfur level does vary a bit between refueling (0.05% 2018 analysis and 0.089% in the UCR 2019 analysis).

Table D-1 MGO fuel bunker report was provided by the vessel



Product Type	MGO
Fuel Usage	UniFuel
Sampling Point	Ship Manifold
Sampling Date	05-Jul-2022
Sampling Method	Continuous Drip
Seal Data	3473021 (VPS, Intact)
Related Seals	3473022, 3473023
Marpol Seal	50147434
Source Of Data	B.D.N.
Density @ 15°C	862.2 kg/m³
Viscosity @ 40°C	3.4 mm²/s
Sulfur	0.0928 % m/m
Volume @ 15°C	232.029 m³
Quantity	199.800 MT

Table D-2 VLSFO fuel bunker report was provided by the vessel



Product Type	VLSFO
Fuel Usage	UniFuel
Sampling Point	Ship Manifold
Sampling Date	04-Jul-2022
Sampling Method	Continuous Drip
Seal Data	3473047 (VPS, Intact)
Related Seals	3473048, 3473049
Marpol Seal	00732760
Source Of Data	B.D.N.
Density @ 15°C	954.4 kg/m³
Viscosity @ 50°C	118.0 mm²/s
Sulfur	0.48 % m/m
Volume @ 15°C	523.687 m³
Quantity	499.230 MT

3. Engine Screen Shot

UCR collected engine data from the control room using a data collection system that relies on photographs. Engine load for the ME were collected from photographs of these systems for specific information on engine load, fuel consumption, temperatures, pressures and other relevant information. Each test point was captured up to four photo-screen shots to quantify stability of readings. In addition, a crew person was collecting engine load data directly from an instrumented drive shaft. The loads from the instrumented drive shaft were used and were found to be more accurate. Examples of the photographs are provided in Figure D-2 through Figure D-6. Figure D7 and 8 show details of the aux boiler tested.

