Black Carbon Measurement Methods and Emission Factors from Ships

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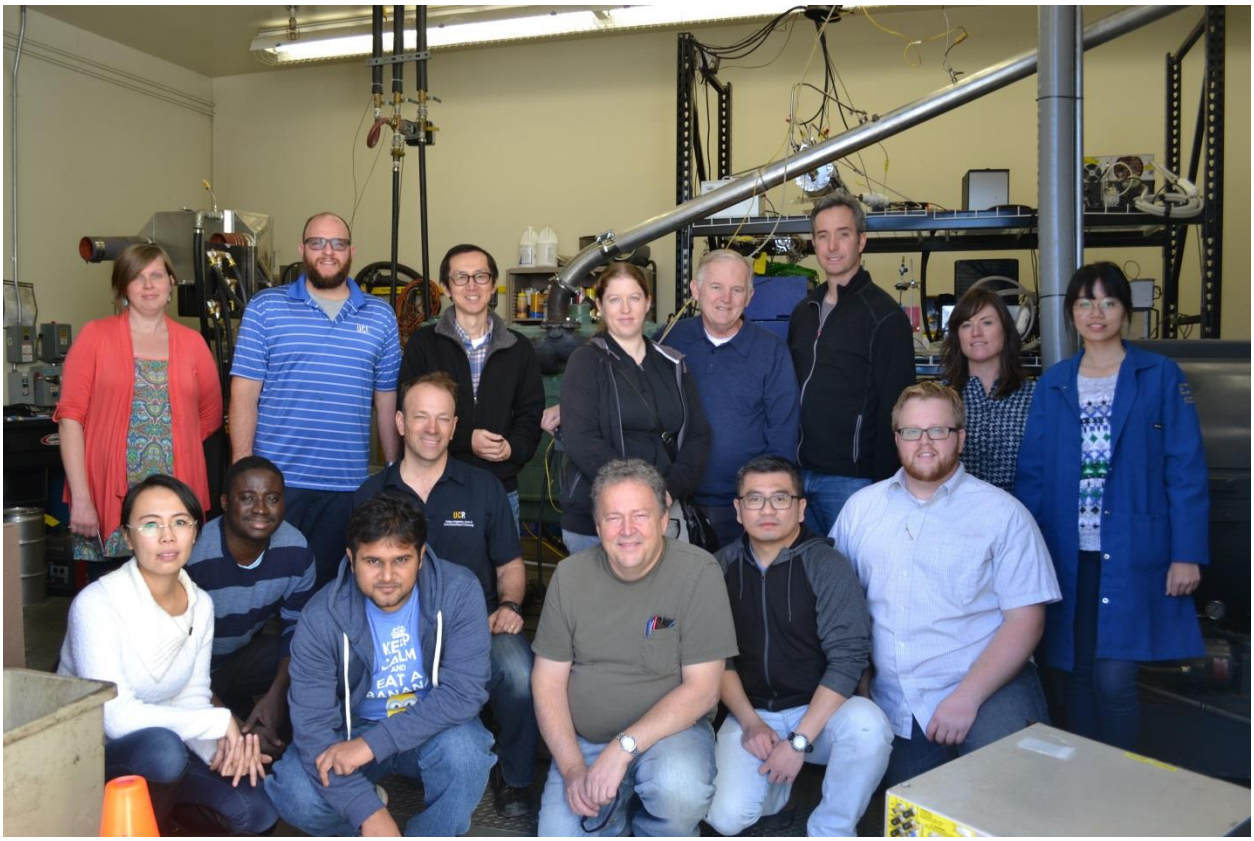

Research team for the Task 1 Marine Black Carbon ICCT Project

Equipment in-kind loans Task 1

- AVL Filter Smoke Number (FSN) **Task 1-3**
- SunSet Labs SemiCont EC/OC
- South Coast Air Quality Management District (SC-AQMD) Aethalometer
- National Resource Canada
  - Two (2) LIIs
  - RAMAN,
  - TEM analysis
- Environment and Climate Change Canada
  - LII
  - Rotating disk dilutor
  - CPC
- UC Riverside
  - GC by GC
  - AMS
  - SMPS
  - CPC
  - PAX 375 nm
  - HTDMA
  - MAAP
- California Air Resources Board EEPS
- NTK-Sparkplugs Stack OBD NO_X /PM/PN Sensor

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Executive Summary

Background

Current research has shown that black carbon (BC) is a contributor to human induced climate warming (Bond et al., 2013). Emissions of BC are also linked to human health issues such as lung cancer, respiratory illness, and cardiopulmonary disease. Because of human health and climate concerns, BC emissions, including those from ships, are of global interest. Despite this interest, BC emission factors (EFs) for marine engines and fuels are uncertain because of the challenges of measuring BC emissions.

Published BC emission factors can vary more than ten-fold, creating uncertainty in estimating impacts on climate and health. To address this uncertainty, a comprehensive study was undertaken by the International Council on Clean Transportation (ICCT), funded through the Climate and Clean Air Coalition (CCAC) and the U.S. Department of Transportation Maritime Administration (MARAD), to measure BC emissions from marine engines and to better understand how engine operating conditions, marine fuel choice, and vessel operations (e.g., vessel speed reduction) impact BC EFs. To accomplish this, the ICCT partnered with principal investigators from the University of California-Riverside (UCR), in collaboration with Environment and Climate Change Canada (ECCC), National Research Council Canada (NRC) and Eastern Research Group (ERG). The study called for three main testing tasks:

- Task 1 (laboratory testing)
    - Develop baseline BC EFs using a variety of measurement methods while varying engine load and fuel using a marine engine in a laboratory.
- Tasks 2 and 3 (at-sea testing)
    - Measure BC EFs from two oceangoing vessels (OGV):
        - One OGV will test the BC emissions of a modern (Tier II) engine and the impact of vessel speed reduction (VSR) on BC EFs
        - Another OGV will primarily test the impact of an exhaust gas cleaning system (EGCS) i.e., a scrubber - on BC EFs

Task 1: Laboratory Testing

Marine BC EFs were measured in the laboratory on a small, 187 kW, two-stroke, naturally aspirated, in-line 6 cylinder, 2300 rotations per minute (RPM) marine engine using a variety of measurement methods. Black carbon EFs were measured under various engine loads and with three marine fuels: distillate (13 parts per mission sulfur), high-sulfur heavy fuel oil (HFO, 32,000 ppm S), and desulfurized residual oil (13 ppm S). The influence of sample conditioning by removing semi-volatile and volatile organic compounds before measuring BC EFs was tested through the use of a custom-built catalytic stripper.

Approach

Before starting the project, the proposed research plan was reviewed and refined at ICCT's 2nd Workshop on Marine Black Carbon Emissions in September 2015 in Utrecht, Netherlands. This review resulted in the addition of a sample conditioning protocol upstream of the BC analytical instruments. The sample conditioning unit consisted of two sections in series: first, a catalytic stripper (CS) to remove hydrocarbons, and second, a sulfur adsorber (SA) unit. The UCR team performed Task 1 with and without sample conditioning to evaluate the updated method and its impact on the results.

Eight BC analytical methods with different operating principles were used during the test stand work. The setup included instruments to measure: particle size distribution, particle density, chemical composition, gas phase species, gas-to-particle interactions, and samples for subsequent transmission microscope analysis. The marine engine was a small displacement (6.7 liter) two-stroke engine. The

exhaust was sampled at three dilution ratios as the engine was operated at a constant speed of 1100 RPM, and 25%, 50% and 75% load points, using three commercial marine fuels. Three of the test points utilized the sample conditioning system and two test points bypassed the sample conditioning system.

***Key Findings**:*

- Good agreement on BC EFs between photo-acoustic spectroscopy (PAS), thermal optical analysis (TOA), laser induced incandescence (LII), and light absorption filter smoke number (FSN) methods.
- Poor agreement on BC EFs from instruments requiring high dilution e.g., multi-angle absorption photometry (MAAP) and the aethalometer.
- Fuel choice influences BC emissions (Figure ES-1):
    - Overall, distillate fuel had the lowest BC emissions of the three fuels tested (distillate, high- sulfur HFO, desulfurized residual oil).
    - Desulfurized residual oil had the highest BC EF of the three fuels tested, despite having a low sulfur content (13 ppm), the lowest viscosity, and lowest carbon residue.
- BC EFs on the small, two-stroke test engine increased as engine load increased (Figure ES-1), an unexpected result, as EFs tend to decrease as engine load increases on large, two-stroke marine engines. The relationship of a higher EF with a higher load does not agree with other investigations and is only for this engine.
- Sample conditioning improved the comparability of BC measurements, but only slightly.
- Simulating common calibration among instruments by applying correction factors to measurements that result in the same BC EF value across instruments at a particular load point for a particular fuel can improve inter-comparability between instruments.
- A predictive equation for fuel and load effects on BC EFs was not found in the data, suggesting that further research might explore the influence of in-cylinder combustion phenomena and or other fuel parameters such as total aromatic content on BC EFs.

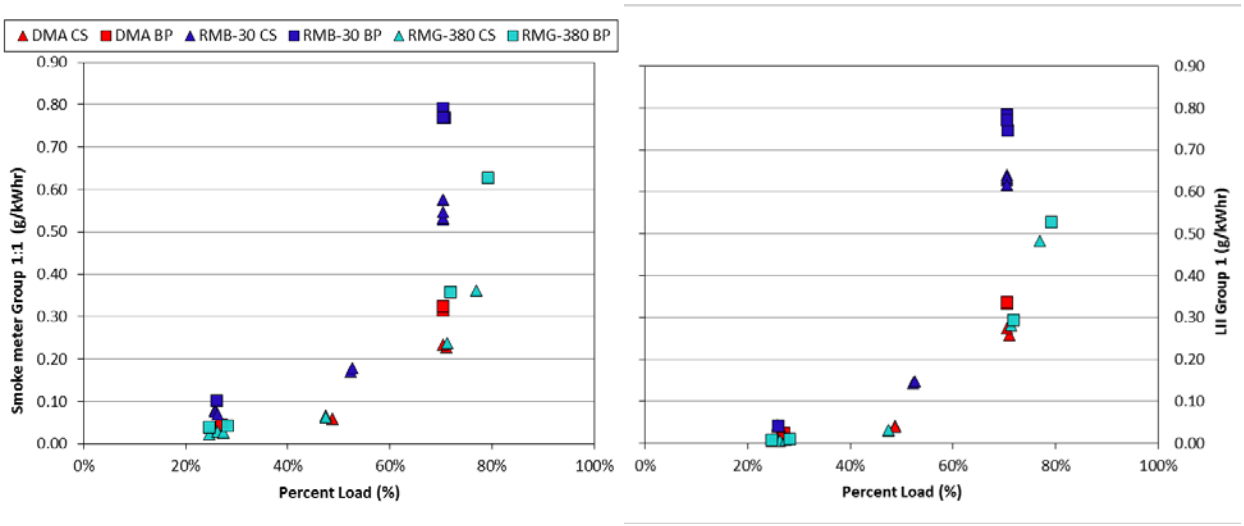


Figure ES-1 eBC from Smoke Meter and rBC from LII as a function of engine load

Tasks 2 and 3: **At-sea Testing**

Testing for Tasks 2 and 3 was performed at-sea while each vessel was operated along its normal route. In Task 2, BC EFs were measured onboard a 8,600 TEU containership built in 2012 with a 70 megawatt (MW), two-stroke, slow-speed model year 2011 engine meeting IMO Tier II exhaust standards for nitrogen oxides (NO_X), burning marine gas oil (MGO, 0.03% S). In Task 3, BC EFs were measured onboard a 1,600 TEU containership built in 1987 equipped with an EGCS attached to the exhaust from its 16.7 MW main engine and two of its 2.1 MW auxiliary engines. The ship tested in Task 3 burned high sulfur HFO (< 3% S).

Approach

Given the complexity and space limitations of at-sea testing, the range of BC measurement methods was reduced from Task 1 for Task 2 and 3. The catalytic sample conditioning system was not utilized, the same ad-hoc calibrations were utilized, and the BC measurements were limited to three systems: the AVL Micro Soot Sensor Photo Acoustic (PA), the Thermal Optical Elemental Carbon method (EC), and the AVL Filter Smoke Number (FSN). For the scrubber-equipped vessel, additional sample heating was incorporated to manage the cool exhaust after the exhaust gas scrubbing system. The remaining dilution and sample conditioning methods followed the protocols of ISO 8178-2 and 40 CFR Part 1065 as for Task 1. The EC and PA measurement were collected from diluted samples and the FSN sampled from the raw exhaust.

Task 2 Results

Total particulate matter (PM) mass and BC emissions were low for the Tier 2 engine equipped vessel. The emission factor for PM mass was about 0.06 g/kWh for 25-57% load as compared with 0.4 g/kWh for the lab engine with the same fuel. For the Tier II engine, the PM emission factor increased to 0.12 g/kWh at 9% load, the VSR speed, where the engine efficiency is lower. The BC EF ranged from 0.0023 g/kg-fuel to 0.051 g/kg-fuel for the PA measurement method where the highest BC EF was at the VSR load. All three BC measurement methods (EC, FSN, and PA) agreed well with each other, with the post-hoc calibration established in Task 1 improving the agreement by 10-20%. The PM fraction was greater than 90% organic carbon by mass as seen in earlier large engine studies and near that of the lab engine

when operating at low loads. The BC emission factors measured with the PA method at various loads are reported in Table ES-1.

Table ES-1 BC Emission factors as a function of engine load (PA method) for a Tier II engine

Load, %	57%	41%	28%	VSR (9%)
Emission Factor (g/kg-fuel)	0.002	0.009	0.051	0.019

Task 3 Results

The EGCS reduced BC and other criteria pollutant emissions across most instruments and load points. The measured emission reductions at each load point and the estimated weighted emissions tested across the EGCS are listed in Table ES-2. The results in general showed that BC emissions are reduced by around 30% for a scrubber system, but individual modes suggest there may be some uncertainties. The post- hoc calibration did not improve the BC comparison for the high sulfur fuel, suggesting that other influences may be biasing the EC measurement method.

Table ES-2 BC Reduction Efficacy of the Exhaust Gas Cleaning System for Various Pollutants[1]

Mode	Load	Total Percent Change From Baseline						
		EC	$eBC_{\_PA}$	$eBC_{\_FSN}$	SO_2	$PM_{2.5}$	$PM_{\_OC}$	$PM_{\_S}$
1	87%	-53%	-29%	-8%	-97%	2%	-17%	3%
2	75%	-43%	-38%	-18%	-97%	-14%	-34%	-10%
3	50%	+3%	-25%	-14%	-97%	-4%	-30%	6%
4	5%	-48%	-43%	-37%	-98%	-37%	-41%	-29%
est ISO Wt		-39%	-36%	-20%	-97%	-10%	-31%	-5%

[1] Load is a percentage of total with the main and generator engines combined. The ISO weighting is estimated. PM_OC is organic carbon as measured by thermal optical methods, PM_S represents sulfate mass, and PM2.5 represents PM fine mass less than 2.5 microns in aerodynamic diameter.

At high loads the total $PM_{2.5}$ and sulfate based PM appeared to increase across the scrubber. The gas phase, fuel sulfur percent was estimated at 0.029% at low load and 0.065% at high load, all of which are below the 0.1% ECA SO_x requirement (Figure ES-2). When the particle bound sulfate particles are added to the sulfur balance (gas + particles), the fuel sulfur percent was estimated at 0.12% to 0.42%, which are above the 0.1%, (Figure ES-2). This suggests the use of low sulfur fuel will reduce sulfur emissions more than an equivalent scrubber system.

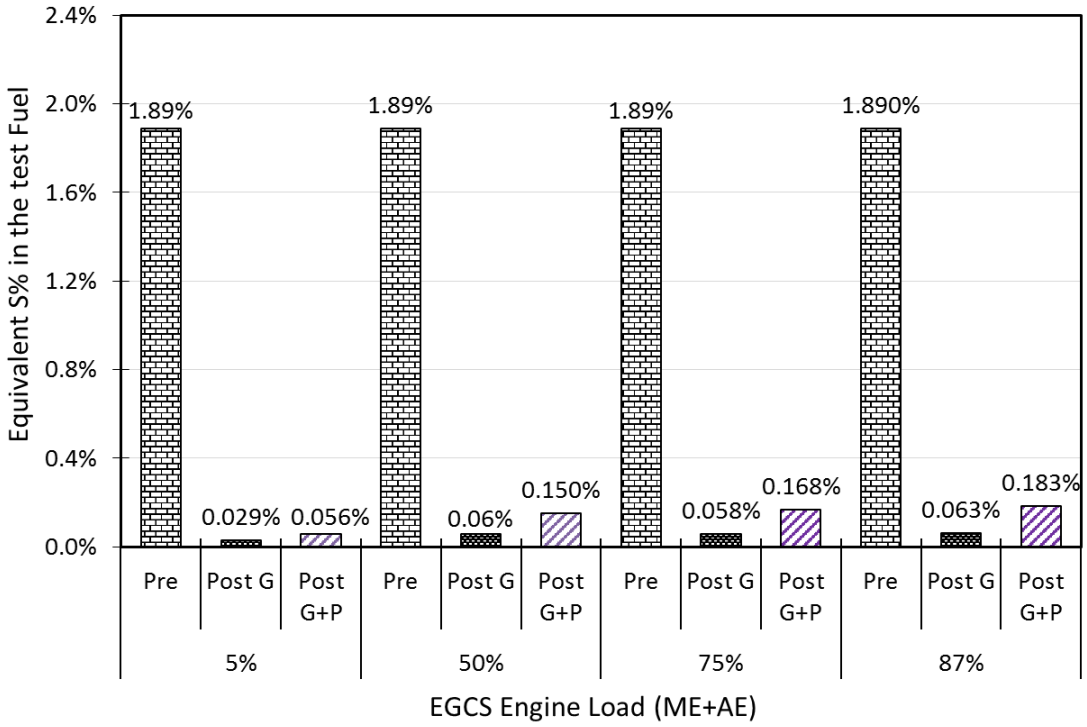


Figure ES-2 Estimated Fuel Sulfur Balance Sulfur Containing Species

Key Findings:

- BC emissions tend to decrease as engine load increases, consistent with the understanding that improved combustion efficiency occurs at higher loads.
- BC EFs were extremely low from the Tier II engine, on the order of 0.002 g/kg MGO fuel at 57% ME load and 0.019 g/kg MGO fuel at 9% ME load (a load associated with VSR operation). This suggests that electronic controls and in-cylinder approaches to reduce NOx may also serve to reduce BC and PM emissions. VSR decreases BC emissions per unit distance, even though it usually increases BC emissions per unit energy (g/kWh) compared to higher loads, except the 28% load, which was found to produce the most gBC/kWh in the Tier II engine exhaust. These results suggest that electronic controls on newer engines may allow for better optimization of emissions under selected operating conditions.
- The EGCS (scrubber) reduced BC emissions on the order of 30%. The reduction efficacy of criteria pollutants varied by test point, with particle phase sulfate concentrations increasing across the scrubber at high loads. Taking this into account, the use of low sulfur marine fuels may reduce total (gas plus particle phase) emissions more than a typical scrubber. The emission factors from the Tier II slow speed diesel (SSD) two-stroke engine are five times lower than what has been published to date. Many previously published results are based on mix of medium speed diesels (MSD) and some older SSD where BC emissions may be higher. As such, the emissions of additional Tier II and Tier III SSD engines should be evaluated for their BC and other emission factors when they become available.

Implications

The results of this research have implications for marine BC measurement approaches, emissions inventories, and reduction options, as discussed next.

Measurement Approaches

The results suggest that some instruments are more promising for measuring marine BC emissions than others. Specifically:

- PAS and FSN showed good correlation in the in-lab and on-board marine BC emissions tests (Tasks 1, 2, and 3) and may be fit for purpose for measuring BC from marine engines.
- TOA methods may be fit for purpose for measuring BC from marine engines when the fraction of BC to total PM is relatively high.
- LII correlated well with PAS, FSN, and TOA in Task 1 and may be fit for purpose for measuring BC from marine engines.
- Instruments designed to measure ambient air pollution (e.g., the MAAP and the aethalometer) are not appropriate for measuring marine BC emissions from the source (i.e., the marine engine exhaust).

Emission Inventories

Based on a review of the results presented in this study, it appears that BC EFs near the lower end of the 0.1 to 1.0 g/kg of fuel range found in the literature are most appropriate for producing marine BC emissions inventories. BC EFs may be significantly lower than 0.1 g/kg fuel for Tier II engines, but more research is needed to validate this result.

Based on this research and past observations from other in-house testing (as presented in Section 6), BC EFs are a function of the following (in order of significance):

1. Slow-speed diesel engines (two-stroke) vs. medium- and high-speed diesel engines (four-stroke): the slow speed two-stroke engines used for the largest oceangoing vessels appear to have lower BC emission factors than higher speed four stroke engines.
2. Engine load: For larger engines, increasing engine load reduces BC EFs; for smaller engines, the reverse relationship seems to hold.
3. Engine displacement: Across a variety of diesel engine types, larger engine displacement correlates with lower relative BC emissions.
4. Engine Tier: The Tier II engine results presented here suggest that modern marine engines with electronic controls and in-cylinder approaches to reduce NO_x emissions have lower BC emission factors.
5. EGCS Systems: Scrubbers installed to meet sulfur fuel standards also provide a modest (~30%) reduction in BC emissions.
6. Fuel: Overall, distillate fuels have the lowest BC emission factors followed by conventional high sulfur HFO. Desulfurized residual fuels capable of meeting existing sulfur requirements had elevated BC emissions.

Reduction options

The research findings indicated potential options for reducing BC emissions from marine vessels:

- The use of newer (e.g. Tier II) engines: While existing engine standards were established to control NO_x, the control strategies utilized may have BC cobenefits. Although further research is recommended to confirm, the use of newer engines, for example through accelerating fleet turnover or vessel repowers, may serve to reduce BC emissions.
- Slow-steaming/vessel speed reduction (VSR): On a mass per unit distance basis, VSR was observed to reduce BC emissions compared to higher speed operations. In contrast, for the (Tier II) engine tested, intermediate speeds (e.g. 28% load point) were associated with higher emissions, suggesting that engine manufacturers may be able to calibrate their engines for lower emissions under typical operations. Further research into the links between BC emissions and

reduced speeds, including mechanisms to ensure that lower speeds result in commensurate emission reductions, is recommended.

- EGCS: The use of scrubbers to meet global or regional fuel sulfur limits may have BC benefits. However, while scrubbers appear to allow compliance with regional (SECA) gaseous phase sulfur limits, they do not appear to control sulfur particulates. This finding has implications for public health and the overall design of IMO's fuel sulfur limits and points to the need for better data on scrubber performance.
- Use of high quality distillate fuels: Overall, distillate fuels had the lowest BC emissions, followed by conventional HFO. The low sulfur residual fuel tested, however, had the highest BC EF of the fuels tested. This raises concerns about the potential impact of IMO's tightened global sulfur limit of 0.5% for marine fuels in 2020 on BC emissions if met primarily through the use of blended fuels.

1 Introduction

This report presents the results of a black carbon (BC) marine emissions study that was led by the University of California-Riverside (UCR). This research was funded by the International Council on Clean Transportation (ICCT) under grants from the Climate and Clean Air Coalition (CCAC) and the U.S. Department of Transportation Maritime Administration (MARAD), with in-kind support from Environment and Climate Change Canada (ECC) and the National Research Council of Canada (NRC).

This research supports the marine component of a two-year project funded by CCAC and implemented by the ICCT to understand BC emissions from the marine transportation sector. The overall object of this study was to: A) validate the emission factors from well-maintained engines under in-use conditions B) help develop a general methodology to account for conditions where BC emissions may differ from values measured under test bench conditions and C) investigate the link between slow steaming and BC emissions.

This research was conducted over three main tasks. In Task 1, laboratory testing was conducted with a marine engine operating on an engine dynamometer with three representative marine fuels to generate and evaluate BC emissions data using a number of measurement approaches. For tasks 2 and 3, emissions measurements were made on ocean going vessels (OGVs) under to in-use conditions to better characterize BC emissions during actual OGV operation. Under Task 2, BC emissions factors were measured from a modern Tier 2 engine on an OGV at normal and VSR conditions. For Task 3, BC emissions factors were measured from an OGV equipped with an exhaust gas control system (EGCS) scrubber to evaluate the impacts of the latest generation of emission control strategies on BC and other emissions. The OGV data collected in Tasks 2 and 3 also provides a comparison with the laboratory testing conducted under Task 1.

The results for Tasks 1, 2, and 3 will inform: (1) an updated global marine BC emissions inventory and (2) a database of effective BC emissions reduction technologies and strategies. Results can also inform ongoing discussions at the International Maritime Organization (IMO) where delegations are working to understand the impact of marine BC emissions on the Arctic. This study was a key topic ICCT's 2nd Technical Workshop to discuss appropriate measurement approaches for marine BC emissions in September of 2015 in Utrecht, Netherlands. The final results were subsequently presented at ICCT's third and final Technical Workshop on Marine BC Emissions that was held in September of 2016 in Vancouver, Canada. This report describes and discusses the results of both the laboratory testing conducted under Task 1 and the on-board marine engine BC testing under Tasks 2 and 3, and the significance of these results in terms of the overall context of characterizing marine BC emissions.

2 Background

2.1 Policy context

The 62nd session of IMO's Marine Environment Protection Committee (MEPC) agreed to a work plan to consider the impact of BC emissions from international shipping on the Arctic. MEPC 62 tasked its Sub-Committee on Bulk Liquids and Gases (BLG) - now Pollution Prevention and Response (PPR) – with:

1. Developing a definition of marine BC
2. Identifying the most appropriate methods for measuring marine BC
3. Investigating appropriate marine BC control measures

While the main focus of the UCR-led research is to support the goals of CCAC by developing an updated marine BC emissions inventory and a database of effective BC emissions reduction technologies and strategies, the present research can also help inform ongoing marine BC policy discussions at IMO related to defining, measuring, and investigating control measures for marine BC emissions.

2.1.1 Defining marine BC

The ICCT held its 1st Technical Workshop on Marine BC Emissions in Ottawa, Canada in September 2014. This workshop focused on building consensus on a definition of BC. Over 35 experts on marine emissions participated in the workshop. A key outcome of this workshop was a general agreement on the definition of BC as defined by Bond et al. (2013): BC is a "distinct type of carbonaceous material, formed primarily in flames, is directly emitted to the atmosphere, and has a unique combination of physical properties." Two properties related to light absorption and heat resistance were considered to be particularly useful for measurement purposes:

- BC strongly absorbs visible light with a mass absorption coefficient (MAC) value above 5 m2 g-1 at a wavelength λ = 550 nanometers (nm) for freshly produced particles
- BC is refractory, with a volatilization temperature near 4000 K

This definition of marine BC was formally accepted by IMO at MEPC 68 in May 2015.

2.1.2 Measuring marine BC

There are many potential methodologies and instruments that one might use to measure marine BC emissions. However, previous attempts to measure marine BC have revealed that the measurement approach can have a substantial impact on BC emission factors. IMO's MEPC 62 recognized the need to identify appropriate measurement methods for marine BC emissions. ICCT's 2nd Technical Workshop on Marine BC Emissions brought together over 30 experts on marine BC representing more than 20 organizations and governments to discuss appropriate measurement approaches. The workshop was held 16-17 September 2015 in Utrecht, Netherlands. The ICCT hosted the workshop in collaboration with the Dutch Ministry of Infrastructure and Environment (IenM) and the Netherlands Organization for Applied Scientific Research (TNO).

Key workshop outcomes included: extensive input from participants to refine UCR's research plan for laboratory and on-board BC testing; collaborative recommendations to enhance the utility of a BC testing reporting protocol developed by the European Association of Internal Combustion Engine Manufacturers (EUROMOT); guidance on the appropriate types, applications, and possible performance criteria for testing instruments; and, identification of data gaps that need to be addressed to create a refined global marine BC inventory and to ensure comparability across instruments and measurement approaches. Workshop participants concluded that more laboratory and onboard testing was needed before one could propose a comprehensive marine BC sampling and measurement protocol.

2.1.3 Control Measures for Marine BC Emissions

Marine BC mitigation strategies including slow-steaming, fuel switching, and scrubbers were examined in Tasks 2 and Task 3 of this research project (onboard testing). Task 2 and 3 results provide important information on how effective marine BC emissions reduction strategies are as a part of ICCT's CCAC project. Task 1, 2, and 3 results were also presented by the UCR team at ICCT's third and final Technical Workshop on Marine BC Emissions that was held in September 2016 in Vancouver, Canada. This workshop focused on marine BC mitigation strategies and information and studies that were relevant to ongoing policy discussions at IMO.

2.2 Black carbon measurement methods

Combustion products are complex and include gases and both solid and condensable particulate matter (PM). Many analytical methods quantify the gases and concentration of atmospheric soot particles and depending on the method used, the non-organic carbon fraction of soot is labeled BC or elemental carbon (EC). Unlike organic carbon (OC), which is emitted from primary sources and is formed from chemical reactions in the atmosphere (secondary OC), BC/EC are only emitted directly into the atmosphere.

One apparent difference in the values for EC and BC are the methods of analysis. When its light-absorbing properties are measured, soot is often referred to as equivalent BC (eBC) (Petzold, 2013). When its concentration is measured by thermal or thermal/optical techniques; however, it is generally referred to as EC. The EPA report notes that BC and EC values from these measurement methods are highly correlated, although "the method-defined values may differ by as much as a factor of two (EPA, 2012)." A significant advantage of monitoring BC by photometry is that it delivers results in real time with a high time resolution. The absorption properties of BC are the reason it is considered a short lived climate forcer, and thus absorption methods are usually viewed as more relevant for climate impact assessment.

Table 2-1 Description of BC Measurement Techniques (EPA, 2012)

Method Type	Method Description	Prevalence of Use
Light absorption/optical	*Filter-based:* Light absorption by particles is measured through a filter loaded with particles; BC is quantified using factors that relate light absorption to a mass concentration.	High
	Photoacoustic: Light absorption by particles is measured by heated particles transferring energy to the surrounding air and generating sound waves; BC is quantified using factors that relate light absorption to a mass concentration.	Low
	Incandescence: Incandescent (glowing) particle mass is measured; BC is quantified by calibrating the incandescent signal to laboratory-generated soot.	Low
Isolation of specific carbon fraction	*Thermal-Optical:* BC is measured as the carbon fraction that resists removal through heating to high temperatures and has a laser correction for carbon that chars during the analysis procedure; BC is quantified as the amount of carbon mass evolved during heating.	High
	Thermal: BC is measured as the carbon fraction that resists removal through heating to high temperatures; BC is quantified as the amount of carbon mass evolved during heating.	Low

In Figure 2-1 the EPA points out that carbon types can be characterized either by measuring their light-absorbing properties, as seen on the left side of the figure or based on measurements of the refractory nature of the material and inertness at high temperatures, as seen on the right side of the figure (ECa and OCa). The EPA and others also discuss another category of Light absorbing carbon (LAC), the so-called Brown Carbon (BrC).

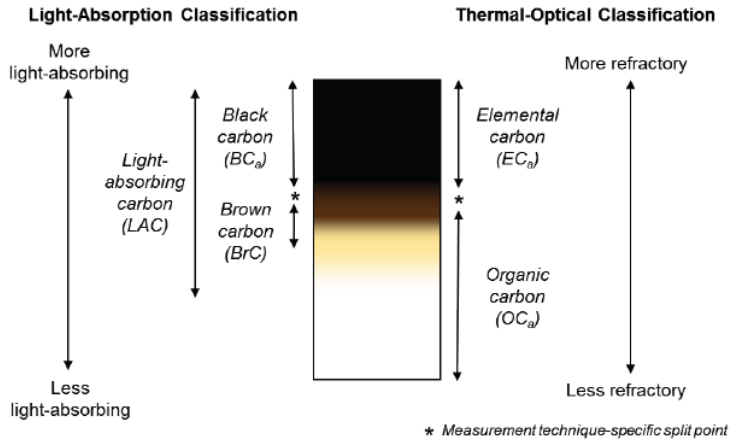


Figure 2-1 Measurement of the carbonaceous components of particles (EPA, 2012)

A summary table of the recommended terminology based on Petzold et al. was listed in Table 2-2.

Table 2-2 Recommended Terminology (Petzold, 2013)

Property	Technical	Instruments	Reported Values	Recommendation
Light Absorption	Light absorption	MSS, Smoke Meter (FSN), Aethalometer, MAAP	Light absorption coefficient δap	Report as δap; Report as equivalent black carbon (eBC) with specify MAC value
Refractory	Thermal radiation	LII	Mass concentration	Report as refractory black carbon (rBC)
Chemical Composition, Carbon Content	Thermal evolution of carbon with optical correction for pyrolysis	Batched and semi-continue EC/OC (IMPROVE, NIOSH 5040) [1]	Mass concentration OC/EC mass fraction	Report as elemental carbon (EC)

[1] Other methods such as EUSAAR-2 have been utilized by others, but were not part of this research (Cavalli, F. et al., 2010)

Also in 2012, the International Council on Combustion Engines (CIMAC) issued a report on BC emissions from large marine engines to include measurement methods, emissions factors and abatement strategies. They recommend that the measurement should mirror the light absorption of BC deposits and suggest LAC is a better term to use instead of BC (CIMAC, 2012). Their review of the methods indicates there may be a correlation between the thermally stable carbon (EC) and BC; however, it is not universal and robust (CIMAC, 2012). For cases where the ratio of EC/OC is low (i.e., large amounts of OC), as in ships, some of the OC may undergo pyrolysis and bias EC measurements high (CIMAC, 2012). CIMAC WG 5 recommended the Filter Smoke Number (FSN) measurement method according to ISO 10054 with equation A.16 of ISO 8178-1 to convert the FSN to BC concentration in the exhaust gas.

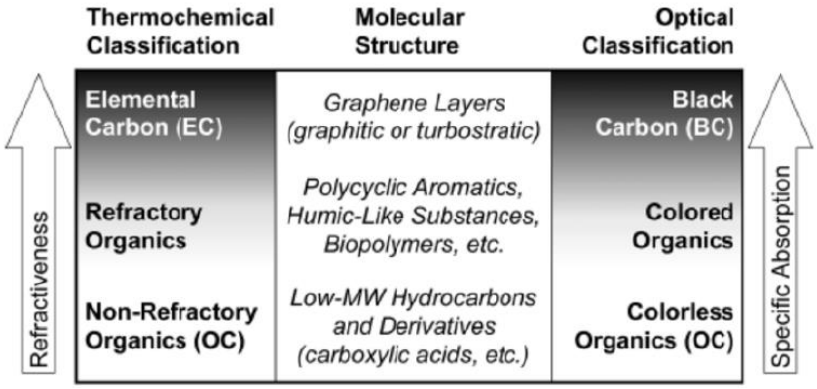


Figure 2-2 Classification of carbon compounds with thermal & optical methods (CIMAC, 2012)

2.3 Marine vessel black carbon emissions

Ports and marine vessels are a large source of diesel particulate matter and black carbon. Black carbon is second to carbon dioxide as the largest contributor to human induced climate warming according to Bond et al. (2013). The EPA study found that "mitigation of diesel-engine sources offers the most confidence in reducing near-term climate forcing from BC." With the landmark, ambitious Clean Truck Program, the Ports of Los Angeles/Long Beach cut PM pollution by 90% as older trucks were permanently banned from the ports and only trucks with DPFs were allowed. Marine vessels face unique challenges in controlling black carbon emissions where DPF systems are not practical due to high concentrations of the sulfate emissions can damage the DPF system, although the sulfur content of marine fuels is restricted in certain regions. Aligned with controlling the sulfur content of the fuels is the allowance of using scrubbers to control the sulfur of the exhaust. In the process additional PM and BC control takes place, but data on the efficiency of scrubbers in removing PM and BC is sparse.

In research to date, measurements of ship-related BC emission factors have ranged from 0.1 to 1 g/kg fuel, as shown in Table 2-3 (CIMAC, 2012). Some say that international shipping contributes approximately 2% of global black carbon emissions (Lack et al., 2012), and 9% of overall diesel BC emissions, with one-third of those emissions occurring north of 40 degrees latitude (ICCT, 2015). But the exact contribution is a matter needing further research given the span of results. For example, from CIMAC study, Lack's low estimate BC emission factor of 0.36 g/kg fuel agreed with Corbett's result, while Lack's high estimate BC emission factor of 1 g/kg fuel was ten times higher than Agrawal's factor, which was close to the BC emission factors of the 4-stroke medium speed engine (CIMAC, 2012). Petzold's studies showed BC emissions factors varied from 0.06 to 0.36 g/kg fuel using optical method (CIMAC, 2012).

Table 2-3 Example BC Emission Factors in Literature (CIMAC, 2012)

BC emission fuel burned	g/kg fuel	Method of determination
Lack et al, 2008	0.36 -1	Optical/photoacoustic
Agrawal et al, 2008	0.1	Thermal
Corbett et al, 2010	0.37	
Petzold et al, 2010	0.179 ± 0.018	Optical
Petzold et al, 2008	0.06 (85% load) 0.36 (10% load)	Optical

The results in Figure 2-3 show BC depends non-linearly with load and fuel properties with an interesting observation that the Light Fuel Oil (LFO) may not have the expected benefits when compared with some

HFOs. CIMAC concluded that switching to distillate fuel (LFO) may not result in reduced black carbon emissions from large engines. UCR believes more data are needed.

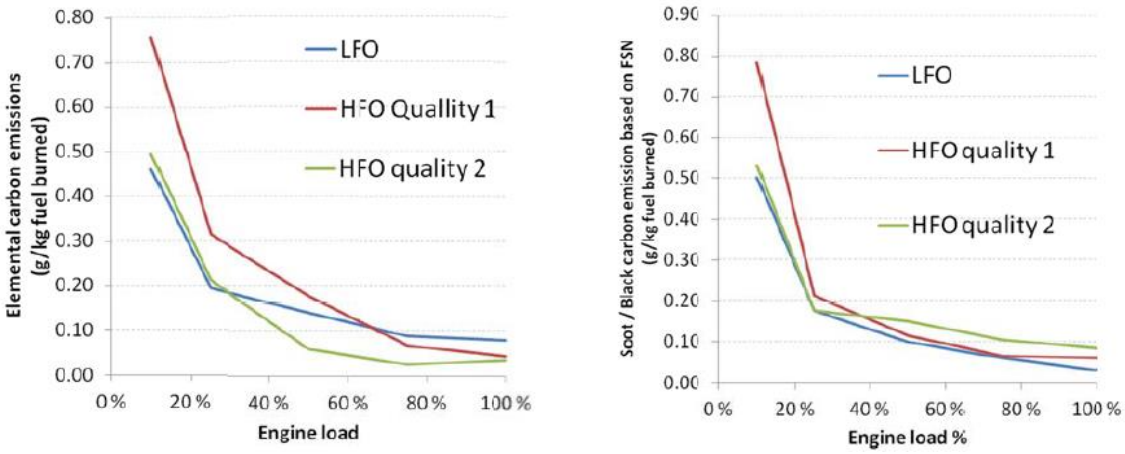


Figure 2-3 Reported black carbon emissions as a function of engine load percent (CIMAC, 2012)

2.4 Objectives

The objectives of this study were to provide information that can be used to update global marine BC emissions inventory and to characterize how effective BC emissions reduction technologies and strategies are in marine applications. The study was carried out in three tasks, with Task 1 being laboratory testing of BC emissions from a marine engine on an engine dynamometer. The objectives of the bench-testing were to evaluate the following, using a marine diesel engine operating over a range of engine loads and fuel types:

1. The effects of fuels and loads on BC emission factors (g/kWh)
2. The effects of sample pretreatment/conditioning methods;
3. The performance of various BC emissions measurement instruments; and,
4. The comparability of BC emissions measurement results across instruments.

Tasks 2 and 3 focused on emissions measurements were made on OGVs under to in-use conditions to better characterize BC emissions during actual OGV operation at sea. For Task 2, an OGV equipped with a Tier 2 main engine was tested, and for Task 3, an OGV equipped with a state-of-the art scrubber EGCS.

2.5 Organization of the Report

This report discusses the results for each of the individual tasks in section 3 (laboratory testing), section 4 (at sea testing of a OGV with a Tier 2 engine), and section 5 (at sea testing of a OGV with a scrubber EGCS). Section 6 provides a discussion of the combined results for all tasks in the context of the broader literature for marine BC emission factors, fuel consumption, the load, VSR, and fuel dependence of BC emissions, and the hygroscopic growth of PM. Section 7 discusses some of the most important conclusions of the work in terms of load effects, VSR, fuel effects, and the observations for each of the individual tasks.

3 Task 1 Engine Test Stand

3.1 Research approach

The laboratory-based portion of the testing campaign took place from November 2015 to January 2016 at UCR's College of Engineering Center for Environmental Research & Technology (CE-CERT) facilities. The approach to the laboratory testing was based on the originally proposed research plan with modifications based on feedback received at ICCT's 2nd Technical Workshop on marine BC emissions, see Appendix H for details. The original plan was to perform five test loads on a marine 2-stroke engine while testing a commercially available Emission Control Area (ECA) compliant fuel, a test fuel outside of ECA compliance, and a new low sulfur residual fuel oil. The UCR consortium presented their proposed testing plan at ICCT's 2nd Technical Workshop on Marine BC Emissions in September 2015 in the Netherlands and modified their experimental approach based on feedback from other experts on marine BC sampling and measurement. Workshop participants suggested that the UCR team explore the influence of exhaust sample pretreatment and conditioning on BC emissions. Participants also suggested that the UCR team use a draft marine BC emissions testing reporting protocol presented by the EUROMOT at the workshop. The UCR consortium accepted both of these suggestions. The original scope of work is provided in Appendix H. The Task 1 research is based on the revised scope of work presented in this section.

The approach section was organized into three main sub sections

- Test article
- Sample conditioning
- Measurements

The test article section discusses details on the engine, fuel, and load points utilized. In addition, there is a discussion on the order of tests, results from the fuel analysis, and results from the engine performance. The sample conditioning section discusses the construction and performance of the sample conditioning system utilized. The sample conditioning performance includes an analysis on the solid particle losses (diffusional and thermophoretic) through the system. The measurement section presents the range of BC instruments and other instruments utilized for the engine test stand work.

3.1.1 Test article

The test article includes the test engine, fuel, and the matrix of tests proposed and as performed.

3.1.1.1 Test engine

The test engine is a 2-stroke Detroit Diesel Model 6-71N (naturally aspirated), with an in-line 6 cylinder configuration (7 liters per cylinder), a maximum rated speed of 2300 RPM (range 1100-2300 RPM), a maximum engine power of 187 kW, a brake mean effective pressure (BMEP) of 641 kPa, and an associated rated brake specific fuel consumption (BSFC) of 307 g/kWh (0.505 lb/hp-hr) at 1100 RPM (N70 injectors used during testing). This type of engine is typically used on small vessels or as an auxiliary engine on ocean going vessels (OGVs). OGVs usually switch to auxiliary engines when approaching port or other areas where more maneuvering is required, making the selected test engine relevant for areas where emissions are most often scrutinized. Appendix G provides a more details on the engine used for testing.

3.1.1.2 Test fuel

Three different fuels, typical of commercially available marine fuels, were used in the project. Two of the fuels, the distillate (DMA) and heavy-fuel oil (HFO), are widely used and the third fuel, a low-sulfur HFO meets SECA specifications and is a recent addition to the marketplace. At the present time, it is only sparingly available at a few places in Europe and the West Coast. The three fuels had widely varying

properties for sulfur; density, viscosity, carbon residue and calculated carbon aromaticity index (CCAI). The CCAI is a measure of the ignition quality of residual fuel oil and is normally a value between 800 and 880; values > 880 are often problematic. CCAI is calculated by:

$$CCAI = D - 140.7\log(\log(V + 0.85)) - 80.6 - 483.5\log\left(\frac{t + 273}{323}\right)$$

Where:

D= density at 15°C (kg/m3);
V= viscosity (cST);
t = viscosity temperature (°C)

Some questioned whether the small engine would operate with the residual fuels, RMG-380 and RMB-30 so we developed two procedural changes to enable the engine to operate on residual fuels. First, the fuels were heated to near 95^{o}C so they could be pumped to the engine, and second, we ran the engine on the distillate fuel at a high load for about an hour before introducing the residual fuels so the piston acted as glow plug allowing combustion to be sustained when the residual fuel was introduced.

It was believed that by selecting a wide range of marine fuel properties in the design that during the analysis phase, the black carbon emissions could be mapped to selected fuel parameters. Table 3-1 shows the fuel properties of the three marine fuels. The RMB-30 fuel had a sulfur concentration of 0.0013% (13 ppm) and a viscosity of 13.7 cSt. The RMG-380 fuel had a sulfur concentration of 3.18 weight percent and a viscosity of 359 cSt, typical of fuels used by ocean going vessels.

Table 3-1 Fuel Properties

Fuel	DMA	RMB-30	RMG-380
Sulfur wt% (ppm)	13	13.2	31,849
Density @ 15˚C (kg/L)	0.8309	0.8586	0.9826
Viscosity @ 40˚C (cSt)	2.696		
Viscosity @ 50˚C (cSt)		13.73	358.9
Micro Carbon Residue (%m/m)	< 0.1	< 0.1	12.84
CCAI_calculated		769	845

3.1.1.3 Test matrix

Testing was conducted using the three fuels under different engine loads (25%, 50%, and 75%) with and without sample conditioning. For each of the three test fuels and varying engine loads, engine sequencing with and without sample conditioning are described in Table 3-1 and Table 3-2, respectively. The effects of sample pretreatment/conditioning on measurement instrument behavior were investigated by running some tests with and without a sample conditioning unit at the 25% and 75% load points. Throughout the measurement campaign the EUROMOT reporting protocol (see Appendix D for details) was used to record relevant test information.

Table 3-2 Engine Test stand Loads and Methods for Each of the Three Fuels

Test point	Sample Conditioning	Unique ID	Engine Load (%)	RPM
M1	Catalytic Stripper	M1_CS	25%	1100
M1	Bypass	M1_BP	25%	1100
M2	Catalytic Stripper	M2_CS	50%	1100
M3	Catalytic Stripper	M3_CS	75%	1100
M3	Bypass	M3_BP	75%	1100

The engine was operated at three load points 25%, 50%, and 75% of maximum power (83.5 kW) at 1100 rpm. The original test plan was to perform five engine load points: 10%; 25%; 50%; 75%; and 100%. Typically, in-use testing limits the actual full load condition due to component aging and safe practices for OGV, so 100% load could not be safely achieved. With the introduction of the sample conditioning system, the 10% and 100% load points were not tested. Instead, BC was measured at the 25% and 75% load points under two conditions: bypass (BP) and CS in order to characterize the impact of the sample conditioning system on marine BC emission factors.

Due to concerns with engine overheating and operating the marine fuels, it was decided to run the lower loads first followed by the higher loads. Typically test stand work is performed from high to low load, but during in-use vessel testing both scenarios are utilized and it has been demonstrated that going from low load to high load produces reproducible and reliable emission factors. Triplicate tests were also part of the plan, but due to test delays and issues with instruments, the test points were sometimes limited. The test varied from 2 to 4 repeats, see Table 3-3. During RMG-380 testing the engine was overheating while trying to perform the repeated 75% loads. As a result, the order that the test points were run was switched between high and low loads to prevent sustained operation at high loads (and high engine temperatures), see Appendix E Table E-1 for actual order.