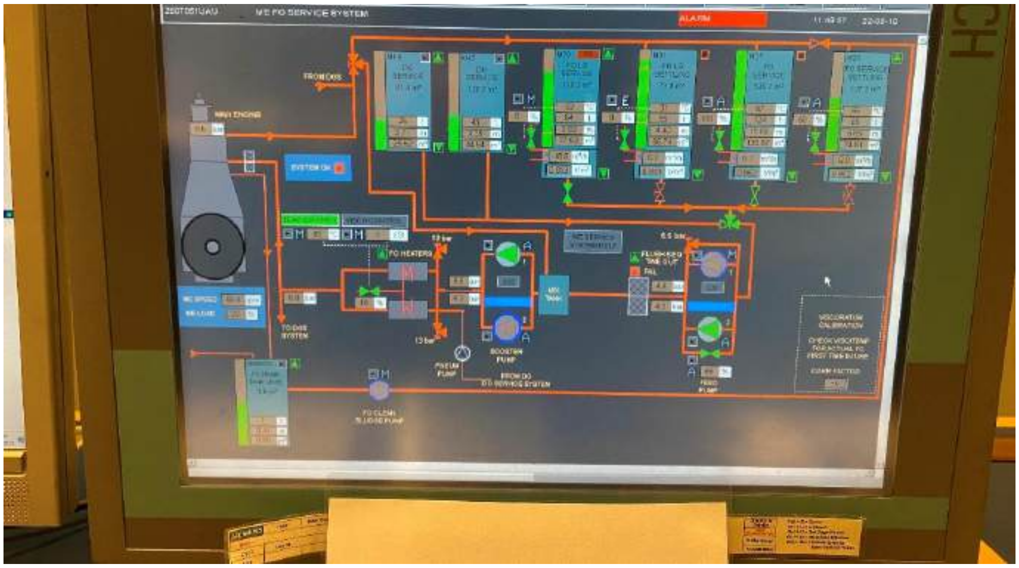


Figure D-1 ME example of data photo utilized: part 1

Figure D-2 ME example of data photo utilized: part 2

Figure D-3 ME example of data photo utilized: part 3

Figure D-4 ME example of data photo utilized: part 4

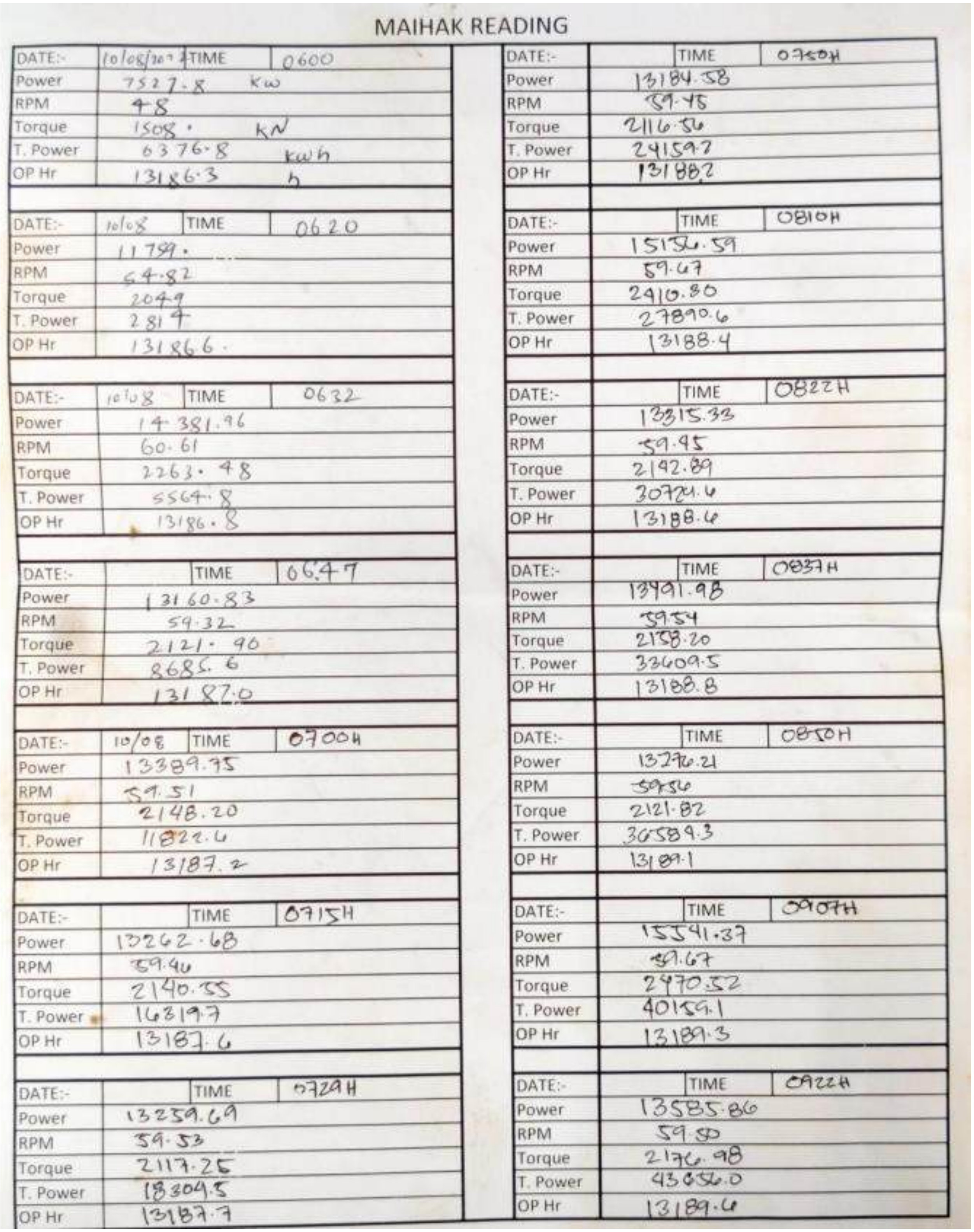
Figure D-5 ME instrumented drive shaft and strain gaguge measurment system

Appendix E – Main Engine Power and Specifications

This appendix presents the engine related results utilized for the mass and brake-specific emission values. These results rely on the data collected from the instrumented drive shaft for actual load, shop trial reference load, and fuel quality (heating value, sulfur levels and such). Thus, this appendix is a summary of the data collected and its use in this report.

The ME measured shaft torque and RPM for each 15-minute interval are presented in Figure E-1. The shop trial brake specific fuel consumption (BSFC) for the tested engine is shown in Figure E-2. The estimated BSFC curve and percent load based on data from Figure E-2 is shown in Figure E-3. The final fuel rate is then calculated from the BSFC curve presented in Figure E-4. The final fuel rate was utilized to calculate exhaust flow and mass emission for all the results presented in this study.

Some systems refer to effective power which is the power available to the crank shaft based on real in-use measurements with real in-use fuels at real in-use conditions. The BSFC fuel flow calculations were based on the measured brake fuel flow from the shop trial reported fuel flow since other measures were not available.



MAIHAK READING

DATE:-	10/08/2017	TIME	0600
Power	7527·8 kw		
RPM	48		
Torque	1508· kN		
T. Power	6376·8 kwh		
OP Hr	13186·3 h		
DATE:-	10/08	TIME	0620
Power	11759·		
RPM	54·82		
Torque	2049		
T. Power	2814		
OP Hr	13186·6·		
DATE:-	10/08	TIME	0632
Power	14381.96		
RPM	60·61		
Torque	2263·48		
T. Power	5564·8		
OP Hr	13186·8		
DATE:-		TIME	0647
Power	13160·83		
RPM	59·32		
Torque	2121·90		
T. Power	8685.6		
OP Hr	13187·0		
DATE:-	10/08	TIME	0700H
Power	13389.75		
RPM	59.51		
Torque	2148.20		
T. Power	11822.6		
OP Hr	13187.2		
DATE:-		TIME	0715H
Power	13262·68		
RPM	59·46		
Torque	2140.55		
T. Power	16319·7		
OP Hr	13187·6		
DATE:-		TIME	0729H
Power	13259.69		
RPM	59·53		
Torque	2117·25		
T. Power	18304·5		
OP Hr	13187·7		

DATE:-		TIME	0750H
Power	13184·58		
RPM	59·45		
Torque	2116·56		
T. Power	24159·7		
OP Hr	13188·2		
DATE:-		TIME	0810H
Power	15156·59		
RPM	59·67		
Torque	2410·80		
T. Power	27890·6		
OP Hr	13188·4		
DATE:-		TIME	0822H
Power	13315.33		
RPM	59·45		
Torque	2192·89		
T. Power	30724·6		
OP Hr	13188·6		
DATE:-		TIME	0837H
Power	13491.98		
RPM	59·54		
Torque	2158·20		
T. Power	33609·5		
OP Hr	13188.8		
DATE:-		TIME	0850H
Power	13276.21		
RPM	59·56		
Torque	2121·82		
T. Power	36589.3		
OP Hr	13189·1		
DATE:-		TIME	0907H
Power	15541.37		
RPM	59.67		
Torque	2470.52		
T. Power	40159.1		
OP Hr	13189·3		
DATE:-		TIME	0922H
Power	13585·86		
RPM	59·50		
Torque	2176·98		
T. Power	43656.0		
OP Hr	13189·6		