The power load levels varied slightly between the different tests run at each of the test modes. Mode 1 ranged from 24% to 28% between the different fuels and sample conditioning setups. Mode 2 load varied from 47% to 52% and Mode 3 load varied from 67.6% to 72.5% of maximum power between the different test points.

The engine had less than 500 hours of operation since its recent overhaul and represents an engine in good operating condition. In summary, the engine load stability, test points order, and repeat count were of sufficient quality to be representative of stable black carbon emissions for the determination of emission factors and measurement comparisons between the test fuels, loads, sampling methods, and instruments.

Table 3-3 Summary of Engine Loads for the Test Matrix

			Engine				Temperature C		Sample
Fuel	Mode	Sample	kW	% Max	RPM	ft-lb	Exh	Fuel	Size n
DMA	1	CS	26.6 ± 1.9	28%	1100	127	191	37.6	3
	1	BP	25.9 ± 0.1	27%	1100	123	194	49.4	2
	2	CS	46.6 ± 0.0	49%	1100	223	272	56.1	2
	3	CS	67.9 ± 0.3	71%	1100	324	366	64.4	3
	3	BP	67.6 ± 0.0	70%	1100	323	368	68.3	2
RMB-30	1	CS	24.8 ± 0.3	26%	1100	118	192	80.4	3
	1	BP	24.9 ± 0.0	26%	1100	119	191	77.5	2
	2	CS	50.1 ± 0.2	52%	1100	239	287	77.2	2
	3	CS	67.6 ± 0.0	70%	1100	323	377	81.4	4
	3	BP	67.7 ± 0.2	71%	1100	323	378	82.6	3
RMG-380	1	CS	25.1 ± 1.3	26%	1100	120	201	97.0	3
	1	BP	22.5 ± 1.6	24%	1100	108	198	96.7	2
	2	CS	45.3 ± 0.0	47%	1100	216	273	98.3	2
	3	CS	70.4 ± 3.0	73%	1100	336	389	95.7	3
	3	BP	72.5 ± 4.8	76%	1100	346	399	96.7	2

3.1.2 Sample conditioning

The sample conditioning consisted of a CS, a sulfur adsorber section, and a dilution system that included no dilution (1:1), 14:1, and 1400:1.

3.1.2.1 Catalytic stripper

Due to the higher sulfur content typical of marine fuels and the two stroke engine design, marine diesel engine emissions generally include co-emitted particle species such as sulfates, water, semivolatile and volatile organic compounds, and ash, in addition to BC. Bond et al. (2013) defined BC by four distinct properties (light absorption, thermal stability, insolubility, and morphology) and there is no one instrument that can measure all of these physical properties simultaneously. Rather, different instruments employ different measurement principles and the presence of semivolatile and volatile organics coating/mixed with BC particles can affect different instruments in different ways and/or to varying degrees. This suggests a system to remove these confounding interferences on BC measurement is of interest.

The purpose of engine exhaust sample pretreatment/conditioning was to remove as much of the co-emitted species as possible, yielding a “purer” BC particle, in order to: achieve the most accurate BC

emissions measurements possible; and, improve the comparability of measurement results across instruments. However, it is worth noting that the sample pretreatment/conditioning stage(s) can potentially lead to BC particle losses and changes in some gaseous emissions. Therefore, care was given to minimize and quantify these effects.

A CS was one of the key components of the sample conditioning systems that was added based on feedback received at the ICCT's 2nd Technical Workshop. A CS is a catalytic device that removes semi-volatile hydrocarbon particles through evaporation and oxidation (Abdul-Khalek, 1995). A 40 L/min CS and two sulfur adsorbers were designed and constructed for this project. The CS consists of three heated flow-through ceramic monoliths that have a platinum and palladium-based washcoat. The design temperature range is 350°C - 400°C and the maximum operating flowrate is 40 L/min. Lower flowrates will increase the removal of semi-volatile material and increase particle loss. The sulfur adsorbers were added because a technical meeting highlighted the need for additional sulfur removal capability (that is beyond the removal due to the "poisoning" effect in which sulfur reversibly adsorbs to the precious metals in the CS).

The CS is a cylindrical, monolithic device with parallel flow-through channels along its axis. Design of a CS requires consideration of the impact of substrate geometry and temperature on particle evaporation rates, particle loss, and the diffusion of gas molecules in the channels (Khalek, 2007) (Swanson, 2013). The ceramic substrate used was coated with a high surface area proprietary washcoat that contained highly dispersed platinum group metal (PGM) crystallites enabling rapid oxidation of hydrocarbons. The catalytically active monolith was retained in a stainless steel mantle with an intumescent mat. The mantle had welded stainless steel cones for attachment to inlet and exit streams. The mantle was resistively heated with the gas temperature set-point of ~380°C based on measurement of the gas temperature along the central axis of the CS midway near the outlet. Table 3-4 shows some geometry and operating conditions of the CS used in the present work, which was based on calculations described in detail elsewhere (Swanson, 2013).

Table 3-4 Specifications and calculated performance of the CS used for Task 1

Catalyst cell density	400	cells/in^2
Catalyst wall thickness	4	mm
Operating temperature	380	°C
Inlet flowrate	20	L/min
$C_{40}H_{82}$ penetration	<0.001	-
d_{50} size	~6-7	nm

[1] The diffusion coefficient used to calculate tetracontane penetration was 7.89 x 10-6 m2/s. The d50 size is the particle size where 50% of particles penetrate.

The CS geometry is fixed though the choice of cell density and physical dimensions, which impacts residence time. For the geometry in Table 3-4, the residence time is about 2 seconds. For a fixed geometry, the operating temperature and flowrate dictate performance, although performance needs may vary depending on application. The design parameters for the CS reflect a balance between solid particle loss, flowrate, residence time, operating temperature, and vapor removal.

3.1.2.2 Sulfur adsorber

To meet this need, two "sulfur adsorbers," consisting of flow-through ceramic monoliths containing barium were constructed. They are designed to capture gas phase SO3 molecules resulting from the oxidation of SO2 to SO3 in the CS, and therefore they were located downstream of the CS. The catalyst

was being operated at a temperature (400C) which more conducive to SO2 oxidation and release (as SO3 /SO_4) than SO_2 storage. Therefore the optimal location for the SO2 scrubber is downstream of the CS, to minimize the likelihood of oxidized S compounds entering the gas stream and impacting the particle measurement. The absorber design temperature range is 100°C - 200°C. Periodic regeneration of the adsorbers was required, using temperatures exceeding 300°C for 2 hours with a slight flow of 2 standard liter per minute (slpm).

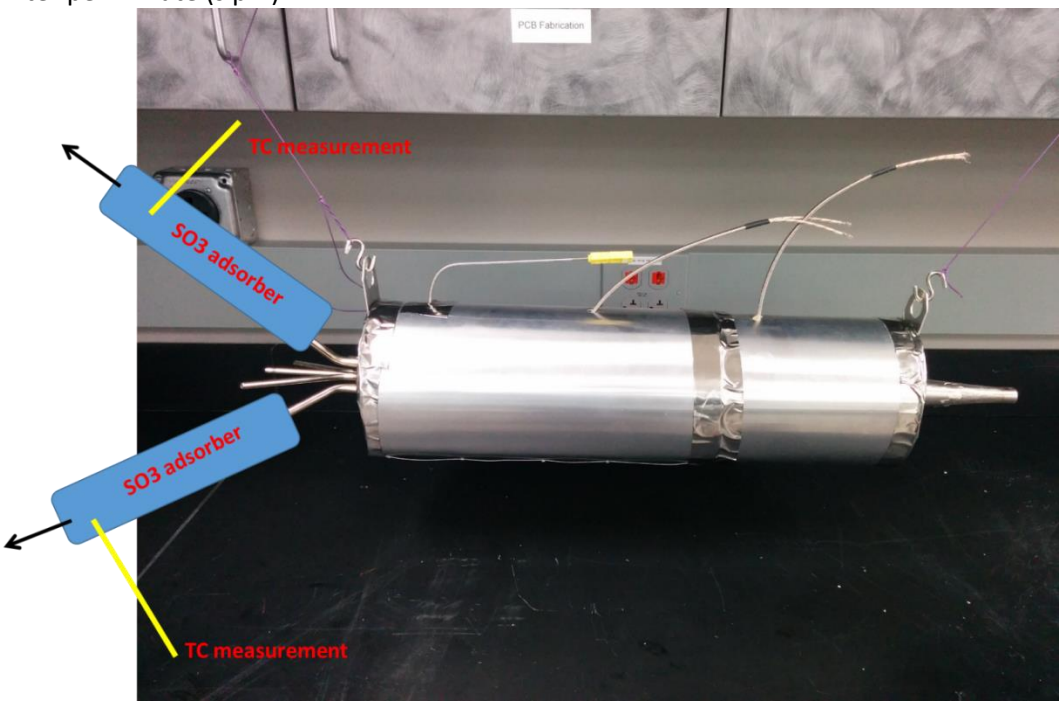


Figure 3-1 Sample conditioning system (CS + Sulfur Absorbers)

3.1.2.3 CS Operation

This section describes the general operating conditions of the CS and dilution systems and some performance evaluations of the CS system using the reductions in the organic carbon fraction of the PM as the basis of its performance. Future results will be provided with sulfate reduction, but those results were not available at the time of this report.

Table 3-5 shows the sample conditioning operating temperatures for the inlet, bed, and sulfur absorber systems (in °C). The CS was operated with a catalyst bed temperature between 350 °C to 400 °C. There were two sulfur absorber systems one for the inlet of the dilution systems (both 14:1 and 1400:1) and one for the raw sample systems. The sulfur absorbers were both operated at around 140 °C (98 °C to 192 °C). When sampling in BP mode, there was no flow through the CS system and, thus, the temperatures are representative of a non-flowing system, which were often lower.

Table 3-5 Summary of sample conditioning system temperatures

Fuel	Mode	Sample	% Load	Temperature C					Sample Size n
				Exhaust	CS In	CS Body	CS Exit 1	CS Exit 2	
DMA	1	CS	28%	191	190	350 ± 12	162	131	3
	1	BP	27%	194	194	237 ± 21	98	67	2
	2	CS	49%	272	274	364 ± 4	140	158	2
	3	CS	71%	366	370	368 ± 5	117	98	3
	3	BP	70%	368	370	241 ± 18	98	68	2
RMB-30	1	CS	26%	192	191	366 ± 1	192	155	3
	1	BP	26%	191	191	256 ± 20	97	65	2
	2	CS	52%	287	288	376 ± 3	174	155	2
	3	CS	70%	377	381	388 ± 2	164	155	4
	3	BP	71%	378	382	251 ± 23	100	69	3
RMG-380	1	CS	26%	201	197	380 ± 17	164	141	3
	1	BP	24%	198	197	269 ± 58	105	73	2
	2	CS	47%	273	273	388 ± 2	171	137	2
	3	CS	73%	389	324	375 ± 10	149	134	3
	3	BP	76%	399	407	247 ± 11	98	69	2

3.1.2.4 BC particle line losses

An important consideration in sampling PM is the potential for line losses in the sampling system. For this section particle line losses were estimated for the BC emissions, to provide a measure of how much particle line losses might be impacting the measured BC emissions. The calculated solid particle penetration in the CS, including the heat exchanger, is shown in Figure 3-2. The curve illustrates both diffusive particle loss (Hinds, 1999) and thermophoretic losses that occur as the sample cools downstream of the CS before measurement or dilution. For particles greater than about 100 nm, the only significant loss mechanism is thermophoresis, which acts independently of particle size in the free-molecular regime (Messerer, 2003). The fraction of particles lost is equal to 1 – penetration (P). There are several expressions to estimate the penetration of solid particles, as shown in Equation (1) (Mulholland, 1989) and Equation (2) (Giechaskiel, 2010b). As shown by the example calculations, these examples differ by just a few percent for the present CS conditions, showing that particle line losses for the present sample conditioning system are approximately 22-24%.

$$P \cong 1 - \frac{(T_{cs} - T_{amb})}{2T_{cs}}, \qquad (1)$$

Example calc: $P(T_{cs} = 380°C, T_{amb} = 70°C) = 0.763$; Loss = 23.8%

$$P \cong \left(\frac{T_{amb}}{T_{cs}}\right)^{0.385}. \qquad (2)$$

Example calc: $P(T_{cs} = 380°C, T_{amb} = 70°C) = 0.78$; Loss = 22.0%

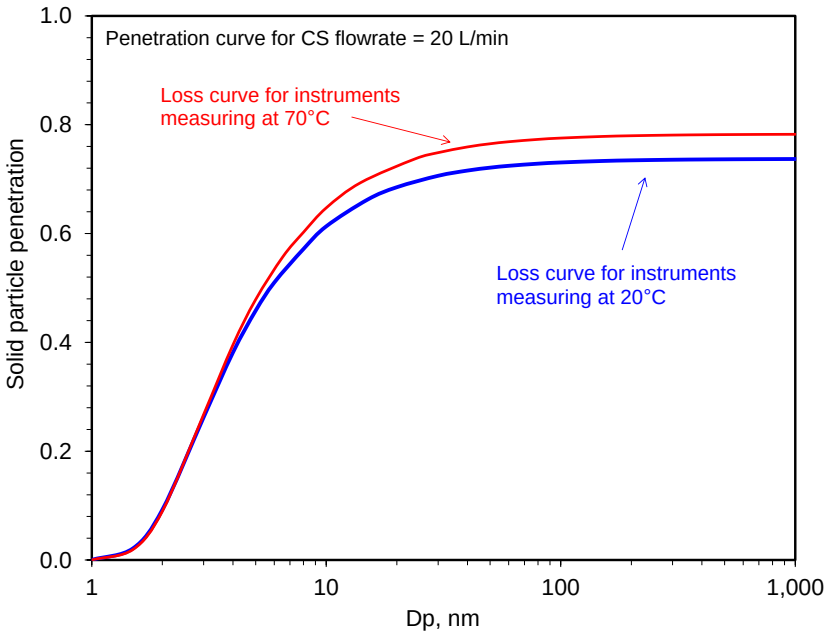


Figure 3-2 Calculated solid particle penetration in the CS

[1] The calculation illustrating Diffusive and thermophoretic particle loss (T_{cs} = 380°C, T_{amb} = 70°C & 20°C).

The thermophoretic loss calculations can be compared against the experimental data for a subset of the data. For example, FSN measurements were collected before and after the sample conditioning system. A comparison of these results is provided in Figure 3-3, for conditions with CS temp (Tcs) = 380°C, ambient temp (Tamb) = 70°C, where Penetration is 0.78 and the particle loses between the instruments should be 22.0%. Figure 3-3 shows that the FSN experimental results for the DMA and RMB-30 fuels show a 22% loss of particles between the two instruments, which matches the result from theoretical calculation. For RMG-380, FSN experimental results show a 32% particle loss. One possible explanation for the differences in the actual compared to the theoretical estimates for the RMG-380 is that the particle loss calculations assume that most of EC diameter is greater than 100 nm, while the peak particle size distribution of RMG-380 is around 30nm-80nm, which is smaller than 100nm.

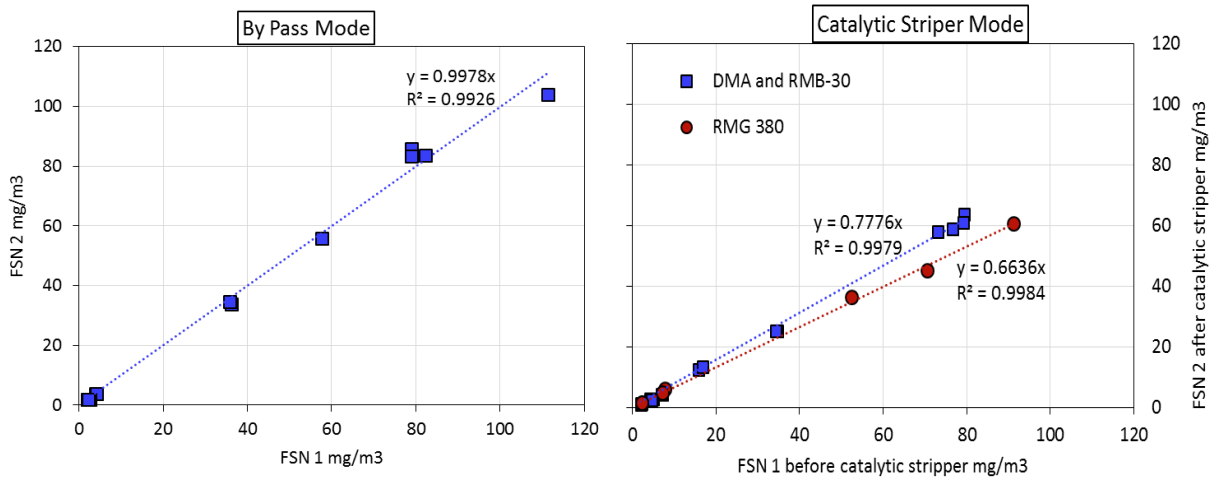


Figure 3-3 Smoke Meter showing 22% particle loss for low sulfur fuels

3.1.2.5 Dilution Ratio

The dilution ratio (DR) for the ISO 8178 compliant 10:1 dilution system was fairly consistent at each mode. The DR varied from 10.4 to 12.3 for the CS samples and 10.7 to 11.1 for the BP sample for all the fuels tested at 25% load. The DR at 50% load points varied from 13.4 to 14.7. For 75% load tests, the DR varied from 15.1 to 16.2 for the CS samples and 16.0 to 18.5 for the BP sample.

The DR for the 1000:1 system was a function of three separate dilutions (see Table 3-6). The first two stages were using a rotating disk dilutor where stage one and two were a nominal 10 to 1 and the final 3rd stage to get 1000:1 was also a 10:1 system, but used the ISO-8178 compliant dilution tunnel venture approach as described in Appendix A. In the first stage of dilution, raw exhaust was mixed with an adjustable amount of HEPA filtered dilution air (at 25 °C) to create a total diluted exhaust flow of about 1.5 slpm. The average DR varied from 1168 to 1945 for all the fuels tested.

Table 3-6 Dilution Ratio Summary

				ISO DR 14:1	DR 1400:1				Sample
Fuel	Mode	Sample	% Load		RDD1	RDD2	ISO 3	Final	Size n
DMA	1	CS	28%	10.4 ± 0.2	13.1 ± 0.0	7.7 ± 0.0	10.4 ± 0.2	1553 ± 0.0	3
	1	BP	27%	11.1 ± 0.2	13.1 ± 0.0	7.7 ± 0.0	11.1 ± 0.2	1553 ± 0.0	2
	2	CS	49%	14.1 ± 0.4	13.1 ± 0.0	8.5 ± 0.0	16.0 ± 0.4	1499 ± 0.0	2
	3	CS	71%	15.5 ± 0.8	13.1 ± 0.0	9.2 ± 0.9	17.3 ± 0.8	1445 ± 62.1	3
	3	BP	70%	18.5 ± 0.8	13.1 ± 0.0	9.2 ± 0.0	18.5 ± 0.8	1445 ± 0.0	2
RMB-30	1	CS	26%	12.3 ± 0.3	13.1 ± 0.0	4.5 ± 0.0	12.3 ± 0.3	1208 ± 0.0	3
	1	BP	26%	11.6 ± 0.2	13.1 ± 0.0	4.5 ± 0.0	11.6 ± 0.2	1208 ± 0.0	2
	2	CS	52%	13.4 ± 0.0	13.1 ± 0.0	4.5 ± 0.0	13.4 ± 0.0	1208 ± 0.0	2
	3	CS	70%	15.1 ± 0.6	13.1 ± 0.0	5.6 ± 2.9	15.1 ± 0.6	1168 ± 135.1	4
	3	BP	71%	16.1 ± 0.5	13.1 ± 0.0	9.9 ± 0.0	16.1 ± 0.5	1408 ± 36.8	3
RMG-380	1	CS	26%	11.1 ± 0.1	13.1 ± 0.0	10.3 ± 0.0	11.1 ± 0.1	1945 ± 824.5	3
	1	BP	24%	10.7 ± 0.3	13.1 ± 0.0	10.3 ± 0.0	10.7 ± 0.3	1484 ± 27.1	2
	2	CS	47%	14.7 ± 1.7	13.1 ± 0.0	10.3 ± 0.0	14.7 ± 1.7	1446 ± 27.1	2
	3	CS	73%	16.2 ± 1.3	13.1 ± 0.0	10.3 ± 0.0	16.2 ± 1.3	1477 ± 22.1	3
	3	BP	76%	16.0 ± 1.5	13.1 ± 0.0	10.4 ± 0.1	16.0 ± 1.5	1472 ± 10.1	2

DR: dilution ratio RDD: Rotating Disk Thermodiluter

3.1.3 Measurements

The goals of this research were to produce EFs that could be used to (1) update the global marine vessel BC inventory (2) generate a database detailing the effectiveness of various practices and technologies in reducing BC emissions and (3) to characterize BC measurement methods. For the Task 1 effort several BC and other instruments were included to consider the particle size distribution, chemical composition, gas phase species and gas-to-particle interactions, and some physical observations with imaging techniques. This section discusses the instruments organized by groups 1) BC and 2) Other.

3.1.3.1 Instruments

The team measured BC emissions using various instruments that employed different measurement principles associated with the four distinct properties of BC. The measurement instruments that were used and their measurement principles are listed in Table 3-7.

Table 3-7 BC Measurement Instruments and Associated Measurement Principles

Instrument	Abbreviation	Measurement Principle
Aethalometer	Aeth.	light absorption and scattering
Laser Induced Incandescence	LII	thermal radiation
Multi-Angle Absorption Photometer	MAAP	light absorption and scattering
Micro-Soot Sensor	MSS	light absorption (photoacoustic)
Semi-continuous	Organic Carbon, Semi-continuous OC/EC, Carbon/Elemental	thermal-optical
Single Particle Soot Photometer	SP2	thermal radiation
Smoke Meter	FSN	light absorption

Engine emissions were also measured by supporting instrumentation that were not designed to measure BC specifically, but were useful for providing a more detailed characterization of soot particles emitted. This enables a more thorough comparison of BC measurement results across instruments. The supporting instruments that were used and the particle properties they measured are listed in Table 3-8. Table 3-9 shows the gaseous measurement collected to determine the overall performance of the engine.

Table 3-8 Supporting instruments and the emission particle property measured

Instrument	Abbreviation	Measured Property
Aerosol Mass Spectrometer	AMS	particle size and chemical composition
Condensation Particle Counter	CPC	particle concentration
DustTrak		particulate matter (particle mass concentration)
Comprehensive Two-dimensional Gas Chromatography	GCxGC	molecular composition
Hygroscopic Tandem Differential Mobility Analyzer	H-TDMA	aerosol hygroscopicity
Raman Spectroscopy Filters		graphite-like microstructure
Scanning Mobility Particle Sizer	SMPS	particle size distribution
Transmission Electron Microscopy	TEM	particle morphology
Aerosol Particle Mass Analyzer	APM	particle mass concentration
Engine Exhaust Particle Sizer	EEPS	particulate size distribution
On-board Measurement PM Sensor	NTK PM Sensor	particle # and mass concentration
Ultra-fine particle mass	$PM_{2.5}$	Total PM mass < 2.5 μm
Photoacoustic Extinctiometer	PAX	Single scattering albedo, absorption

Table 3-9 Supporting instruments for gaseous emissions measurements

Instrument	Abbreviation	Measured Property
PG 350 gas analyzer	PG350	CO, CO_2, O_2, NO_X, and SO_X concentration
NTK Stack sensor	NTK	NO_X, O_2, and NH_3 concentrations

3.1.3.2 Layout

Figure 3-4 provides a graphical representation of the measurement scenarios for four test Groups (0through 3), as well as the layout of sample pretreatment/conditioning, measurement instruments, and supporting instrumentation.

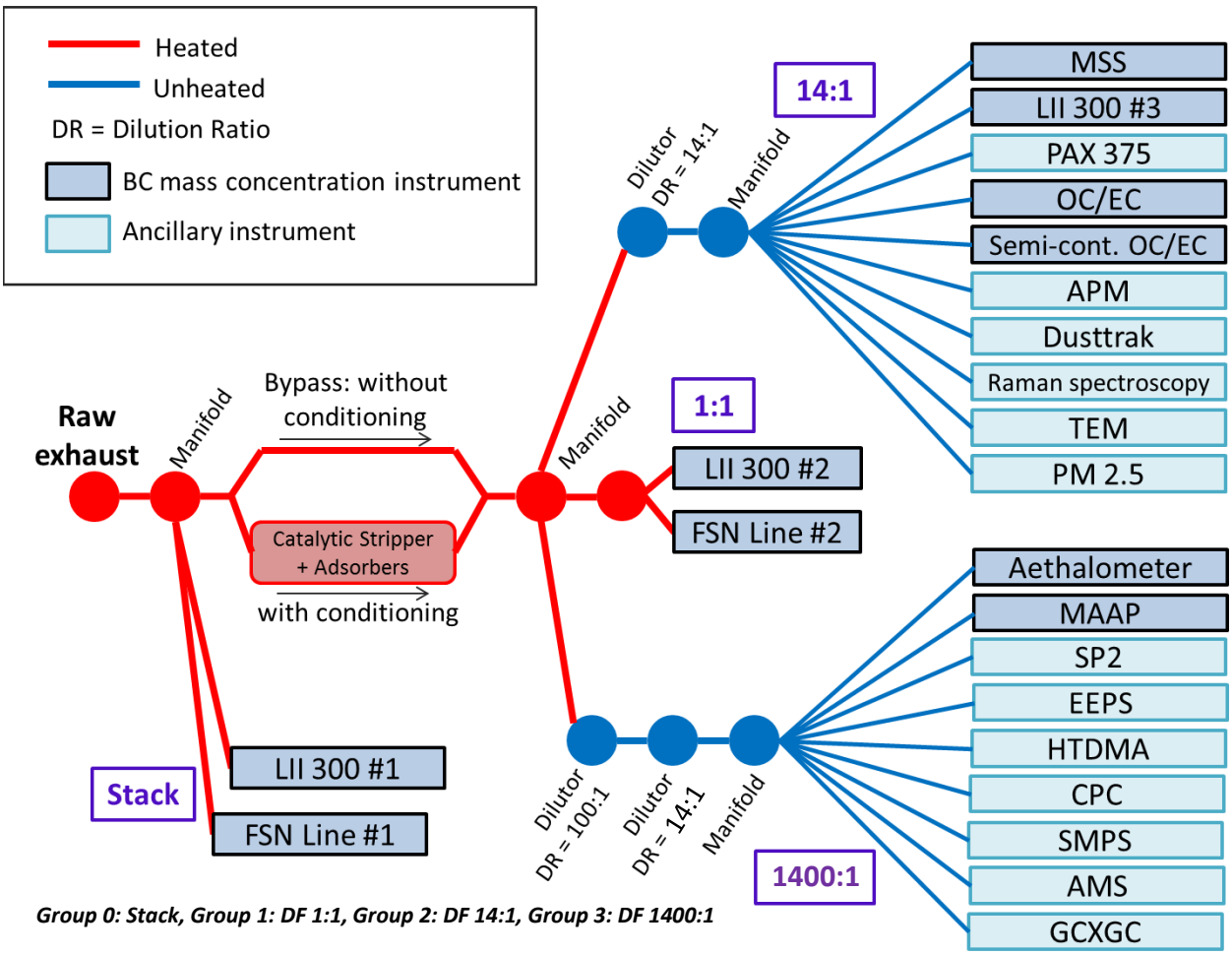


Figure 3-4 Schematic depiction of the planned experimental layout

[1] SOURCE: IMO: PPR3 PRESENTATION BY CANADA

As graphically illustrated in Figure 3-4, some tests employed sample pretreatment/conditioning via a CS/absorber unit placed between the exhaust and instruments (with the exception of Group 0). Further, in order to accommodate the different types of instruments and their respective operational characteristics, sample conditioning was also included different sample temperatures and dilution levels.

The use of heated lines (red lines in Figure 3-4) prevented condensation of water and semivolatile and volatile organics on the tubes, instruments, and BC particles to be measured. These will be employed between the exhaust and instruments in Groups 0 and 1, as well as between the exhaust and dilution points in Groups 2 and 3. For the latter two groups, heated lines were not needed after the point of dilution because conditioned air made up most of the sample air and condensation was less likely to occur.

Groups 0 and 1 were measured undiluted in order to allow comparison of measurements with and without sample pretreatment/conditioning. Groups 2 and 3 were diluted in order to adapt the sample to the operational ranges of the various instruments. Group 2 were diluted to a ratio of roughly 14 to 1 and Group 3 to a ratio of roughly 1400 to 1.

3.1.3.3 Instrument/method descriptions

The *Smoke Meter* uses the filter paper method to measure the soot content in the exhaust. UCR used an AVL Smoke Meter 415 SE with two heated sample lines to measure soot concentration of the exhaust by determining the filter paper blackening. The AVL Smoke Meter has a wide applications range due to its variable sampling volume and thermal exhaust conditioning. The lower detection limit of the AVL Smoke Meter is 20 $\mu g/m^3$ and the resolution is 10 $\mu g/m^3$.

The laser induced incandescence (LII) is a real-time method that applies a high-energy pulse laser to incoming particles to heat up the BC particles close to their sublimation temperature (~4000 K). The incandescence signal released from the BC particles is proportional to the mass of the particle. It is also a function of the particle temperature. Particle temperature can be determined from two-color pyrometry and combined with incandescent signal strength to determine refractory Black Carbon (rBC) particle mass concentration..

The *Micro Soot Sensor (MSS)* operates based on the photoacoustic measurement principle to measure soot concentrations in the exhaust gas. UCR used an AVL 483 MSS with the high sensitivity of 0.01 $\mu g/m^3$ and detection limit 1 $\mu g/m^3$ with a laser operating at 870 nm. The acoustic signal detected by microphone is directly proportional to the soot concentration in the exhaust. The MSS is a system for transient measurement of soot concentration.

The *Photoacoustic Extinctiometer (PAX)* operates based on the photoacoustic measurement principle by using a modulated diode laser to simultaneously measure light scattering and light absorption. UCR used a Droplet Measurement Technologies PAX with laser operating at 375nm wavelength.

The *Semi-Continuous OC-EC Field Analyzer (SEMICONT. EC/OC)* uses integrated filter collection method to measure the element carbon (EC) and organic carbon (OC) concentration in the exhaust. UCR used a Sunset Laboratory Model-4 SEMICONT. EC/OC instrument, which can provide a time-resolved OC/EC analyses. The minimum quantifiable levels of SEMICONT. EC/OC is 0.5 $\mu gC/m^3$ for each of OC and EC. Due to the duration of each test point, a compressed NIOSH 5040 analysis protocol was designed by Sunset Laboratory and used for this instrument.

The *Aethalometer* operated based on filter paper and optical analysis method to determine the mass concentration of Black Carbon from the exhaust. UCR used a Magee Scientific model AE22 Aethalometer. Two channels of laser wavelength are available to measure the concentration of optically absorbing particulates in the exhaust.

The *Multiangle Absorption Photometer (MAAP)* uses glass fiber filters and multi angle absorption photometer method to measure black carbon content in the exhaust. UCR uses a Thermo Scientific 5012 MAAP with a light source of 670nm wavelength.

Teflo filters (Whatman brand) with 47mm diameter 2µm pore were used to collect the mass concentrations of ultra-fine PM ($PM_{2.5}$). The filters were measured for net gains using a UMX2 ultra precision microbalance with buoyancy correction following the weighing procedure guidelines of the Code of Federal Regulations (CFR).

Quartz filters are used to collect EC and OC emissions. Diesel $PM_{2.5}$ primarily consists of EC, OC, sulfate and ash. $PM_{2.5}$ mass were collected on Tissuquartz filters after a cyclone and elemental and organic carbon fractions were determined off-line using the NIOSH 5040 protocol.

A *Hygroscopic Tandem Differential Mobility Analyser (H-TDMA)* measures the hygroscopicity of aerosol emitted from the engine running with different load and fuels. The hygroscopic growth of particles emitted from an engine running with different fuels. The hygroscopic growth of aerosol particles influences particle residence time in the atmosphere, deposition efficiency in lungs, and also influences optical properties. Thus the hygroscopicity of ambient particles has been a concern of previous research and was measured on selected points for this research.

The *Transmission Electron Microscopy (TEM)* imaging was performed on the emitted particles at NRC's laboratories. Particles were collected on carbon-coated copper TEM grids using an electrostatic particle sampler (FHNW TEM Sampler, Switzerland) on the 14:1 dilution.

The Engine Exhaust Particle Sizer Spectrometer (EEPS) Model 3090 from TSI was used for measuring the size distribution of particles, UCR used an EEPS, which measures particle emissions in the sub-micrometer range from 5.6 to 560 nm with data collected at 10Hz. The EEPS spectrometer displays measurements in 32 channels total (16 channels per decade) and operates over a wide particle concentration range, including down to 200 particles/cm3. This instrument allowed us to monitor a continuous time resolved size distribution of the particles

DustTrak In addition to the PM mass measurements, UCR took data with a Nephelometer (TSI DustTrak 8520) as the combustion process is highly transient. Nephelometers are fairly simple and compact instruments with excellent sensitivity and time resolution. Nephelometers measure light scattered by aerosol introduced into their sample chamber. However, scattering per unit mass is a strong function of particle size and refractive index. If particle size distributions and refractive indices in diesel exhaust strongly depend on the particular engine and operating condition, this may not be an effective way to measure exhaust particle mass. However, UCR has shown that mass scattering efficiencies for both on-road diesel exhaust and ambient fine particles have values around 3 m^2/g. For this project, a TSI DustTrak 8520 nephelometer measuring 90° light scattering at 780nm (near-infrared) was used. While the instrument displays its measurement as mass density (i.e., units of mg/m^3) the output was calibrated with the mass on the Teflon filters.

PG350 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-350 portable multi-gas analyzer. The PG-350 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 eternet 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-350 was tested and verified under the U.S. EPA ETV program.

3.1.3.4 BC and PM calibration

The BC and PM instruments were calibrated according to the routine manufacturers' procedures. These calibration procedures differed between instruments. Because different instruments use different measurement methods to measure black carbon, and because black carbon emissions have different physical and chemical characteristics depending on their source (on-road, aviation, different fuels), it is important that a calibration be done on a source of emissions similar to the samples of interest. Prior to starting the measurement campaign, each of the PM instruments sampled three calibration sources. These included 0 mg/m^3 (or heap filtered zero air), 0.2 mg/m^3 soot, and 2.0 mg/m^3 soot from a MiniCAST system. Although these calibrations were performed, differences were still found between different instruments and methods.

Although the different instruments' response was roughly proportional to each other, the spread between the instruments was fairly large. As such, an additional normalization or post-hoc calibration was performed using the test results from one of the fuels to allow the trends in the data for different instruments to be compared on a common basis. As an attempt to improve instrument agreement, a was performed. In this case, a calibration on a common source of black carbon was done a posteriori, using the marine engine running on one of the marine fuels (DMA) as a calibration source. We decided to use the DMA fuel for calibration rather than the RMB-30 or RMG-380 because it is a fuel that is typically used in a marine context, it is the easiest to access, and it has a low sulphur content (thus less potential to interfere with the measurement methods). As with the rest of this report, the MSS was used as the instrument relative to which all other instruments are adjusted. We performed two post-hoc calibrations: one with the conditioning system and one with the bypass. On the basis that the emissions have different characteristics depending on whether or not the sample has been conditioned, the BP calibration is applied to BP emissions and the CS calibration to CS emissions.

Figure 3-5 Marine test cell setup overview 1

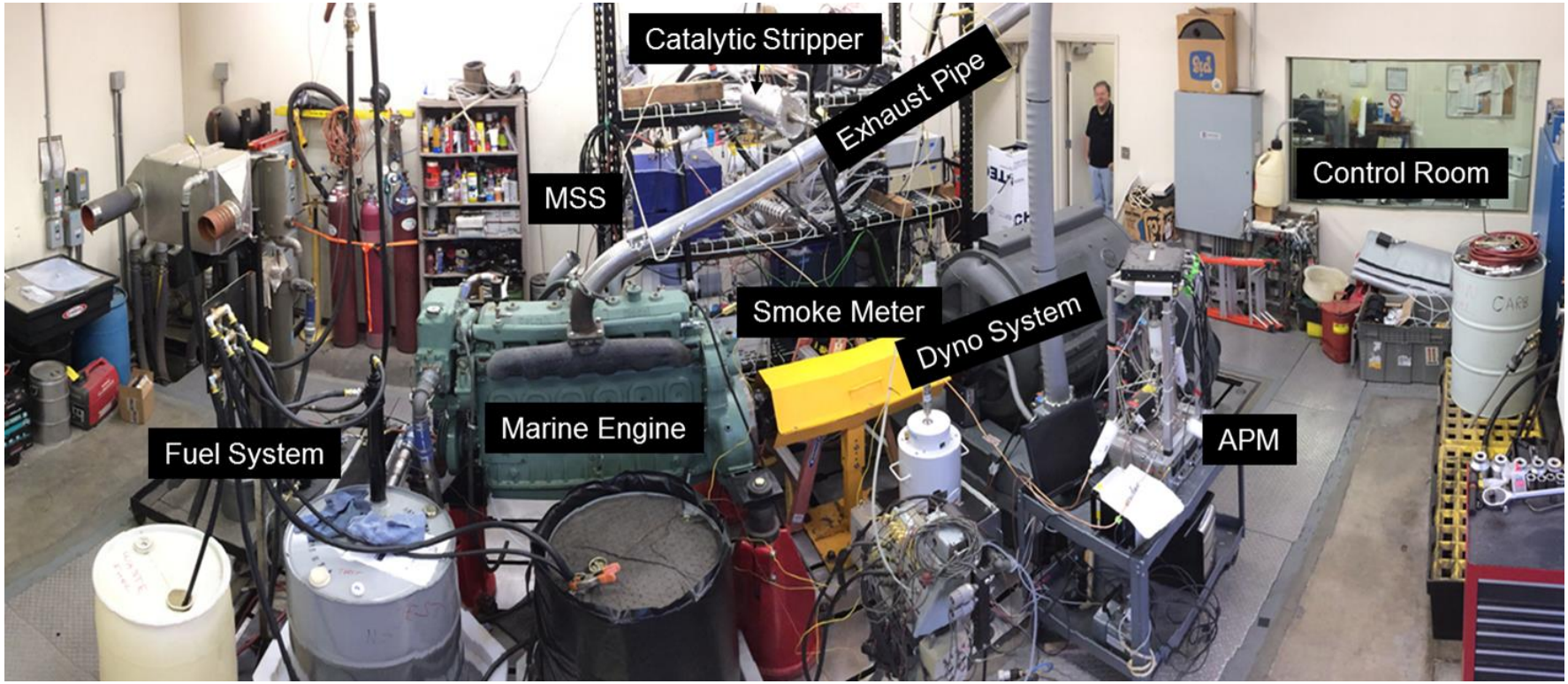


Figure 3-6 Marine test cell setup overview 2

3.2 Results

The results section is organized based on the types of emissions measured including regulated emissions, BC emissions, and other emissions (particle imaging, hygroscopicity, number, and size distribution). Within the BC emissions section, the results for the various instruments are presented based on their sampling and dilution ratio conditions. It should be noted that for the remainder of this report the sample conditioning system is referred to as the "CS" system and includes the CS and sulfur adsorbers. Repeats were performed at each test point. These repeats were not averaged for the paired statistical analysis, in order to provide a more robust dataset for that analysis. Paired analysis is commonly used for the comparison of means and confidence intervals. When correlations are performed with two instruments operating simultaneously it is statistically meaningful to consider the points independent of averaging since their means are not as relevant as the individual points.

As discussed earlier there were BC losses which could impact the BC comparisons between instruments as modes and fuels change. Due to the complex nature of the project, no BC loss corrections were applied to the results in this project, but will be discussed where needed. In order to avoid significant discrepancy of particle losses between different instruments, we matched the residence time of the sample for every BC instrument. Thus, the data presented represent the "as measured" results from the engine test stand, which was not corrected for losses but corrected for dilution.

3.2.1 Regulated emissions (g/kWh)

3.2.1.1 Gaseous

The CO_2 and NO_X emissions provide an assessment of the load and combustion efficiency for each fuel. The CO_2 emissions were relatively stable for the different test fuels at the same load with the differences smaller than 0.6%, except for 25% CS mode (see Figure 3-7). CO_2 emissions showed a trend of declining emissions on a g/kWh basis with increasing load, which is typical and compares with other 2-stroke diesel engines. The brake specific CO_2 emissions agree with the specifications of the engine which suggests that the engine load and combustion efficiency were relatively similar.

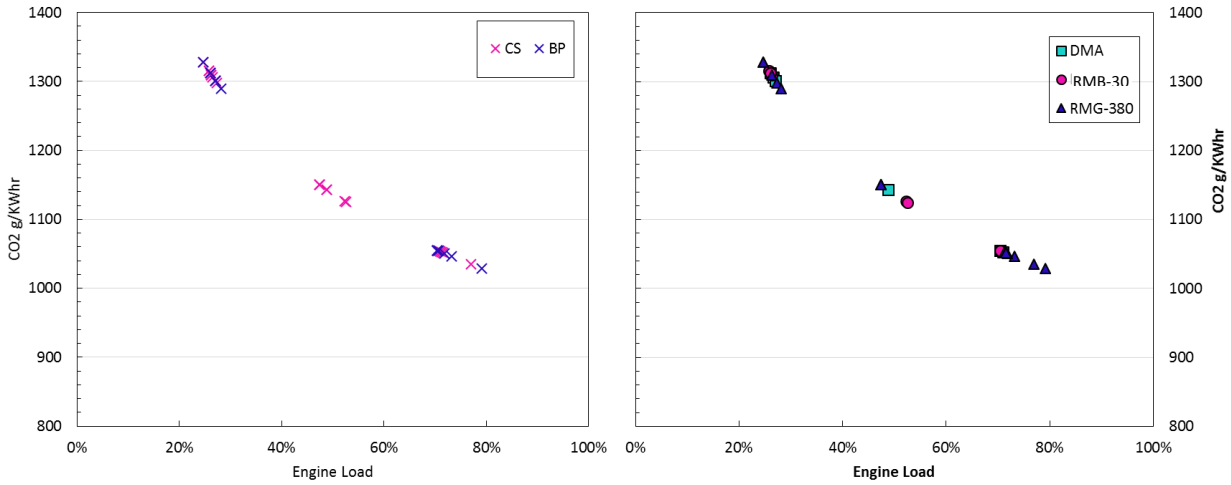


Figure 3-7 CO_2 emission as a function of engine load

The NO_X emissions were relatively stable for the different test fuels at the same load (see Figure 3-8). NO_X emissions showed a trend of declining emissions on a g/kWh basis with increasing load, which is typical for diesel engines. The NO_X emissions suggest that the engine load and combustion efficiency

were relatively similar. Two different instruments measured NO_X emissions: a NTK in-situ stack measurement in the raw exhaust and a Horiba PG-350 in the diluted exhaust. These instruments showed relatively good correlation, as shown in Figure 3-8, indicating good consistency in the NO_X measurements. The PG-350 did show slightly lower reading for the some of the tests conducted with a CS, indicating that there may have been some loss of NO_X as the exhaust sample passed through the CS.

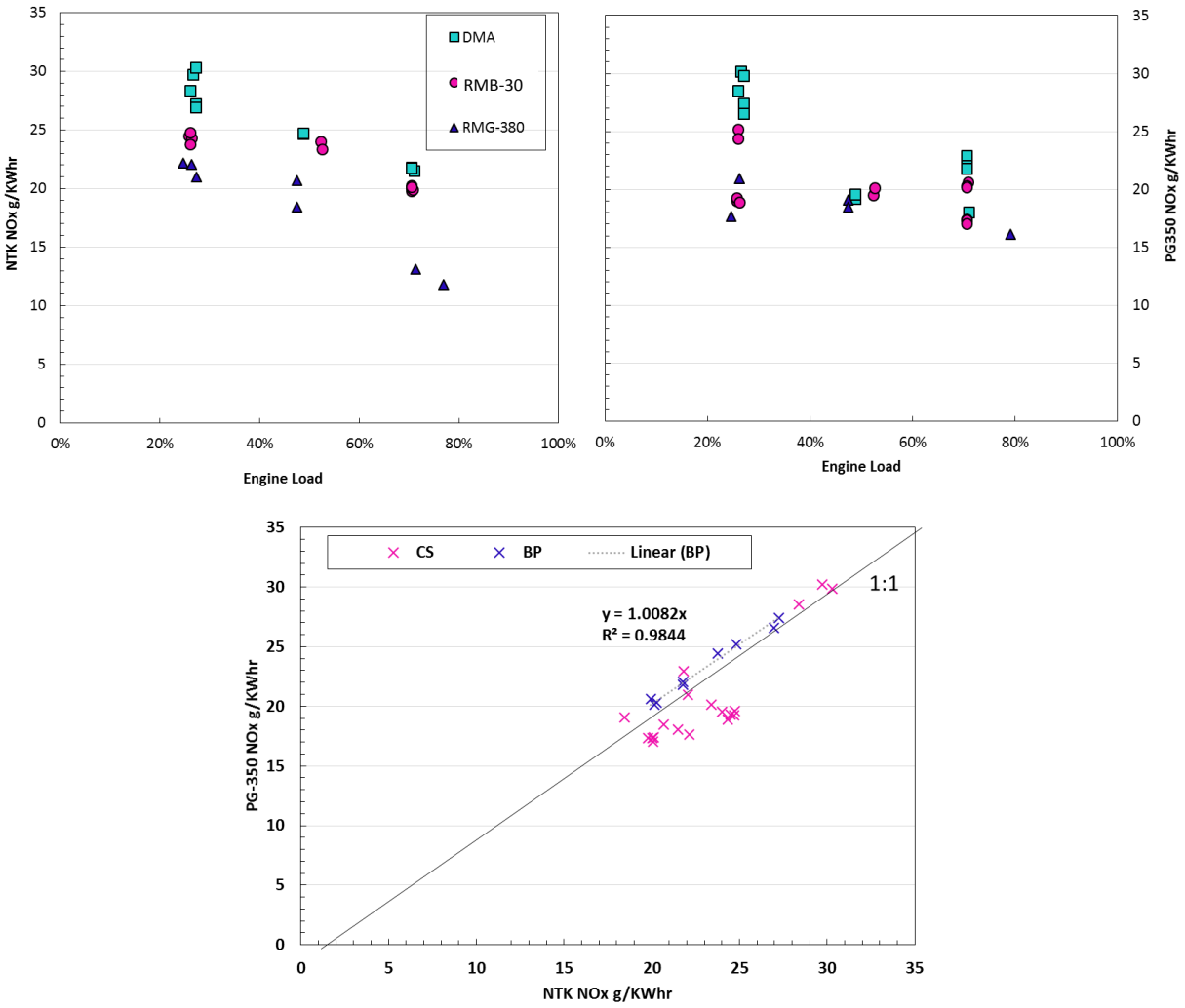


Figure 3-8 NO_X emission as a function of engine load

[1] Top left NO_X as a function of percent load NTK, Top right PG350, and bottom center correlation of NTK and PG350 results.