Figure E-1 Example data log for the load calculations

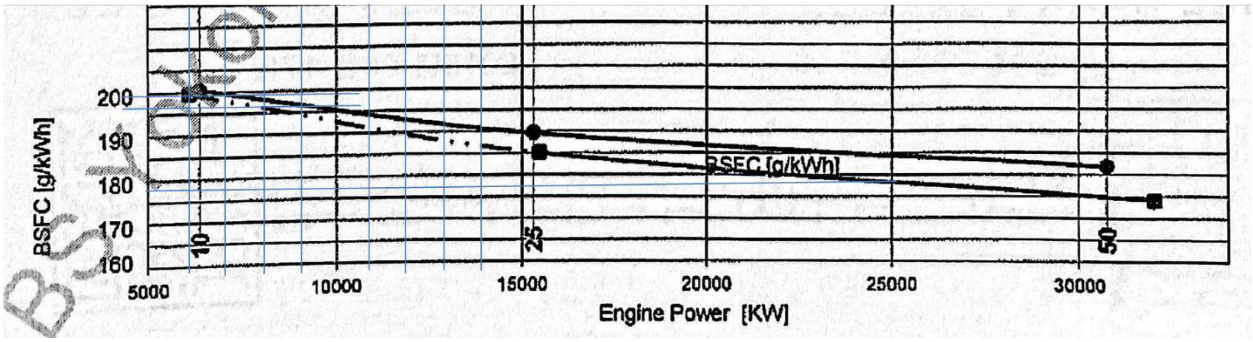


Figure E-2 Shop trial brake specific fuel consumption curve for the tested engine

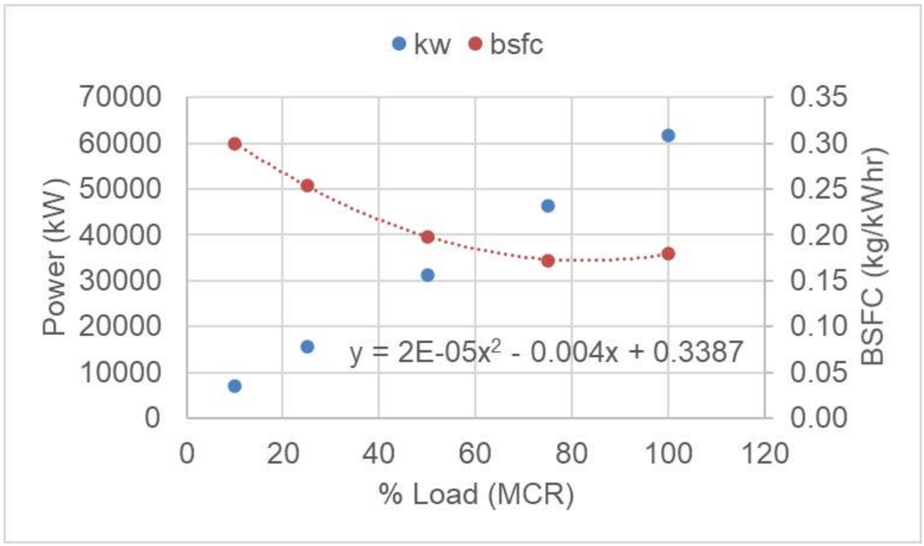


Figure E-3 Estimated BSFC curve and percent load based on data from Figure E-2

Power	bsfc	fuel rate
kW	gfuel/kW	kg/hr
6000	200.0	1.20
7000	198.0	1.39
8000	196.2	1.57
9000	194.6	1.75
10000	192.7	1.93
11000	191.2	2.10
12000	189.5	2.27
13000	188.0	2.44
14000	186.9	2.62
20000	180.2	3.60
25000	176.8	4.42
30000	175.0	5.25

z

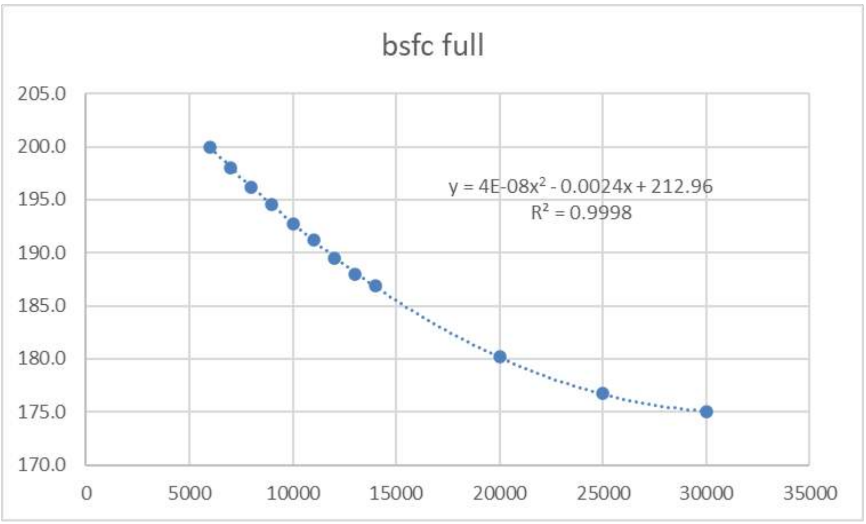


Figure E-4 BSFC curve used to calculate fuel rate utilized in this project

Table E-01 Summary of ME power, exhaust flow, and test conditions

Time	Power	RPM	bsfc	FuelRate	Time	Power	RPM	bsfc	FuelRate	Time	Power	RPM	bsfc	FuelRate
hh:mm	kW		kg/kWhr	kg/hr	hh:mm	kW		kg/kWhr	kg/hr	hh:mm	kW		kg/kWhr	kg/hr
6:00	7528	48.00	0.30	2237	9:52	13928	59.66	0.26	3661	13:37	15538	59.66	0.26	3963
6:20	11759	54.82	0.27	3220	10:07	13175	59.51	0.27	3512	13:52	15089	59.45	0.26	3881
6:32	14382	60.61	0.26	3748	10:22	13096	59.45	0.27	3497	14:07	13700	59.82	0.26	3616
6:47	13161	59.32	0.27	3509	10:37	12961	59.53	0.27	3469	14:22	12787	59.45	0.27	3434
7:00	13390	59.51	0.27	3555	10:52	14671	59.70	0.26	3803	14:37	9058	51.60	0.29	2612
7:15	13263	59.46	0.27	3530	11:07	12888	59.49	0.27	3454	14:52	1410	24.99	0.33	472
7:29	13260	59.53	0.27	3529	11:22	12578	59.50	0.27	3391	15:07	1603	25.34	0.33	535
7:50	13185	59.45	0.27	3514	11:37	13149	59.40	0.27	3507	15:22	4168	36.11	0.32	1323
8:10	15157	59.67	0.26	3894	11:52	13136	59.57	0.27	3505	15:37	6524	44.33	0.30	1977
8:22	13315	59.45	0.27	3540	12:07	15257	59.50	0.26	3912	15:52	2811	32.62	0.33	916
8:37	13492	59.54	0.27	3575	12:22	13492	59.74	0.27	3575	16:07	3423	34.80	0.32	1102
8:50	13276	59.56	0.27	3533	12:37	13012	59.51	0.27	3480	16:22	3422	34.82	0.32	1102
9:07	15541	59.67	0.26	3964	12:52	13941	59.12	0.26	3663	16:37	6093	43.90	0.31	1862
9:22	13586	59.50	0.26	3594	13:07	14090	59.71	0.26	3692	16:52	5979	43.84	0.31	1831
9:37	12732	59.38	0.27	3423	13:22	12866	59.73	0.27	3450	17:03	5993	43.81	0.31	1835

Appendix F –Raw Data and Analysis

The summary results in this Appendix include raw data used to generate the values in the report including outside laboratory results. The tables of data show the results for the ME for gaseous and PM emissions. The EC/OC results were sent to an outside laboratory and were analyzed using the NIOSH thermal optical method. The sulfate PM data presented below are not measured values but calculated from fuel sulfur mass fractions and correlations from previous testing.

Table F-01 – Table F-02 shows the average and standard deviation (sigma = 1) data for the triplicate sampled emissions from the ME. Tables F-03 through Table F-4 show all the individual results and conditions of the testing such as dilution ratio, dry to wet correction, and NO_x humidity correction factors.

The overall sampling for the main engine went well and the stability for each test conditions can be seen in Figure F-1.

Figure F-2 shows the correlation between of PM sulfate mass and fuel sulfur weight percent. Figure F-3 shows the contribution of calculated sulfate PM mass with total mass and the measure EC OC mass.

Table F-01 Summary of ME average results for selected species (g/kWhr), n=varies

Test	Fuel	Condition	n size	Load %	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_TC	kH
1	LSF	Cold Start	2	21.4%	25.84	2.30	701.90	0.25	2841	1.25	0.13	0.52	0.65	1.034
2	LSF	Hot	3	21.5%	25.63	1.89	702.82	0.21	2459	0.40	0.02	0.20	0.22	1.039
3	HSF	Transition	3	21.6%	25.34	1.07	704.25	0.58	2277	0.34	0.01	0.13	0.15	0.992
4	HSF	Hot	3	22.2%	25.31	0.90	704.45	0.90	2383	0.30	0.01	0.11	0.12	0.973
5	LSF	Transition	2	21.8%	25.99	1.19	703.78	0.58	2634	0.26	0.02	0.12	0.14	0.970
6	LSF	Hot	3	22.7%	27.66	1.50	703.41	0.34	2481	0.37	0.04	0.16	0.20	0.997
7	HSF	Low Load	2	2.4%	26.34	4.29	697.74	0.33	4278	0.86	0.22	0.37	0.59	1.006

[1] Only two samples (n=2) were possible for the cold start, slow speed, and the second transition from HSF to LSF due to operational logistics with the testing program.

Table F-02 Summary of ME stdev (σ=1) results for selected species (g/kWhr), n=varies

Test	Fuel	Condition	n size	Load %	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_TC	kH
1	LSF	Cold Start	2	0.1%	0.29	0.22	0.48	0.03	188.0	0.17	0.06	0.17	0.22	0.017
2	LSF	Hot	3	0.1%	0.30	0.14	0.25	0.02	50.3	-	-	-	-	-
3	HSF	Transition	3	0.3%	0.23	0.19	0.31	0.26	16.7	0.02	0.00	0.01	0.01	0.015
4	HSF	Hot	3	2.2%	0.65	0.07	0.20	0.05	110.0	0.15	0.00	0.01	0.01	0.005
5	LSF	Transition	2	1.4%	0.15	0.12	0.19	0.03	6.7	0.01	0.01	0.02	0.02	0.008
6	LSF	Hot	3	2.3%	0.37	0.14	0.22	0.12	54.6	0.02	0.01	0.00	0.01	0.005
7	HSF	Low Load	2	0.2%	0.01	0.96	1.72	0.04	284.6	0.14	0.04	0.16	0.20	0.001

[1] Only two samples (n=2) were possible for the cold start, slow speed, and the second transition from HSF to LSF due to operational logistics with the testing program.

Table F-03 Main engine results by test point part 1 of 3.