3.2.1.2 $PM_{2.5}$

PM mass emission results are provided in Figure 3-9 as a function of engine. These figures include measurements collected in a bypass mode (BP) as well as those collected with a CS sampling conditioning systems. For the bypass mode measurements, PM mass emissions were relatively similar on a g/kWh basis between the 25% and the 75% loads. The RMG-380 fuel showed the highest emissions while the DMA fuel showed the lowest emissions for the 25% load. At the 75% load, the PM emissions for the RMG-380 and RMB-30 fuel were similar, with the DMA fuel providing the lowest emissions. Interestingly, the measurements made with the CS showed a trend of higher emissions at the 75% load point compared to the 25% and 50% load points, with generally smaller differences between fuels.

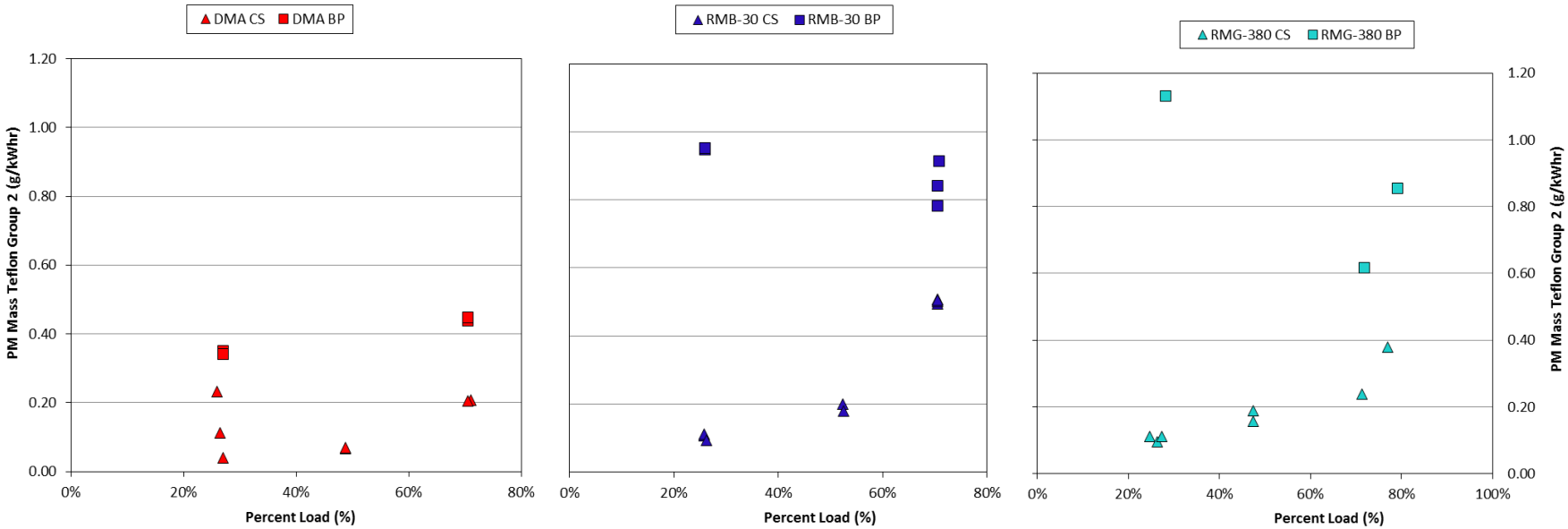


Figure 3-9 $PM_{2.5}$ mass as a function of engine load

The PM mass emissions results can be better understood by looking at the PM composition. The PM mass composition is provided in Figure 3-10 on a total mass basis and in Figure 3-11 on a percentage basis. These figures show that the PM mass collected in the BP mode is largely organic and elemental carbon for the DMA and RMB-30 fuels, but is more predominantly sulfate for the RMG-380 fuel. For the DMA and the RMB-30 fuels, the PM mass is almost entirely organic carbon at the 25% load, but consists of about equal parts of organic and elemental carbon at the 75% load. Figure 3-10 shows that organic carbon and sulfate are largely eliminated going through the CS, leaving a PM mass that is more predominantly EC. The greater tendency for the EC to form at the higher 75% load point compared to the lower load test points explains why the total PM mass increases with increasing load for the CS measurements.

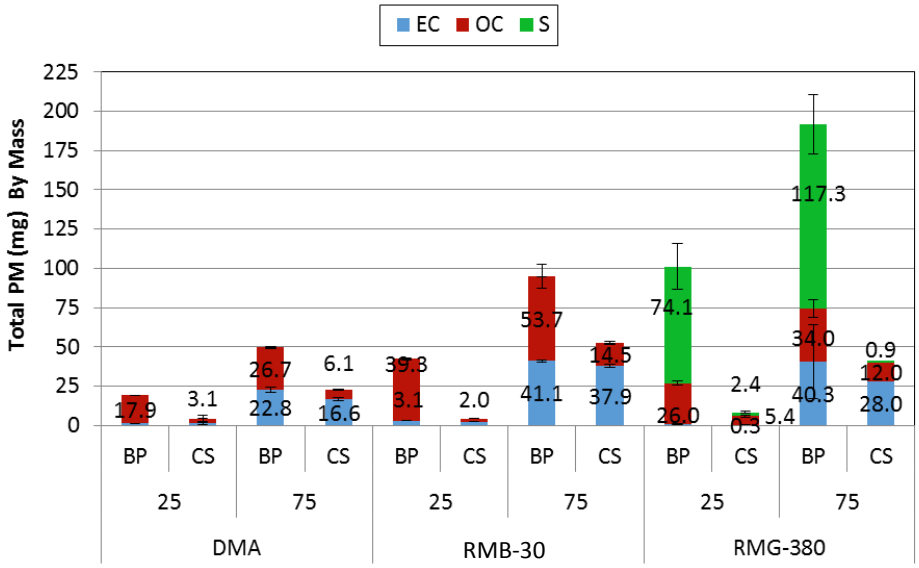


Figure 3-10 $PM_{2.5}$ mass as a function of composition and engine load percent

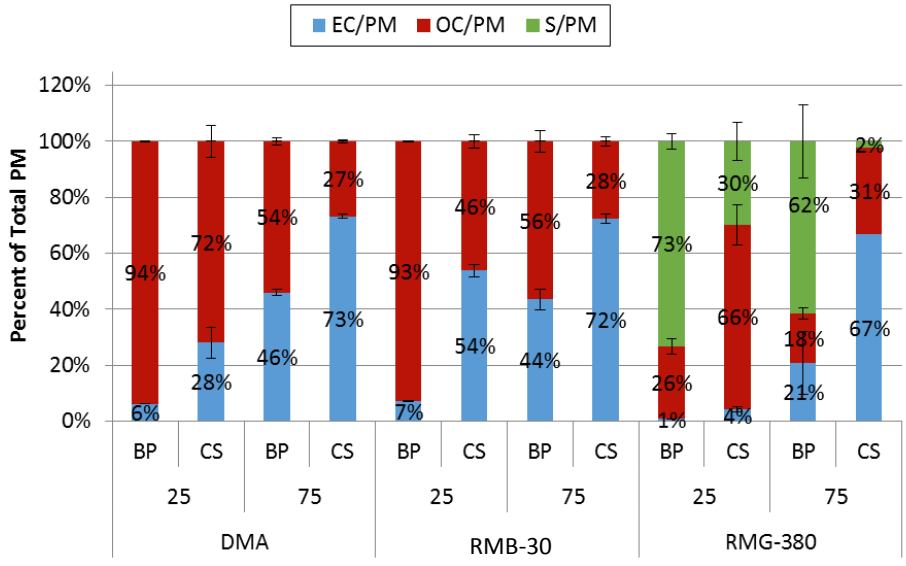


Figure 3-11 $PM_{2.5}$ composition on a percent of total pm mass basis

PM mass was also collected with the NTK measurement system, as shown in Figure 3-12. These measurements showed a stronger trend of PM mass decreasing as a function of increasing load for the

BP mode, which is more similar to the trends seen for the CO2 and NO_X emissions. The differences between the trends for the PM filters compared to the NTK system are probably attributable to the differences in the measurement methods. In particular, NTK measurement principal is based on counting particles and then determining the PM mass based on an assumed density. Hence, the NTK system is more sensitive to particle number and particle size than the PM filters. As discussed below in section 3.3, particle number and particle size measurements show that there is a greater prevalence of smaller particles at the lower load points, leading to higher particle counts. This would tend to bias the NTK PM mass measurements higher at the 25% load compared to the 75% load.

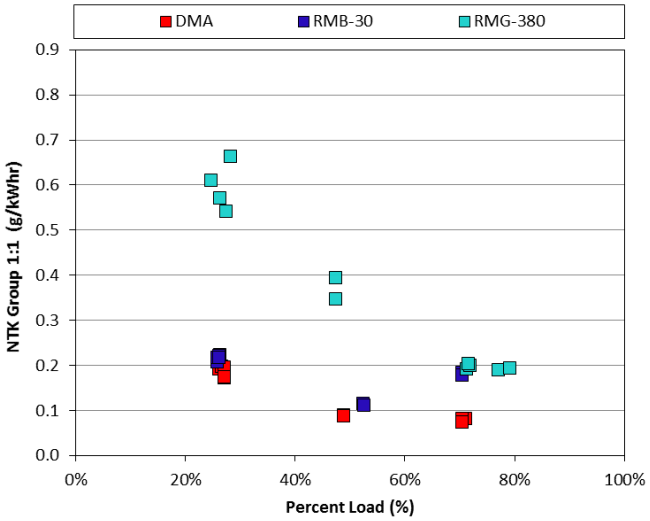


Figure 3-12 PM mass from NTK as a function of engine load

3.2.2 BC emission factors (g/kWh)

The black carbon emission factors are presented by sample condition groups to allow a more direct understanding of each measurement method and the BC emission factor. A discussion of the impacts of load and fuel effects is presented in a later section after all the BC measurements are introduced due to the relatively similar trend between most BC instruments. Some discussion on biases will be presented within each of the following sub-sections as it relates to uniqueness for each measurement approach. Note that the BC emission factors presented in this report are not corrected for the particles loss or adjusted with the post-hoc calibration.

As discussed earlier, there are various definitions for the BC measurements principles, such as elemental carbon (EC), refractory black carbon (rBC), and equivalent black carbon (eBC). These definitions have not been included in the report to avoid distracting the reader from the added details.

3.2.2.1 Raw sampling effects –no conditioning

A smoke meter and LII system were the two methods that sampled from the raw exhaust. The results for the raw exhaust smoke meter and LII are shown in Figure 3-13. Note that the LII was only available for the DMA tests. These instruments both show a trend of increasing emissions with increasing load. This trend is consistent with the prevalence of EC at the higher load point. The smoke meter measurements were higher than those for the LII for corresponding tests conducted with the DMA fuel. The smoke meter showed a trend of higher emissions for the RMB-30 for the 25% and 50% load points, with comparable results within the experimental variability at the 75% load point. It should be noted that the two sets of data points for the RMG-380 at the 75% represent slight differences in load

between tests, and show the potential sensitivity of PM emissions to small load changes at the higher load points. The DMA fuel showed the lowest emissions of the fuels for the smoke meter measurements at the 75% load point, but not at the 25% and 50% load points.

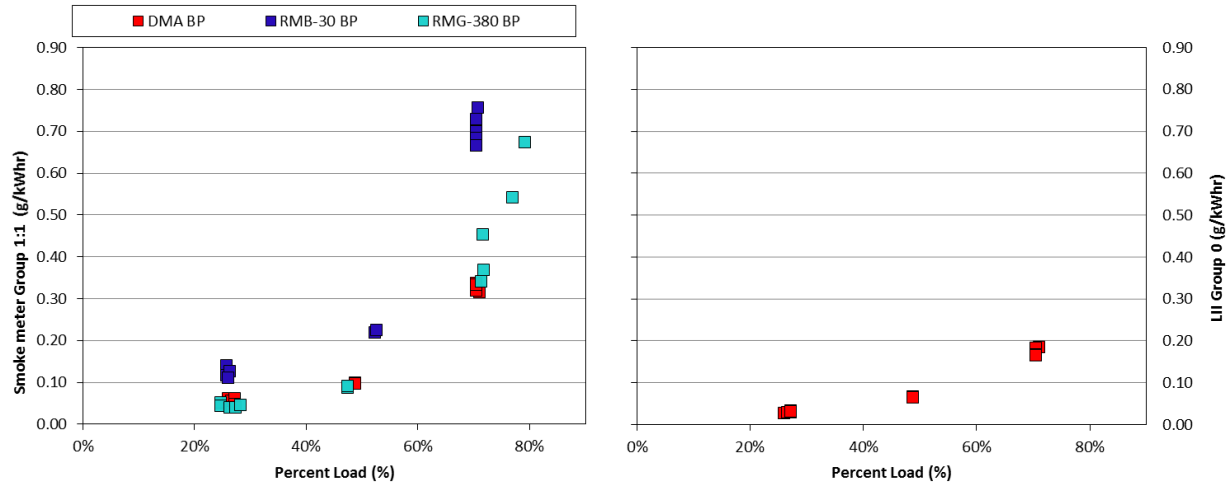


Figure 3-13 eBC from Smoke Meter and rBC from LII as a function of engine load

3.2.2.2 Raw sampling effects – with conditioning

A second smoke meter and LII instrument were placed downstream of the sampling conditioning system. The results of these measurements are presented in Figure 3-14. These instruments should show readings similar to the upstream instruments in the raw exhaust when the sample conditioning system is in the BP mode, but reflect the impact of the sampling conditioning for the tests with the CS. The smoke meter and LII both show trends of increasing BCwith increasing load. These instruments also show relatively good correlation in terms of the magnitude of the BCemissions that are measured for the different test points, as can be seen in comparing the two graphs in Figure 3-14. The fuel trends are similar to those seen above in Figure 3-14. It should be noted that the CS measurements are generally below those of the corresponding BP measurements for individual test points, but they are not significantly lower. This suggests that the CS has some impact on the black carbon emissions in addition to the strong reductions seen for the OC and sulfate.

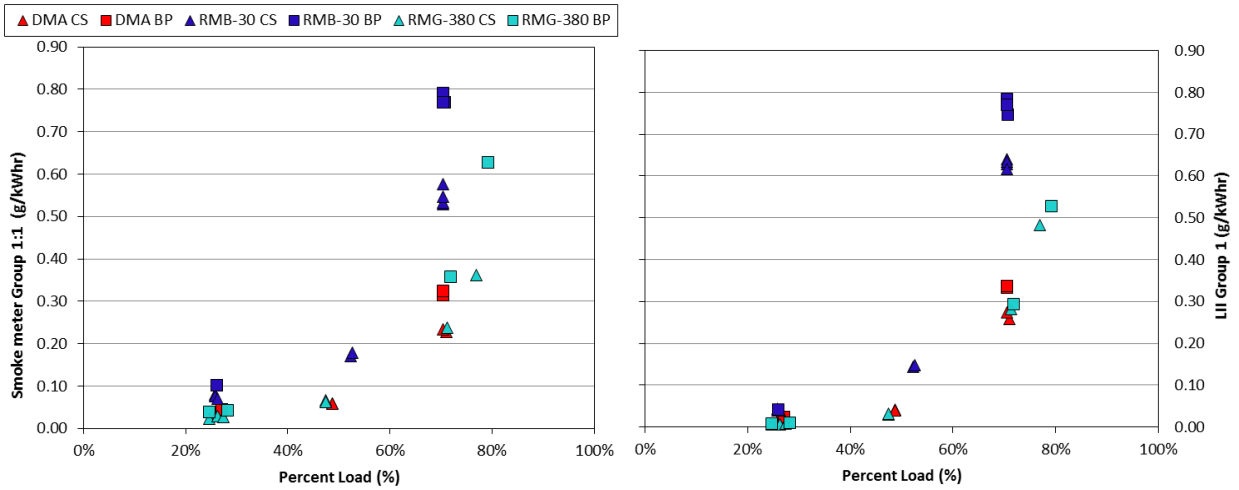
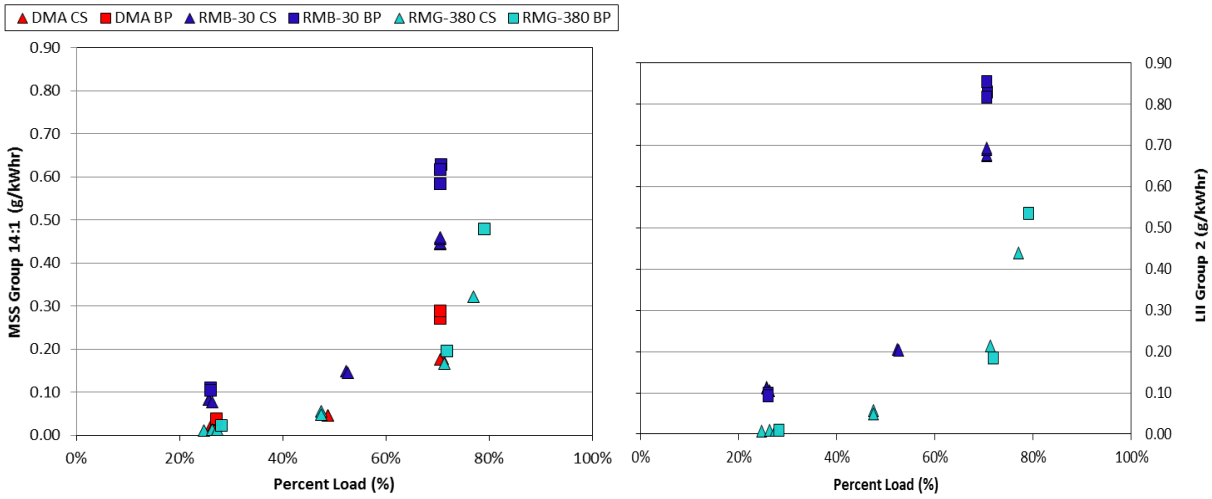


Figure 3-14 eBC from Smoke Meter and rBC from LII as a function of engine load

Determining BC mass concentrations by optical-based techniques is complicated (Bond et al., 1999; Horvath, 1993). Many studies suggest that light absorption by black carbon particles can be enhanced due to the presence of non-absorbing coatings on black carbon particles. The absolute magnitude of such an enhancement could vary depending on factors, such as the refractive index of the coating materials, the size and location of the black carbon core, and even the wavelength of the light (Fuller et al., 1995; Lack and Cappa, 2010; Shiraiwa et al., 2010). Measuring black carbon mass concentrations through an optical-based method with the use of a filter medium can further be complicated depending on the sample collection time, amount of mass loading on the filter, and even the type of filter fiber materials. Several studies have concluded that artifact corrections would be needed for Aethalometer and Particle Soot Absorption Photometer (PSAP) measurements in order to yield consistent measurements when compared to other real-time techniques without the use of filter media (Weingartner et al., 2003; Collaud Coen et al., 2010; Shrestha et al., 2014; Bond et al., 1999). Among various filter-based optical instruments, FSN is often not involved in these studies due to its lack of sensitivity at the low concentration ranges encountered in these highly diluted studies. However, given the operating principle of the FSN, it is expected that the non-absorbing materials present on the black carbon particles would also cause some degree of absorption enhancement on the FSN BC measurements. Observations given in Figure 3-14 demonstrate that the differences between the BP and CS FSN measurements for any particular fuel type and engine load condition are generally larger than that for the LII.

3.2.2.3 Dilution effects = 14 to 1

A greater number of instruments were sampled via the primary dilution system at a dilution ratio of 14 to 1. This included the MSS and LII (see Figure 3-15). MSS was used to measure eBC and LII measured rBC while the wavelength PAX was not appropriate for BC measurements. These instruments showed the same trends of increasing soot emissions with load as were seen for the raw exhaust measurements. In general, the emission levels are comparable between the different instruments for the different test fuels, with a wider spread of emissions for the 75% test load point.



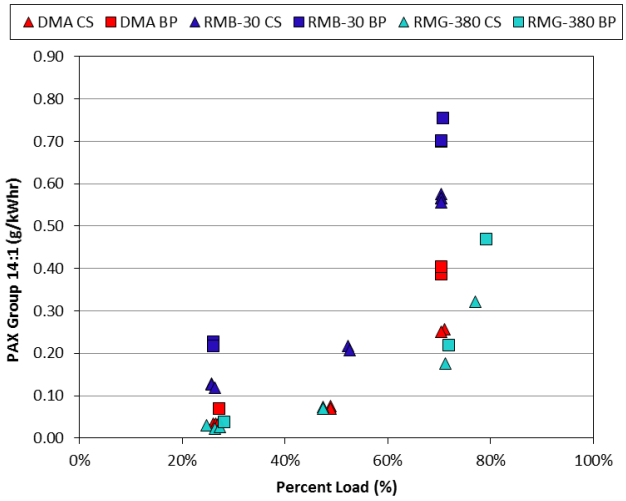


Figure 3-15 eBC from MSS, rBC from LII and PAX a function of engine load

EC and OC were measured both from quartz filters thermal-optical analysis, in a batch mode and with a Semi-Continuous OC-EC Field analyzer. The results comparing these measurements are provided in Figure 3-16 for EC and in Figure 3-17 for OC. The elemental carbon measurements show similar trends. Both instruments in general showed lower readings that those seen for the other real-time black carbon instruments discussed above, with the batch EC measurements generally being lower than those of the Semi-Continuous OC-EC Field analyzer.

The OC measurements showed the opposite trend with respect to engine load, with OC emissions decreasing with increasing engine load. Lower OC at lower loads has been observed in other OGV tests and could be the results of greater prevalence for OC from incomplete combustion, whereas at higher loads there will be a greater prevalence of more rich combustion zones to form black carbon. The OC measurements also show that OC is significantly reduced for measurements made with the CS, consistent with the CS removing most of the OC PM. There is a slight trend of higher OC emissions for the RMB-30 fuel and lower emissions for the DMA fuel. The fuel differences are greater at the low load point where OC emissions are more prevalent. In contrast with the EC measurements, the batch filters show higher readings than the Semi-Continuous OC-EC analyzer. The opposite trends seen for the EC and OC readings between the two measurements suggests that the methods are measuring similar levels of total carbon, but have differences in the OC-EC split (Birch, 1996).

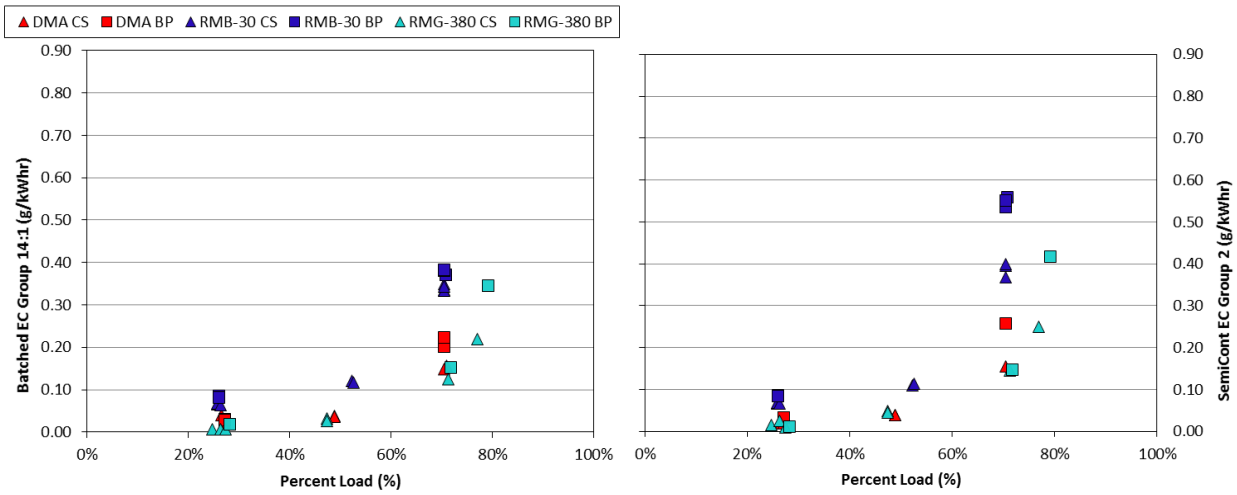


Figure 3-16 EC from Batched and Semicont. as a function of engine load

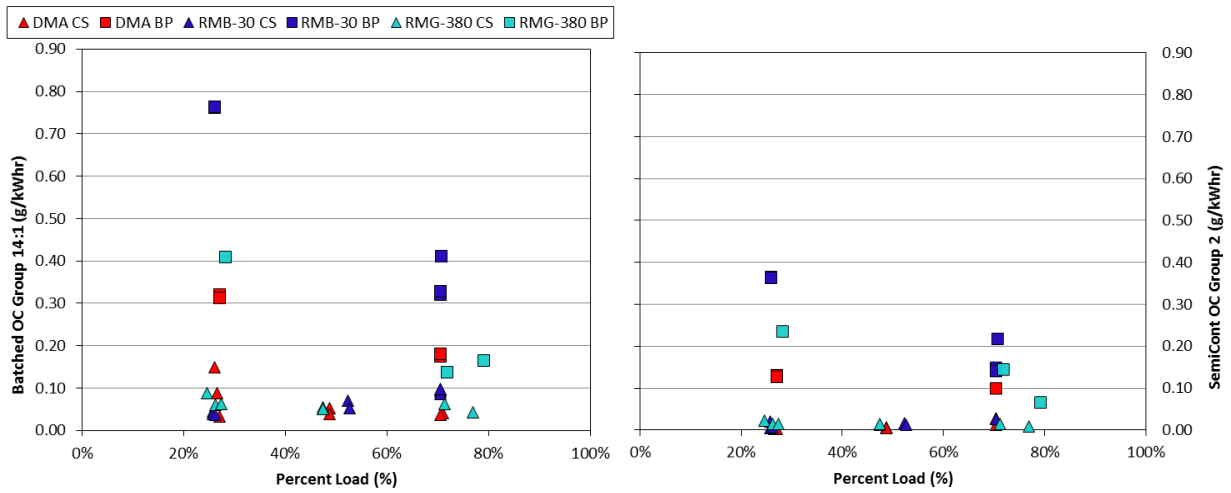


Figure 3-17 OC from Batched and Semicont. as a function of engine load

3.2.2.4 Dilution effects = 1400 to 1

Two black carbon instruments, a MAAP and Aethalometer, were sampling at a higher dilution of 1400 to 1. The MAAP and Aethalometer results are shown in Figure 3-18. These instruments also showed similar trends to the black carbon instruments sampling from the raw exhaust and at the lower 14 to 1 dilution ratio. The Aethalometer showed higher readings than the MAAP that were more similar to the instruments measuring in in the raw exhaust and at the lower dilution ratio. This was particularly evident at the 75% load point.

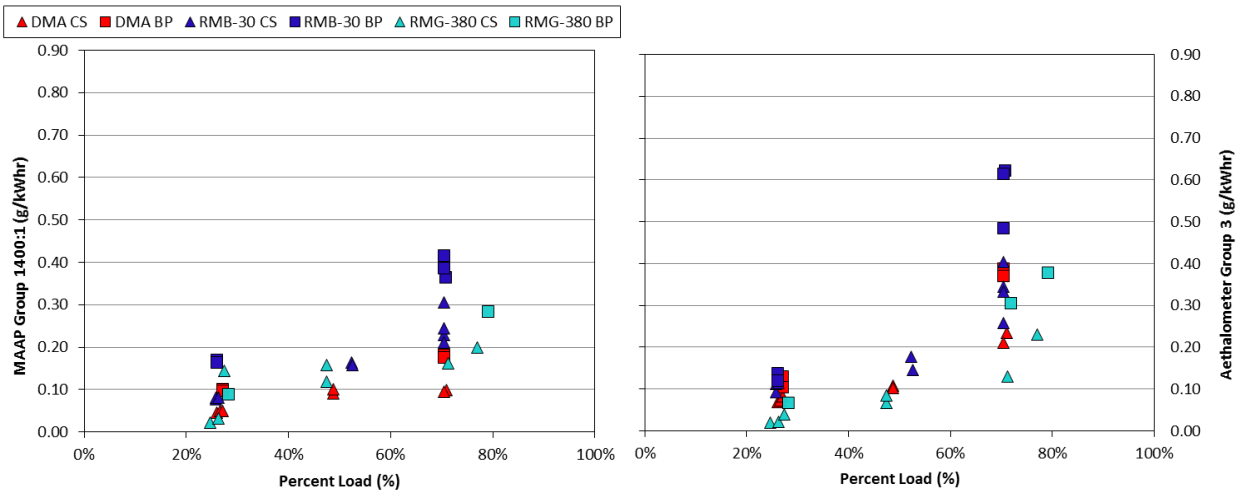


Figure 3-18 eBC from MAAP and Aethalometer as a function of engine load percent

3.2.3 BC instrument correlations

3.2.3.1 No calibration

In examining the black carbon instruments as a whole, it can be seen that the instruments all generally measured similar trends for the black carbon measurements. Black carbon was found to increase with load, with higher emissions at 25 than 75% load. Black carbon readings did show some variation from instrument to instrument in the magnitude of the black carbon emissions at a given test point, however. Figure 3-19 and Figure 3-20 provide a comparison between the various BC measurement methods and the MSS for the BP and CS mode tests for the DMA fuel. Similar graphs for the RMB-30 are provided in Figure 3-21 and Figure 3-22 and similar graphs for the RMG-380 fuel are provided in Figure 3-23 and Figure 3-24. Note that for these figures the MSS is utilized as the basis for comparison, as this instrument has undergone a full compliance testing at part of the U.S. EPA's heavy-duty In-Use testing Measurement Allowance program.

The regression analyses show the spread of instruments with about half the instruments below and half the instruments above the 1 to 1 comparison line. For the DMA fuel for the BP testing, the slope of the regressions for the FSN, LII Gr1, and the Semi-continuous EC measurements all ranged from approximately 0.89 to 1.20, indicating agreement to within 20% of the MSS, with the slope for the other instruments ranging from 0.64 to 1.41. For the RMA fuel for the BP testing, the slope of the regressions for the FSN Gr0, PAX, Semi-continuous EC measurements, and aethalometer all ranged from approximately 0.89 to 1.21, indicating agreement to within ~20% of the MSS, with the slope for the other instruments ranging from 0.62 to 1.36. For the RMG-380 fuel for the BP testing, the slope of the regressions for the LII Gr1, PAX, LII Gr2, Semi-continuous EC measurements, and aethalometer all ranged from approximately 0.85 to 1.15, indicating agreement to within ~15% of the MSS, with the slope for the other instruments ranging from 0.60 to 1.47.

The regression analyses for the CS tests were similar to those for the BP tests, but generally showed a slightly greater spread. For the DMA fuel for the BP testing, the slope of the regressions for the FSN, LII Gr1, and the Semi-continuous EC measurements all ranged from approximately 0.87 to 1.05, indicating agreement to within 15% of the MSS, with the slope for the other instruments ranging from 0.60 to 1.81. For the RMA fuel for the BP testing, the slope of the regressions for the FSN Gr1 and Semi-continuous EC measurements ranged from approximately 0.85 to 1.21, indicating agreement to within ~20% of the MSS, with the slope for the other instruments ranging from 0.56 to 1.54. For the RMG-380

fuel for the BP testing, the slope of the regressions for the PAX and Semi-continuous EC measurements ranged from approximately 0.79 to 1.01, indicating agreement to within ~20% of the MSS, with the slope for the other instruments ranging from 0.69 to 1.92.

Overall, regression analyses comparing the MSS with the other black carbon instruments showed a slope ranging from 0.62 to 1.47 for the CS mode testing and from 0.60 to 1.92 for the BP mode testing.

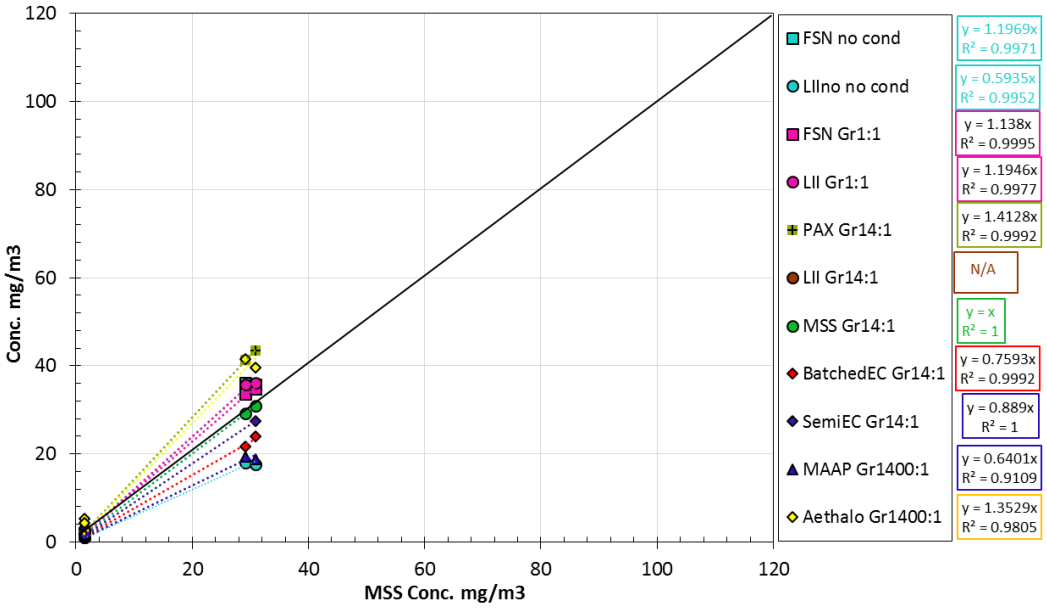


Figure 3-19 BP mode EC VS. MSS on DMA fuel basis

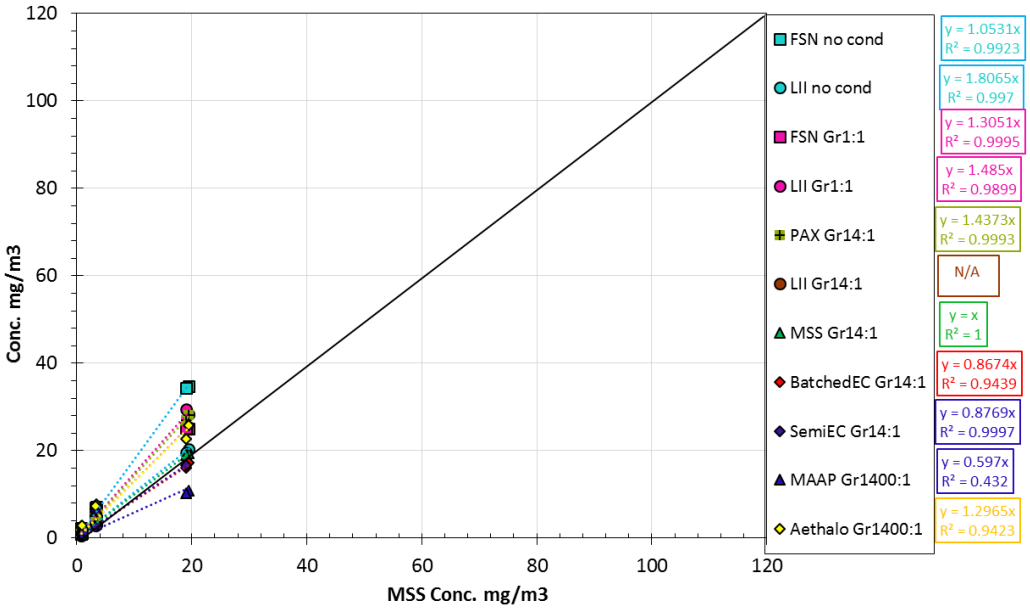


Figure 3-20 CS mode EC VS. MSS on DMA fuel basis

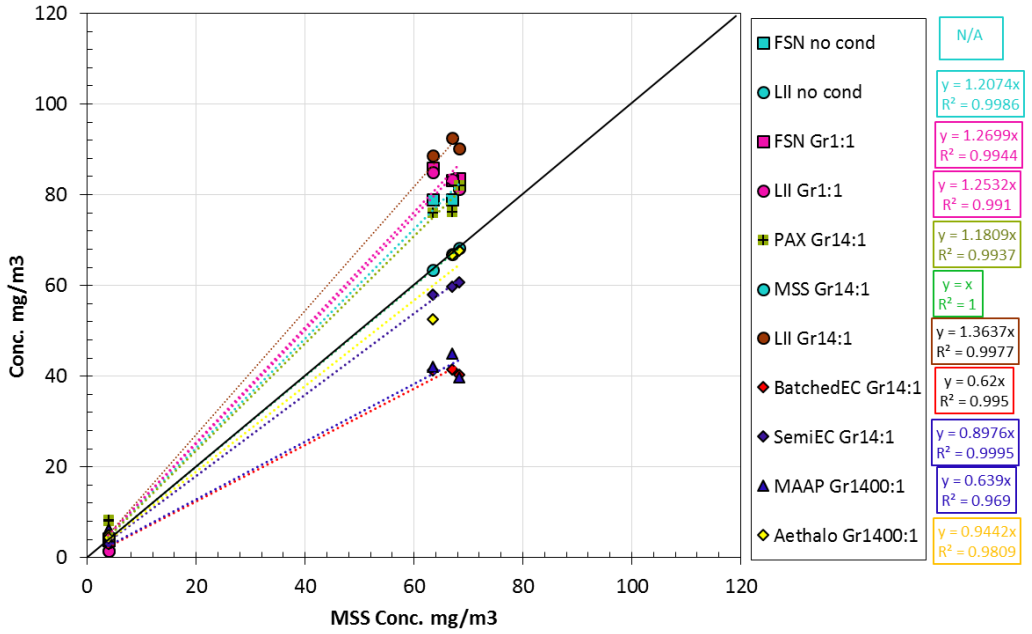


Figure 3-21 BP mode EC VS. MSS on RMB-30 fuel basis

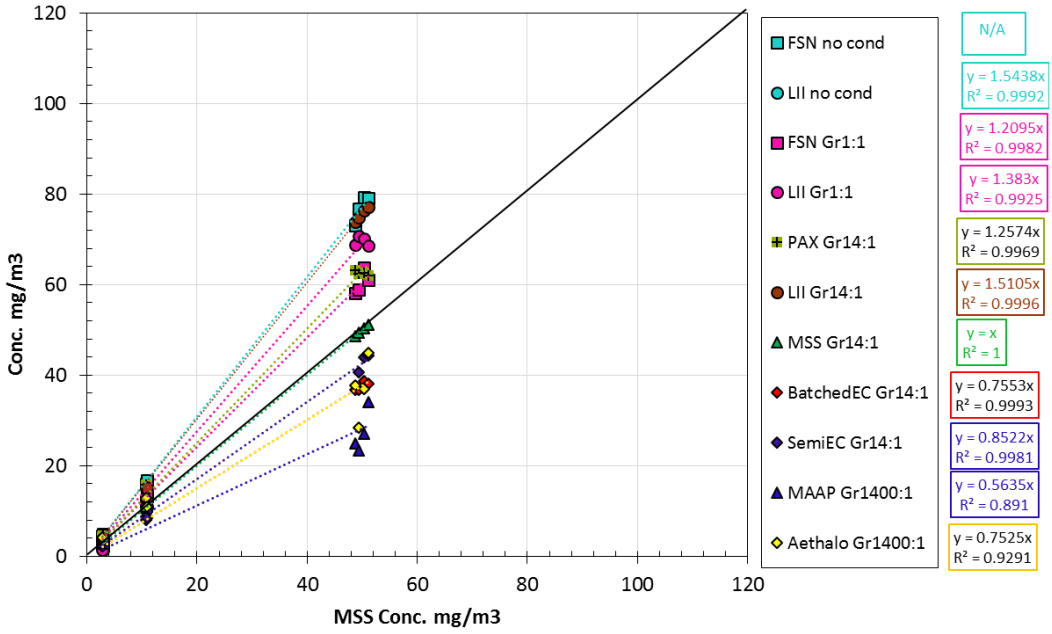


Figure 3-22 CS mode EC VS. MSS on RMB-30 fuel basis

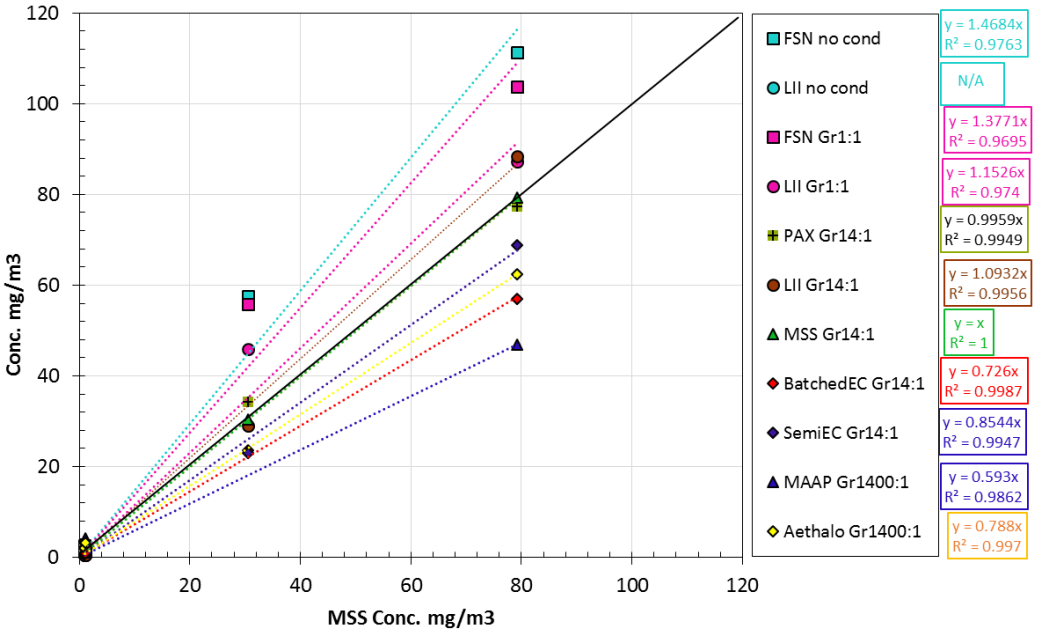


Figure 3-23 BP mode EC VS. MSS on RMG-380 fuel basis

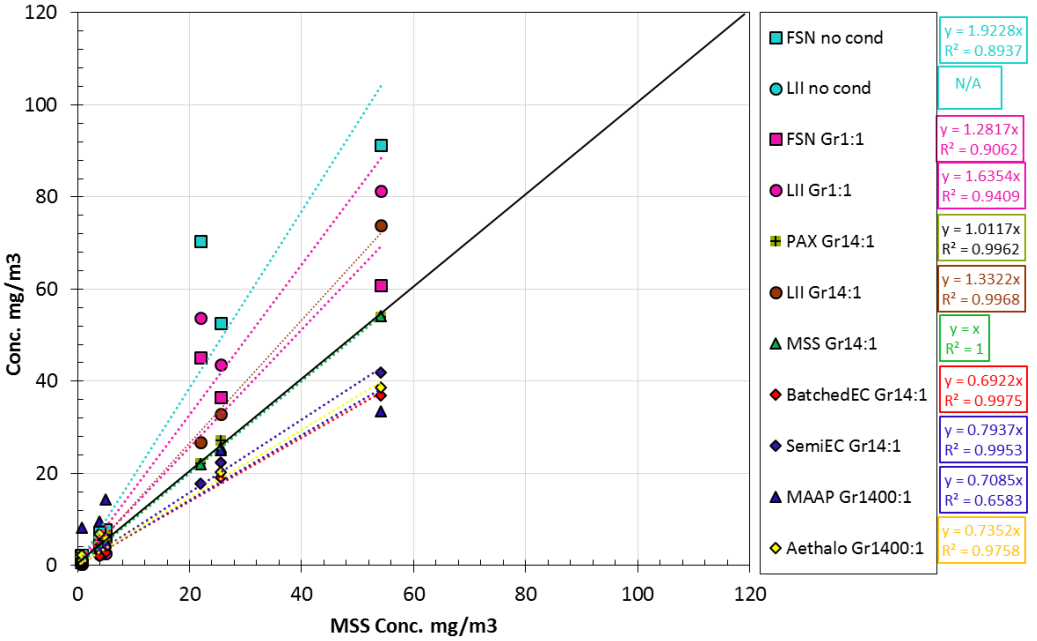


Figure 3-24 CS mode EC VS. MSS on RMG-380 fuel basis

3.2.3.2 Post-hoc Calibration

This section describes the calibration correction for the RMB-30 and RMG-380 test fuels. The DMA fuel was used as the calibration source so that fuel will not have a calibration correction, see the Measurement section (3.1.3.4) for details. Figure 3-25 shows the instruments' response to increasing DMA BC emissions, upon which the results of the two calibrations were based. Table 3-10 shows the slopes and intercepts for the bypass and the sample conditioning calibrations. These slopes and

intercepts, based on the DMA fuel, were applied to the results from the remaining two fuels. Note that the LII (DR 14:1) was not functioning on the DMA fuel test day and the slopes and intercepts from the LII (DR 1:1) were applied instead. The calibrated results for RMB-30 emissions are shown in Figure 3-26 and those of RMG-380 in Figure 3-27.

Table 3-10 Slopes and Intercepts, from the DMA Fuel, are Applied for BP and CS Calibrations

	By Pass (BP)		Conditioning System (CS)	
Instrument	**Slope**	**Intercept**	**Slope**	**Intercept**
FSN (DR 1:1)	1.13	0.13	1.30	0.00
LII (DR 1:1)	1.22	-0.83	1.56	-1.16
MSS (DR 14:1)	1.00	0.00	1.00	0.00
SemiOCEC (DR 14:1)	0.89	-0.01	0.88	-0.09
LII (DR 14:1)	N/A	N/A	N/A	N/A
OCEC (DR 14:1)	0.76	0.03	0.85	0.15
MAAP (DR 1400:1)	0.53	3.24	0.42	2.91
Aeth (DR 1400:1)	1.25	2.93	1.14	2.53

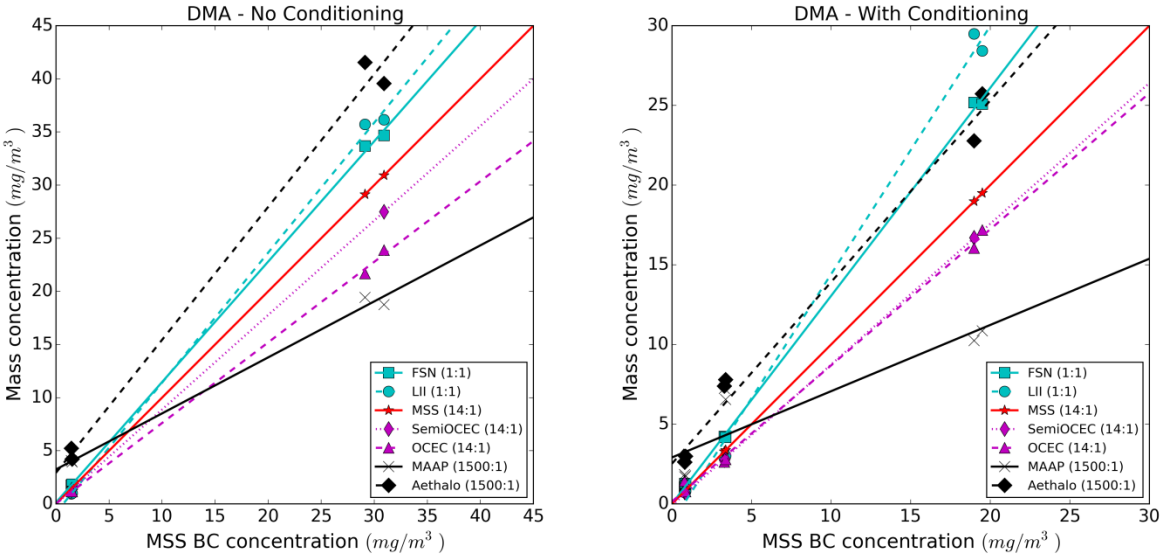


Figure 3-25 BC instrument response as a function of MSS mass concentration: DMA fuel.

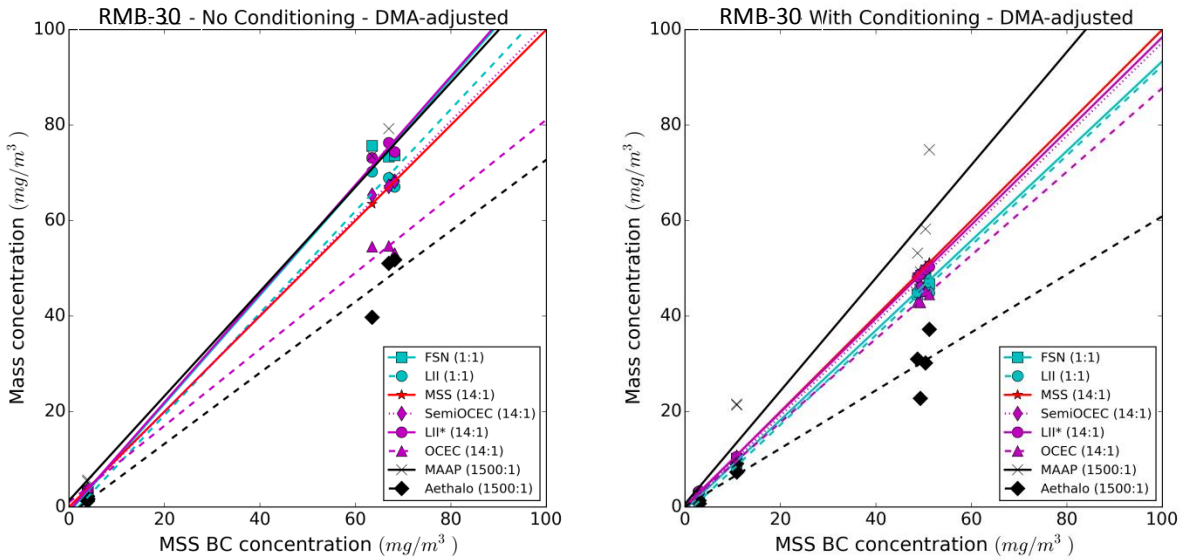


Figure 3-26 RMB-30 calibrated BC Mass concentration as a function of MSS-based BC

[1] Calibration is a post-hoc calibration using the DMA fuel.

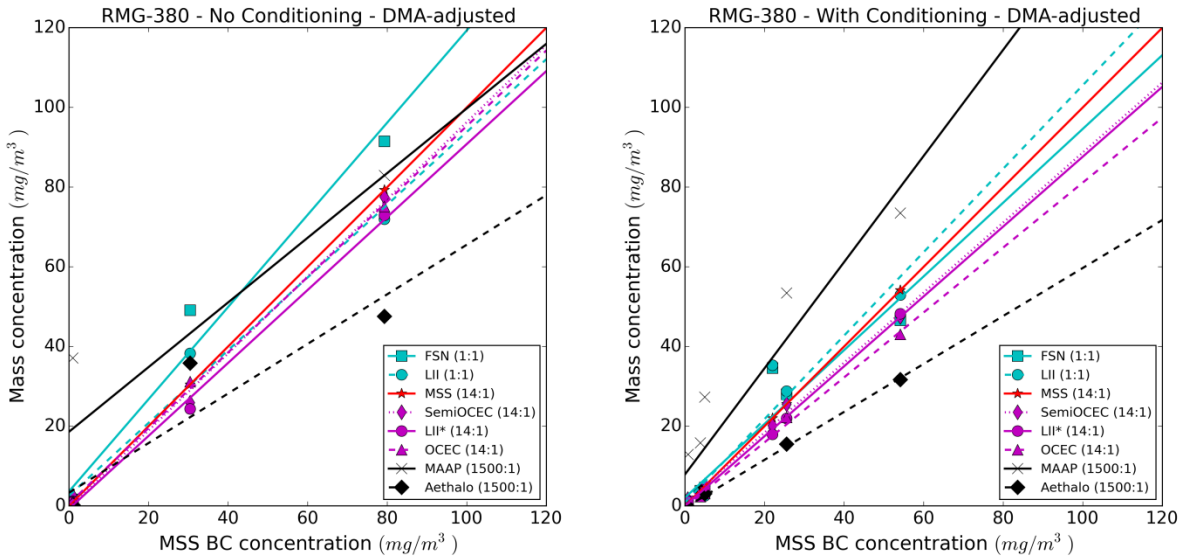


Figure 3-27 RMG-380 calibrated BC mass concentration as a function of MSS-based BC

[1] Calibration is a post-hoc calibration using the DMA fuel.

The post-hoc calibration on the basis of the DMA fuel improved instrument agreement for the other two fuels. Table 3-11 shows the half-spreads between the instruments for each fuel, in BP and CS mode, as well as the uncalibrated and calibrated results. The spread is defined as the difference between the biggest and the smallest slope divided by the average of the two. Half-spreads are spreads divided by two. The spreads include slopes from all the instruments listed in Figure 3-27 with exception of the MAAP and the Aethalometer because their behavior tended to be non-linear, or have very big intercepts. This behavior is likely due to their sampling at a 1500:1 dilution ratio.

Table 3-11 Post-Hoc calibration differences between Instruments in BP and CS Mode

	By Pass		Sample conditioning	
Fuel	**No Calibration**	**Calibration**	**No Calibration**	**Calibration**
DMA	23%	--	29%	--
RMB-30	39%	17%	34%	7%
RMG-380	29%	12%	40%	12%

[1] Since the fuels are calibrated based on the DMA fuel, DMA calibrated spreads are null.

Before any calibrations were applied, the half-spread between instruments was higher in CS mode than it was in BP mode for RMB-30 and RMG-380. In all cases, calibration to a common source improved instrument agreement. This improvement was even more marked in cases where the emissions underwent conditioning. In by pass mode, RMB-30 improved by 22% and RMG-380 by 17%; in CS mode, RMB-30 improved by 27% and RMG-380 by 28%.

3.2.4 Particulate emissions

3.2.4.1 TEM

TEM imaging was performed on the emitted particles at NRC's laboratories. Particles were collected on carbon-coated copper TEM grids using an electrostatic particle sampler (FHNW TEM Sampler, Switzerland) with a 14:1 dilution. Sampling took place over the entire run for each mode, i.e., 10 minutes for the DMA and RMB-30 fuels and 5 minutes for the RMG-380 fuel. Also, TEM sampling for the DMA fuel was limited to runs with 75% engine loads. High (45000X) and low (6300X) magnification images were taken. The particles shown in Figure 3-28 to Figure 3-30 are all taken from high magnification images.

Black Carbon particles, as stated in the Bond et al. (2013) definition, are aggregates of spherules (see e.g. Figure 3-28 and Figure 3-30). In the case of the DMA fuel (Figure 3-28), the particles look like aggregates of spherules, and perhaps look slightly denser in the non-conditioned case than they do with conditioning. The pictures for the conditioning runs exhibit long chains of spherules and appear to be lighter in color.

In the case of the RMB-30 fuel (Figure 3-29), the BC particles, both those that did go through conditioning and those that didn't, look like aggregates of spherules, opened, with occasional long chains of spherules. There is no immediately noticeable difference between the particles collected with and without conditioning.

In the case of the RMG-380 fuel (Figure 3-30), conditioned particles and non-conditioned particles are very distinct. The particles without conditioning are incased in an organic coating and appear to have been collapsed into denser sphere-like configurations, where the individual spherules making up the aggregates are difficult to distinguish because of the coating. One can also notice organic traces that look like satellite shadows around the particles. The conditioned particles, however, look opened with long chains of spherules, similar to those seen for the low sulfur fuels. This shows that the conditioning system consisting of a CS and sulfur adsorbers remove the organic vapors before they have a chance to condense on the aggregates and impact their shape.

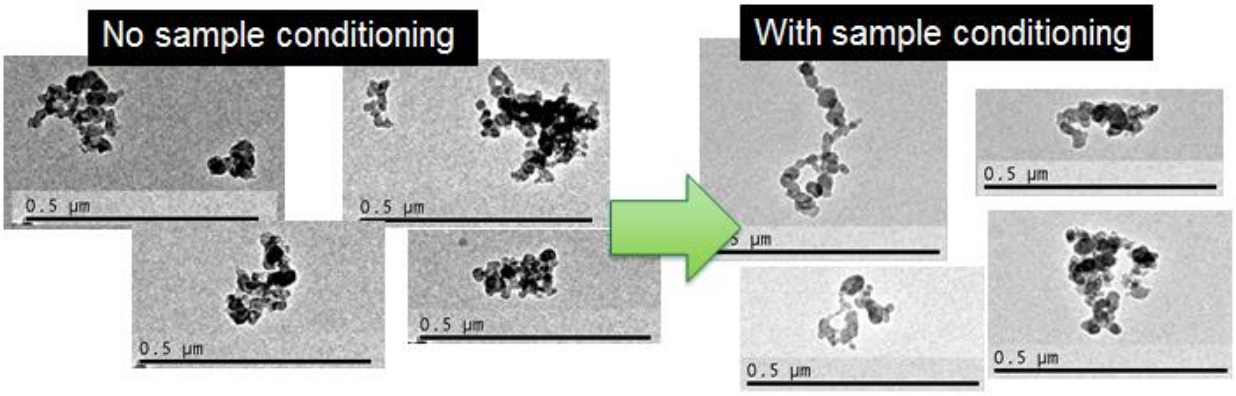


Figure 3-28 Effect of sample conditioning on BC particles (DMA)

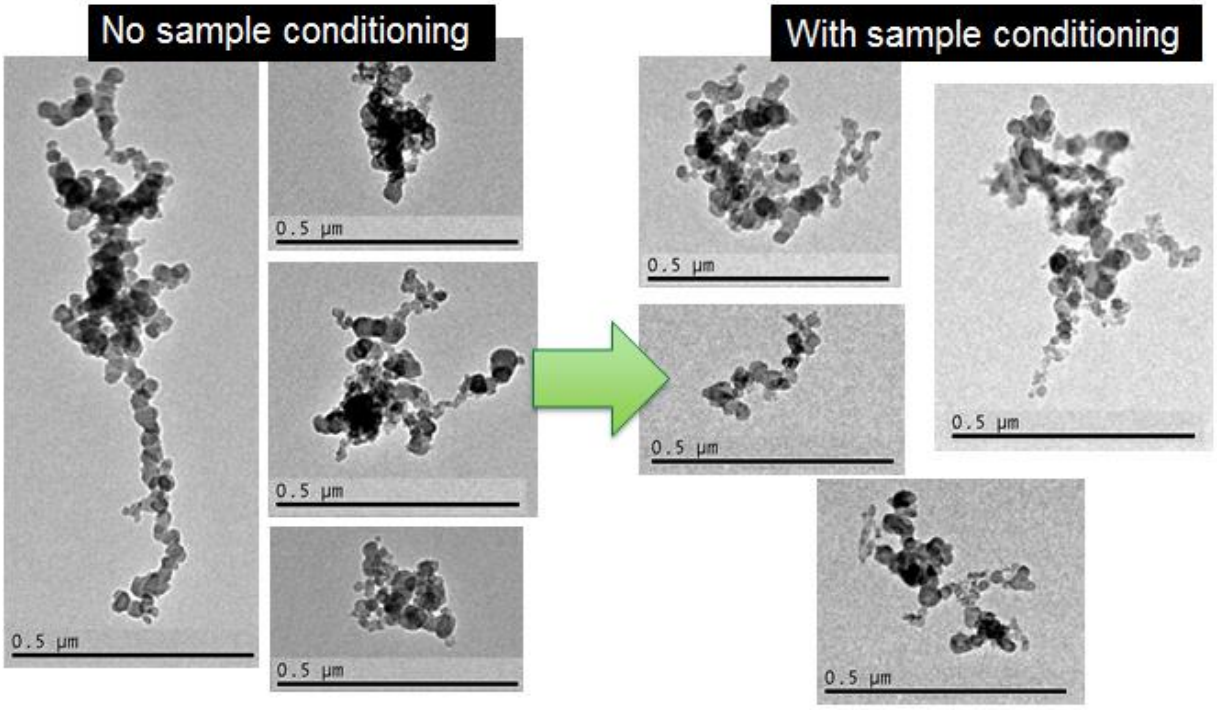


Figure 3-29 Effect of sample conditioning on BC particles (RMB-30)

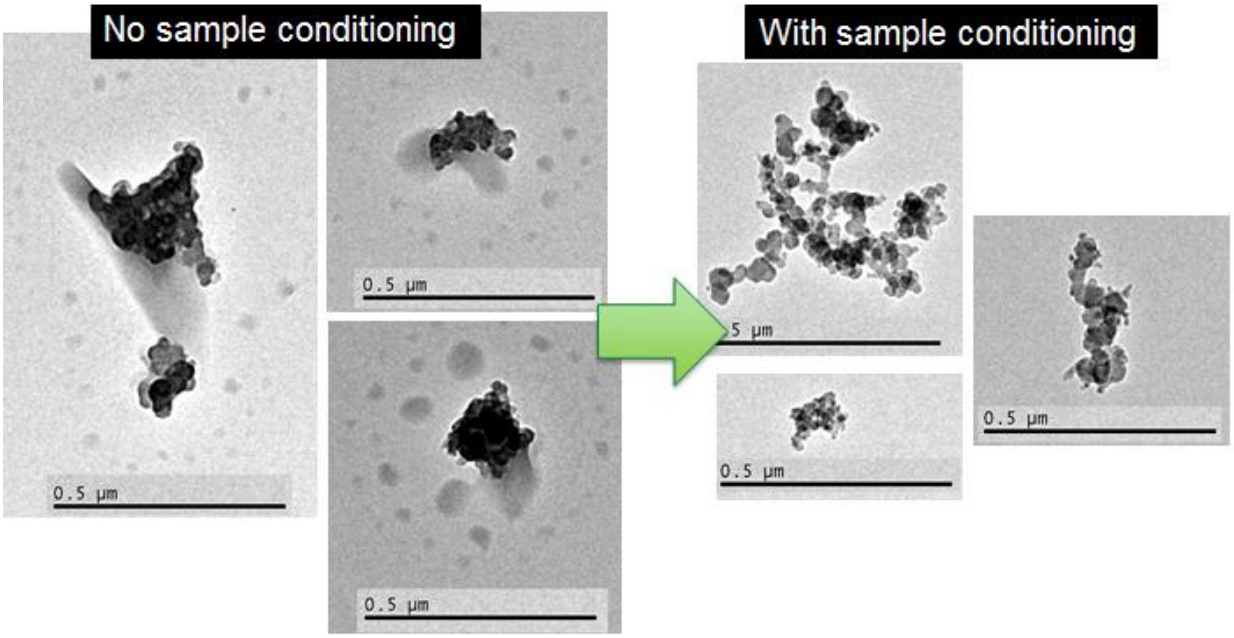


Figure 3-30 Effect of sample conditioning on BC particles (RMG-380)

3.2.4.2 Hygroscopicity

Figure 3-31 shows the d_0=81.3nm particle hygroscopic growth as a fuction of relative humidity percent. The comparison was completed with DMA, RMB-30 and RMG-380 fuels a) without and b) with conditioning. Figure 3-32 shows GF at given RH is in the order of decreasing fuel sulfur content namely RMG-380 (3.18 wt. % S), RMB-30 (0.001 wt. % S). Without CS conditioning the sulfur component remained on the surface of diesel soot enhanced the hygroscopicity of particles. The data from particle diameter (D_0) =73nm diesel engine particle growth (1kw load using 0.25 wt. % S) was also displayed from Weingartner et al. (1997)'s study for comparison. The data show that the particle growth without sample conditioning is much larger (around 15%) than previous research with conventional fuels.

The CS system removes semivolatiles including sulfur compounds effectively. Figure 3-34 shows no significant hygroscopic growth as RH increases and measured trends match those from other researchers. This trend is consistent with the behavior of fresh combustion particles produced by a spark ignition engine using leaded fuel (Weingartner et al., 1995) and a diesel engine using diesel fuel with sulfur content <0.05% (Weingartner et al., 1997).

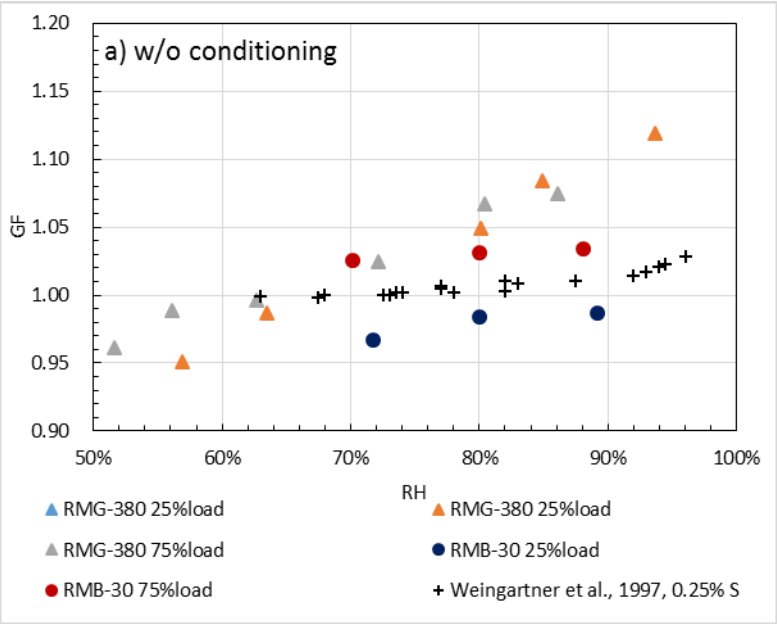


Figure 3-31 Fuel and load effects on BC emissions without CS (i.e., In BP Mode)

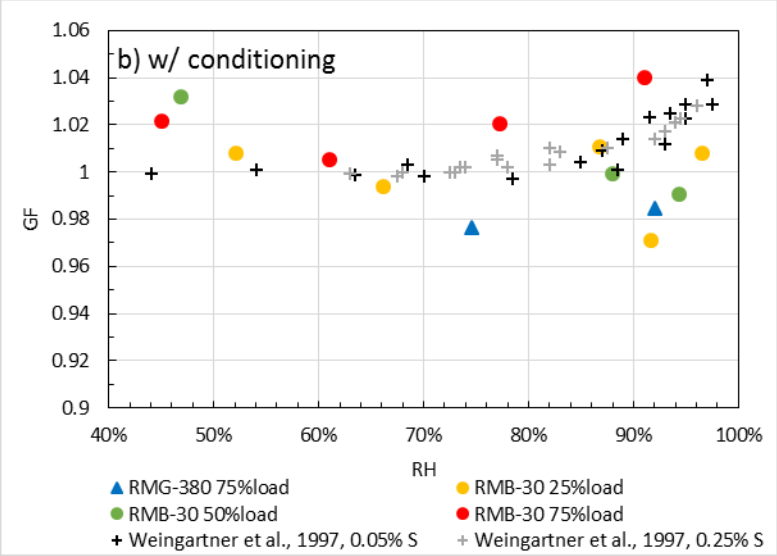


Figure 3-32 Fuel and load effects on BC emissions with CS

3.2.4.3 CPC

Particle number measurements collected with a CPC are shown in Figure 3-33. The particle number measurements made in the BP mode showed a trend of decreasing emissions with increasing engine load. This is the opposite of the trend seen for the EC, but directionally consistent with the OC measurements. Significant reductions were seen for the measurements made in the CS mode compared to the BP mode.

The particle number results coupled with the OC and CS results, suggest that the particles in the BP mode at low loads are small volatile particles that are primary composed of OC. This is also consistent

with the particle size distribution data, as discussed below, that show the prevalence of small particles at low loads.

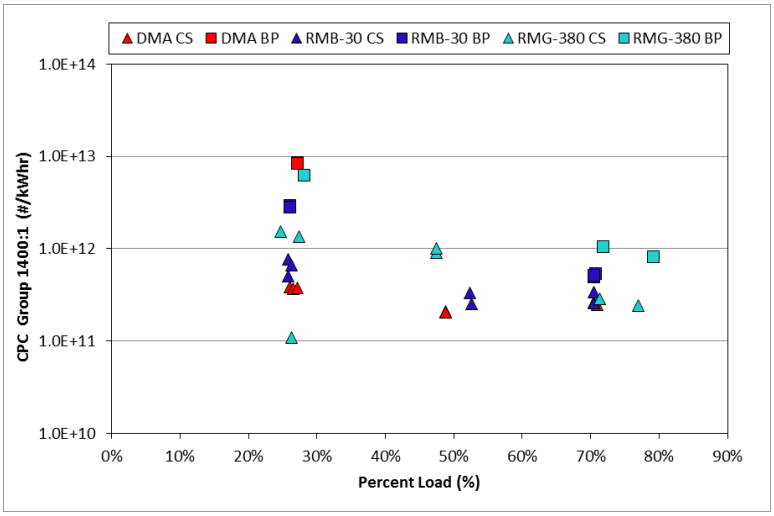


Figure 3-33 Particle number from CPC as a function of engine load

3.2.4.4 PSD

Particle size distributions (PSDs) collected with an EEPS are shown in Figure 3-34 for each of the test fuels at the 25% and 75% load. The results show that the PSDs for the 25% load point are comprised predominantly of small particles in the BP mode, with higher emissions for the DMA and RMG-380 fuels. The PSDs for the CS tests at the 25% load show a significant reduction in particle number, consistent with the particles being volatile in nature. At the 75% load point, the PSDs show larger particles in the range slightly above 100 nm for the DMA and RMB-30 fuels. The PSDs for the DMA and RMB-30 fuels at the 75% load point are similar for the BP and CS suggesting these particles are solid, consistent with the trend of higher levels of EC at the 75% load point. The RMG-380 fuel showed particles in the 40 nm range for the 25% load point with a BP mode. The particle size distributions for the RMG-380 for the 75% load point decrease in magnitude and shifted to larger sizes when sampled through the CS. This suggests a more volatile nature for the RMG-380 particles, consistent with the higher levels of sulfate for the RMG-380 particles sampled in the BP mode.

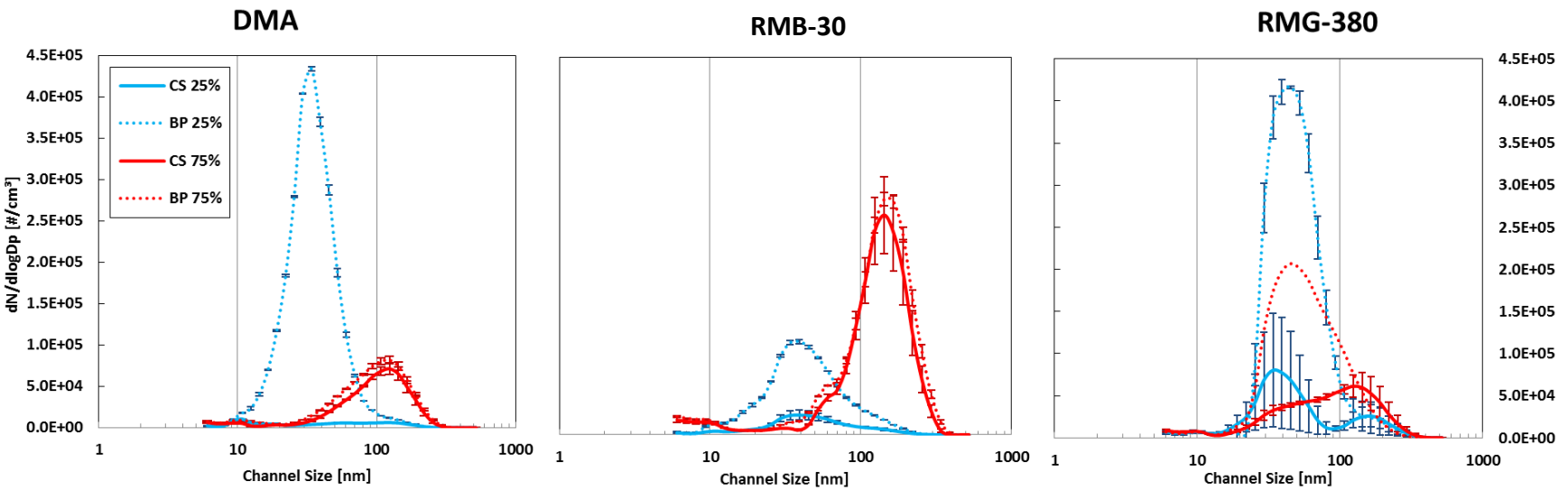


Figure 3-34 Particle size distribution from EEPS as a function of engine load

3.3 Recommendations for On-Board Testing

This section provides a discussion on the recommendations for in-use OGV testing, instrument usage, and operational modes of interest.

3.3.1 Recommended instruments

UCR has tested on several OGVs with some level of BC emission factor measurements, see Table 3-12. Photoacoustic (PA) and EC were the methods used to quantify BC emission factors. Based on the laboratory measurements, the EC, PA, and LII measurements were in best agreement post calibration without sample conditioning. The FSN is currently the standard method for making on-board BC measurements, and it also agreed well with the top three BC measurement approaches when sample conditioning (CS + SO_2 adsorption) was used. Given the FSNs wide use in industry for OGV engine developers and the EC and PA close agreement and historical usage at UCR, with the methods recommended for the at sea testing on the OGVs were the PA (AVL 483 MSS), EC (EC/OC), and Smoke Meter (AVL 415SE Smoke Meter) measurement methods.

Table 3-12 Review of OGVs BC Measurements Made Previously by UCR

Engine Name/Rating	Vessel/Engine Name/Type	Fuel	PM Controls	BC Method of determination	PM Method of determination	Load Points [1]	BC factors (g/kWhr)
Four-MAN B&W 6L48/60, 6.3 MW2-stroke	Very Large Crude/Main	HFO <0.1% S	-	EC/OC, PA-MSS	tPM2.5, SMPS, Pegasor PSS-M	80,60,40, 20,VSR	0.009-0.154
Four-MAN B&W 6L48/60, 6.3 MW 2-stroke	Very Large Crude/Main	MGO <0.1% S	-	EC/OC, PA-MSS	tPM2.5, SMPS, Pegasor PSS-M	60,40,30, 20,VSR	0.004-0.147
2000 MAN B&W ML-0241, 74.6 MW 2-stroke	Container 2600 TEU /Main	HFO, 0.9%	-	EC/OC, PA-MSS, PA-DMT	tPM2.5	60,40,30, 20,VSR	0.008-0.068
2000 MAN B&W ML-0241, 74.6 MW 2-stroke	Container 2600 TEU /Main	MGO, 0.3%	-	EC/OC, PA-MSS, PA-DMT	tPM2.5	60,40,20 VSR	0.003-0.062
MAN B&W 7L32/40 3.2 MW 4-stroke	3-Engines /Aux	MGO, 0.3%	Scrubber	EC/OC, PA-MSS, MAPP[2], Aethalometer[2]	tPM2.5	60,30,10 %	0.004-0.009
1995 MAN B&W 11k90MC, 50.27MW 2-stroke		HFO	-	EC/OC, Light Scattering	PM2.5, Sulfate, Ash	75,75,50, 25,VSR	0.002-0.004
1995 MAN B&W 11k90MC, 50.27MW 2-stroke		HFO+ Water	-	EC/OC, Light Scattering	PM2.5, Sulfate, Ash	75,75,50, 25,VSR	0.004-0.013
Sulzer 6RTA72, 15.7 MW 2-stroke	Suez Max Tanker/Main	HFO ~3%	-	EC/OC, Light Scattering	PM2.5, Sulfate, Ash	85,60,40, 20,VSR	0.008-0.031
Wartsila Vasa 6R22/26, 0.9MW 4-stroke	Suez Max Tanker/Aux	MGO <0.5%	-	EC/OC, Light Scattering	PM2.5, Sulfate, Ash	75,50,25 %	0.007-0.015
MAN B&W 12k90MC, 54.84 MW 2-stroke	Post-Panama Class/Main	HFO 3%	-	EC/OC, Light Scattering	PM2.5, Sulfate, Ash	90,75,50, 25, VSR	0.006-0.008
MAN B&W 12k90MC, 54.84 MW 2-stroke	Post-Panama Class/Main	MGO 0.2%	-	EC/OC, Light Scattering	PM2.5, Sulfate, Ash	90,75,50, 25, VSR	0.004

[1] Load points for auxiliary engines are percent of max electrical load and the load points for the main engine is a percent of maximum engine rating. Typically, vessel owners limit maximum power to less than 100% for safety reasons. (Tier 1 2000 and 2011 Tier 2)

[2] The MAPP and Aethalometer both were over ranged and needed more than 100 to 1 dilution which was not available at the time of testing, thus no useful data for these instruments was provided.

Recently, UCR has tested some scrubbers that have shown significant differences between retrofit approaches. In one case, BC reductions were found to range from 40% to 0% from high to low load. In a second test, there was very little reduction at any load and sulfate PM was only slightly reduced. Thus, it is becoming apparent that main engine OGV PM scrubber technology is still evolving and that measurements are needed to characterize proper in-use performance and BC reduction understanding.

As part of this research, representative at-sea vessels were targeted that will fill the research gaps for BC EF. Figure 3-35 shows a distribution of vessels tracked by the U.S. Army Corp of Engineers (USACE) operating in the global network. This represents USACE entrances and clearances for (mainly) foreign flagged ships that call on U.S. ports, although the distribution should also be representative of the global fleet make up. The figure suggests bulk carriers, tankers, container ships and crude vessels are most representative vessels, and these categories were targeted for UCR's at sea testing. One of the goals of this project are to consider more modern vessels. Figure 3-36 shows the percent of the total inventory that are Tier 0 through 3 for the USACE entrances and clearances. The results show that very few vessels are Tier 1 and newer, so availability became a critical element in selecting a newer vessel.

Table 3-13 lists the vessels used for the in-use testing in Task 2 and 3 of this research project. Both tasks had goals of evaluating BC measurement approaches and emission factors, with Task2 considering these goals during vessel speed reduction (VSR) and Task 3 considering them during PM control. The following criteria were utilized to select the OGVs, where it is expected that a combination of goals could be performed on the selected vessels:

- Vessel speed reduction
- PM controls (scrubbers)
- Tier 1 or 2 engine categories
- Fuel switching

As part of the at sea testing, UCR selected a limited number of instruments to bring onto the vessel in order to maximize the chances of success of the project. At sea testing is complex and requires significant planning, so the instrumentation was limited to three methods to manage the effort for testing. The Smoke Meter (FSN) was selected due to its performance in the laboratory testing, its robustness, and lack of need for dilution. The MSS or LII were UCR's second choice, but since UCR owns an MSS and has more experience operating it and can troubleshoot most issues, the MSS was selected over the LII. The EC measurement was also used since it is very low cost and already a part of UCR's at sea measurement system. Since the benefits of the sample conditioning appear to be outweighed by the uncertainty introduced due to increased losses of BC in the sampling system and the added complexity of setting up the measurements, sample conditioning was not performed on the at sea vessels. As such, for the at-sea testing UCR proposes, the FSN, MSS, and EC/OC measurements without sample conditioning were utilized. Additionally UCR compared the measured results with and with-out the post-hoc calibration.

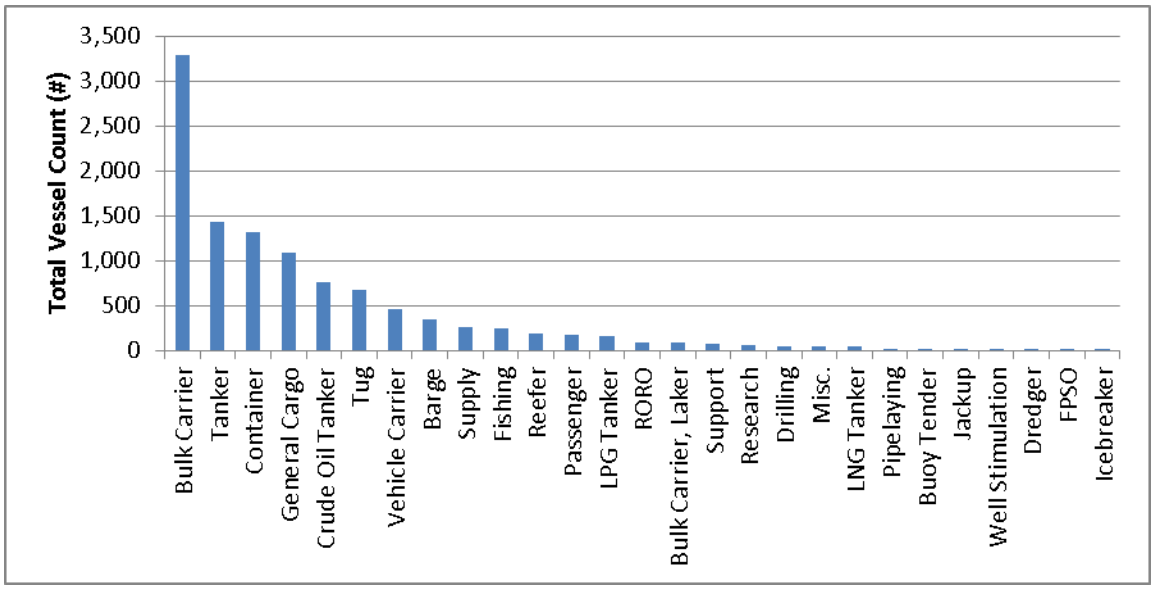


Figure 3-35 Ship inventory count by vessel category (ERG 2015)

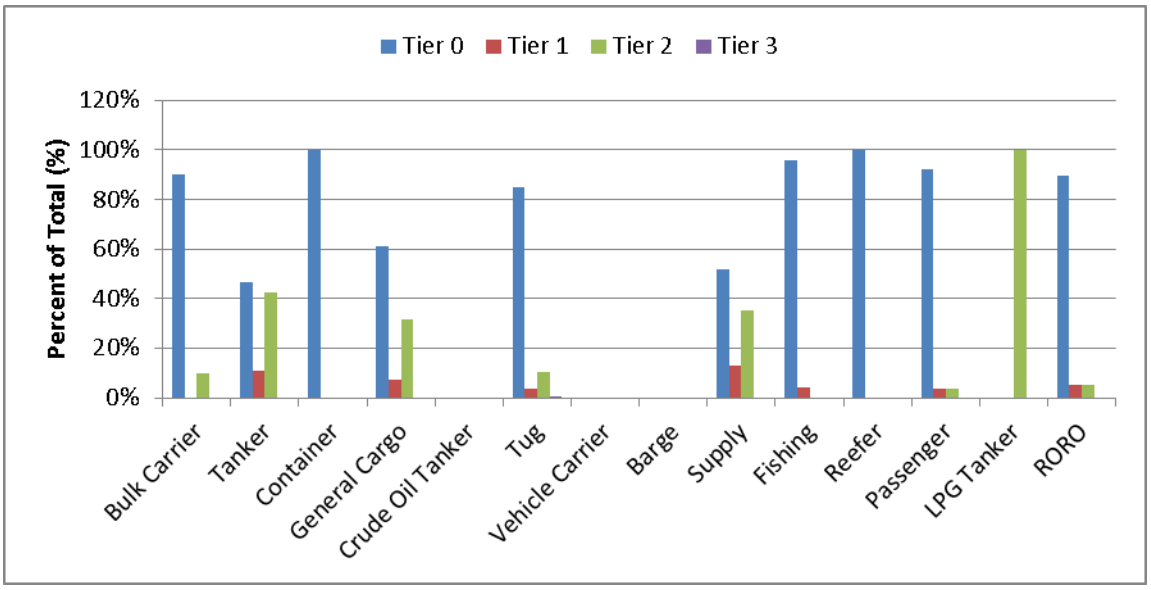


Figure 3-36 Ship inventory fraction of Tier 0, 1, 2, and 3 by vessel category (ERG 2015)

Table 3-13 Planned OGV tested for in-use BC evaluation

Engine Type	Vessel/Engine Name/Type	Fuel Switch	PM Controls	VSR	Load Points [1]
2011 MY ME Tier 2	Container **67 MW** Mitsui MAN B&W	No	No	Yes	[75,50,25, 9%]
1987 MY ME Tier 0	Container **16 MW** Mitsui MAN B&W	No	ME Scrubber	No	95%, 75%, 50%, 5%

[1] Typically vessel owners limit maximum power to less than 100% for safety reasons. AE sampled separately for the Tier 2, but integrated into the exhaust for the Scrubber system.

[2] In addition to BC measurements (EC/OC, PA-MSS and FSN) UCR will collect PM2.5, regulated gaseous, SO2, and other sampling parameters.

4 Task 2 At-Sea: Modern Engine and VSR

On-board testing of oceangoing vessels has been designed into this program to: A) validate the emission factors from well-maintained engines under in-use conditions, B) help develop a general methodology to account for conditions where BC emissions may differ from values measured under test bench conditions, and C) investigate the link between slow steaming and BC emissions. Task 2 focuses on validating the modal and overall BC emissions factors from a modern Tier 2 engine at normal and VSR conditions and includes a comparison with the bench testing.

4.1 Approach

The approach includes the test article (vessel, engine, maintenance records, and fuels), sampling approach, measurements, and calculations. The test article sections cover details on the specifics of the vessel and any details of importance to the stability of the emission and the validity of the testing. The sampling approach describes the vessel usage, where the samples were collected from the exhaust, the test matrix, and the test protocol. The measurements section describes the measurement methods for gaseous, PM, and BC. The calculations section provides details on the exhaust flow, emission factors, and in-use estimated calculations.

4.1.1 Test article

4.1.1.1 Ocean going vessel

The modern engine testing was performed on an Asian-flagged Post Panamax II container vessel built in 2012 that moves up to 8,626 TEUs and 700 reefers. It was the first ever in-use Tier 2 vessel tested. The draught is 12 meters, the length is 333.2 meters, and the breadth is 43 meters. The vessels service speed is up to 25.6 knots. The gross and net tonnages are 90,532 and 55,413, respectively. Tank capacity includes: 30,409 m^3 for ballast, 10,257 m^3 for HFO, 701 m^3 for MGO and 566.5 m^3 for fresh water.

Figure 4-1 Modern ocean going container vessel tested as part of this research.

4.1.1.2 Engine

The OGV was equipped with one direct drive 2011 model year (MY) main engine (ME), four auxiliary engines (AEs), and one boiler, see Table 4-1. The ME is a MAN B&W two-stroke, 12 cylinder, electronically controlled, low-speed propulsion marine engine, with a model number of 12K98ME6.1, and with an IMO Tier II certification. The engine is rated at 69.68 MW, with a cylinder bore of 980 mm

and stroke of 2,660 mm. It is equipped with a constant pressure turbo and crosshead design, with pressure-charge single stage air aspiration and a conventional injection system. The ME maximum continuous rating (MCR) is 93,360 kW at 94.0 rpm with a propulsion power of 68,666 kW. The nominal continuous rating (NCR) is 84,024 kW at 90.8 rpm with a propulsion power of 62,657 kW. The ME on the vessel has a reported brake specific fuel consumption (BSFC) of 171.8 + 5% g/kWh for the normal operating range for the IMO Tier II NOx regulation. The mean effective pressure for the ME is 18.2 bar at MCR. Also, the ME on the vessel has a reported break specific lubrication oil consumption (SLOP) of 0.60 g/KWh.

The AEs were all 2011 MY Daihatsu 8DC32e, 3.2 MW, medium speed (720 rpm), 4-stroke, 8-cylinder diesel engines. The mean effective pressure for these engines is 2.05 MPa. The AE specification records show a BSFC of 195 + 5% g/kWh and lube oil consumption rate of 0.8 g/kWhr. The engine hours for each of the test engines were recorded and are presented in (Table 4-1).

Table 4-1 Specifications of emission sources on the Tier 2 OGV [1]

Source	*Engine Mfg.*	*MY and Model*	*Engine Power kW*	*Run Hours*	*EGCS*
ME	Mitsui MAN B&W	2011 12K98ME6.1	68,666	25,985	no
AE1	Daihatsu	2011 8DC32e	3,162	11,129	no
AE2	Daihatsu	2011 8DC32e	3,162	13,104	no
AE3	Daihatsu	2011 8DC32e	3,162	3,172	no
AE4	Daihatsu	2011 8DC32e	3,162	15,251	no
Boiler	AALBORG INDUSTRIES K.K.	2011 MISSION OS	n/a	12,700	no

[1] Main engine (ME) is a 2011 Tier II two-stroke, slow speed direct drive engine. The AEs are MY 2011 medium speed (720 rpm) 4-stroke diesel engines. An exhaust gas cleaning system (EGCS) is not included on this vessel. Run time hours are based on conditions when measurements were made.

4.1.1.3 Maintenance records

PM emissions are known to vary with the condition and age of diesel engines. OGVs accumulate engine hours at high rates in comparison with other diesel engines, so PM and BC emissions can be significantly impacted by the hours accumulated between overhaul and maintenance periods. At the time of the test, conversations with the chief engineering indicated that maintenance on the ME was done once per trip. Also, the chief engineer indicated that ME pistons 5 and 6 were overhauled during the last maintenance. The No. 5 piston was overhauled on 3/24/2016 at 24,924 engine hours and the No. 6 piston was overhauled on 3/18/2016 at 24,878 hours. At the time of the testing, 25,985 hours had accumulated on the ME, so the testing was conducted after approximately 1,000 hours had accumulated on the engine since its last major maintenance. Typically, it is recommended to test a vessel either before an overhaul or at least 500 hours (ME basis) after an overhaul to evaluate the PM from the vessel under normal operating conditions. In general, the ME maintenance records suggest the PM emissions from the proposed Tier II ME are representative of a properly operating OGV that was suitable for testing. For more details on maintenance records see Appendix D Sub-section 1 “Maintenance Record Summary”.

4.1.1.4 Fuels and lube-oil

Standard commercial marine fuels and lubricants were used during testing. For the testing campaign the vessel was operated in an emissions control area (ECA) zone where low sulfur MGO fuel must be used. One fuel sample was collected to represent the fuel used while the engine was being tested. The fuel sample was analyzed for selected properties that included, but were not limited to, sulfur, viscosity, and density. A fuel bunker report and UCR's independent analysis of the MGO test fuel are provided in Appendix G, and are listed in Table 4-2. The sulfur was low, around 0.03%, which is well below ECA requirements. Outside the ECA zone, the vessel is designed to operate on a maximum of 3.5% sulfur, according to its maintenance records. Since all the testing was performed within an ECA area, no testing was performed on this high sulfur fuel.

The vessel utilized CASTROL Cyltech 70 for the ME cylinder oil, ENERGOL OE-HT30 for the ME system, and camshaft oil during testing. Only a ME cylinder lube-oil sample was collected, but this sample was not analyzed because the emission results did not suggest that there was extensive lube-oil exhaust contamination.

Table 4-2 Task 2 test fuel selected properties

Tests	Units	Method	Bunker Results	Method	UCR Analysis
API@60		D4052		D4052	37.8
SPgr@60				D4052	0.8360
Density@15	g/ml		0.8565	D4052	0.8356
Viscosity	cSt	D445 40c	3.7	D445 50c	2.39
Cetane Index		D4737B	48.88	D4737B	48.88
Residue	m/m	D482	0	D4530	0.07
Sulfur	ppm	D5453		D4294	<100
Sulfur	**%**	**D5453**	**0.03**	**D4294**	**<0.1**
CCAI	n/a	calc.	772.45	calc.	-

4.1.2 Sampling approach

There are three unique combustion sources on most OGVs: an ME, AEs, and a boiler, see Figure 4-1 for pictorial layout (note: the sources do not include the incinerator). The approach used for testing this vessel was to prioritized the ME first and the AE engines second. The boiler was not included as part of this test.

The sampling approach section provides a discussion of the selection of sample locations (PM representativeness and accessibility), the load points (achievable and practical), the test matrix (proposed load points to meet EPA desires), and the test protocol (methods of sampling).

4.1.2.1 Vessel operation

Testing for this vessel occurred during a one day voyage between Port of Long Beach and Port of Oakland. Testing started as the vessel maneuvered away from the terminal and out of the harbor. The vessel then entered a whale protection zone near Santa Barbara channel between Los Angeles and Santa Barbara where vessel operators maintained a speed of less than 12 knots for approximately 8 hours. During the test, which occurred entirely in an ECA zone, the vessel was operated in a slow steaming, fuel economy mode with one turbocharger cut off. This is the mode typically used by the vessel for operations at all locations according to the chief engineer, as it provides approximately a 59% savings in fuel.

The container vessel used for testing operates on a schedule that includes short one to three port-to-port operations and long ten day plus operations. Most of the time when the vessel operates at sea, the ME operates at cruising speeds at a 53% load (in fuel economy mode with one turbocharger cut off) and one AE operates at a 50% load. The boiler is predominantly used while the OGV is in port and when the engine is started. At these typical load conditions, the ME, AEs, and boiler exhaust volumes represent 90%, 5%, and 5% of the total exhaust, respectively, see Table 4-3 below. In general, the ME represents 90% of the total exhaust volume and is the main contributor to PM and BC emissions and, thus, is the focus of this measurement campaign.

Table 4-3 Vessel usage estimates [1]

Vessel Operation	Vessel Usage		Engine Usage			Combined	Exhaust Fraction		
	Time	Fraction	% of Max			Exh Flow [2]	% of Total		
n/a	(days)	%	ME	AE [2]	Boiler	m^3/hr	ME	AE [2]	Boiler
At Sea	10.0	90%	80	50	50	245,328	90%	5%	5%
Port Side	1.0	9%	0	50	50	23,754	0%	52%	48%
Maneuvering	0.083	0.75%	50	75	75	174,114	80%	11%	10%
Departing (VSR)	0.083	0.75%	20	50	50	79,147	70%	16%	14%

[1] Usage estimates are based on discussions with vessel operators. Port side operation assumes shore power is not provided. These estimates are for a container vessel with electrical loads for reefers.

[2] Exh Flow is the total vessel estimated exhaust flow at the specified operational mode (units are normal m3/hr). Flows are estimated from BSFC, % load, and maximum engine/system ratings.

4.1.2.2 Sample locations

The sampling locations were determined after meeting with crew members on-board the vessel and are shown in Figure 4-2. There were two thermopile ports available that were removed to accommodate one probe for the gaseous/PM/MSS system and another for the filter smoke meter (FSM), see the description below for more details.