Date	Fuel	Nom Fuel S%	Test	Start Time	Load	g/hr													Fuel Rate	SO2 calc	H20 Fraction	O2 Conc
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%MCR	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	(kg/hr)	g/hr	%	%
8/10/2022	MGO_Cold Start	0.0928	1	6:42:00	21.3%	337,412	32,304	9,233,143	3,546	39,143,605	18,004	2,251.4	8407	0.0	10658	10088	12340	0.00	2901	6925	2.3	15.8
8/10/2022	MGO_Cold Start	0.0928	2	7:14:00	21.5%	345,374	28,486	9,313,562	3,025	35,919,524	14,888	1,217.9	5332	0.0	6550	6399	7617	0.00	2922	5908	2.5	15.5
8/10/2022	MGO_Hot LSF_1	0.0928	3	7:37:00	21.5%	342,628	26,316	9,316,895	2,955	33,078,199	5,345	282.5	2637	0.0	2919	3164	3447	0.00	2921	5770	2.6	15.3
8/10/2022	MGO_Hot LSF_1	0.0928	4	7:56:30	21.3%	335,174	23,639	9,268,785	2,535	31,953,638	-	-	-	-	-	-	-	-	2906	-	2.7	15.2
8/10/2022	MGO_Hot LSF_1	0.0928	5	8:17:30	21.6%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8/10/2022	HS-Fuel_Transition	mix	6	8:38:06	21.8%	342,409	17,364	9,496,924	4,180	30,860,536	4,227	197.8	1846	0.0	2044	2215	2413	0.00	2970	8164	2.8	15.0
8/10/2022	HS-Fuel_Transition	mix	7	8:56:30	21.8%	342,354	15,694	9,499,778	5,594	30,609,397	4,516	214.6	2003	0.0	2218	2404	2618	0.00	5940	10925	2.9	15.0
8/10/2022	HS-Fuel_Transition	mix	8	10:03:30	21.3%	337,014	12,047	9,281,936	10,086	29,740,306	4,434	165.8	1644	0.0	1810	1973	2138	0.00	2904	19699	2.9	15.0
8/10/2022	HS-Fuel_Transition	mix	9	10:18:00	21.2%	327,651	11,738	9,226,373	10,929	30,036,278	4,663	168.5	1615	0.0	1784	1938	2107	0.00	2887	21345	2.9	15.1
8/10/2022	HS-Fuel_Hot HSF	0.4760	10	10:31:00	21.0%	322,629	11,060	9,132,215	11,440	29,808,765	6,146	166.5	1596	0.0	1762	1915	2082	0.00	2859	22343	2.9	15.1
8/10/2022	HS-Fuel_Hot HSF	0.4760	11	10:59:30	20.9%	322,060	11,074	9,080,105	12,407	30,163,608	2,937	113.6	1429	0.0	1543	1715	1828	0.00	2844	24232	2.8	15.1
8/10/2022	HS-Fuel_Hot HSF	0.4760	12	12:00:00	24.7%	397,637	14,859	10,744,460	13,219	38,255,490	3,236	154.4	1615	0.0	1770	1938	2093	0.00	3338	25817	2.6	15.2
8/10/2022	MGO_Transition_2	mix	13	13:01:00	22.8%	367,617	15,523	9,918,419	8,448	37,173,845	3,590	160.4	1547	0	1707	1856	2017	0.00	3095	16499	2.5	15.3
8/10/2022	MGO_Transition_2	mix	14	13:21:00	20.8%	333,018	16,441	9,053,424	7,162	33,822,812	3,397	239.5	1708	0	1947	2049	2289	0.00	2839	13987	2.5	15.3
8/10/2022	MGO_Hot LSF_2	0.0928	15	13:40:00	25.2%	424,985	21,439	10,931,605	7,555	39,129,587	5,347	490.0	2413	0	2903	2896	3386	0.00	3397	14754	2.6	15.1
8/10/2022	MGO_Hot_LSF_2	0.0928	16	14:00:00	22.2%	384,628	20,007	9,638,189	4,056	33,129,196	5,389	523.8	2200	0	2724	2640	3163	0.00	3013	7921	2.7	15.0
8/10/2022	MGO_Hot LSF_2	0.0928	17	14:20:00	20.7%	352,263	21,039	8,991,405	3,223	32,042,553	4,691	531.8	2027	0	2559	2432	2964	0.00	2823	6294	2.6	15.1
8/10/2022	MGO_LSF_Low Load	0.0928	18	15:45:00	2.3%	37,147	5,091	985,518	422	5,747,588	1,072	277.1	357	0	634	428	705	0.00	447	825	1.7	16.5
8/10/2022	MGO_LSF_Low Load	0.0928	19	16:04:00	2.6%	42,216	7,974	1,116,779	573	7,181,188	1,547	403.6	778	0	1181	933	1337	0.00	487	1118	1.6	16.8

Table F-04 Main engine results by test point part 2 of 3.

Date	Fuel	ATS	Test	Start Time	Load	g/kWhr													Calculated g/kWHr			NOx Cor.
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%MCR	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	BSFC	Sulf %	SO2/CO2	Kh
8/10/2022	MGO_Cold Start	0.0928	1	6:42:00	21.3%	25.64	2.45	702	0.2694	2,974	1.37	0.171	0.64	0.00	0.810	0.767	0.938	0.00	220.4	0.12%	-	1.02
8/10/2022	MGO_Cold Start	0.0928	2	7:14:00	21.5%	26.04	2.15	702	0.2281	2,708	1.12	0.092	0.40	0.00	0	0	1	0.00	220.3	0.11%	2.2311	1.05
8/10/2022	MGO_Hot LSF_1	0.0928	3	7:37:00	21.5%	25.84	1.98	703	0.2228	2,495	0.40	0.021	0.20	0.00	0	0	0	0.00	220.3	0.10%	2.1785	1.05
8/10/2022	MGO_Hot LSF_1	0.0928	4	7:56:30	21.3%	25.42	1.79	703	0.1923	2,424	-	-	-	-	-	-	-	-	220.4	0.09%	1.8786	1.03
8/10/2022	MGO_Hot LSF_1	0.0928	5	8:17:30	21.6%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8/10/2022	HS-Fuel_Transition	mix	6	8:38:06	21.8%	25.38	1.29	704	0.3098	2,287	0.31	0.015	0.14	0.00	0.151	0.164	0.179	0.00	220.1	0.14%	3.0237	1.01
8/10/2022	HS-Fuel_Transition	mix	7	8:56:30	21.8%	25.37	1.16	704	0.4146	2,269	0.33	0.016	0.15	0.00	0	0	0	0.00	440.2	0.19%	4.0450	1.00
8/10/2022	HS-Fuel_Transition	mix	8	10:03:30	21.3%	25.58	0.91	705	0.7656	2,257	0.34	0.013	0.12	0.00	0.137	0.150	0.162	0.00	220.4	0.35%	7.4648	0.99
8/10/2022	HS-Fuel_Transition	mix	9	10:18:00	21.2%	25.02	0.90	705	0.8345	2,294	0.36	0.013	0.12	0.00	0.136	0.148	0.161	0.00	220.5	0.38%	8.1373	0.97
8/10/2022	HS-Fuel_Hot HSF	0.4760	10	10:31:00	21.0%	24.89	0.85	705	0.8827	2,300	0.47	0.013	0.12	0.00	0.136	0.148	0.161	0.00	220.6	0.41%	8.6056	0.98
8/10/2022	HS-Fuel_Hot HSF	0.4760	11	10:59:30	20.9%	24.99	0.86	705	0.9627	2,340	0.23	0.009	0.11	0.00	0.120	0.133	0.142	0.00	220.7	0.44%	9.3864	0.98
8/10/2022	HS-Fuel_Hot HSF	0.4760	12	12:00:00	24.7%	26.06	0.97	704	0.87	2,507	0.21	0.010	0.11	0.00	0.116	0.127	0.137	0.00	218.8	0.40%	8.451	0.97
8/10/2022	MGO_Transition_2	mix	13	13:01:00	22.8%	26.1	1.10	703.9	0.600	2,638	0.25	0.011	0.11	0.00	0.121	0.132	0.143	0.00	219.6	0.28%	5.85	0.96
8/10/2022	MGO_Transition_2	mix	14	13:21:00	20.8%	25.9	1.28	703.6	0.557	2,629	0.26	0.019	0.13	0.00	0	0	0	0.00	220.7	0.26%	5.43	0.98
8/10/2022	MGO_Hot LSF_2	0.0928	15	13:40:00	25.2%	27.4	1.38	703.6	0.486	2,518	0.34	0.032	0.16	0.00	0.187	0.186	0.218	0.00	218.6	0.22%	4.75	0.99
8/10/2022	MGO_Hot_LSF_2	0.0928	16	14:00:00	22.2%	28.1	1.46	703.5	0.296	2,418	0.39	0.038	0.16	0.00	0.199	0.193	0.231	0.00	219.9	0.14%	2.89	1.00
8/10/2022	MGO_Hot LSF_2	0.0928	17	14:20:00	20.7%	27.5	1.65	703.2	0.252	2,506	0.37	0.042	0.16	0.00	0.200	0.190	0.232	0.00	220.7	0.12%	2.46	1.00
8/10/2022	MGO_LSF_Low Load	0.0928	18	15:45:00	2.3%	26.3	3.61	699.0	0.300	4,076	0.76	0.197	0.25	0.00	0.450	0.304	0.500	0.00	317.1	0.14%	2.94	1.01
8/10/2022	MGO_LSF_Low Load	0.0928	19	16:04:00	2.6%	26.3	4.97	696.5	0.357	4,479	0.96	0.252	0.49	0.00	0.737	0.582	0.834	0.00	304.0	0.16%	3.52	1.01

Table F-5 Main engine results by test point part 3 of 3.