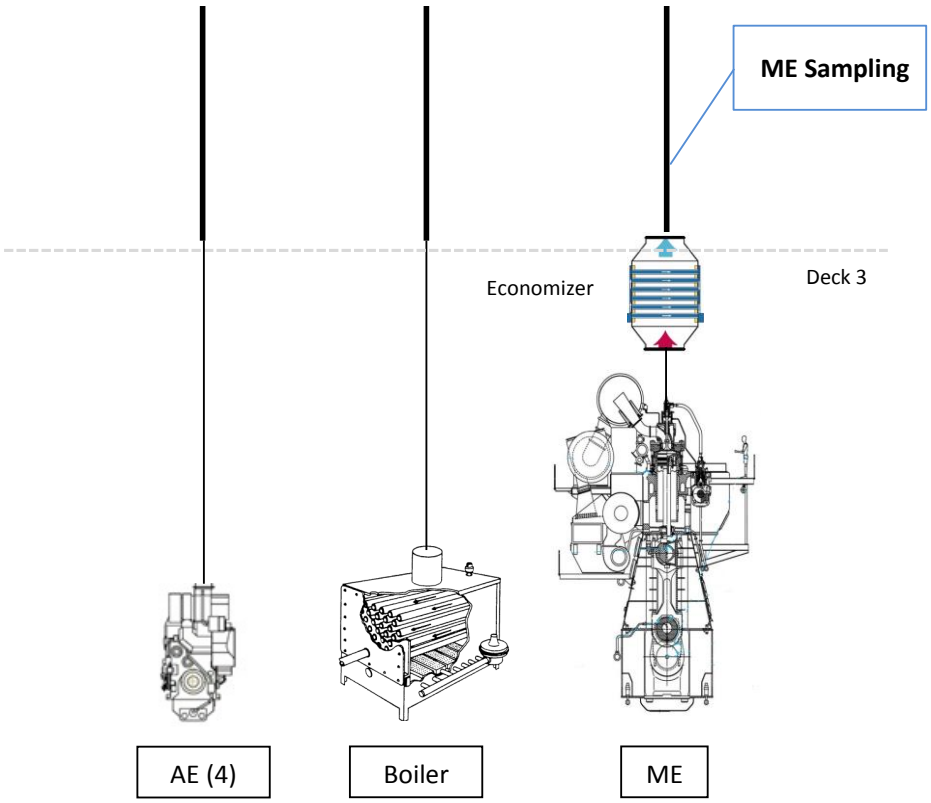


Figure 4-2 Schematic diagram for the test OGV engine layout

[1] Emission sources are one main engine (ME), four auxiliary engines (AE) and a fuel oil boiler

Typically sampling around an economizer can be difficult since PM adsorption and desorption at the coil surface is common. During waste heat recovery (heating water to make steam for the ship's needs), the heat exchanger's surfaces cool the exhaust gas constituents and PM (predominantly EC and BC) adsorbs on the cool surfaces (these losses are described by thermophoretic models). This can lead to underestimated stack PM emissions (~10%) over short periods of time (hours), although the PM emissions will tend to normalized out over long periods of time (weeks). Routine cleaning procedures are utilized to prevent excessive PM build-up, so it is important to ensure a cleaning operation does not take place during sampling, as PM released while cleaning the coils could lead to overestimated PM emission factors. The selection of a sampling location around the economizer is often determined by space constraints and desired measurement practices (e.g., the potential to sample from straight sections of exhaust). On this vessel there was relatively easy access to several straight sections of the exhaust system after the economizer and a floor area to set instruments and work on. The other possible sampling port was above the main engine, but this would have required a ladder to get to that point and the building of a special rig for testing. As such, the sample location selected for this campaign was after the economizer.

The vessel uses a tube type economizer with specific automated cleaning procedures. The timing for the cleaning procedures was coordinated with the vessel chief engineer to ensure these procedures did not occur during sampling from LA to Oakland.

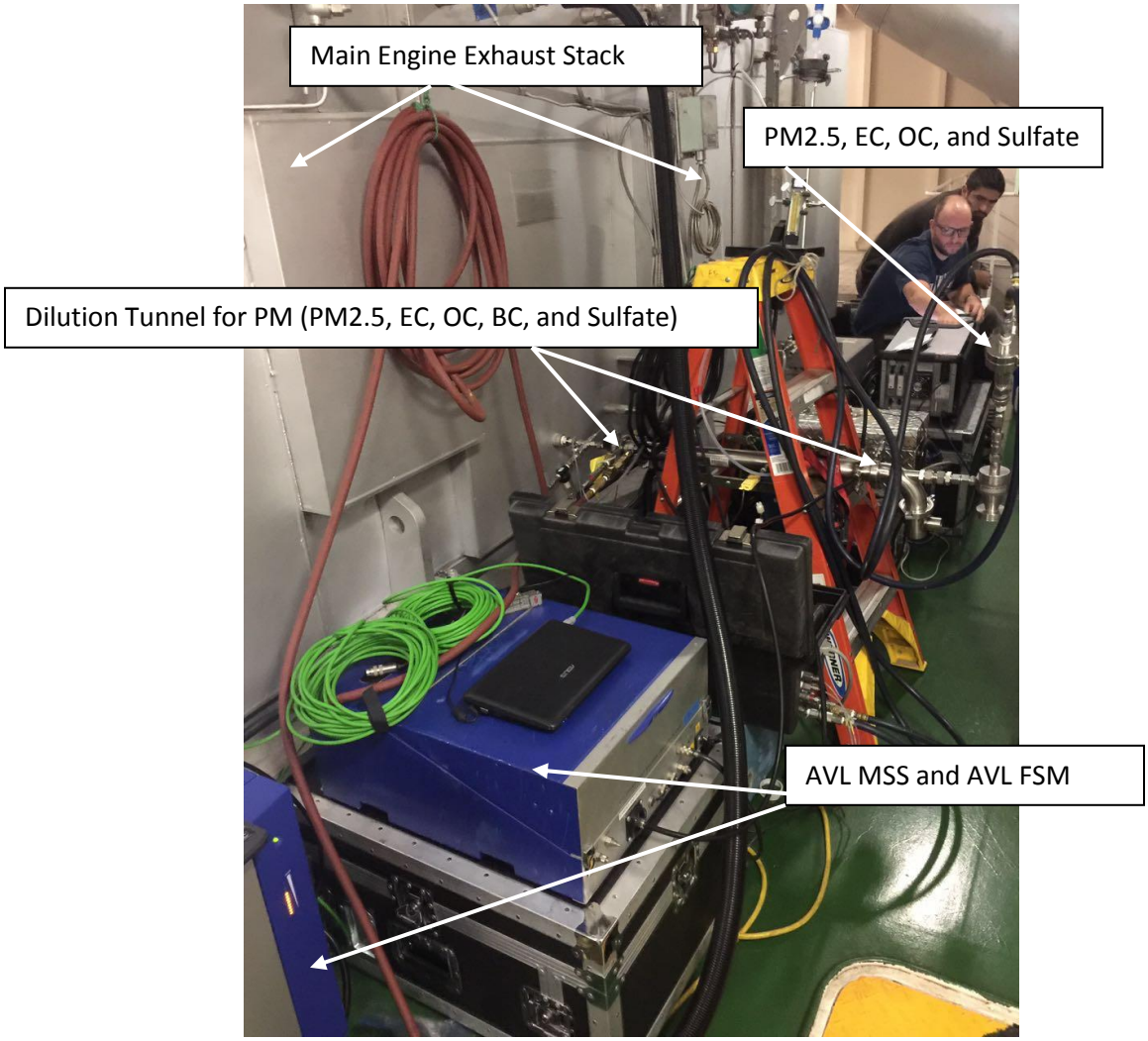


Figure 4-3 Sample setup for the Tier 2 main engine

4.1.2.3 Test matrix

The ME is directly connected to the propeller. To increase vessel speed, the engine speed (rpm) is increased with the load, following the propeller curve. Direct drive, low speed engines are certified per the ISO 8178 4 E3 variable speed propulsion test cycle (Table 4-4) and constant speed AEs follow the ISO 8178 4 D2 auxiliary cycle (Table 4-5) (see Appendix C for more details). Achievable load points are determined at the time of testing and depend on several factors, including constraints by navigational details, engine/vessel configurations, currents, wave patterns, regulations, and wind speed/direction. These loads are selected by the Chief Engineer, or ship Master. For this test, only the ME was sampled due to time and safety considerations. If the AEs were sampled, this would have only provided sufficient time to collect duplicates instead of triplicates for the ME measurements. Given that this is the first on-ocean BC emissions test on a Tier 2 ME, it was important that the team focused on collecting high quality data from this source.

Table 4-4 Test cycle for main engine variable engine speed fixed propeller

Main Engine Testing (ISO 8178-E3)				
Mode	1	2	3	4
RPM Speed (%)	100	91	80	63

Power (%)	100	75	50	25
Weight Factor	20%	50%	15%	15%

[1] Vessel speed reduction (VSR) is also of interest for BC inventories and typically represents a 5th mode at around 10% load and 42% of maximum rpm speed.

Table 4-5 Test Cycle for Constant-Speed Auxiliary Engines

Auxiliary Engine Testing (ISO 8178-D2)					
Mode	1	2	3	4	5
Speed (%)	Rated RPM				
Torque (%)	100	75	50	25	10
Weight Factor	5%	25%	30%	30%	10%

[1] AEs were not planned for testing due to time constraints for ME testing between available ports. This table is provided for completeness.

Based on the goals of this research, vessel operation, and port-to-port time constraints, test points were limited to four modes in order to complete testing in a 12 hour shift. The four test points for the ME testing are presented in Figure 4-9. While consulting with the vessel captain and chief engineer, efforts were made to measure emissions at loads as close as possible to those proposed in the tables. Typically a 100% load is not an option on OGVs, except during sea trials. On this voyage, the available upper load was at 57%, due to the slow steaming, fuel economy mode operation. The next two load points were 41% and 28%. The 4th point was the vessel speed reduction (VSR) load point of ~9%. While the highest three load points for the test to not exactly match the load points of the ISO 8178-E3 test, they are in the general range of the lowest three load points for the ISO 8178-E3 test, (i.e., ~75%, 50%, and 25%) that represent the majority of the ISO 8178 weighting factor (80%), as shown in Table 4-5 above, where the weighting factor is the percentage contribution that is given to each mode in determining the final composite emission factor for the test.

Table 4-6 ME Test Matrix (MGO fuel, triplicate)

Mode	Load %MCR	Vessel [2] Speed (knots)	Engine (rpm)	Sample Duration (min)
1	MAX%[1]	21	77.8	20
2	40%	18	69.9	20
3	25%	16	62.1	20
4	VSR 10%	9-11	~38-43	20

[1] Max load targeted (% of MCR) was ~60% based on discussions with the captain and chief engineer. It is expected this will be around an 80%-85% load. Values shown in the table are for an 85% load.

[2] Vessel speed is estimated based on past measurements of sped and rpm on similar vessels, and might vary slightly from vessel to vessel.

4.1.2.4 Test protocol

Measurements on the vessel were performed going from the low load point to the high load. The VSR load point was tested as the ship left the harbor. The remaining load points (28%, 41%, and 57%) were tested after leaving the whale protection zone. Triplicate tests were performed at each load point. The triplicates were all performed at one time for each load point (i.e. mode 1, 1, 1, change load, mode 2, 2, 2, change load, etc.…). Based on experience testing OGVs, repeating test points with this approach is needed to minimize the time it takes between different load points and to prevent issues when navigating in areas with speed restrictions. Prior to testing in the VSR mode, the ship had operated for approximately 2 hours at the VSR speed to ensure the engine was sufficiently warm and the emissions

were stabilized. This differs slightly from the ISO protocol, which specifies that the engine should be operated for about 30 minutes at the highest power possible for engine warmup, but was adequate in achieving stabilized emissions. For the higher load points, the engine was brought up the desired load and then CO_2 emissions were monitored until they stabilized prior to testing. 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 and no longer than 30 minutes (such that approximately 500 µg of filter mass is collected at a minimum dilution ratio of 4:1).
- Record engine RPM, boost pressure, and intake manifold temperature in order to calculate the mass flow rate of the exhaust via a methodology that considers the engine as an air pump. 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 measurements will be used for validation of the measurement systems.
- Calculate emission factors from the measured pollutant concentration data and calculate mass flow rates.

4.1.3 Measurements

This section discusses the data collection and measurement approaches for emissions, engine performance, and black carbon. The emissions were measured by equipment provided by UCR. The vessel provided performance information that was recorded by UCR staff from vessel screen shots, hand logs, and electronic records provided by the vessel.

4.1.3.1 Gaseous and PM emissions

Best recommended practices for OGV exhaust gas measurements follow 40 CFR Part 1065 for PM measurements with specific details following ISO 8178-1 for dilution and exhaust gas sampling. The measurement approach is summarized here, with more details available in Appendix A. UCR's quality control practices for all its gaseous and PM measurements are provided in Appendix B.

The PM emission measurements use a partial dilution system that was developed based on the ISO 8178-1 protocol (detailed information is provided in Appendix A). The concentration of gases in the raw exhaust and the dilution tunnel were measured using a Horiba PG-350 portable multi-gas analyzer. The PG-350 can simultaneously measure up to five separate gas components. Major features of the PG-350 include a built-in sample conditioning system with sample pumps, filters, and a thermoelectric cooler. The signal output of the instrument was interfaced directly with a data acquisition system in order to record the measured values continuously. Emissions for CO, CO_2, and NO_x gases were measured from the raw exhaust gases (see Table 4-7).

Total PM mass ($PM_{2.5}$) was measured from the diluted exhaust gas as per federal regulation's (40 CFR Part 1065), which utilize Teflon filters weighed offline and after conditioning. The dilution ratio for the dilution tunnel was verified at each test point by raw and diluted comparisons of the gaseous emissions using the Horiba PG-350, as per ISO 8178 methods. In addition to measured criteria emissions, the project measured EC and OC fractions of the PM composition, but not sulfate PM due to the low sulfur fuel being used. For further qualitative assurance, UCR used a continuous PM monitor (TSI DustTrak 8520) to ensure that the PM concentrations were stabilized while the filters were collecting samples.

Table 4-7 Summary of Emissions Proposed to be Measured by UCR

Species Sampled			
NDIR CO	NDIR CO_2	CLD NO_x	SO_2
Total **$PM_{2.5}$** Gravimetric method	PM **EC/OC** by NIOSH method	PM **Sulfate** Not measured for DMA Fuel	Photoacoustic Soot
Thermal optical Elemental Carbon	Light absorption Filter Smoke Number		

[1] Because the fuel is a low sulfur fuel sulfate PM is not recommended as the measurements will be insignificant for sulfur levels of 100 ppm and lower (as verified by the fuel analysis and C-of-A bunker reports in appendix G).

4.1.3.2 Black carbon emissions

BC measurements were made using three measurement methods. These were the AVL 483 Micro Soot Sensor (MSS) photoacoustic, the thermal optical reflectance NIOSH filter method, and the AVL Smoke Meter 415 SE (FSN) light absorption methods. These methods were selected based on their performance during the engine test stand work.

During the test stand research, the EC filter, MSS, and LII measurements showed the best agreement (± 10%) after the post calibration for measurements made without sample conditioning. With sample conditioning (CS + SO_2 adsorption), the FSN also agreed well with the top three BC measurement approaches. Given the FSN's wide use in industry for OGV engine developers, and the MSS closed agreement and historical usage at UCR, UCR recommended incorporating the MSS, EC filters, and FSN measurement methods for the OGV testing. The LII also performed well, but it was not selected for the OGV testing due to logistical issues in acquiring this instrument and the added personnel needed to operate it where space is limited for staff and instruments.

The selected BC instruments report BC measurements based on the definition of EC for the EC method and eBC for the MSS and FSN methods.

4.1.3.3 Vessel emission measurements

Chapter 6 of the NO_x Technical Code "Procedures for demonstrating compliance with NO_x emission limits on board,"[1] provides detailed instructions for the required measurements for on-board testing. These measurements as well as EPA requested measurements are included in UCRs measurement approach. Additionally specific engine performance parameters are measured and/or calculated for each mode during the emissions testing are shown in Table 4-8. The records vary depending on available information for the ME and MG.

Table 4-8: Engine Parameters Measured and Recorded [1]

Parameter	Units
Load	kW
Vessel speed	Knots
Engine Speed	RPM

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

Generator Output [2]	amps, volts, kW, PF (where available)
Fuel consumption	kg/hr
Brake specific fuel consumption	kg/kWhr
Air intake pressure, temperature	Psi, °C
Exhaust stack pressure, temperature	inH20, °C
Ambient pressure, temperature	kPa, °C

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

[2] Alternator efficiency will be estimated from previous OGV alternator reports or actual mfg values will be used when available.

4.1.4 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, time specific, and fuel specific emission factors are also provided.

4.1.4.1 Exhaust flow rate

Since the analytical instruments measure the concentration in the exhaust, it is essential to have an accurate measure of the exhaust mass flow in order to calculate emission rates and emission factors. UCR calculated the exhaust flow rate from the reported displacement volume of the diesel engine cylinder and from the following measured values: engine rpm, intake temperature, and intake manifold air pressure. This ISO 8178 approved "air pump" method was utilized for the exhaust flow calculations as a cross check. The exhaust flow rate calculated from "air pump" method was applied to calculation due to the calibration of the fuel flow meter on-board was not found to be sufficiently reliable. See Appendix A for exhaust flow calculation details.

4.1.4.2 Emission factors

Emission factors were calculated at each mode from: the measured gaseous and $PM_{2.5}$ concentrations, the reported engine load in horsepower (hp or kW), and the calculated mass flow in the exhaust. An overall weighted emission factor representing the engine is determined by weighing the modal data according to the ISO 8178 E3, E2 (see Table 4-4 and Table 4-5). The equation used for the overall emission factor is as follows:

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

Where:

A_{WM} = Weighted mass emission level (CO, CO_2, $PM_{2.5}$, or NO_x) in g/hp-hr
g_i = Mass flow in grams per hour
P_i = Power measured during each mode, and
WF_i = Effective weighing factor (see Table 4-4 and Table 4-5 for factors)

4.1.4.3 In-use emission factor estimations

Comparing emisisons to the certification values for Category 3 vessels requires matching ISO loads during at-sea conditions. Typically it is not possible to match the ISO loads for the at-sea condition where estimation is needed to present in-use emissions with the certification value. The modern engine was tested up to 57% MCR where the certificaiton values of 100% and 75% were not collected. To estimate the 75% and 100% loads, a 3rd order polynomial model was used and previous experience

testing at higher loads. Previous experince suggests bsNOx is flat from 50 to 80% load and slighly increases with loads close to 100% load. Figure 4-4 shows the measured poitns (in blue) in addtion to the estimted points (in red). The curve has a good fit (R^2 = 0.994), is relativly flat from 50% to 85% with a slight increase at 100% load.

This model is used for the determination of the NOx emissions as they compare to the certification value. The NOx emission results are comparable to the certification values for a Tier 2 engine. Based on the reuslts generated from this test and the ISO weighting factors, the estimated weighted NOx emissions are 15.5 g/kWhr, which is 7% higher than the current Tier 2 NOx regulation. However, the results are within reasonable in-use allowance (20% allowed for on road trucks) and hold reasonable measurment uncertainties.

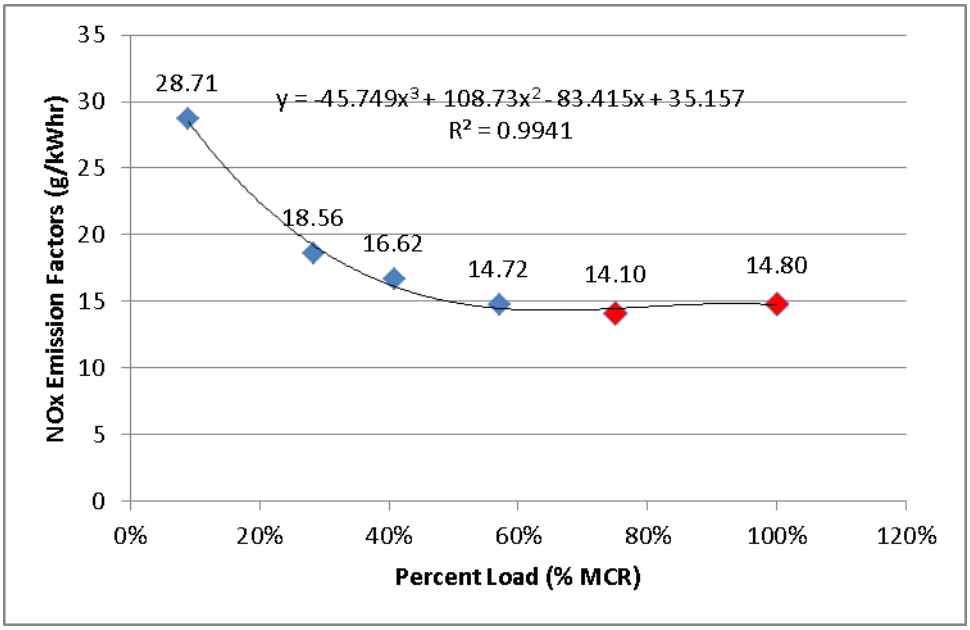


Figure 4-4 Estimated NOx emission factors to determine ISO weighting

4.2 Results

The testing spanned two days starting at 15:00 on 5/22 and ended at 05:30 on 5/23, Figure 4-5. The vessel operated in VSR mode while leaving the port and maintained this mode for ~7 hours. After exiting the VSR area, the captain brought the vessel up to 62 rpm and held it there for UCR to start its measurements. After VSR, UCR performed three speeds at 62 rpm, 70 rpm, and 78 rpm. Figure 4-5 shows the real time eBC (via the MSS), CO_2 and NO_x concentrations and the sample intervals when the batched filters (EC/OC, and PM2.5) were collected (see green "Xs"). The sample times at the end of the voyage were reduced from 30 minutes to 20 minutes in order to complete the testing prior to reaching the destination.

The real time results show that the VSR, 70 rpm, and 78 rpm were stable for all the species. The 62 rpm mode shows some variability (decreasing concentration with time) for NO_x and eBC where by the end of the 62 rpm mode the NOx and eBC looked stabilized. Interestingly the vessel was stable at the 62 rpm load point for an hour before testing started as can be seen by the relatively constant CO_2 concentration for the entire mode. It is unclear why the PM and NO_x emissions were not stable when the CO_2 concentration looked stable. In summary, the remainder of the data presented in this section is based on the analysis during the batched sample intervals.

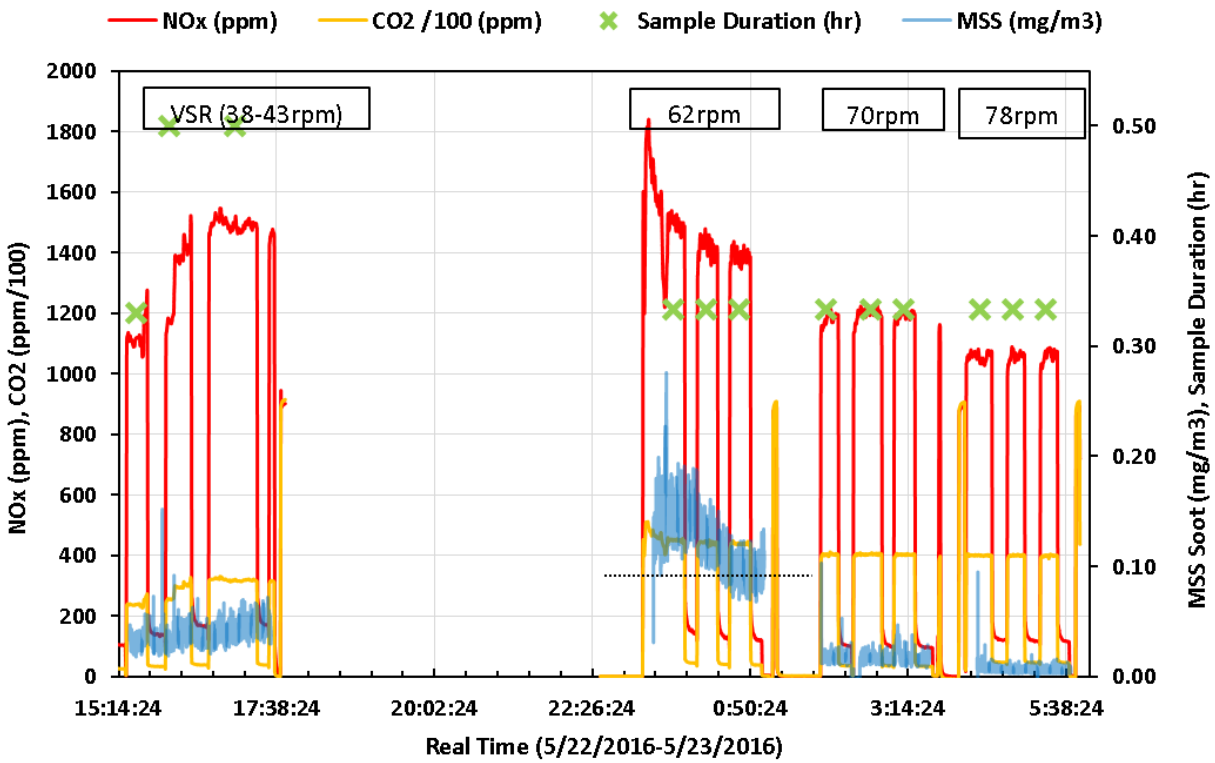


Figure 4-5 Real time response for selected emissions species with test notes

4.2.1 Gaseous

The NO_x emissions results for the main engine test are shown in Figure 4-6 in g/kWh as a function of engine load (MCR). The results show 4 test points representing load points comparable to those used in the ISO 8178-E3 test, with the exception of the full load test point and the VSR test point (show at 9%).

NO_x emissions ranged from 14.7 to 28.7 g/kWh over the different load points. The results show a declining trend with increasing load, as is typical of marine engines. The results show good repeatability at each of the load points with a slightly higher variability with the 28% load. The repeatability at each load points indicates consistency in the testing.

The NO_x emission results are comparable to the certification values for a Tier 2 engine. Based on the results generated from this test and the ISO weighting factors, the estimated weighted NO_x emissions are 15.5 g/kWhr, see details of this estimation in the Calculation Section. The weighted value is 7% higher than the Category 3 Tier 2 NO_x regulation. However, the results are within reasonable in-use allowances and reasonable measurement uncertainties (Note there is an EPA 20% in-use measurement allowance for on road heavy duty trucks). Future regulations will require more than a 75% NO_x reduction in order to meet the 2016 Tier 3 NO_x regulation for category 3 engines in ECA zones. It is expected 75% reduction cannot be met with engine control and NO_x aftertreatment will probably be required.

The test engine was operated in a fuel economy mode that utilizes one of two turbo chargers (i.e. one turbo charger is cut out), which has been shown by other to lead to higher NO_x emissions (Hountalas, 2014). The shop trial for this engine was also operated in the same fuel economy mode which suggest the economy mode is normal for this engine.

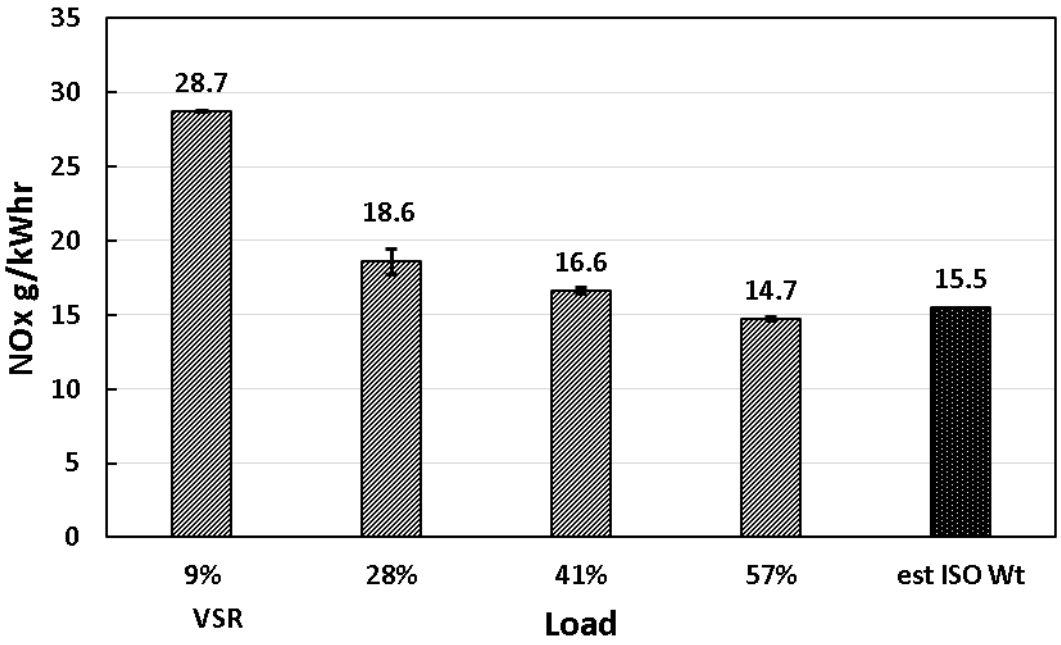


Figure 4-6 NO_x Emissions for the main engine in g/kWhr

Table 4-9 Category 3 slow speed engine ISO weighted NO_x limits (n < 130 RPM)

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

The CO emissions results for the main engine test are shown in Figure 4-7 in units of g/kWhr. The CO emissions were relatively constant as a function of load, with most test points in the range of 0.25 to 0.3

g/kWhr. The results show repeatability for most of the load points. The 28% load point showed different trends than the other load points, with higher emissions from ~0.25 to ~0.41 g/kWh and a greater testing variability. The CO emissions are not regulated, but are typical very low and are below the certification for Category 1 and 2 marine engines. No estimated ISO weighing was performed for CO emissions since these emissions are not reported as part of the Category 3 certification process.

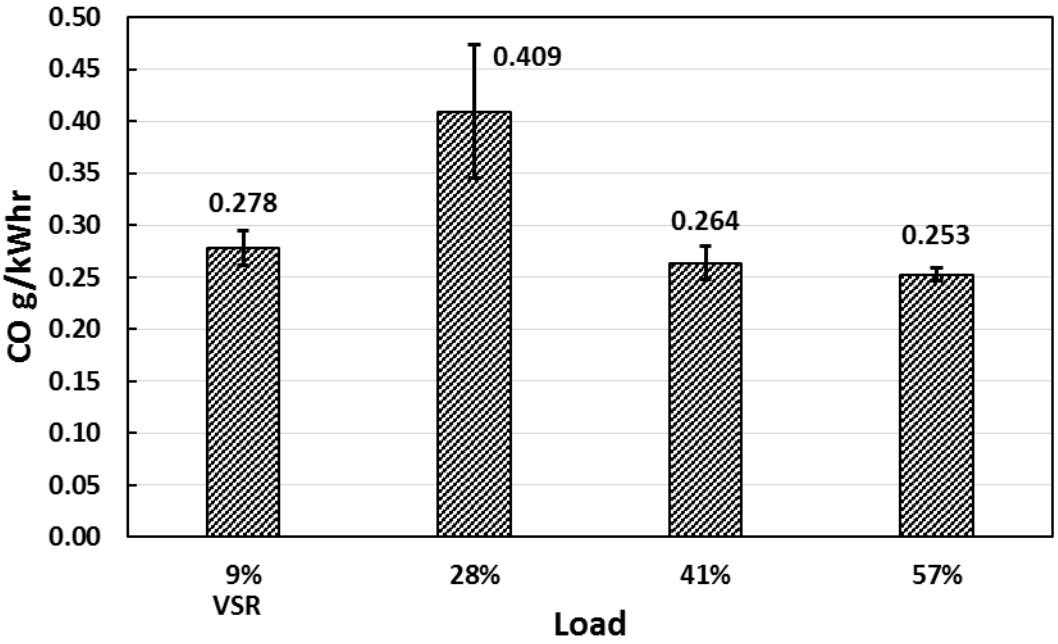


Figure 4-7 CO Emissions for the main engine in g/kWhr

The CO_2 emissions results for the main engine test are shown in Figure 4-8 in units of g/kWhr. CO_2 emissions ranged from 568 to 631 g/kWh over the different load points. The results show a declining trend with increasing load, as is typical of marine engines where fuel efficiency improves with higher engine load up to about 85% MCR load. The results show repeatability at each of the load points, indicating consistency in the testing. The CO_2 emissions represent the efficiencies of the engine and are consistent with the shop trial and previous testing of large marine 2-stroke engines.

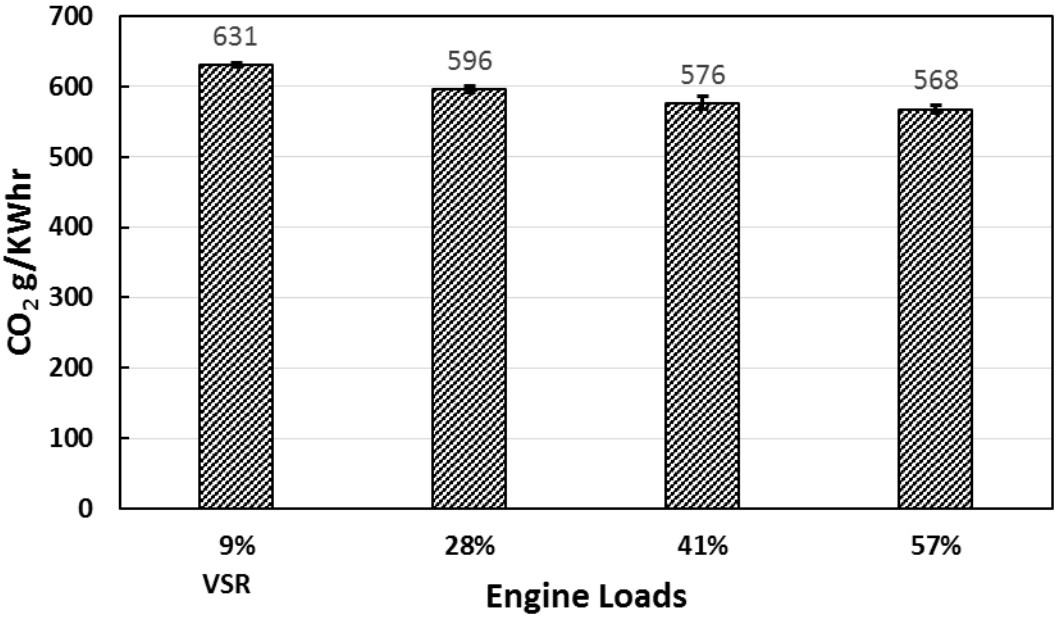


Figure 4-8 CO_2 Emissions for the main engine in g/kWhr

The SO_2 emissions results for the main engine test are shown in Figure 4-9 in units of g/kWhr. SO_2 emissions were low and relatively constant at 0.02 g/kWh for the higher load points, with slightly higher emissions of 0.028 to 0.037 g/kWh for the VSR test point. The fuel was a low sulfur distillate where one expects low SO_2 emissions. The higher SO_2 emissions at VSR is a result of not higher SO_2 concentration, but the much lower load and thus higher break specific emissions for SO_2. In general the SO_2 emissions from this vessel are consistent with the sulfur content of the fuel sample.

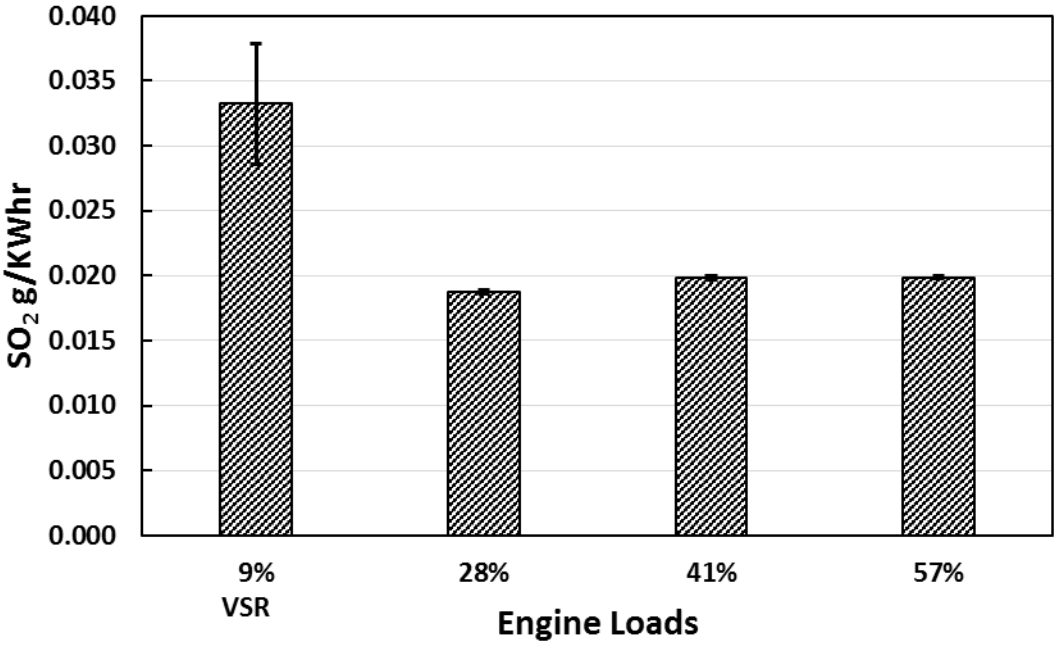


Figure 4-9 SO_2 Emissions for the main engine in g/kWhr

4.2.2 PM2.5

During the Task 1 campaign, PM losses were found to be very large due to the large temperature deltas (> 200C) in the sample conditioning system. The sample conditioning system was not utilzed for the at-sea tests so PM losses are estimated at less than 2% and are not recommended as they are not part of the sampling method. As such all PM measurements are reported as measured for the Task 2 and Task 3 results.

The $PM_{2.5}$ emissions results for the main engine test are shown in Figure 4-10 in units of g/kWhr. $PM_{2.5}$ emissions ranged from 0.05 to 0.15 g/kWhr. The $PM_{2.5}$ emissions did not show a strong trend with respect to load. Interestingly, the $PM_{2.5}$ emissions at the 60% load point were higher than those for the 40% load point. The results showed repeatability at the higher load points, but had greater variability at the lower load test points which may have been the result of engine speed differences (VSR mode) and load transition for the 28% load (see Figure 4-10 for details). There are no $PM_{2.5}$ emissions reported for category 3 engines so there is no good reference point. These emission factors compare well with other OGVs where low sulfur MGO fuels are used.

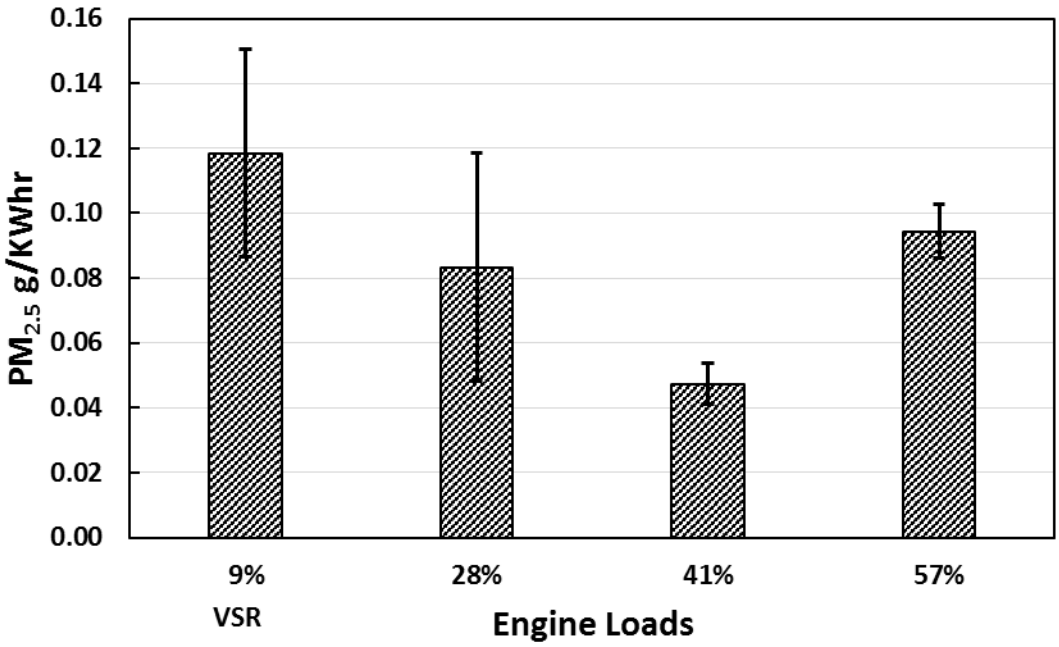


Figure 4-10 $PM_{2.5}$ Emissions for the main engine in g/kWhr

4.2.3 BC

The BC emissions results for the ME tests are shown in Figure 4-11 in units of g/kWh for the different BC methods (MSS, FSN, and EC). The BC emissions were in the same range and showed similar trends for all methods and ranged from 0.00043 to 0.011 g/kWh for the different loads. BC emissions showed a trend of decreasing emissions with increasing load, with the exception of the 28% load point, which showed the highest BC emissions. BC emissions on a fuel specific basis are provided in Figure 4-12 in units of g/kg-fuel. The fuel specific emissions varied from 0.0023 g/kg-fuel to 0.069 g/kg-fuel (see Appendix E for a compete table of fuel specific emissions). The results showed repeatability for most of the load points, with greater repeatability at the 28% test point.

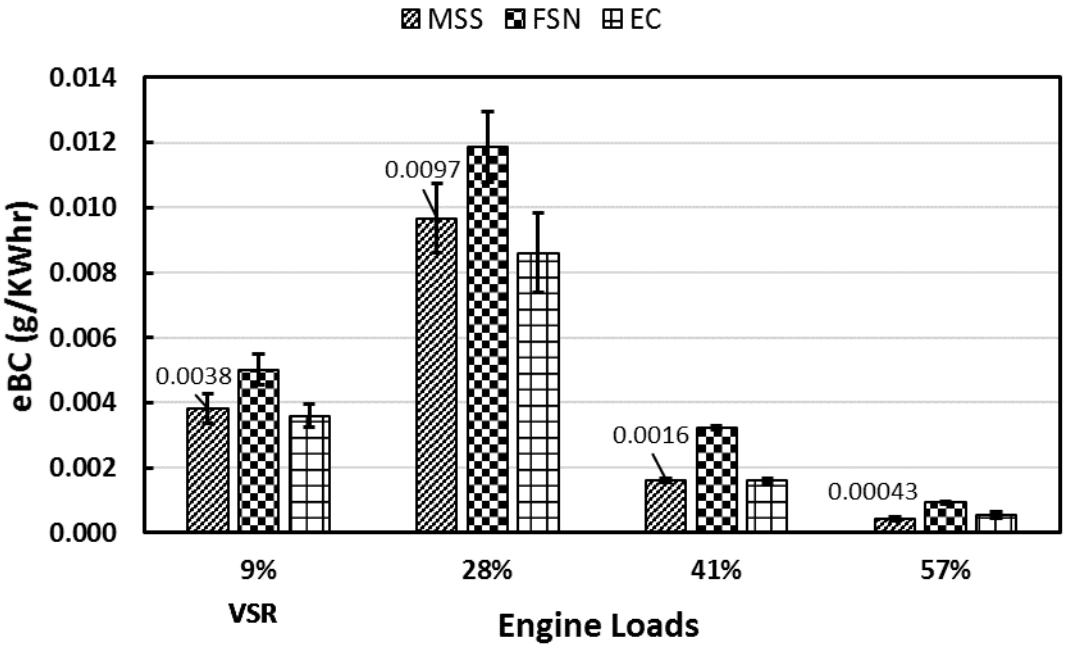


Figure 4-11 BC Emissions for the main engine in g/kWhr

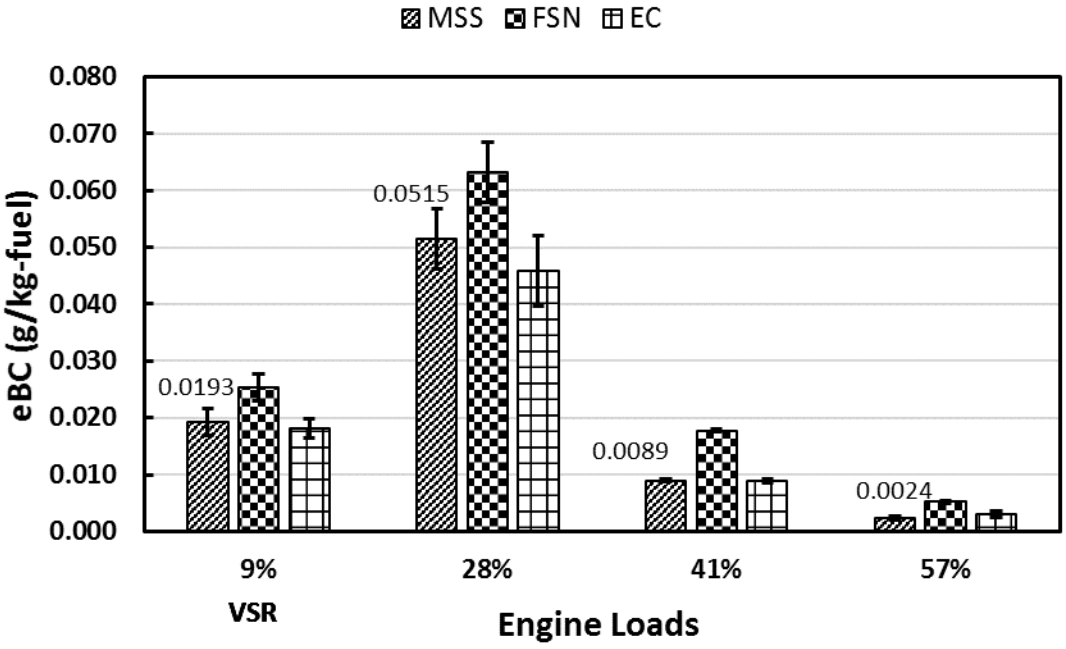


Figure 4-12 BC Emissions for the main engine in g/kg-fuel

The BC emissions were also plotted on a per nautical mile basis to consider the benefit of lower load points and lower vessel speeds. The BC emissions at the 25% load point are significantly higher (3 to 13 times higher) than the VSR and 5% loads, respectively. It is not clear why the engine would show such a high BC emission at the 25% load point. The higher BC emissions could be a result of some engine operation at this point that is not optimized by the engine control system. The VSR mode and 57% load appear to be well controlled modes for this vessel. The significantly higher 25% load point suggests this

load should not be utilized by the vessel. Fortunately, the vessel owner commented that the 25% load point are not utilized except to go between VSR and during regular steaming (57% load).

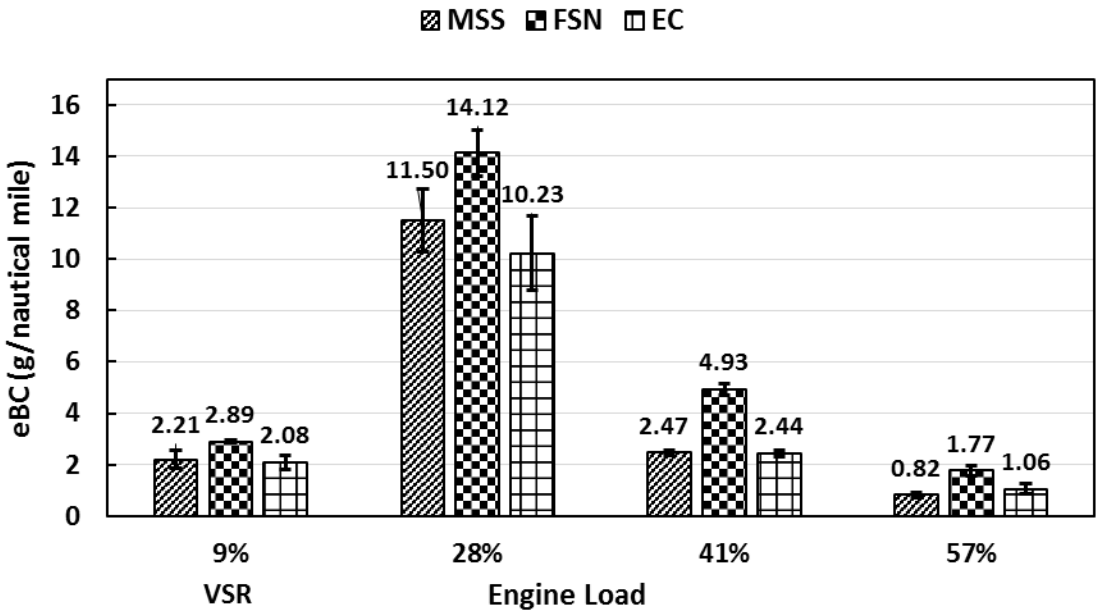


Figure 4-13 BC Emissions for the main engine in g/nautical mile

4.2.4 PM mass speciation

The PM composition results for the main engine test are shown in Figure 4-14 in units of g/kWhr. The EC and OC values were determined via the thermal optical reflectance improve filter method. Overall, there was a decent comparison between the $PM_{2.5}$ and the EC+OC results, indicating that the measurements are consistent, and that the $PM_{2.5}$ is composed of primarily carbonaceous material. The total carbon is dominated by OC emissions for all the test points, with no strong trends as a function of load. EC emissions represented a relatively small percent of the total carbon emissions. The EC results are also consistent with the MSS and FSN results presented above.

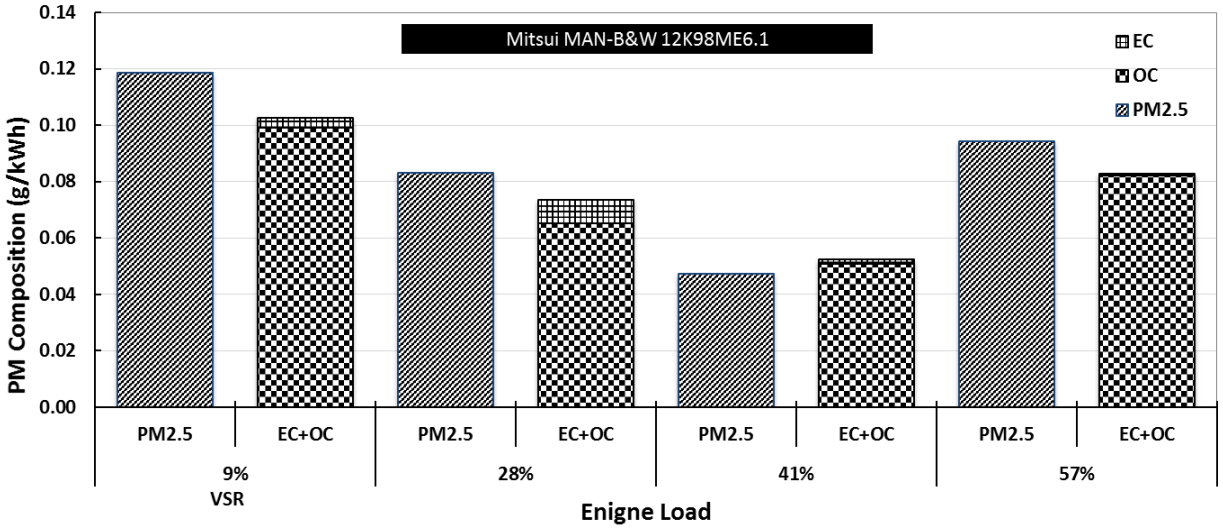


Figure 4-14 PM Composition Results for the main engine in g/kWhr

4.2.5 BC methods correlation

One of the main tasks of this research was to compare the BC emission factors between measurement methods. The three methods considered during at-sea conditions were the PA, FSN, and batch EC methods (see Section 3.1.3 for details). During the Task 1 work, it was shown that calibration can have a significant improvement in the comparison between methods. It was also shown that BC calibration is problematic and difficult to perform since you cannot purchase a reference like with gaseous measurements. The same post-hoc calibration was performed on the Tier 2 BC data and is presented with the non-calibration corrected data for comparisons.

The correlation between the BC measurement systems is presented in Figure 4-15 through Figure 4-17. Figure 4-15 shows the brake specific "as-measured" correlation with the PA method (MSS) as the x-axis reference and Figure 4-16 shows the same correlation, but on a concentration basis (mg/m3). The BC concentration varied from 0.05 mg/m3 to just over 1.5 mg/m3. The engine test stand works showed DMA concentrations up to 50 mg/m3. Given the higher concentrations used during the post-hoc calibration and the daily zeros performed on all the BC instruments, it is recommended to utilize a correlation correction that is forced through zero, see Table 4-10. The post-hoc results presented in this section utilize the calibration corrections when forced through zero.

Table 4-10 Utilized post-hoc calibration coefficients based on test stand work

Instrument	Original		Revised	
	slope	intercept	slope	intercept
FSN	1.133	0.1334	1.138	0
EC	0.7583	0.0279	0.759	0

Figure 4-17 shows the correlation utilizing the post-hoc calibration as determined during the Task 1 test stand work. The as measured correlation showed a good correlation (R^2 of 0.9 or higher) and a slope that varied from 1.2 (FSN) to 0.91 (EC) on a brake specific basis (concentration basis was similar). When the test stand post-hoc calibration was applied the slopes for the FSN and EC methods improved slightly where the FSN slope improved to 1.09 and the EC slope improved to 1.05. The improved correlation from a previous testing campaign suggest BC measurement methods for the PA, FSN, and EC methods

may be robust and instrument dependent where only periodic calibrations are required and not "daily" calibrations. This would be a significant finding to help improve our BC inventory and increase its measurement given the difficulty for daily BC calibration while on a vessel.

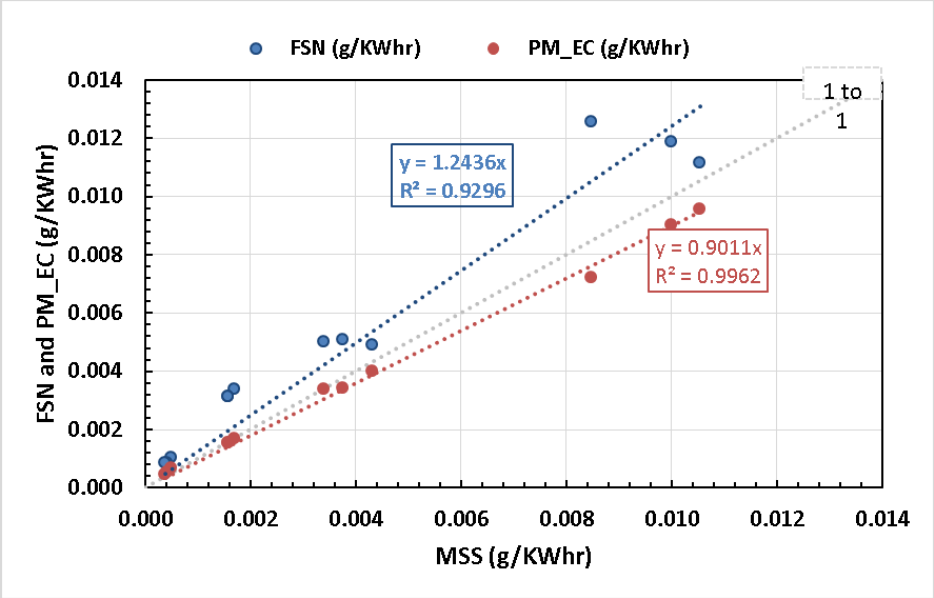


Figure 4-15 Tier 2 BC instrument correlation for all load points (g/kWhr)

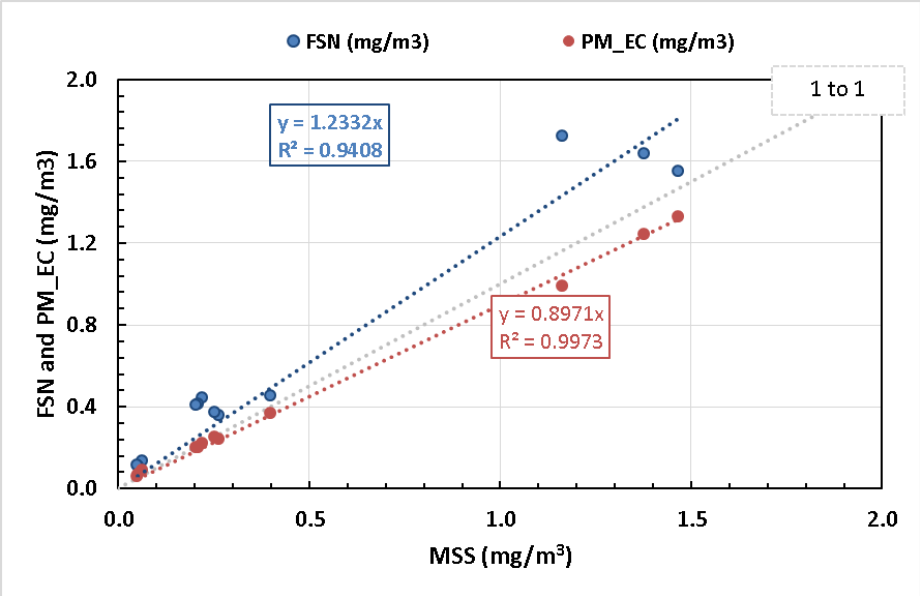


Figure 4-16 Tier 2 BC instrument correlation for all load points (mg/m^3)

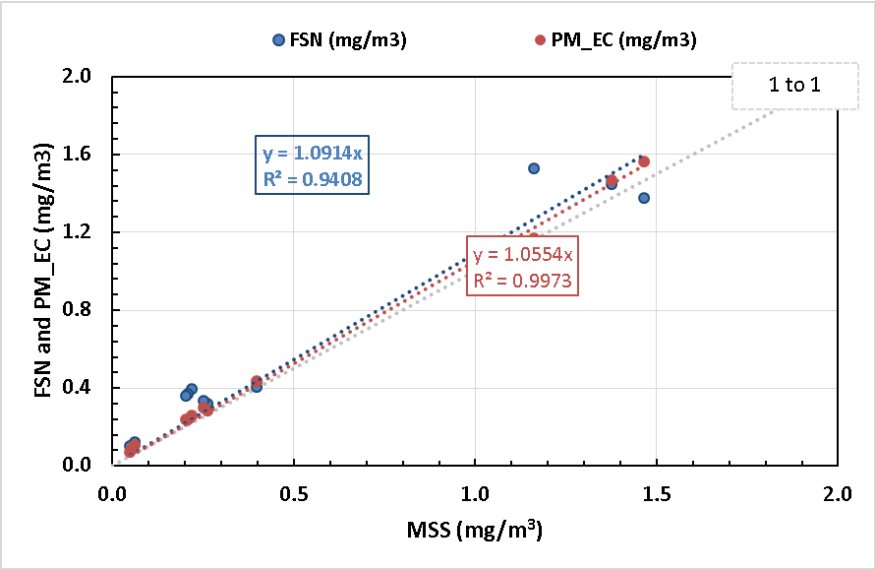


Figure 4-17 Post-hoc corrected Tier 2 BC instrument correlation for all load points (mg/m^3)

5 Task 3 At-Sea: PM Scrubber Control

In addition to the modern engine tested in the previous section, this section considers the on-board testing of PM control systems to study the impacts on BC measurements and emission factors. This task investigates the BC measurement methods for a modern PM scrubber system on high sulfur residual in-use fuels. Both pre- and post- scrubber BC and regulated emissions are measured for this Task.

5.1 Approach

The approach section includes the test article (vessel, engine, maintenance records, and fuels), sampling approach, measurements, and calculations. The test article sections cover details on the specifics of the vessel and any details of importance to the stability of the emission and the validity of the testing. The sampling approach describes the vessel usage, where the samples were collected from the exhaust, the test matrix, and the test protocol. The measurement section describes the measurement methods for the gaseous, PM, and BC methods. The calculations section provides details on the exhaust flow, emission factors, and in-use estimated calculations. It should be noted that many of the methods utilized for the PM scrubber OGV were similar to those utilized for the Tier 2 OGV testing discussed above. These methods are described in similar detail to the approach section provided in section 4.1 for completeness, leading to some redundancy between sections 4.1 and 5.1.

5.1.1 Test article

5.1.1.1 Vessel

The PM scrubber control vessel is a D7 class container vessel built in 1987 that moves up to 1676 TEUs and up to 249 reefers. The summer load line draught is 10.1 meters, the length 216.4 meters, and the breadth is 23.8 meters. The vessels service speed is up to 20.0 knots. The gross tonnage is 20,965. Tank capacity includes: 6,335 m^3 for ballast, 2,550 m^3 for HFO, 581 m^3 for MGO and 430 m^3 for fresh water. The test vessel is equipped with one main engine (ME), four generator engines (GEs), and one boiler. Additionally, the vessel incorporated an exhaust gas control system (EGCS) system to allow the use of HFO fuels while operating in ECA compliant areas since January 1, 2015 under MARPOL Annex VI regulations. The ME and the two larger AEs are connected to the EGCS, but the two smaller AEs and boiler are not connected to the EGCS (see details in Table 5-1 and photo in Figure 5-1). The boiler and AEs running on MGO were not tested.

Table 5-1 Scrubber vessel specifications

MY	*Class*	*TEUs*	*Draught*	*Length*	*Breadth*	*Service Speed*
1987	D7	249	10.1	216.4	23.8	25.6
HFO m^3	***MGO Capc. m^3***	***Ballast***	***Fresh Water***	***ME***	***AEs***	***Boiler***
2550	581	6335	430	1	4	1

Figure 5-1 Ocean going vessel tested for the PM Control task

5.1.1.2 Engine

The ME is a direct drive 1987 MY, Tier 0, Mitsui B&W two-stroke, low-speed, propulsion marine engine rated at 16.6 MW at 98.1 RPMs, see Table 5-3. The ME shop trial was performed on February 12th, 1986 from 50% to 110% of the engine's rated maximum load. This trial showed a BSFC of 167 g/kWh at an 85% load (assuming a net heating value of 10,130 kcal/kg). The two AEs included in the testing were both Wartsila, 6R32D 2.1 MW, medium speed, 4-stroke diesel engines, see Table 5-2 and Table 5-3.

Table 5-2 Specifications of emissions sources on the EGCS equipped OGV [1]

Source	*Engine Mfg.*	*Model*	*Engine Power kW*	*Run Hours*	*EGCS*	*Exhaust Fraction[2]*
ME	Mitsui B&W	7L70	16,578	177,962	yes	93%
AE_1s	Wartsila	6R32D	2,105	70,096	yes	0%
AE_1p	Wartsila	6R32D	2,105	79,020	yes	7%
AE_2s	Wartsila	4R32BC	1.263	63,211	no	n/a
AE_2p	Wartsila	4R32BC	1.263	55,067	no	n/a
Boiler	n/a	n/a	n/a	n/a	no	n/a

[1] Main engine (ME), auxiliary engine 1 (AE_1) and (AE_2).

[2] Exhaust fraction based on test point #1 at-sea conditions, which is representative of the vessels primary operation. AE_s is off and AE_p is on at 50% load.

Table 5-3 Specifications Planned Emission Sources

Source	*Mfg.*	*Model*	*Max Power MW*	*Disp (l)*	*Max RPM*	*Stroke*
ME	Mitsui B&W	7L70	16,578	6110	98	2
AE_1	Wartsila	6R32D	2,105	193	720	4
Source	*Tier*	*Fuel*	*BSFC g/kWhr*	*Injection*	*Max Exh Flow m3/hr*	
ME	0	HFO	195	Conv.	51,000	
AE_1	0	HFO	215	Conv.	6,000	

At the time of UCR's site visit, the ME accumulated hours were 177,962 (Table 5-2) and 70,096 to 79,020 hours for the two AEs (starboard AE_1s and port AE_1p, respectively). The ME recommended cylinder

overhaul interval is 20,000 hours where the current “hours to go” (i.e. hours before the next overhaul interval) for each cylinder ranged from 3,000 hours to 18,400 hours with a relatively similar difference for most cylinders of 2,000 to 4,000 hours. Cylinder #4 was the next scheduled overhaul at 3,000 hours, which equates to about 4 months of continuous use. After an overhaul, some 2-stroke engines utilize greater lubrication during the running-in period where PM emissions are elevated. It is recommended to test the vessel either before the overhaul or at least 500 hours after the overhaul to ensure the PM emissions from the vessel are representative of normal operating conditions.

Similar records of overhaul maintenance intervals were available both the port and starboard AE engines. The next major interval (new injector tips) for the AE engines was more than 4,000 hours. If an engine overhaul is performed for an AE, it is recommended to wait 200 hours for a 4-stroke engine before its emissions are stabilized. In general, the ME and AE maintenance records suggest the PM emissions from the proposed ME and selected AEs are representative of a properly operating OGV and are suitable for testing.

5.1.1.3 EGCS

The vessel is equipped with a new (MY 2015) PM scrubber system that was retrofitted to the engines exhaust pipes, see Figure 5-2. The EGCS is designed to operate with the one ME and two of the vessel’s AEs. The other emissions sources (the two smaller AEs and a boiler) were not designed to be operated with the EGCS. EGCS is designed and outfitted to operate in both the “open loop” and “closed loop” modes such that exhaust gas can be cleaned in any geographical area in which the ship may operate. In the “open loop” mode exhaust gas is cleaned by sea water pumped to the scrubber and then discharged overboard. In the “closed loop” mode, the exhaust gas is cleaned by a fresh water/sodium hydroxide (NaOH) solution that is recirculated through the scrubber.

Figure 5-2 Scrubber installed on the ME and AE engine of the OGV

The ME and AEs can be placed in either by-pass mode or EGCS mode during operation. The EGCS mode includes by-pass valves, a jet section, and an absorber section. The by-pass valves are used to allow engines to either by-pass the EGCS or go through the EGCS. The jet section is employed to accelerate the particles to create more areas of impact for PM removal. The absorber section is used to slow down the

exhaust, collect mist, and remove the remaining particles by gas phase absorption. The absorber section is critical for proper mist removal. If the mist is not removed then the sulfur containing species can exit the stack as hydrated particles and may be collected as PM mass with the gravimetric sampling methods.

The ME and AEs can be operated on either high or low sulfur fuels. For this testing campaign, the ME and AEs were operated on high sulfur fuels with ME and the AEs in EGCS operating mode. The EGCS had accumulated approximately 36 hours of in-service operation at the time of the site inspection and approximately 200 hours at the time of testing.

5.1.1.4 Fuels and lube-oil

Standard commercial marine heavy fuel oil and lubricants were used during testing. For the testing campaign, the vessel was operated in the ECA zone using high sulfur fuels (HFO) and its PM scrubber system. The scrubber is designed to work with sulfur levels up to 3%. One fuel sample was collected during testing, and subsequently submitted to SwRI for analysis of selected properties that included, but was not limited to, sulfur, viscosity, and density.

The vessel that was tested used a Mobilgard 300 for the ME cylinder oil and Mobilgard 560 for the ME system and camshaft oil. Only a ME cylinder oil sample was collected, but this sample was not analyzed because the emission results did not suggest that there was extensive lube-oil exhaust contamination.

5.1.2 Sampling approach

There are three unique combustion sources on most OGVs: an ME, the AEs, and a boiler, see Figure 5-10 for pictorial layout (note the sources do not include the incinerator). The sampling approach included both pre and post scrubber samples to evaluate the performance of the scrubber for gas-phase, PM (mass and composition), and black carbon emissions removal.

The sampling approach section provides a discussion of the selection of sample locations (PM representativeness and accessibility), the load points (achievable and practical), the test matrix (proposed load points to meet objectives), and the test protocol (methods of sampling).

5.1.2.1 Vessel operation

Common operational modes for the vessel include normal at-sea conditions (fully loaded and partially loaded), entering and exiting ports, and in port. Table 5-4 shows typical ME and AE operation for the vessel. While at sea, the ME typically operates at 80-85% load. Higher ME loads are uncommon, but are possible for short durations if requested. While on a voyage, one AE is operated for ship services, hotel facilities, maneuvering, and reefer power. The generator load typically varies from 45% to 65% and depends on the reefer's needs. During port entry and exit maneuvers, the ME power is reduced to 25% to 50% per load while the AE remained at 45%-65% load. While in port (loading and unloading goods), the AE is typically at a load between 45% and 65% (i.e., without shore power) with the ME off and at 0%. Most of the vessels operation is based on at-sea conditions that are estimated to be 90% of the vessel operation, while approximately 1% (or less) is representative of port exit and entry and 9% is representative of dock conditions.

Table 5-4 Expected Vessel EGCS Operation Modes

Activity	HFO/MGO			Est. Time Fraction
	ME	AE_s	AE_p	
At Sea w/ reefers	80-85%	0%	65%	90%
At Sea w/out reefers	80-85%	0%	45%	
Port enter/exit w/ reefers	25-50%	0%	65%	1%
Port enter/exit w/out reefers	25-50%	0%	45%	
At Dock w/ reefers	0%	0%	65%	9%
At Dock w/out reefers	0%	0%	45%	

[1] AE_s and AE_p are the main generators (2MW) and AE_s and AE_p are the auxiliary generators (1.4MW). The scrubber is only utilized by the ME and AE_s and AE_p. There are no VSR requirements for this vessel operation so VSR was not proposed for this testing.

5.1.2.2 Sample locations

The sampling locations are shown in Figure 5-3. The pre-scrubber source samples were collected before the scrubber and economizer for the ME and the post scrubber samples were collected approximately 1 m after the top of the absorber and approximately 0.5 m below the EGCS continuous emissions monitoring system (CEMS). The AEs were also tested, where a third test setup was needed to test the AE emissions prior to the EGCS and before the by-pass valves, as shown in Figure 5-3. For this testing, two sample ports were utilized to accommodate one probe for the gases, PM, and MSS system and the second for the FSN.

Sampling around an economizer is complex 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 prevent the economizer from fouling, 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.

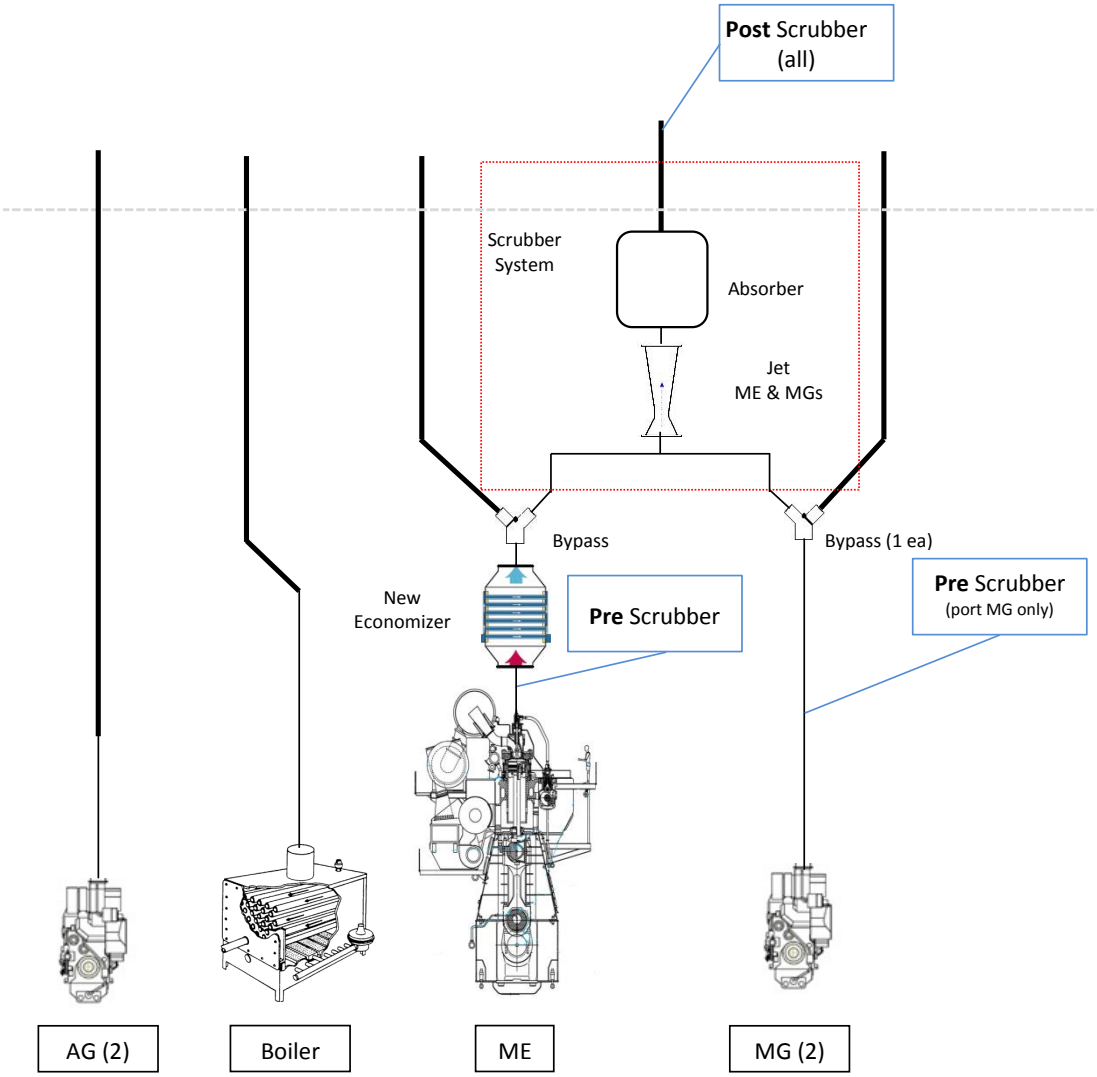


Figure 5-3 Schematic Diagram for the Test OGV Engine Layout

The selection of a sampling location around the economizer is often determined by space constraints and desired measurement practices (e.g. attempting to take samples from straight sections of exhaust pipe). On this vessel, it is difficult to test the exhaust system because there are many tight bends, short distances, and hard to reach areas between the economizer and the scrubber. Due to these and other issues, sampling was done prior to the economizer for the pre-scrubber sample. Thermophoretic loss models and exhaust stack conditions were both taken into consideration in evaluating the impact the economizer has on the PM and black carbon losses, as reported in section 5.2.

The vessel uses a new style, tube type economizer that was replaced as part of the EGCS retrofit. The economizer is a smoke tube type economizer with no procedures for conventional cleaning, but instead uses a continuous cleaning method (unique to most economizers). The design is based on maintaining a high gas velocity through the tubes to prevent soot from accumulating. A real time chemical injection is also used to prevent soot particles from attaching to the tube surfaces. The chemical injection process was disabled during our testing campaign to prevent post scrubber impacts on the overall PM assessment.

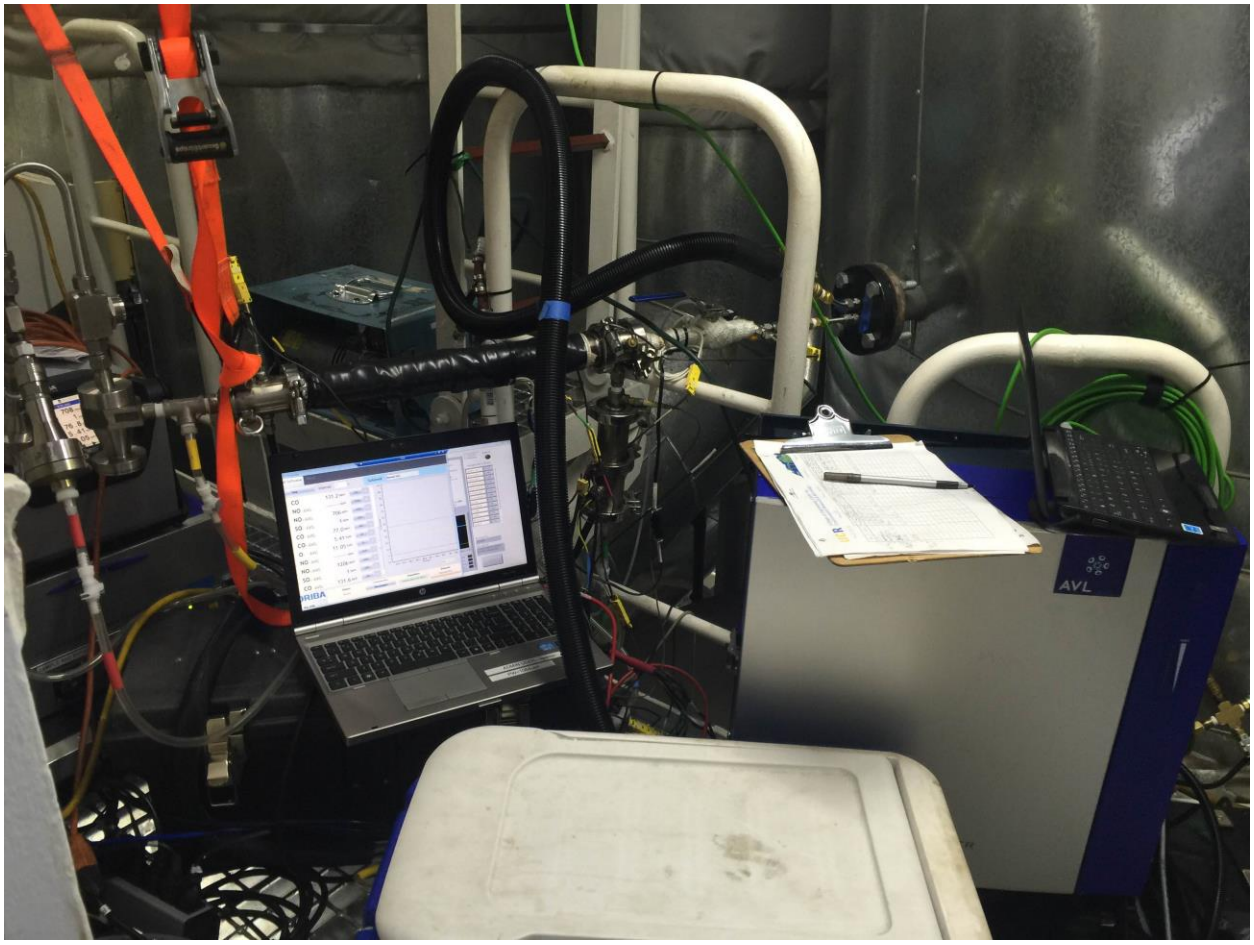


Figure 5-4 Scrubber vessel sample location setup

5.1.2.3 EGCS sampling location

During previous scrubber evaluations, the post scrubber sample location has been problematic due to low exhaust temperatures (20˚C) and high water contents (possibly oversaturated if scrubber mist collection is less than ideal). During these conditions, PM formation mechanisms could be different between pre- and post-EGCS sampling.

According to the scrubber manufacturer (based on personnel communication), the best sample location is 1 to 1.5 meters from the exit of the absorber section. There is a second sample port approximately 3-5 meters after the absorber section, but the exhaust will continue to cool and increase in RH (if not fully saturated) as it moves up the stack. A sample port was located about 1 m after the absorber, while the manufacturer's CEMS are located about 1.5 meters after the absorber. UCR used the 1 meter sample port after the absorber (0.5 meters below the CEMS) to minimize water sulfur interactions during PM sampling. Additionally, UCR heated the dilution air to maintain a filter temperature that was closer to the 47˚C so as to maintain consistency between pre and post scrubber sampling (as recommended by the CFR and ISO).

5.1.2.4 Test matrix

The test matrix subsection covers the engine certification cycles, proposed test modes, the impact these modes had on the EGCS, and the sequence of performing these modes.

Engine certification: The main engine is directly connected to a controllable pitch propeller where engine speed is relatively constant and vessel speed varies. These types of engines are typically certified per the ISO 8178 4 E2 constant speed propulsion cycle (Table 5-5) and constant speed AEs follow the ISO-8178-4 D2 auxiliary cycle (Table 5-6) (see Appendix C for more details). The maximum achievable load may be less than 100% and can depend 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.

Table 5-5 Test Cycle for Main Engine Constant Speed (Variable Prop)

Main engine testing (ISO 8178-E2)				
Mode	1	2	3	4
Speed (%)	Rated RPM			
Torque (%)	100	75	50	25
Weight Factor	20%	50%	15%	15%

Table 5-6 Test Cycle for Constant-Speed Generator Engines

Generator engine testing (ISO 8178-D2)					
Mode	1	2	3	4	5
Speed (%)	Rated RPM				
Torque (%)	100	75	50	25	10[1]
Weight Factor	5%	25%	30%	30%	10%

[1]Vessel speed reduction (VSR) is also of interest to EPA and typically represents a 5th mode at around 10% load and 50% speed. The KOKIAK does not operate in areas that utilize VSR, thus, the 10% point is not recommended.

The matrix of test points tested on the voyage is provided in Table 5-5Table 5-7. This included testing the ME at a 0, 50, 75%, and maximum load and the AE at 0% and 50% load. Efforts were made in consulting with the Master and Chief to target loads as close as possible to those in Table 5-5. Although slight deviations from the target loads may have occurred, due the constraints of the in-use ship operations, overall, the actual loads were found to be very representative of the target loads.

EGCS max flow: The sample points shown in Table 5-7 covered almost the full range of the scrubber exhaust flow design. An 85% ME load and 50% AE load, typical of at-sea operation, represents 90% of the total ECGS scrubber exhaust flow design. A 0% ME load and 50% AE load, typical of at dock operation without shore power, represents 5-10% of its design capacity, where the intermediate points cover the range in-between. The EGCS testing evaluated from 90% to 10% of its exhaust flow range.

EGCS control: The EGCS is designed for open loop (OL) and closed loop (CL) modes. The OL mode is used while the vessel is at-sea and the ocean provides the alkalinity for proper scrubber performance. During port conditions, the alkalinity needs to be controlled with the CL mode. During testing the OL vs CL mode was evaluated with a test on Day 4, see Table 5-7. The results from the OL vs CL test are provided in the Appendix E under Task 3 and did not appear to be statistically different.

Sequence of events: Due to the various pre- and post- scrubber sample locations, several setups were needed. Table 5-7 shows the sequence of events in moving between different sampling locations. Overall, it took four days to do the work, with each setup taking approximately 6 to 8 hours, so moves were minimized by focusing on the three proposed setups, AE_s pre-scrubber, ME pre-scrubber, and ME & AE_s post-scrubber. We started testing in Tacoma on the AE_p (deck 3) prior to leaving the dock. Next we moved to the ME pre-scrubber location on deck 2 and tested the pre-scrubber on one day and the

post-scrubber (moved to deck 5) on the second day. Then we tested the final point for the AE_p (deck 5) in Anchorage, AK with the ME off. Testing on different days will not inherently impact the emission factors of the vessel as long as the loads can be similarly maintained. During testing the ME loads were similar from test to test, but the AE varied from port to at-sea as discussed in the Calculations section.

Table 5-7 Proposed Test Sequence

Day	Location	Special Notes [3]	Deck	Source	Scrubber	Mode	ME Load	AE Load
1	dock [1]	-	3	AE	Pre	4	0%	50%
2	at-sea	-	2	ME	Pre	3	50%	50%
2	at-sea	-	2	ME	Pre	2	75%	50%
2	at-sea	**High DR**	2	ME	Pre	2	75%	50%
2	at-sea	-	2	ME	Pre	1	92%	50%
3	at-sea	-	5	ME+AE	Post	1	92%	50%
3	at-sea	-	5	ME+AE	Post	2	75%	50%
3	at-sea	**High DR**	5	ME+AE	Post	2	75%	50%
3	at-sea	-	5	ME+AE	Post	3	50%	50%
3	at-sea	**No AE**	5	**ME-only**	Post	1	92%	50%
4	at-sea	**CL Mode**	5	ME+AE	Post	2	75%	50%
5	dock [2]	-	5	AE	Post	4	0%	50%

[1] Testing of the pre-scrubber AE occurred in Tacoma, WA [2] Testing of the post-scrubber AE occurred in Anchorage, AK [3] The scrubber was operated in open loop (OL) mode (during at-sea conditions) as designed and closed loop (CL) mode at the ports (as designed).

Dilution ratio: Other PM scrubber evaluations have sampled at high dilution ratios (~20) as allowed by ISO 8178 methods. EPA 1065 recommendations are to target 6:1 at your maximum load point. During this testing the dilution ratio was targeted at 6:1 following the EPA recommendations as specified in Appendix A. To consider the impact of dilution ratio, Mode 2 was performed at two DR one was 20:1 and the other was 8:1 to consider the impact of DF, see Table 5-7. In general, the DR results did not show any significant change in emission factors for any species, see details in Appendix E under Task 3.

5.1.2.5 Test protocol

When following the ISO cycles, the engine was operated for about 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 (ie mode 1, 1, 1 change load, mode 2, 2, 2 change load, etc.…). Based on experience in 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 and no longer than 30 minutes (such that approximately 500µg of filter mass is collected at a minimum dilution ratio of 4:1).
- 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.
- Calculate emission factors from the measured pollutant concentration data and calculated mass flow rates.

5.1.3 Measurements

This section discusses the data collection and measurement approaches for emissions, engine performance, and BC. The emissions were measured by equipment provided by UCR. The engine related performance information was recorded by UCR staff from vessel screen shots, hand logs, and electronic records provided by the vessel crew.

5.1.3.1 Gaseous and PM emissions

Best recommended practices for OGV exhaust gas measurements follow the federal regulations (40 CFR Part 1065) for PM measurements with specific details following ISO 8178-1 for dilution and exhaust gas sampling. More details are available in Appendix A.

Gaseous: The PM emission measurements used a partial dilution system that was developed based on the ISO 8178-1 protocol (detailed information is provided in Appendix A). The concentrations of gases in the raw exhaust and the dilution tunnel were measured using a Horiba PG-350 portable multi-gas analyzer. The PG-350 can simultaneously measure up to five separate gas components. Major features of the PG-350 include a built-in sample conditioning system with sample pumps, 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 record measured values continuously. Emissions for CO, CO_2, NO_x, and SO_2 gases were measured from the raw exhaust gases (O_2 was also measured), see Table 5-8.

PM: Total PM mass ($PM_{2.5}$) was measured from the diluted exhaust gas as per 40 CFR Part 1065 recommended practices which utilizes Teflon filters weighed offline and after conditioning. During previous scrubber testing UCR dilution and filter temperature control was found to be inadequate. Updates were performed to control dilution ratio and filter face temperature as shown in the revised schematic in Figure 5-4. In addition to measuring criteria emissions, the project measured EC and OC fractions of the PM composition, and sulfate PM. For further qualitative assurance, UCR used a continuous PM monitor (TSI DustTrak 8520) to ensure that the PM concentrations were stabilized while the filters were collecting samples.

PM sampling with EGCS: EGCS utilized cold sea water to scrub out PM from exhaust stacks which reduces the exhaust temperature and impacts the PM formation mechanism (as part of the EGCS design). Due to low EGCS exhaust gas exit temperatures (~20˚C vs 300˚C without an EGCS), sample heating was needed to maintain a filter face temperature ~47˚C, which is above the saturation point of water (as discussed in Section 5.1.2.3). Consistent filter face temperatures have been shown to improve PM sampling and are recommended by the 40 CFR Part 1065 and are optional (but still better) as per ISO 8178. For the EGCS evaluation, UCR maintained a filter face temperature of within 10˚C between pre- and post- scrubber testing setups.

PM updated approach: UCR has implemented active dilution air and sample heating on all samples collected for EGCS equipped vessels, see details in Figure 5-4. The heating section was utilized for all samples both pre and post scrubber in order to maintain similar PM losses in the PM collection system. The design of the system has around 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. During pre-EGCS sampling, the active heating section may be operated at a lower temperature to prevent over heating the PM filter during sustained high load conditions, as pre-EGCS exhaust temperatures are high.

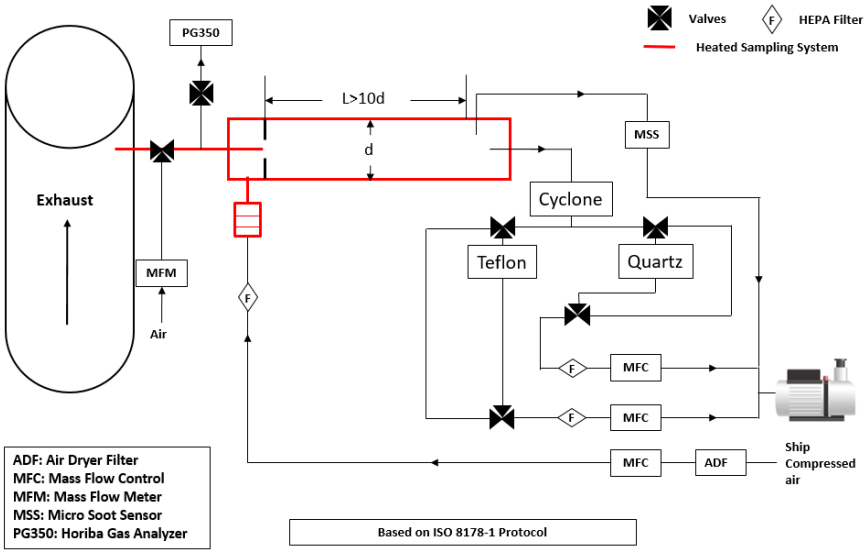


Figure 5-4 Schematic of the Dilution Sampling System

Table 5-8 Summary of Emissions Measured by UCR

Species Sampled			
NDIR CO	NDIR CO_2	CLD NO_x	-
NDIR SO_2	Total **$PM_{2.5}$** Gravimetric method	PM **EC/OC** by NIOSH method	PM **Sulfate** Reported as H_2SO_4*6.65H_2O
Photoacoustic Soot	Thermal optical Elemental Carbon	Light absorption Filter Smoke Number	

Because the fuel is a low sulfur fuel sulfate PM is not recommended as the measurements will be insignificant for sulfur levels of 100 ppm and lower (as will be verified by the fuel analysis and C-of-A bunker reports).

5.1.3.2 Black carbon emissions

BC measurements were made with three measurement methods. These are the AVL 483 MSS Photoacoustic, the thermal optical EC NIOSH filter, and the AVL Smoke Meter 415 SE light absorption methods. These methods were selected based on their performance during the engine test stand work.

During the test stand research, the EC, MSS, and LII measurements showed the best agreement (± 10%) after the post calibration for measurements made without sample conditioning. With sample conditioning (CS and SO_2 adsorption) the FSN also agreed well with the top three BC measurement approaches. Given the FSN's wide use in industry for OGV engine developers and the MSS close agreement and historical usage at UCR, UCR recommended incorporating the MSS, EC, and FSN measurement methods for the OGV testing. The LII also performed well, but it was not selected for the OGV testing due to logistical issues in acquiring this instrument and the added personnel that would have been needed to operate it where space is limited for staff and instruments.

The selected BC instruments and reported BC measurements are based on the definition of EC for the EC method and eBC for the MSS and FSN methods.

5.1.3.3 Engine

Chapter 6 of the NO_x Technical Code "Procedures for demonstrating compliance with NO_x emission limits on board,"[2] 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 5-9. The records vary depending on available information for the ME and MG.

Table 5-9: Engine Parameters Measured and Recorded [1]

Parameter	Units
Load	kW
Vessel speed	knots
Engine Speed	RPM
Generator Output [2]	amps, volts, kW, PF (where avail.)
Fuel consumption	kg/hr
Brake specific fuel consumption	kg/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.

[2] Alternator efficiency is estimated from previous OGV alternator reports (actual mfg. values are used when available).

5.1.3.4 EGCS

The EGCS had several operating screens that were captured during testing of the vessel. The reported values included a SO_2:CO_2 ratio, exhaust temperatures, exhaust pressures, and water pH.

5.1.4 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, time specific, and fuel specific emission factors are also provided.

5.1.4.1 Exhaust Flow Rate

Since the analytical instruments measure the concentration in the exhaust, it is essential to have an accurate measure of the exhaust mass flow in order to calculate emission rates and factors. UCR has calculated the exhaust flow rate from the reported displacement volume of the diesel engine cylinder and from the following measured values: engine rpm, intake temperature, and intake manifold air

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

pressure. This ISO 8178 approved "air pump" method has been used in combination with possible fuel consumption carbon balance comparisons, and possible on-vessel bsFC comparisons.

5.1.4.2 Emission Factors

Emission factors were calculated at each mode from: the measured gaseous and $PM_{2.5}$ concentrations, the reported engine load in horsepower (hp or kW) and the calculated mass flow in the exhaust. An overall single emission factor representing the engine has been determined by weighting the modal data according to the ISO 8178 E3, E2 and the weighting fractions of the equation below. The equation used for the overall emission factor is as follows:

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

Where:

A_{WM} = Weighted mass emission level (CO, CO_2, $PM_{2.5}$, BC, SO2 and NO_x) (g/kWhr)
g_i = Mass flow in grams per hour (g/hr)
P_i = Power measured during each mode (kW)
WF_i = Effective weighing factor.

Since the vessel was operated with a combination of the ME and AE engines into a single EGCS system, the ISO weighted emission factors were adjusted to match the loads utilized. Table 5-10 shows the suggested weighting factors. These weighing factors were used for the overall performance of the EGCS system.

Table 5-10 Suggested weighting factors for the EGCS system

ISO 8178 E2		Measured			Suggested
Load	Factor	ME Load	AE Load	Combined	Factor
100	0.20	92.1%	56.8%	86.6%	0.22
75	0.50	75.5%	56.0%	74.6%	0.52
50	0.15	50.1%	56.3%	49.8%	0.21
25	0.15	0.0%	45.7%	5.2%	0.05

5.1.4.3 EGCS efficiency calculations

The scrubber was installed on both the ME and AE engines where there was not a sample port available for the combined mixture prior to the PM scrubber system. As such, the pre scrubber emission factors were based on separate AE and ME measurements where the post scrubber results were based on the combination of the ME and the AE engines. In order to compute the scrubber efficiency the pre-scrubber test results need to be combined to provide a complete estimate of the scrubber performance. The equation below shows how the scrubber efficiency was calculated for each of the species.

$$A_{WMi} = \frac{C_{AE} * Q_{AE} + C_{MEi} * Q_{MEi}}{P_{AE} + P_{MEi}}$$

Where:

A_{WMi} = Mass emission level for Mode "i" where (CO, CO_2, $PM_{2.5}$, BC, SO2, and NO_x) in g/kWHr
i = mode number where mode 1 (i =1) is the maximum load mode and mode 3 is i = 3
C_{AE} = Concentration of the species for the AE
Q_{AE} = Exhaust flow for the AE at 50% nominal load

C_{ME} = Concentration of the species for the ME
C_{MEi} = Exhaust flow for the ME at Mode 1, 2, 3 (mode 4 is ME = 0)
P_{AE} = Power measured during each mode for the AE
P_{MEi} = Power measured during the "i" mode for the ME

5.1.4.4 Aux engine load variability

The testing of the scrubber was performed in separate segments in order to complete the work in one route where the refer loads would be most consistent. To do this the AE was sampled while at the departing port and the ME and post scrubber tests were performed at sea. Then the final AE only test post scrubber was sampled with the ME off which had to be at the destination port.