Date	Fuel	ATS	Test	Start Time	Load	g/kg-fuel (kg/tonne-fuel)													Vessel
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%MCR	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	knots
8/10/2022	MGO_Cold Start	0.0928	1	6:42:00	21.3%	116.32	11.14	3183.1	1.2225	13494	6.207	0.7762	2.90	0.0000	3.674	3.478	4.254	-	15.3
8/10/2022	MGO_Cold Start	0.0928	2	7:14:00	21.5%	118.20	9.75	3187.4	1.0352	12293	5.095	0.4168	1.82	0.0000	2.242	2.190	2.607	-	15.2
8/10/2022	MGO_Hot LSF_1	0.0928	3	7:37:00	21.5%	117.28	9.01	3189.2	1.0114	11323	1.830	0.0967	0.90	0.0000	0.999	1.083	1.180	-	14.9
8/10/2022	MGO_Hot LSF_1	0.0928	4	7:56:30	21.3%	115.35	8.14	3189.9	0.8724	10997	-	-	-	-	-	-	-	-	14.9
8/10/2022	MGO_Hot LSF_1	0.0928	5	8:17:30	21.6%	-	-	-	-	-	-	-	-	-	-	-	-	-	15.7
8/10/2022	HS-Fuel_Transition	mix	6	8:38:06	21.8%	115.29	5.85	3197.8	1.4076	10391	1.423	0.0666	0.62	0.0000	0.688	0.746	0.812	-	14.7
8/10/2022	HS-Fuel_Transition	mix	7	8:56:30	21.8%	57.64	2.64	1599.4	0.9418	5153	0.760	0.036	0.337	0.000	0.373	0.405	0.441	-	14.7
8/10/2022	HS-Fuel_Transition	mix	8	10:03:30	21.3%	116.06	4.15	3196.6	3.4736	10242	1.527	0.0571	0.57	0.0000	0.623	0.679	0.736	-	15.1
8/10/2022	HS-Fuel_Transition	mix	9	10:18:00	21.2%	113.48	4.07	3195.6	3.7854	10403	1.615	0.0584	0.56	0.0000	0.618	0.671	0.730	-	15.1
8/10/2022	HS-Fuel_Hot HSF	0.4760	10	10:31:00	21.0%	112.85	3.87	3194.2	4.0014	10426	2.150	0.0582	0.56	0.0000	0.616	0.670	0.728	-	15.3
8/10/2022	HS-Fuel_Hot HSF	0.4760	11	10:59:30	20.9%	113.25	3.89	3193.0	4.3629	10607	1.033	0.0399	0.50	0.0000	0.542	0.603	0.643	-	15.1
8/10/2022	HS-Fuel_Hot HSF	0.4760	12	12:00:00	24.7%	119.108	4.451	3218.380	3.959	11459	0.969	0.046	0.48	0.000	0.530	0.581	0.627	-	15.9
8/10/2022	MGO_Transition_2	mix	13	13:01:00	22.8%	118.8	5.02	3204.9	2.7297	12,012	1.160	0.0518	0.50	0.0000	0.552	0.600	0.652	-	13.9
8/10/2022	MGO_Transition_2	mix	14	13:21:00	20.8%	117.3	5.79	3188.7	2.5224	11,913	1.196	0.0844	0.60	0.0000	0.686	0.722	0.806	-	14.2
8/10/2022	MGO_Hot LSF_2	0.0928	15	13:40:00	25.2%	125.1	6.31	3218.0	2.2239	11,519	1.574	0.1442	0.71	0.0000	0.855	0.852	0.997	-	14.1
8/10/2022	MGO_Hot_LSF_2	0.0928	16	14:00:00	22.2%	127.6	6.64	3198.5	1.3460	10,994	1.788	0.1738	0.73	0.0000	0.904	0.876	1.050	-	14.5
8/10/2022	MGO_Hot LSF_2	0.0928	17	14:20:00	20.7%	124.8	7.45	3185.4	1.1416	11,352	1.662	0.1884	0.72	0.0000	0.906	0.862	1.050	-	13.4
8/10/2022	MGO_LSF_Low Load	0.0928	18	15:45:00	2.3%	83.1	11.39	2204.2	0.9448	12,855	2.398	0.6198	0.80	0.0000	1.418	0.958	1.577	-	7.5
8/10/2022	MGO_LSF_Low Load	0.0928	19	16:04:00	2.6%	86.6	16.36	2290.9	1.1745	14,731	3.174	0.8280	1.60	0.0000	2.424	1.915	2.743	-	7.7

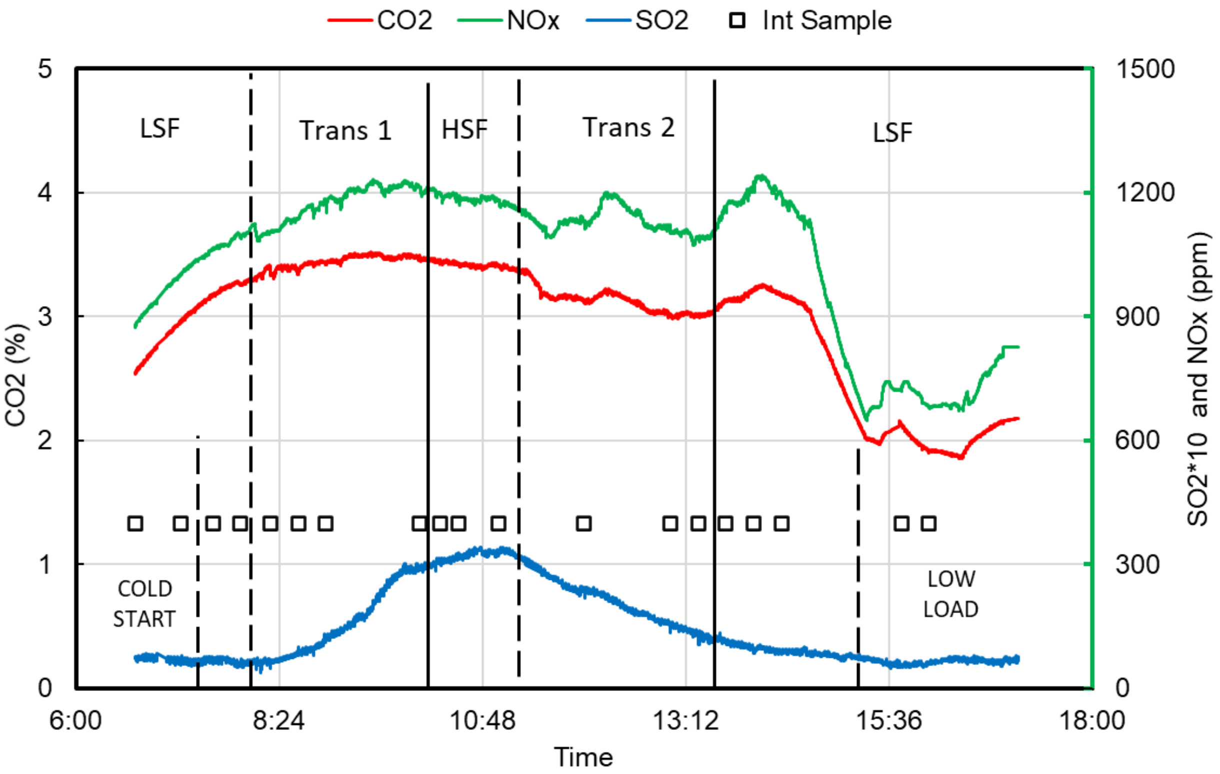


Figure F-1 Measured SO_2, CO_2 and NO_x emissions for the ME HSF and LSF

[1] Int Sample refers to when the PM filter was collected. For example, there were two PM filter sampled during the LSF cold start between 6 am – 7 am. There were two samples for the final low load low speed condition as well (from 15:30 to the end ~18:00).