It turns out the departing and destination ports showed lower AE engine loads as compared to the at-sea AE engine load. The AE load at the departing port was 29.4% of MCR and at sea it was 56.3% of MCR (45.7% of MCR at the destination port). Since the AE exhaust flow and power are about 1/10th of the ME the AE difference in load should have a minor impact on emission factors of most species expect for PM and BC. The AE PM and BC was approximately 10 times more BC so care had to be considered. This section describes the impact and possible uncertainty for the reported values due to the lower pre scrubber engine load. In summary it is expected the engine load will have a minor (< 10%) impact on the overall results.

The engine load varied from pre scrubber (pre-meas) to post scrubber (post-meas) values from 29.4% to 45.7%, see Figure 5-5. Even the "at-sea" AE engine load was higher than both port AE engine loads and averaged 56.3%. Because the AE could not be measured without the ME post scrubber we estimated AE emissions by running a mode with the AE on and off then looking at the difference in the mass emissions. The post-est bar shown in the figure is this estimated AE post scrubber point. As you can see the load was higher for the AE while at sea. The impact this has on the EF can be seen by looking at Figure 5-5 through Figure 5-8. It is unclear how much of an impact this will have on the overall scrubber efficiency, but it is expected to be small as shown in Appendix E Section Task 3 data logs.

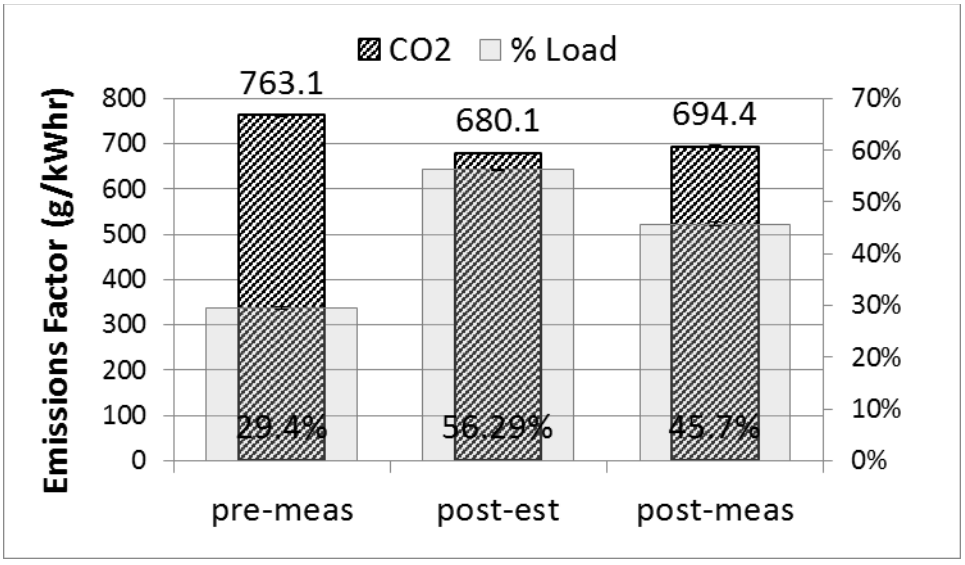


Figure 5-5 bsCO2 emission factors for the AE with estimated post scrubber results

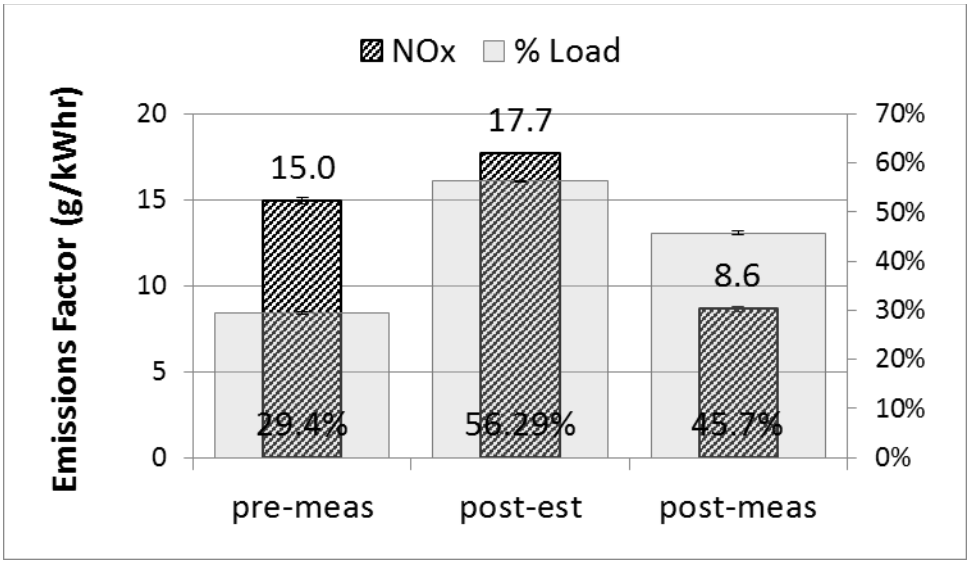


Figure 5-6 bsNOx emission factors for the AE with estimated post scrubber results

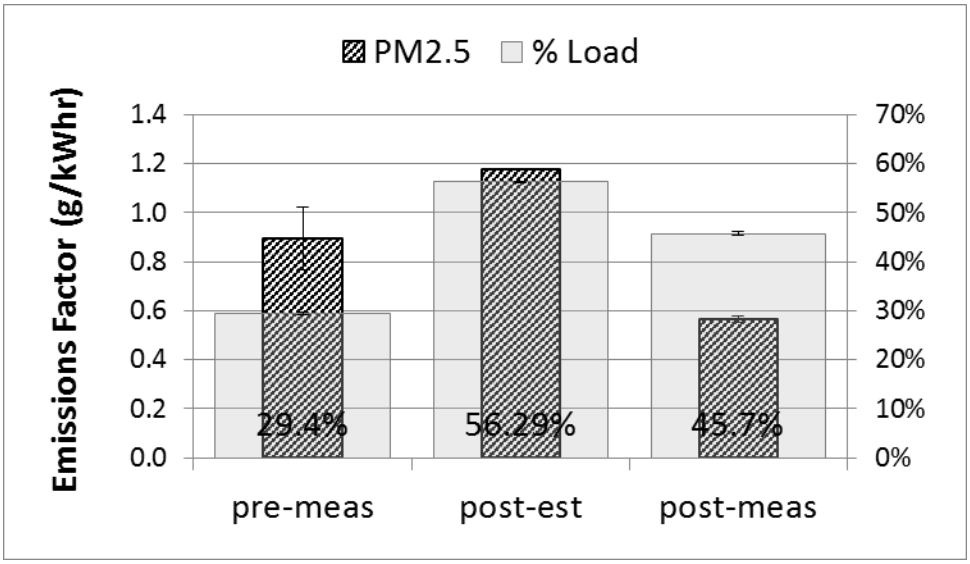


Figure 5-7 bsPM emission factors for the AE with estimated post scrubber results

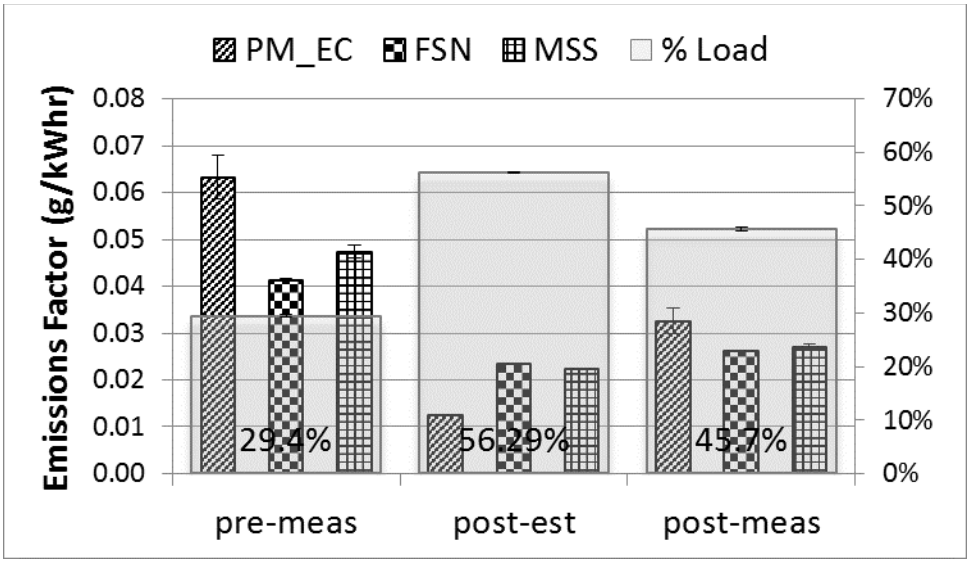


Figure 5-8 bsBC emission factors for the AE with estimated post scrubber results

5.2 Results

The results for the scrubber system are described in this section. Because the scrubber was designed for both the AEs and ME sources, the analysis considers the combined results from the engines. As such the loads on the x-axis represent EGCS loads or the sum of the two engines (AE + ME). For example the 4% load represents the ME at 0% and the AE at 50% load and Mode 1 is with the ME at 92% load and the AE at 50% load for a combined 85% EGCS load. This approach allows for an evaluation of the EF for the vessel as a whole.

Figure 5-10 shows the real time NO_x, CO_2, and MSS soot concentrations for the pre-scrubber testing portion of this project. The emissions were stable for all load points on all test days (the graph is of testing on a single day), see Appendix E Task 3 for details. In general the emissions from the vessel were stable and the results in this report are representative of a properly operating vessel and scrubber system.

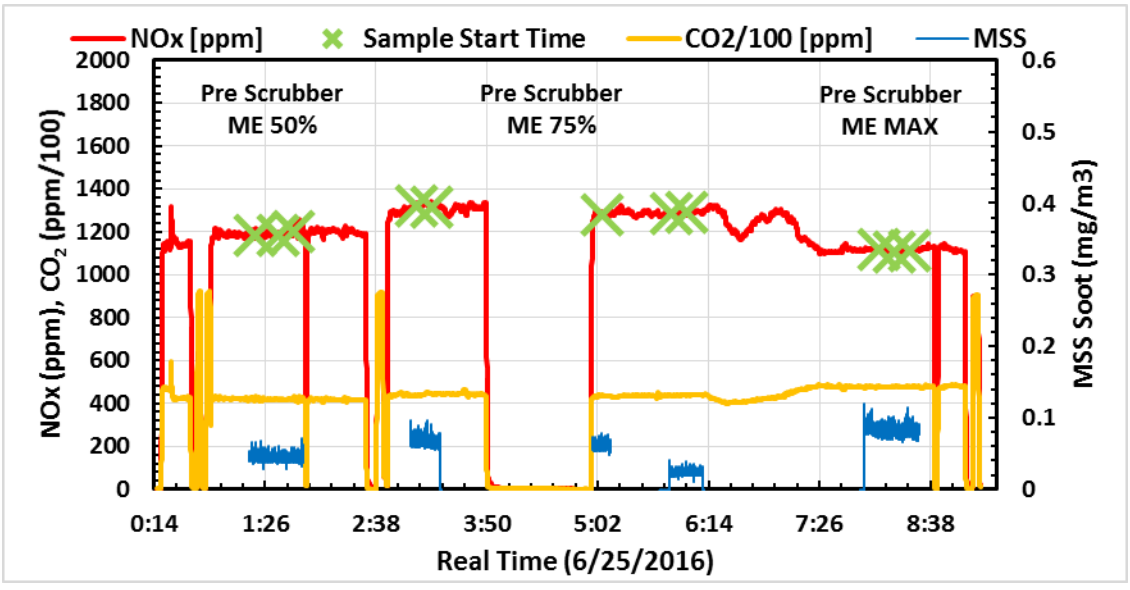


Figure 5-9 Real time response for selected emissions species with test notes

5.2.1 Gaseous

The NOx emissions before and after EGCS are shown in Figure 5-10 in units of g/kWhr. The results show four test points representing load points comparable to those used in the ISO 8178-E3 test (ME 50%, 75%, and near 100%) and one extra load for the AE (50% load). The target percentage for operating the auxiliary engine, which also feeds into the EGCS, was set at 50% for all tests, as shown in Table 5-7, but the end results ended up being percentages of loads varying from 29% to 56%. There is a short discussion here and a more detailed discussion in Section 5.1.4 on the impact the low AE load might have on the EF from the scrubber.

In general the Tier 0 engine NOx emissions ranged from about 14 to 17 g/kWh (ME) and down to 8.6 g/kWh (AE only) over the different load points. These results are comparable to the engine tests in Task 1 (except for the AE results) and are comparable to the certification values for a Tier 1 engine. Interestingly, the ME NOx emissions at each load contrast with typical results that show a declining trend with increasing load for marine engines. Part of this could be the fact that the emissions factors include both the ME and AE exhaust streams. In general the results show repeatability at each of the load points, indicating consistency in the testing, with slightly larger bars of error for the 48% load point pre-EGCS test.

The AE engine showed a large variation in load over the course of testing and varied from 29.4% of MCR at the port to 56.3% of MCR at-sea. The large difference in the AE engine load could be the cause for the change in NOx emissions shown in Figure 5-10. In general, the EGCS is not expected to have a big impact on NOx emissions, and is not likely the cause for the increased NOx emissions. As such, the differences in ME NOx emissions for the pre- and post-EGCS tests are likely a function of the load differences, reproducibility of the test between different days, and different points in the vessel's operation along the trip. More discussion is presented in the Calculation section to expand on this discussion.

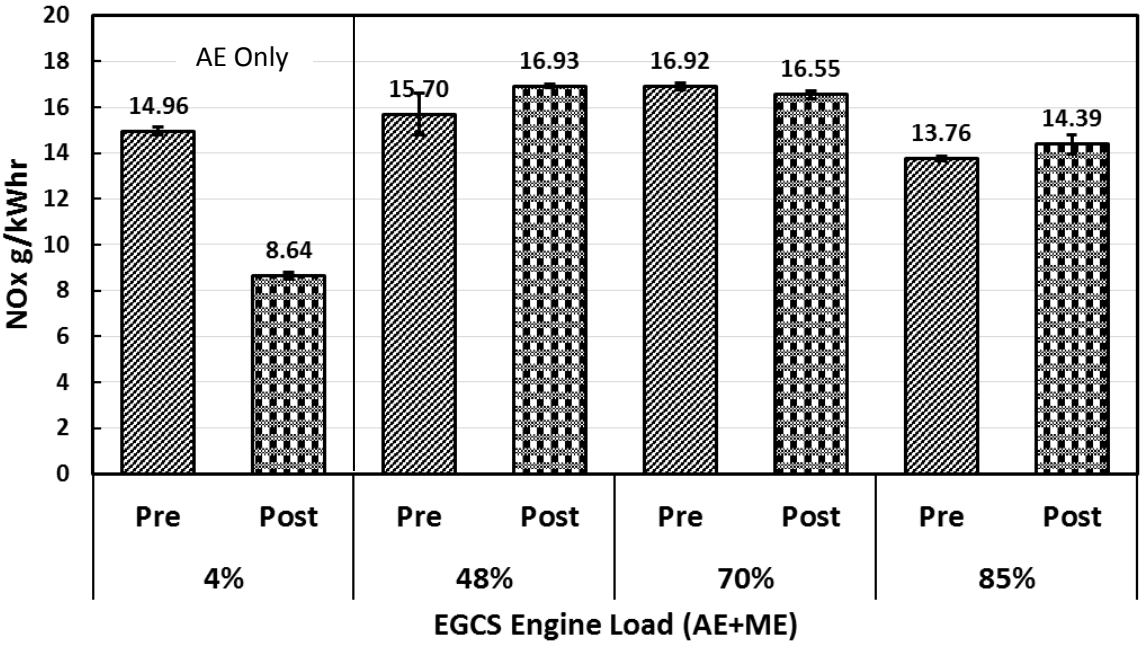


Figure 5-10 NOx Emissions for the Pre- and Post-EGCS Tests in g/kWhr

The CO emission results for the pre- and post-EGCS tests are shown in Figure 5-11 in units of g/kWhr. CO emissions were relatively constant as a function of load, with test points in the range of 0.2 to 0.3 g/kWhr. The CO emissions are comparable to those found from other testing campaigns. The post-EGCS test results did not statistically show significant reductions in CO emissions compared to the pre-EGCS tests, suggesting the EGCS does not provide any reductions in CO emissions. Again the large difference for the AE on the 4% load point is a result of the load differences and not of a scrubber reduction benefit. See discussion in the Calculation Section 5.1.4

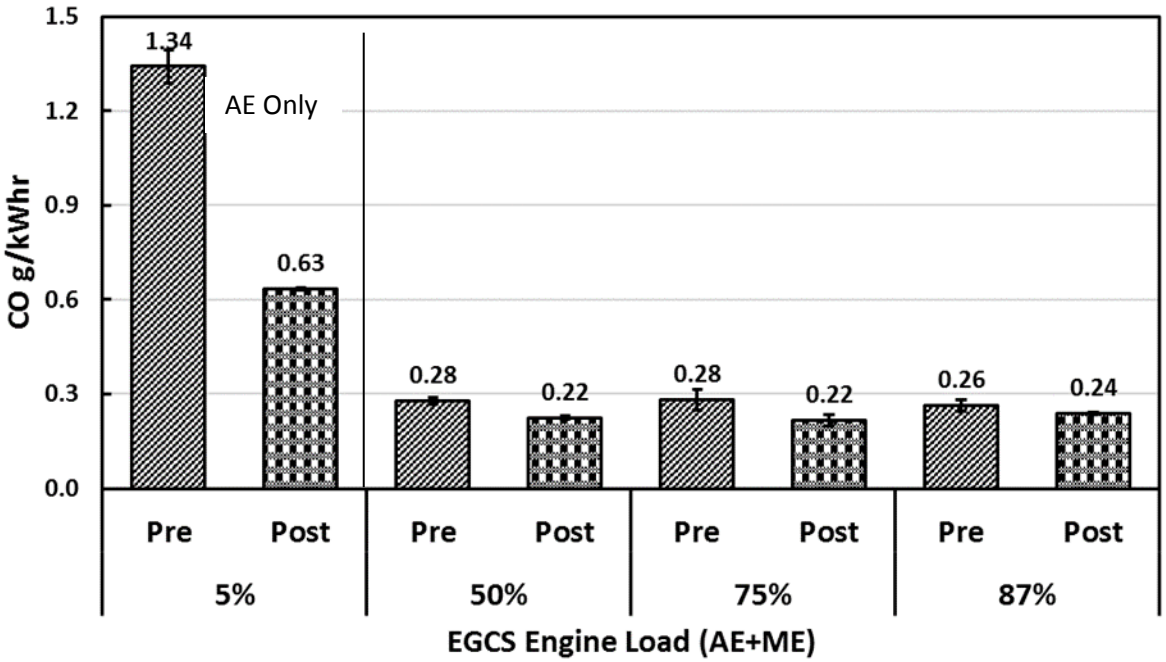


Figure 5-11 CO Emissions for the Pre- and Post-EGCS Tests in g/kWhr

The CO_2 emissions results for the pre- and post-EGCS tests are shown in Figure 5-12 in units of g/kWhr. CO_2 emissions were about 600 g/kWh for all the different load points, except for the AE where the bsCO2 ranged from 763 to 694 g/kWHr. The CO_2 emissions were comparable to those for other ME and AE engine tested at-sea and on an engine stand at the different load points. The results show a flat trend of emissions as a function of load (ME), in contrast to the typical declining trend with increasing load of marine engines. The AEs have a higher bsCO2 emissions compared to the ME due to lower combustion efficiencies for the smaller displacment engines and differences between 4-stroke and 2-stroke designs. The results show repeatability at each of the load points, indicating consistency in the testing. The post-EGCS test results are comparable to or higher than the results for the pre-EGCS tests. Again, the EGCS is not expected to have a big impact on CO_2 emissions, so the differences in CO_2 emissions for the pre- and post-EGCS tests are likely a function of the reproducibility of the test between different days and different points in the vessel's operation along the trip.

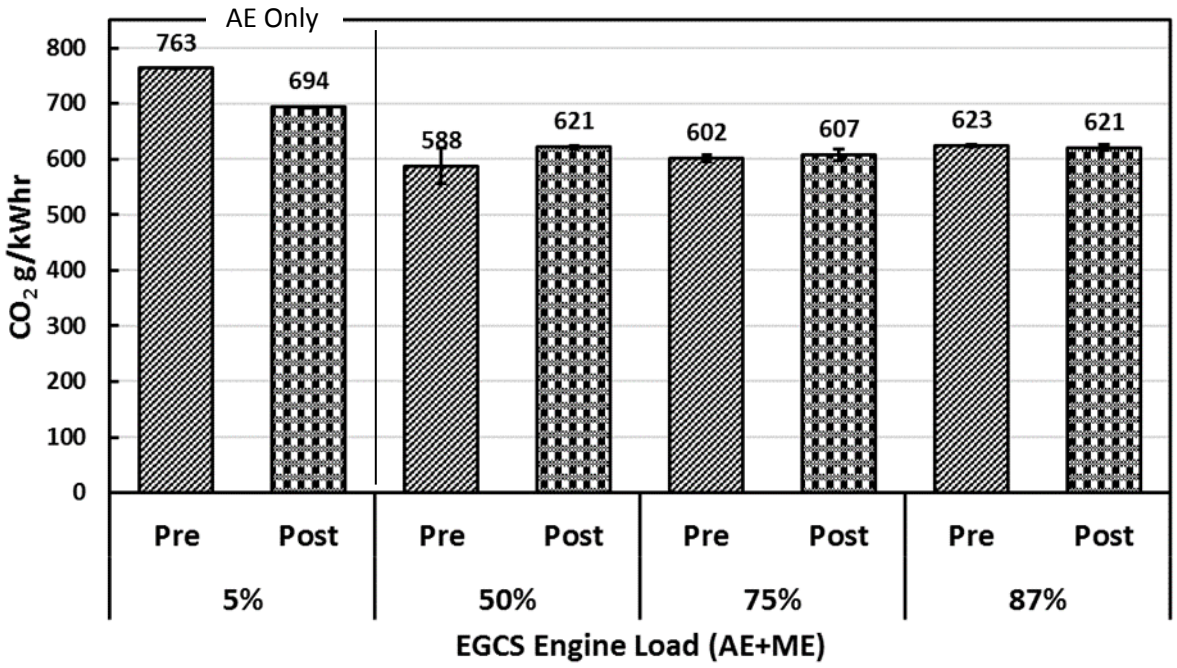


Figure 5-12 CO_2 Emissions for the Pre- and Post-EGCS Tests in g/kWhr

The SO_2 emission results for the pre- and post-EGCS tests are shown in Figure 5-13 in units of g/kWhr. Pre-EGCS SO_2 emissions were relatively constant at approximately 3.82 to 4.5 g/kWh for the different ME test points and up to 6.61 for the AE engine, with a slight reduction in SO_2 emissions as a function of increasing load. The results indicate consistency in the testing. Note that the pre-EGCS SO_2 values are higher than those seen for the Tier 2 vessel described in section 4. This can be attributed to the higher sulfur fuel used for this test, as opposed to the Tier 2 vessel. The post-EGCS results show that the EGCS provides significant reductions in SO_2 emissions on the order of 96.7 to 98.4 percent. The reduction efficiency is sufficient enough to meet fuel sulfure requirments for scrubber systems. With this reduction efficiency, the SO_2 levels are brought down to levels of 0.10 to 0.13 g/kWhr, which is comparable to or lower than those found for the Tier 2 vessel operating on the lower sulfur fuel.

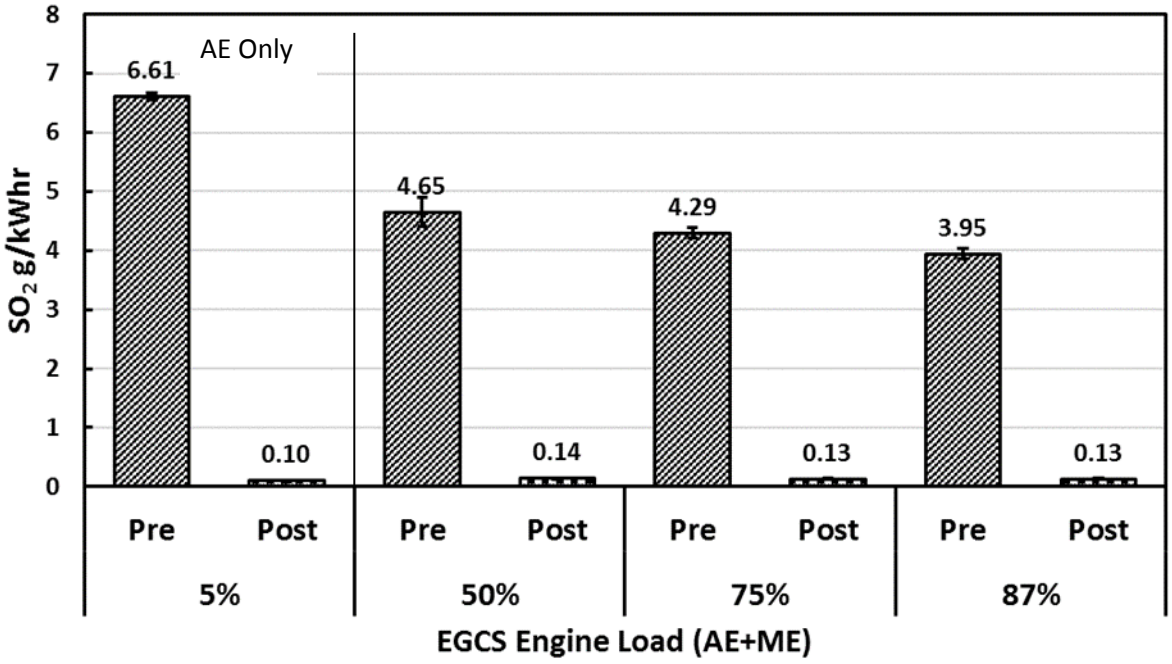


Figure 5-13 SO_2 Emissions for the Pre- and Post-EGCS Tests in g/kWhr

5.2.2 PM2.5 and Composition

The $PM_{2.5}$ mass emissions and PM composition results for the pre- and post-EGCS tests are shown in Figure 5-14 in units of g/kWhr. The EC and OC values were determined via the thermal optical reflectance IMPROVE filter method, while the sulfate emissions were determined via ion chromatography. $PM_{2.5}$ emissions ranged from about 0.9 to 1.4 g/kWhr. The $PM_{2.5}$ emissions did not show a strong trend with respect to load. The PM composition results show that the PM is predominantly composed of sulfate, with smaller contributions from OC PM, and very small contributions from EC PM. The post-EGCS test results are comparable to the results for the pre-EGCS tests, with the exception of the 75% load point. This is seen for both the Total PM2.5 mass as well as the PM composition results. The ISO weighted sulfate PM pre scrubber emissions were 0.935 g/kWh and the post-scrubber sufate PM emissions were 0.888 g/kWh (a 5% ISO weighted PM reduction). The differences in $PM_{2.5}$ emissions for the pre- and post-EGCS tests are likely a function of the reproducibility of the test between different days and different points in the vessel's operation along the trip.

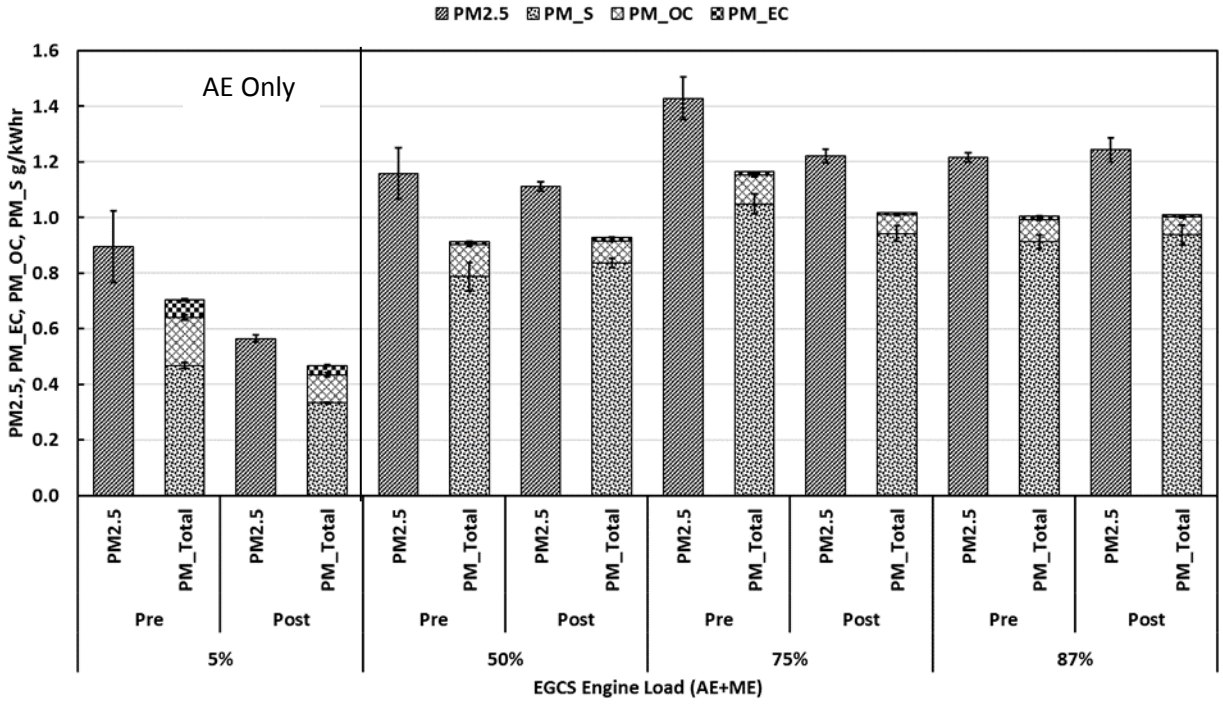


Figure 5-14 $PM_{2.5}$ Emissions for the Pre- and Post-EGCS Tests in g/kWhr

5.2.3 BC

The BC emissions results for the pre- and post-EGCS tests are shown in Figure 5-15 in units of g/kWh for the MSS (eBC), EC, and FSN (eBC) measurements. The results show that BC emissions ranged from 0.003 to 0.009 g/kWh over the different loads and pre- and post-EGCS for the ME and up to 0.063 g/kWh for the AE. This is consistent with the speciation results from section 5.2.2, which showed that EC determined via the thermal optical reflectance IMPROVE filter method represented only a very small fraction of the overall PM mass. The FSN EC values were consistently higher than those for the MSS. This is consistent with the results from the laboratory marine engine testing in section 3. Although the FSN and MSS values show differences between the pre- and post-EGCS measurements, these differences are probably due more to test reproducibility, as opposed to changes in BC concentration that occur as a result of the EGCS.

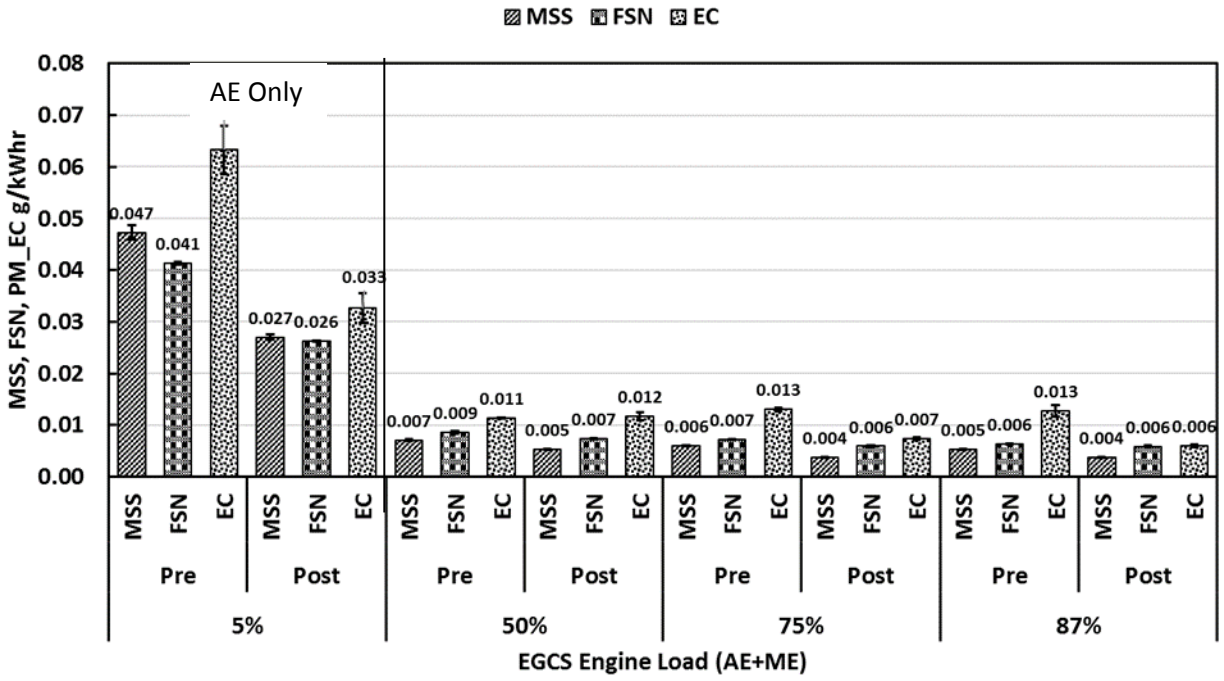


Figure 5-15 BC (MSS and FSN) emissions for the Pre- and Post-EGCS Tests in g/kWhr

5.2.4 Scrubber efficiency

The scrubber efficiency for the regulated and selected PM composition species are provided in Table 5-11 with a sulfur analysis (g/kWh) presented in Figure 5-16. The largest percent reduction is for the gaseous SO_2 emissions as would be expected since scrubbers are designed for > 95% reduction is SO_2 emissions. The particle phase sulfur emissions varied from -6% to a 28.8% reduction (i.e. an increase in sulfate PM). This was also found when testing other OGV equipped with scrubber systems. If the total particle phase sulfur and gaseous phase sulfur species are combined the overall percent reduction ranges from 77% to 93% where the percent reduction decreases with increasing load. The trend of decreasing sulfur (particle + gas) emissions with increasing load suggest a design constraint within the scrubber system may be the cause.

The organic PM reductions were fairly large and ranged from 41% to 13% with an ISO weighted reduction of 28%. The organic PM appears to be lower at higher loads and higher at lower loads which may be the result of lower residence times at higher load. The slight difference in CO2 is not necessarily due to the scrubber, but due to load and repeatability as suggested previously.

Table 5-11 Regulated and selected PM scrubber efficiency results (with AE)

Mode	DR	Exh Flow	Engine Load		Total Percent Reduction from baseline (pre-scrubber) sample location						
		m3/hr	ME	AE	NOx	CO	CO2	SO2	PM2.5	PM_OC	PM_S
1	6	51,114	15.3	0.91	-4.2%	9.4%	0.5%	96.7%	-2.2%	17.3%	-2.6%
2	8	43,635	12.5	0.90	1.6%	23.3%	-1.0%	96.9%	14.5%	33.8%	10.2%
3	12	31,394	8.28	0.90	-8.2%	19.2%	-5.7%	96.9%	4.0%	30.0%	-6.3%
4	20	2,698	0.00	0.79	42.2%	52.7%	9.0%	98.4%	36.9%	41.2%	28.8%
ISO Wt	9	40,663	11.61	0.90	0.4%	26.1%	-1.0%	97.0%	9.9%	30.7%	5.0%

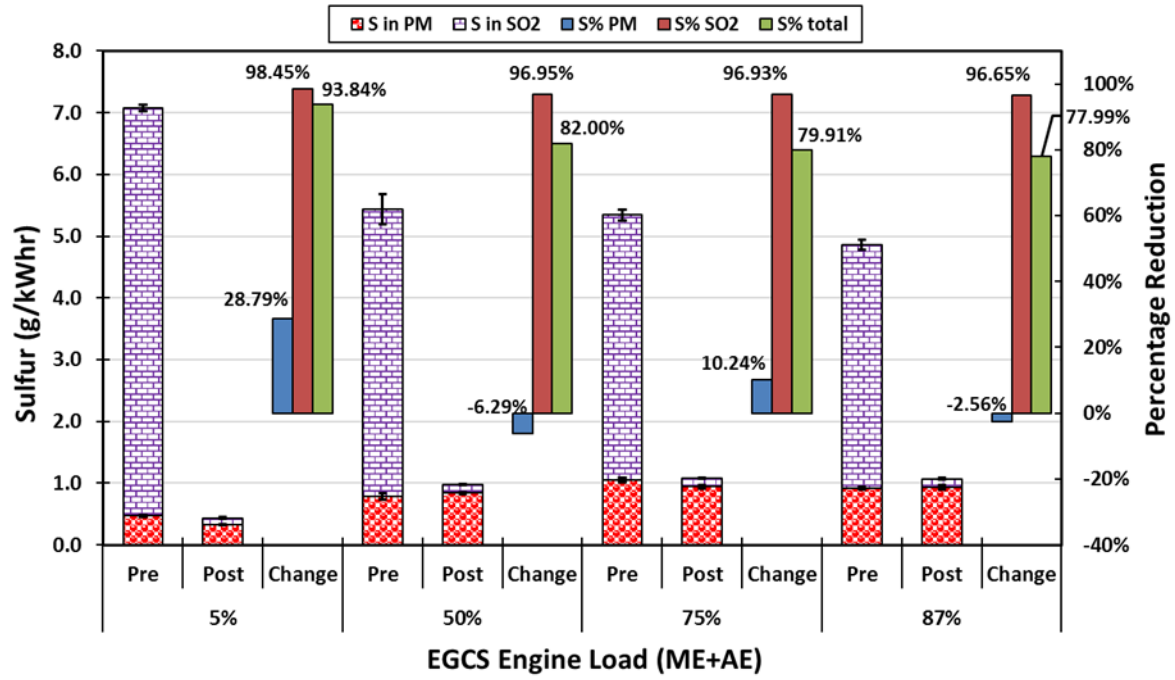


Figure 5-16 Overall Sulfur emissions (gas and particle phase) in g/kWhr

Table 5-12 lists the BC percent reductions over the scrubber for the three methods evaluated. The BC scrubber reduction percentages vary between the methods and modes. The MSS, FSN, and EC measurements show a weighted BC reduction across the scrubber that vary from 36% (EC and MSS) to 20% (FSN). Although the weighted results compare well between the methods, the mode-by-mode comparison did not. For the EC method mode 3 was in fact negative (-2.9%) while the MSS and FSN were both positive. (24 and 14%). Deeper analysis suggests the batched EC filter weight detection limits may have played a role in the discrepancy. In anticipation of PM reduction, the sample times for the pre-scrubber test were reduced to 5 minute samples and up to 20 minute for the post scrubber tests. The reduced sample time puts the EC method at a disadvantage as the filter mass was much lower for mode 3 between the pre and post filter weights which were low for the pre-scrubber test in comparison to the post-scrubber test (39.7 vs 6.2 ug/filter) where the measurement uncertainty with a clean filter is around 0.5 ug. Also these overall scrubber results are impacted by the variability in the AE engine load and the high BC emission factor of the AE engine as described in the Calculation section earlier.

In summary, the BC reduction from the scrubber appears to be around 30-35% using the MSS (eBC), around 20% using the FSN (eBC), and 40% for the EC method (with the outlier), estimated to be 50% with the mode 3 outlier removed. There is no clear trend of increasing or decreasing BC emission reductions across the scrubber as has been reported previously while utilizing the MSS and EC methods.

Table 5-12 BC scrubber efficiency results for all methods (with AE)

Mode	DR	Exh Flow	Engine Load		Total Percent Reduction		
		m3/hr	ME	AE	eBC_EC	eBC_MSS	eBC_FSN
1	6	51,114	15.3	0.91	53.3%	29.4%	8.1%
2	8	43,635	12.5	0.90	43.3%	37.6%	17.8%
3	12	31,394	8.28	0.90	-2.9%	24.8%	14.1%
4	20	2,698	0.00	0.79	48.5%	42.9%	36.6%
ISO Wt	9	40,663	11.61	0.90	38.9%	35.6%	19.9%

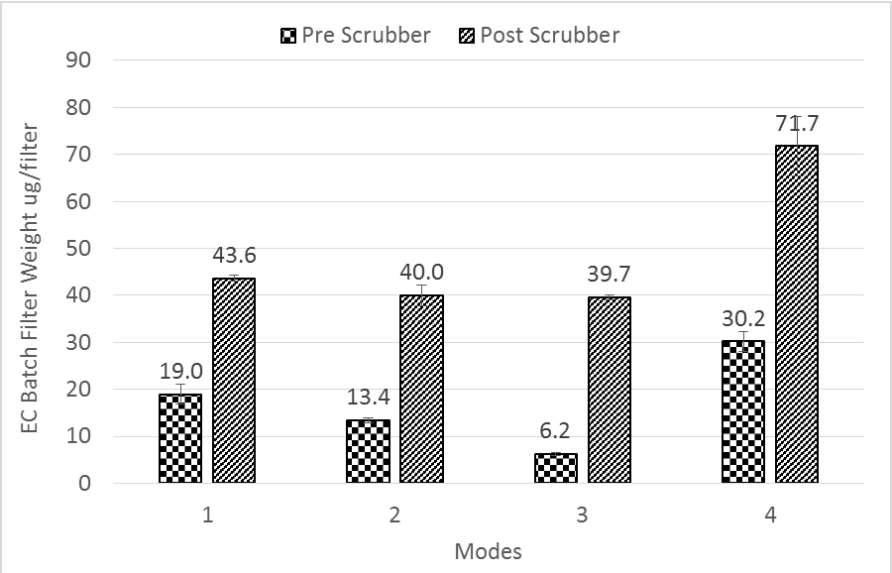


Figure 5-17 BC measurement sensitivity for the EC method scrubber data (ug/filter)

5.2.5 Scrubber sulfur balance

To control SO_x emissions, the IMO Annex VI regulations include caps on the sulfur content of fuel oil, which indirectly reduces PM emissions where IMO does not have any explicit PM emission limits. For the Emission Control Areas (SO_x ECA or SECA) IMO has special fuel quality provisions to control SO_x emissions. The sulfur limits and implementation dates are illustrated in Figure 5-16. The provision shows that sulfur fuel drops from 1% in 2015 to 0.1% in ECA areas, from 3.5% to 0.5% in 2012 globally, and then may drop to 0.5% in 2020 globally. Solutions to meet these low SO_x emissions can be achieved with low sulfur fuels or other devices such scrubber systems. This discussion compares the total sulfur balance to the fuel sulfur rule to see how well the tested scrubbers performed in comparison to fuel rule.

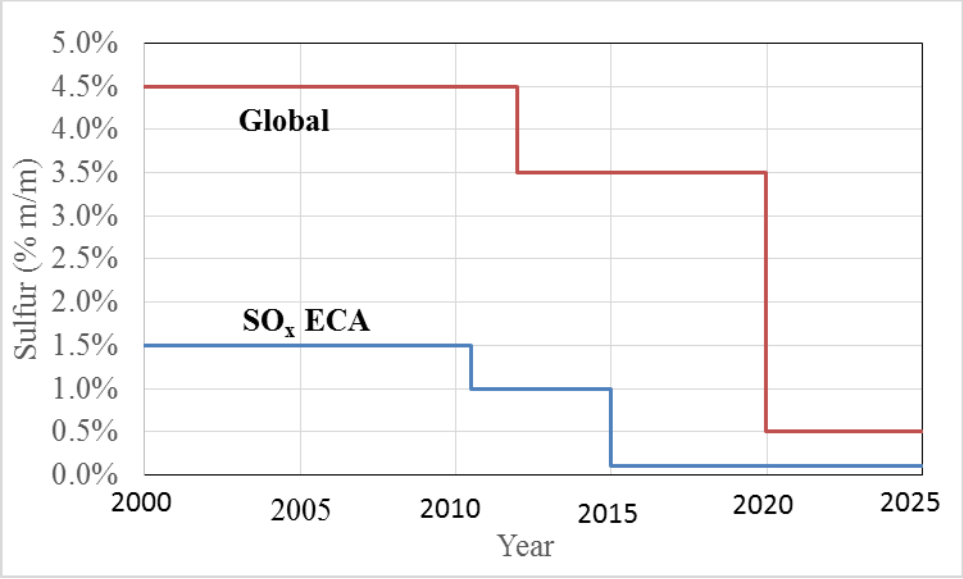


Figure 5-18 Global and ECA fuel sulfur limits

To perform this analysis the sulfur containing species, that is going to be considered, must be in the gaseous and particle phases. The scrubber system meets the fuel sulfur rule (as shown by the results in Figure 5-19), though this applies to the gas phase only. At each of the modes the fuel sulfur percent was estimated at 0.029% at low load and 0.065% at high load (all of which are below the 0.1% ECA SO_x requirement). Figure 5-20 shows the same results but includes the sulfur PM contribution to the fuel sulfur estimate. In this figure the estimated fuel sulfur ranges from 0.12% to 0.42% from low to high load. When the particle phase sulfate species is added to the gas phase species the total sulfur balance suggests that the scrubber system is not as effective as the fuel sulfur rule and that sulfur PM emission may be higher as shown in Figure 5-20.

Scrubber systems are required to include a continuous monitor of the SO_2/CO_2 (ppm_v/%_v) ratio using a CEMS. The requirement is that the ratio must be less than 4.3 which corresponds to a 0.1% sulfur fuel. Using this approach simply considers the sulfur in the gas phase and not the sulfur in the particle phase. As such the validation method does not account for all the sulfur species and may be underestimating the scrubber performance as it relates to the fuel sulfur rule.

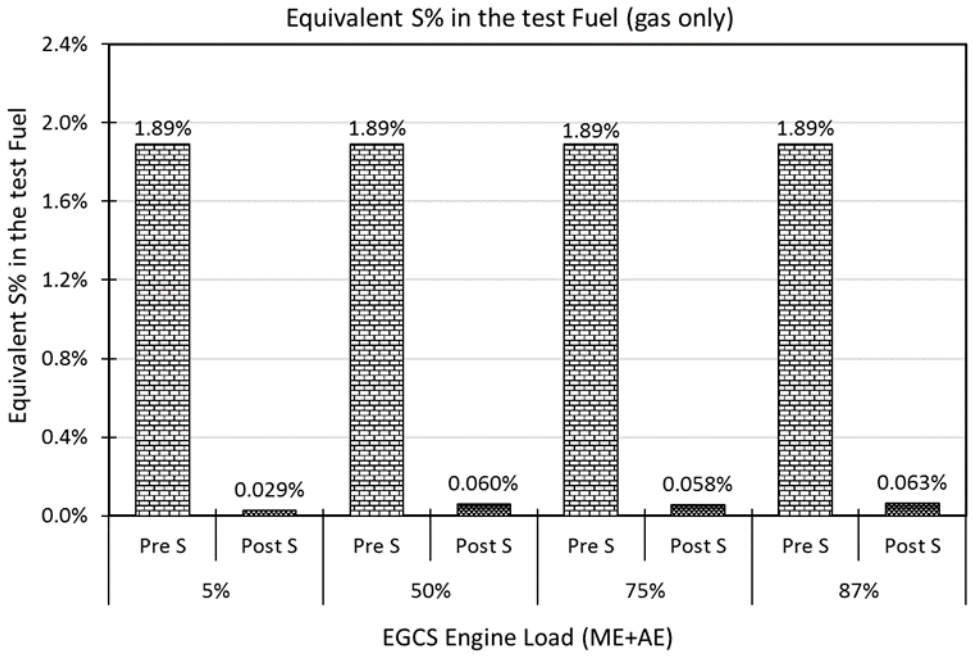


Figure 5-19 Equivalent Sulfur % in the Test Fuel (gas only)

[1] Only the SO_2 gaseous emissions were used to estimate the sulfur percent equivalent fuel.