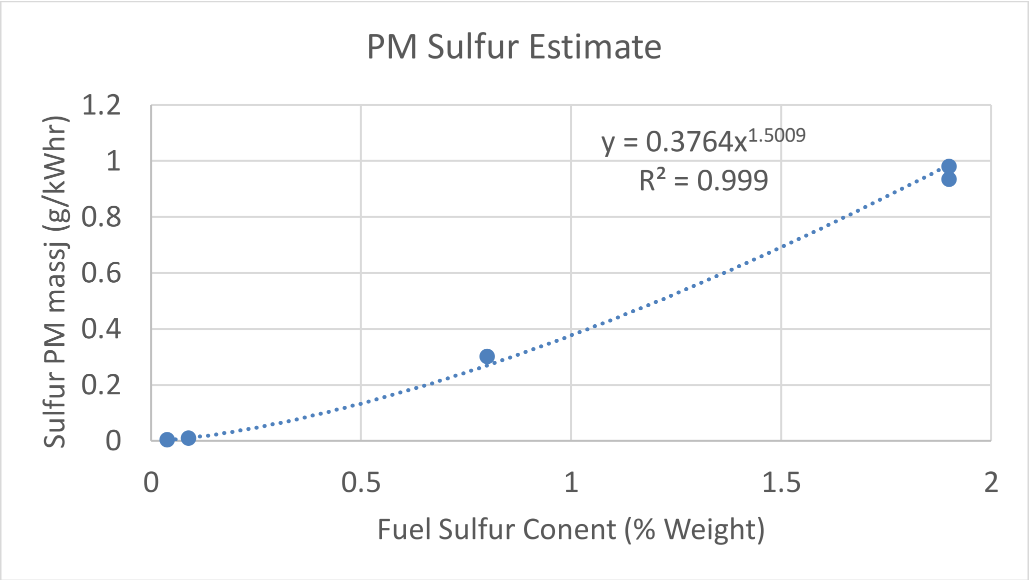


Figure F-2 Estimated fuel sulfur PM mass from previous measurements on OGV

[1] Int Sample refers to when the PM filter was collected. For example, there were two PM filter sampled during the LSF with varying sulfur levels. Used to estimate sulfate PM for low sulfur fuels (0.5 S and lower)

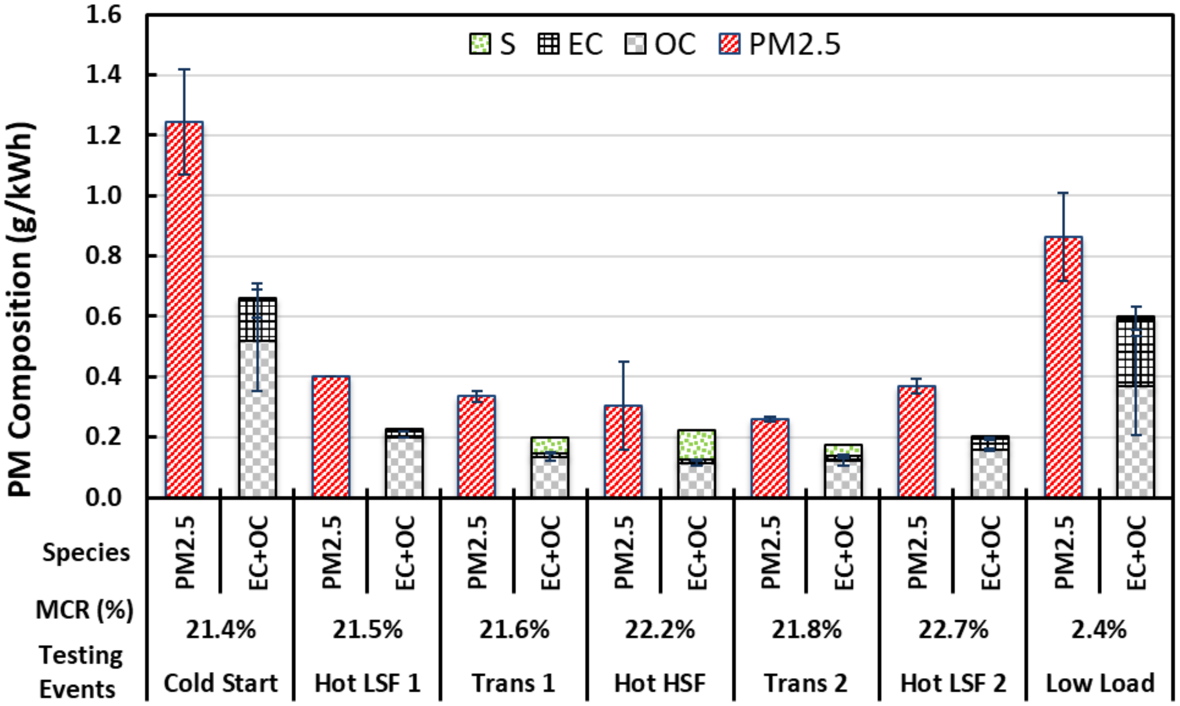


Figure F-3 Total PM and speciated PM with estimated Sulfur

[1] Estimated sulfur was calculated using the relationship in the previous figure for Sulfur PM vs Sulfur fuel content. This relationship works well below 0.5% sulfur weight fraction where the total Sulfur PM is 20% or lower of the total mass. For example, there were two PM filter sampled during the LSF is impacted by up to 30% due to the sulfur in the fuel. This suggest there are less organic and elemental carbon PM for the higher sulfur fuel compared to the MGO fuel.