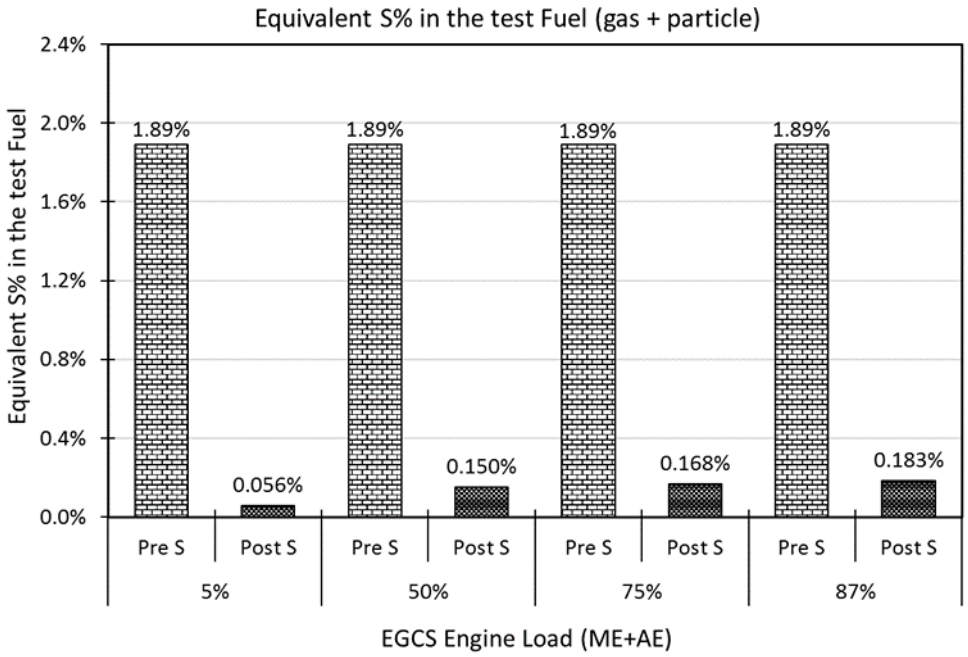


Figure 5-20 Equivalent Sulfur % in the Test Fuel (gas and particles)

[1] This figure includes the gaseous SO_2 emissions and the sulfate PM emissions to estimate the sulfur percent equivalent fuel.

5.2.6 BC methods correlation

The correlation between the three BC instruments is presented in this sub section. Since the BC emissions for the AE engine were more than 10 times higher than the emissions for the ME, the analysis includes the AE+ME and the ME only. The correlation for all the test points (ME and AE) is shown in Figure 5-21. The BC concentration varies from 0.5 mg/m^3 to 8.0 mg/m^3. The R^2 was greater than 0.9 for both methods, but this time the FSN response was less than the PA and the EC was higher than the PA method. The two higher clusters of BC emissions (see green ovals) are from the AEs. If the AE data is removed, the R^2 reduces significantly ($R^2 < 0.1$) and both slopes become positive with the EC slope increases from 1.34 to 2.3 and the FSN slope increases from 0.93 to 1.60, see Figure 5-22.

If the Task 1 post-hoc calibration was applied the correlation for the both the FSN and EC methods would result in a slope further from unity for the AE + ME results, see Figure 5-23. The ME only tests the post-hoc calibration which causes the slope to move further from unity than the EC method (from 2.26 to 2.97), however the FSN the slope improved slightly (from 1.59 to 1.4).

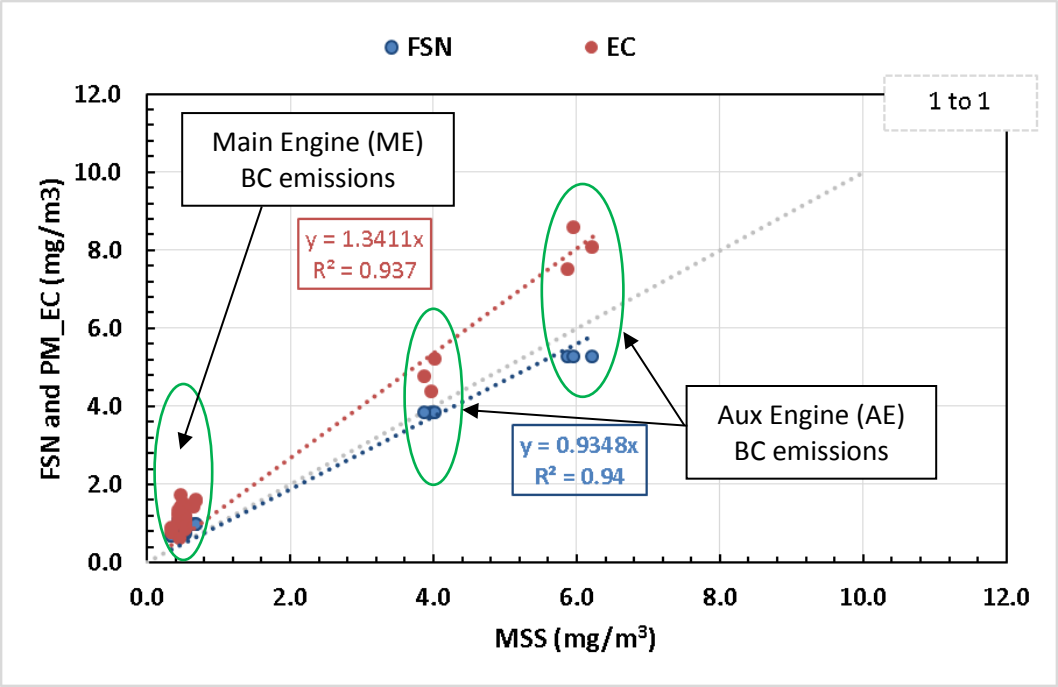


Figure 5-21 Scrubber BC instrument correlation for AE and ME load points (mg/m³)

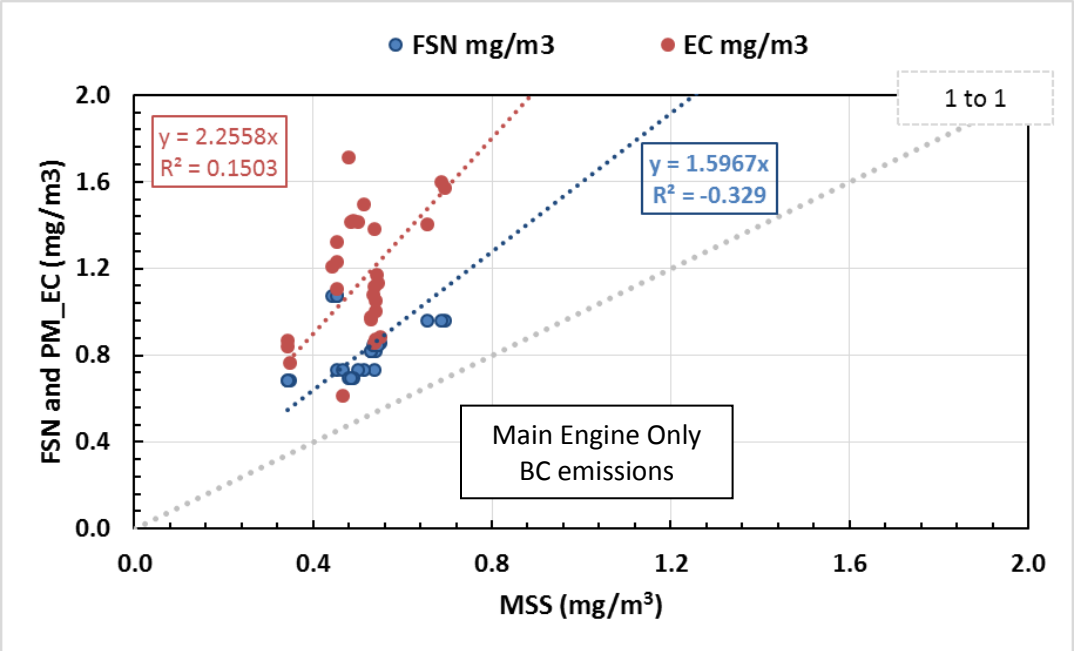


Figure 5-22 Scrubber BC instrument correlation for ME load points only (mg/m³)

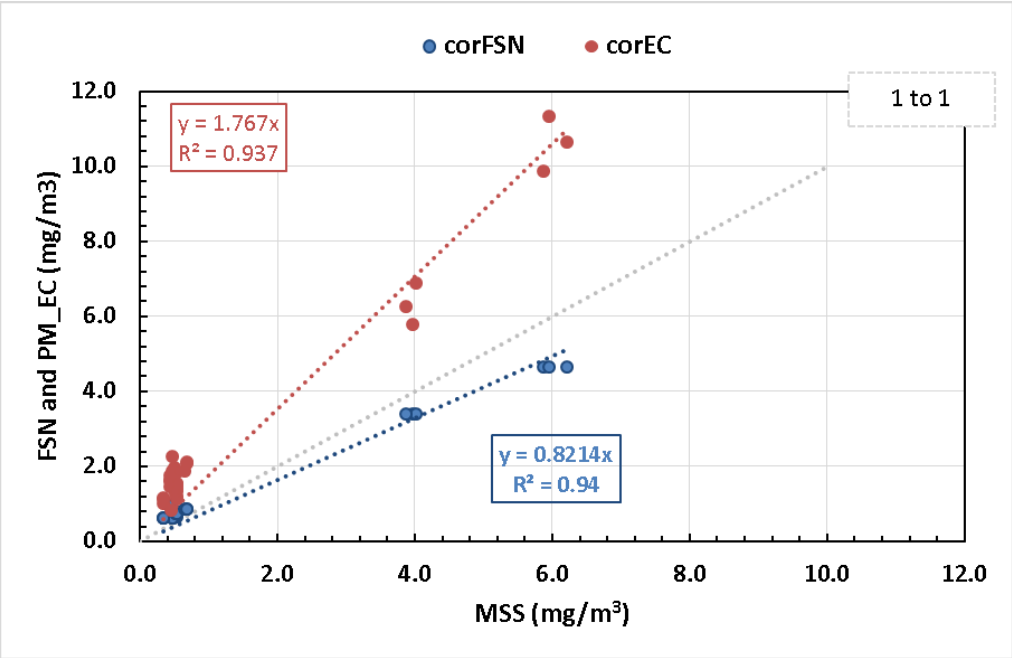


Figure 5-23 Post-hoc corrected BC instrument correlation for AE and ME load points (mg/m³)

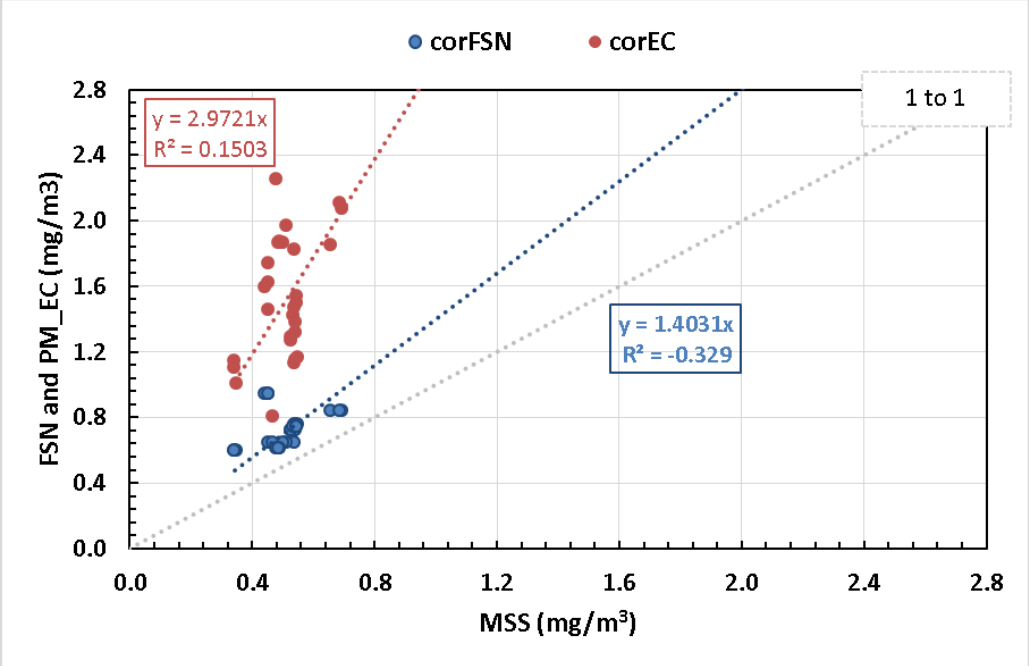


Figure 5-24 Post-hoc corrected BC instrument correlation for ME load points only (mg/m³)

One question to ask may be, "Why did the BC correlation look so poor for the ME (ME only not the AE) on the high sulfur fuel compared to the Task 2 and Task 3 results?". One difference between the ME results and the AE, Task 2 and Task 1 are the much lower BC percent of total PM. Figure 5-25 shows the percent BC (from the MSS method) as a ratio to the total PM ($PM_{2.5}$). The $BC/PM_{2.5}$ ratio changed significantly for the 4% load (AE only) compared to 48%, 70%, and 85%. The 4% load test showed the highest $BC/PM_{2.5}$ ratio (6%) and also represented the highest BC emission factor. The $BC/PM_{2.5}$ ratio was less than 0.5% for the other test points (48%, 70%, and 85%). During Task 1 the $BC/PM_{2.5}$ varied from ~5% to 50% (BP mode) for the various fuels (DMA, RMB-30 and RMG-380) suggesting the fuel alone is

not a cause for the change in the correlation between measurement methods. Interesting though that when the BC/$PM_{2.5}$ ratio became low (less than 0.5%) the correlation became very poor between the methods and showed biases up to 3 times.

The BC results from the scrubber testing suggest that there may be some influences on the BC measurement methods that depend BC fraction of the exhaust. Others have suggested the sulfur in the fuel contribute to the BC emission factor correlation (Lack 2008, 2014, Buffaloe 2012). Interesting no correlation issues were observed from the test stand work where low and high sulfur fuels were used, but significant impact to the EF were observed for the low BC/$PM_{2.5}$ ratio conditions. As such, these results are confounding and will need additional studies to clarify.

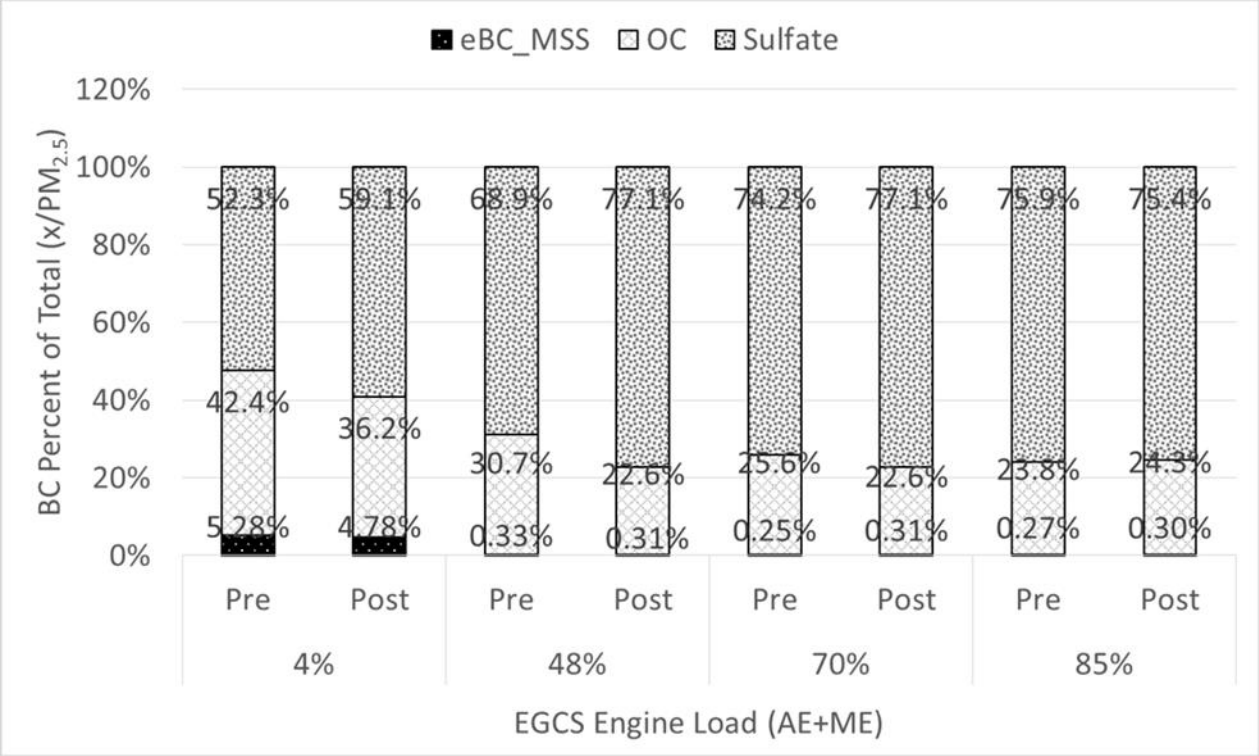


Figure 5-25 BC (MSS) divided by total PM ($PM_{2.5}$) as a function of load and location

6 Discussion

This section was prepared to provide context between the different Tasks and to address the overall question designed for the research project: "What are the impacts of load, fuel switching, VSR on BC emission factors?". This discussion includes data from Tasks 1, 2, and 3, in addition to data from UCRs previous testing campaigns. There are also some questions to the representativeness of the selected test stand engine due to its relatively small size compared to Category 3 engines. As such, this section also includes a discussion on the test stand engine representativeness from a fuel consumption and BC emissions factor standpoint.

6.1 Fuel consumption

The test stand engine was much smaller than an OGV main propulsion engine in order to manage costs for test stand laboratory work. There is some question on the emission factors for the selected test engine. This section discusses the representativeness from a fuel consumption and BC emissions factor standpoint.

The Break Specific Fuel Consumption (BSFC, also reported as $bsCO_2$) is known to increase with decreasing engine size. Figure 6-7 shows a comparison of the measured $bsCO_2$ for selected engines tested by UCR in comparison to the 6-71 N used in this research (green squares) at loads varying from 10% up to 100% (Note the 6-71N bsCO2 emissions are estimated at 10% and 100% using a curve from 25% to 75% load). The figure shows that at 100% load, $bsCO_2$ is lowest for the 40 MW 2-stroke engine (blue diamonds; 563 g/kWh) and highest for in the smaller test stand engine 6-71 N (728 g/kWh). The test stand engine showed 30% higher $bsCO_2$ emissions compared to the 40 MW 2-stroke engine. The $bsCO_2$ emissions were more comparable to those of the 2-stroke 2 MW and 4-stroke 4 MW engines, however, suggesting that the test stand engine are still demonstrative of a broader range of engines used in marine applications.

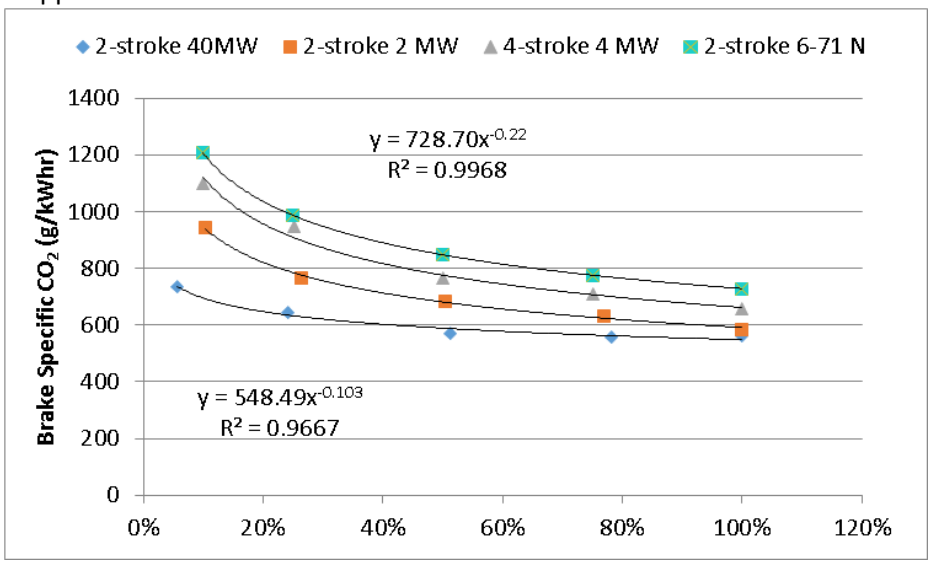


Figure 6-1 Comparison of Brake Specific CO_2 Emissions for Various Marine Engines

During the Task 2 testing of a modern vessel (Tier 2 59.6 MW engine) the bsCO2 ranged from 631 to 576 g/kWh (low to high load) which matches the larger 2-stroke engine results in Figure 6-7. The Task 3 vessel (Tier 0) represented a lower power engine (16 MW) and showed a slightly higher bsCO2 that ranged 763 to 694 g/kWh (from low to high load) which matches well with smaller powered engines. As

such, the two at-sea tests represent and reinforce the results in Figure 6-7 and are adequate stand-ins of well-maintained vessels.

6.2 BC Emission Factors

Figure 6-2 show the BC emission factors for heavy duty diesel 4-stroke and 2-stroke engines on a g/kg-fuel basis. These results include previous UCR studies in addition to the current ICCT results (see green diamonds). The results in Figure 6-2 show heavy duty diesel engines have a BC emission factors ranging from 0.01 to 5.00 g/kg-fuel where BC EFs increase with decreasing engine power. The Task 1 results are illustrative of smaller power engines (see green oval in Figure 6-2) and show BC emissions of 0.1 to 1 g/kg-fuel. Task 3 is in the middle with a 2-stroke 16 MW rated engine with an emission factor of 0.1 to 0.01 g/kg-fuel. Task 2 (modern Tier 2 engine) is at the far right for a large 2-stroke marine engine rated at 69.6 MW with an emission factor slightly lower than previous OGV engines of a similar size where the EF ranged from 0.01 to 0.002 g/kg-fuel.

The fuel specific BC emission factors for the Task 1 (test stand) are also shown in Figure 6-3 for both the BP and CS operational modes and each of the tested fuels. The BC EF ranged from 0.03 to about 1.8 g/kg-fuel for the BP condition (left figure) and 0.03 to 1.4 g/kg-fuel (right figure). The Task 1 results were similar for both the BP and CS modes suggesting the sample conditioning system did not impact the EF. The results in this study are consistent with those measured in previous studies especially when maximum rated engine power is considered as shown in Figure 6-2.

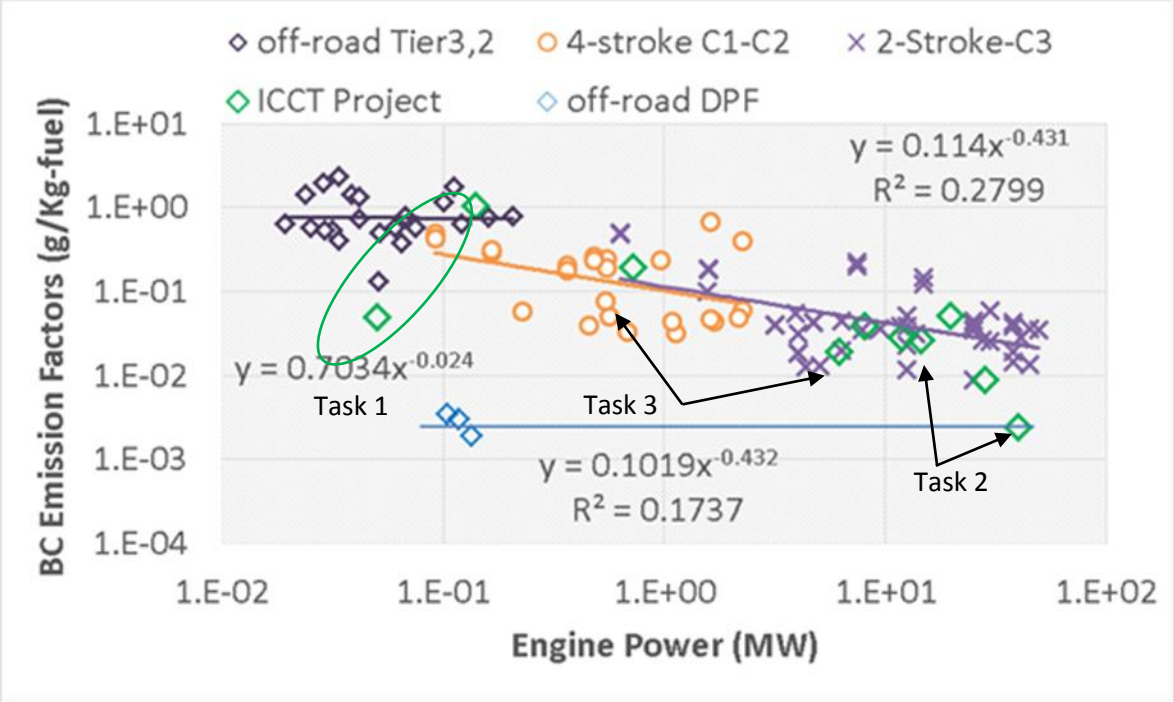


Figure 6-2 Comparison of BC Emissions for Various Marine Engines: Diesel Engines

[1] Data sources are from UCRs previous test reports that vary

The 6-71N test stand engine did show similar BC EFs to those of other marine engines. Previous studies have shown that OGV engines often show decreasing BC EFs as load increases. With the test stand engine all the instruments show a trend of increasing BC emissions with increasing load under both CS and BP sampling conditions. This is consistent with the increased prevalence of EC at the higher load

point. An exponential relationship was found between the brake specific BC emissions and different engine loads for the CS mode (see Figure 6-4) and for the RMG-380 fuel under BP sampling conditions. Increases in BC emission factors were seen in going from the 25% to 75% load point for the DMA and RMB-30 fuels for the BP sampling condition, but only two load points (25% and 75%) were tested for these fuels, so the curvature of the line between these points could not be estimated. For the CS mode, BC emissions for the 25% and 50% load points were similar for both the DMA and RMG-380 fuels. It should be noted that the actual testing loads for the 75% load point were around 70%-72% for all fuels, except for the RMG-380 fuel which was also tested at loads of 77%-79%. Although the increase in load from 70-72% to 77-79% is relatively modest, there was a considerable increase in BC emissions between these different test points for the RMG-380 fuel, providing further evidence of the exponential nature of the BC increases, particularly at higher loads.

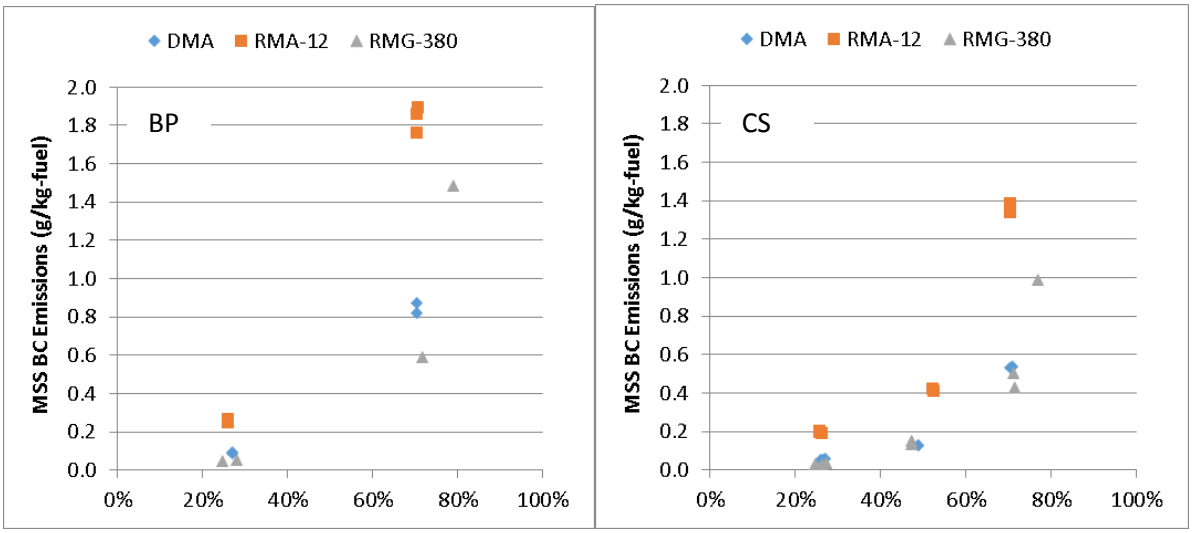


Figure 6-3 Fuel Specific BC Emissions for the 6-71n Test Stand Engine (MSS Results)

[1] Left figure is BP and right figure is CS modes

6.3 Load dependence and VSR

Figure 6-4 shows the BC emission factors measured on different vessels as a function of engine percent load (MCR) for large 2-stroke marine engines and Figure 6-4 shows the same results, but for smaller 2-stroke and 4-stroke marine engines. The large 2-stroke engines show BC emissions that decrease with increasing load, but the smaller engines show a mixed set of results. The Task 1 test stand engine showed an increasing BC EF as load increased which is in line with the 3.2 MW AE engine results. The Task 3 (Tier 0 16 MW 2-stroke engine equipped with a scrubber) results are in the middle of the EF data as shown in Figure 6-4. However, the Task 2 (Tier 2 69.6 2-stroke engine) results are significantly lower than all previously tested ME. This is the first Tier 2 engine tested by UCR and there may be some combustion improvements for NOx control that are also offer low BC emissions. More at-sea tests of Tier 2 engines are needed to corroborate these results. It is unclear if Tier 3 engines will have similar Tier 2 BC emissions since even more engine controls will be required to meet those standards.

VSR: VSR is a voluntary speed reduction program that rewards vessels for slowing to 12 knots or less in selected areas near coastal communities and areas. The goal of programs like this one is to reduce emissions from ocean going vessels. UCR has tested several vessels during VSR operation and this data has been plotted with the data collected in this research project. The VSR data is shown in circled area of Figure 6-4 at the far left of the figure at the lowest load point. Typically VSR is represented by 7 to 11% load and 38 to 45 rpm. For all the Tier 0 and Tier 1 ME tested VSR always showed the highest BC EF

when compared to 25%, 50% and higher engine loads. The Tier 2 BC emissions were 0.0193 g/kg-fuel at VSR speeds and were 0.0515 g/kg-fuel at 25% load. The Tier 2 BC emissions were higher at 25% load as compared to VSR which is the first time UCR experienced BC emission factors to be lower at VSR speeds compared to other loads, see Figure 6-4. There is some speculation that the engine controls for the Tier 2 vessel may incorporate designs for VSR given its widespread use. This suggests significant improvement in BC emissions can be realized for BC emissions when newer vessel designs are developed. It is unclear what a BC regulation would do to the design of modern engines, but these results are encouraging.

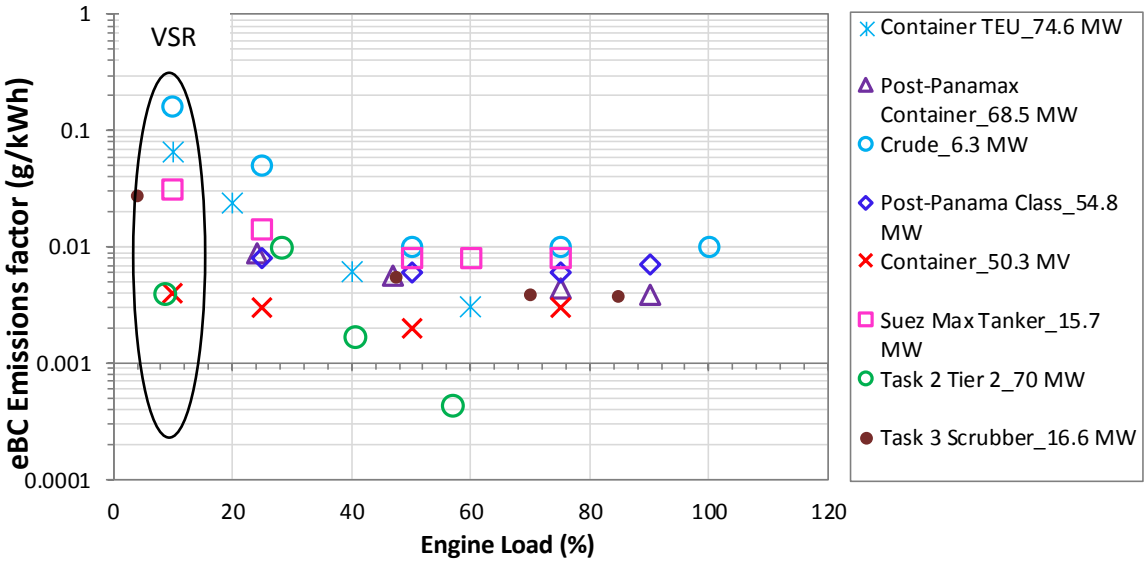


Figure 6-4 BC Emissions for Various C3 Marine Engines: x-axis % MCR load

[1] Data sources are from UCRs previous test reports that vary

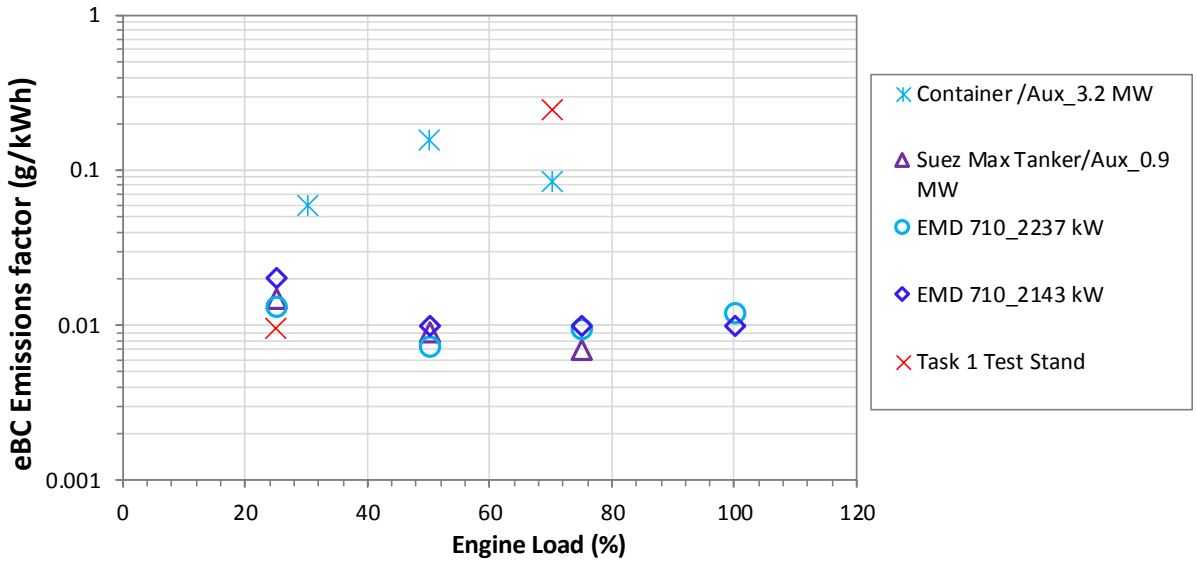


Figure 6-5 BC Emissions for Various C1 and C2 Marine Engines: x-axis % MCR load

[1] Data sources are from UCRs previous test reports that vary

6.4 Fuel impacts

Figure 6-6 shows the BC EF as a function of fuels tested at UCR during at sea testing projects. There is limited data in the figure and the spread of the data (100 fold) proposes a relationship between fuel and BC emissions that cannot be determined. The results in this study suggest there was a significant impact in BC emission for the low sulfur fuels. More investigation is needed to quantify BC EF with fuels. Also the finding that BC emissions from the Task 3 HFO scrubber results (section 5) suggest that BC concentration, as a fraction of total PM, may play a role for the relationship between BC and EF. More research is needed in this area at low BC emission factors to consider the impact of fuels and measurement methods.

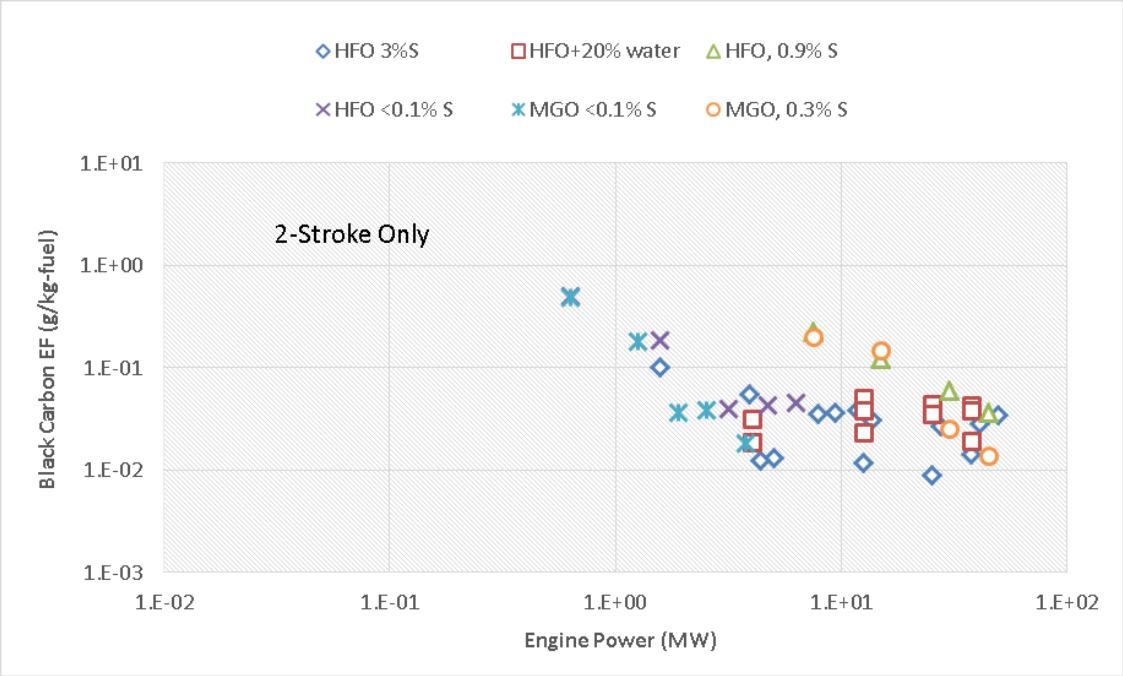


Figure 6-6 Comparison of BC Emissions for Various Marine Engines: Various Fuel

[1] Data sources are from UCRs previous test reports that vary

Three different marine fuels with varying sulfur content were tested during Task 1 of this project. Figure 6-7 shows measurements under CS and BP sampling conditions. Generally speaking, the RMB-30 fuel showed the highest BC emissions, while the DMA fuel showed the lowest emissions at the 75% engine load under CS condition, except for some measurements for the Aethalometer. Note that this does not consider the RMG-380 results that were done at the 77-79% loads, as the BC emissions at these load points were affected by the additional load, as discussed above. At 25 and 50% load points, the BC emissions for the RMG-380 fuel were similar to those for the DMA fuel and were both lower than the BC emissions for the RMB-30 fuel. For the BP mode, the highest BC emissions were found for the RMB-30 fuel, while the BC emissions for the DMA and RMG-380 did not show consistent trends between the different instruments. The BC emissions from the RMG-380 fuel tended to be similar to the DMA fuel, or slightly higher.

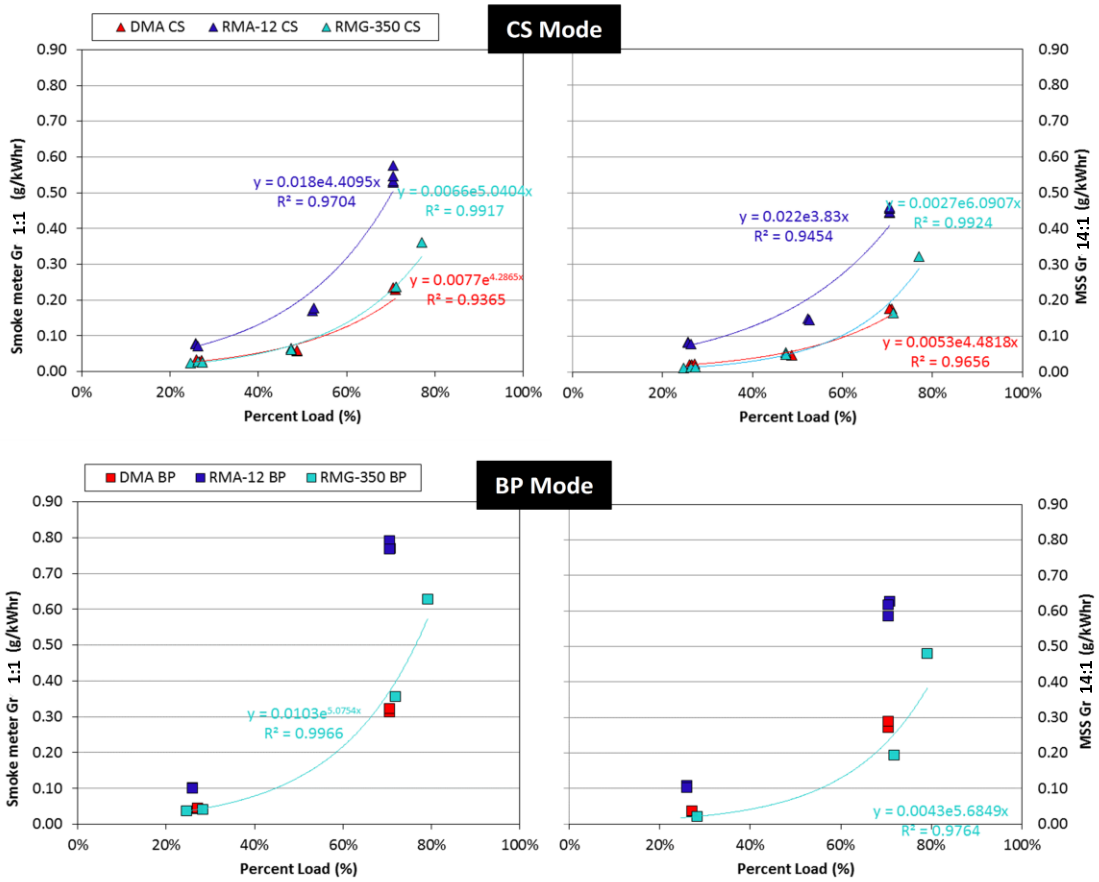


Figure 6-7 Fuel and Load Effects on BC Emissions (Task 1)

Fuel Switch LS HFO vs MGO: In addition to the results from this research, UCR has tested several OGVs where fuel switching was performed. The results presented below represent previous studies by UCR where a single OGV was tested to evaluate the emissions change before and after a fuel switch. The results presented below have been presented elsewhere (Kahn 2012), and are repeated here for relatability to the BC measurements from the OGVs. There are three previous 2-stroke marine main engine fuel switch studies presented here, 1) MAN B&W 6.3 MW 2-stroke ME, 2) MAN B&W 74.6 MW 2-stroke, and 3) Hyundai B&W 68.5 MW engine. For each of the projects, the goal of the testing was to characterize the emissions change from the fuel switch. Included in the measurements were black carbon emissions utilizing the PA (eBC) and EC methods. The first vessel was a fuel switch from LS (0.1%) HFO to a LS MGO, the second vessel was a fuel switch from a HS (0.9%) HFO to a LS MGO, and the third vessel was a fuel switch from a HS (2.4%) HFO to a LS MGO. The fuel details and engine loads can be found in Table 6-1.

Figure 6-8 and Figure 6-9 show the PM and BC emissions for the 6.3 MW engine and Figure 6-10 and Figure 6-11 show the PM and BC emissions for the 74.6 MW and 68.5 MW engines, respectively. For all three OGVs tested the fuel switch did not amount to significant change in the BC emissions. For the LS HFO fuel switch the percent difference in BC emissions was less than 10% for all modes except for the highest load points where the EF was low and the slight change in EF represented a 50% change in BC. The second test using the HS (0.9%) HFO, showed a 67% BC reduction (60% load) and a 38% BC increase (20%) for the different modes. At VSR the BC emissions only decreased by 18%. For the higher HS (2.4%) HFO fuel the percent BC reduction was 61% at the one load point tested. In general, these results are mixed, but there is a slight trend where the BC emissions are lower with the MGO fuel as compared to the HS HFO fuels.

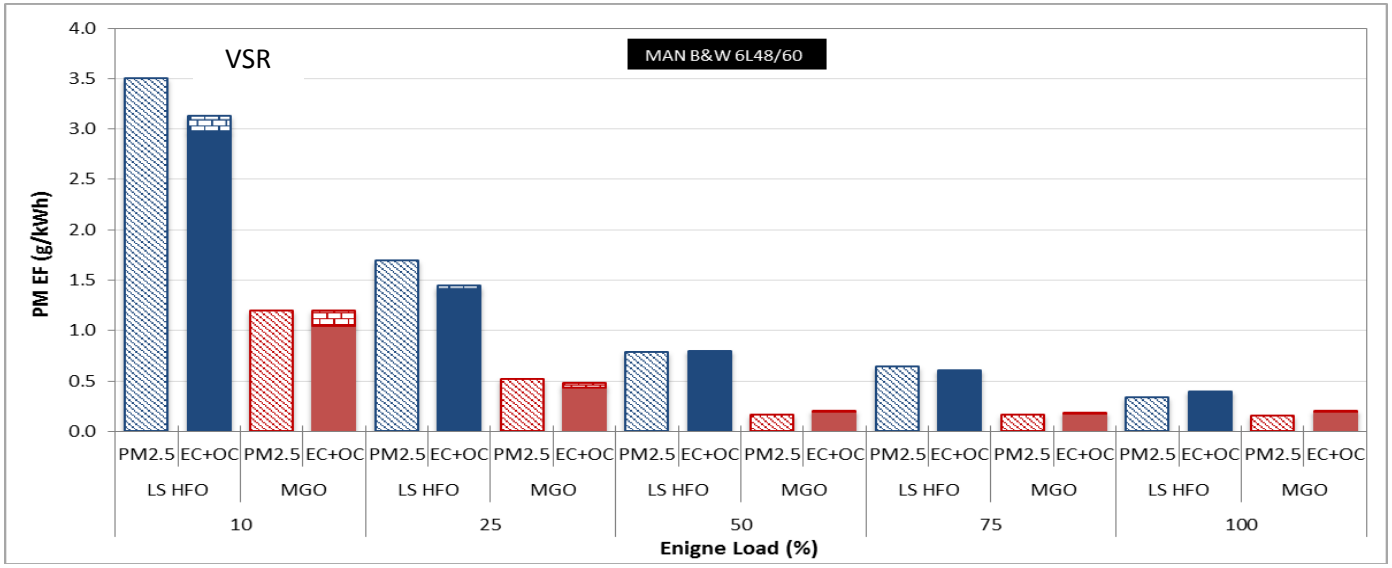


Figure 6-8 Comparison of bsPM Emissions for LS HFO and MGO fuels

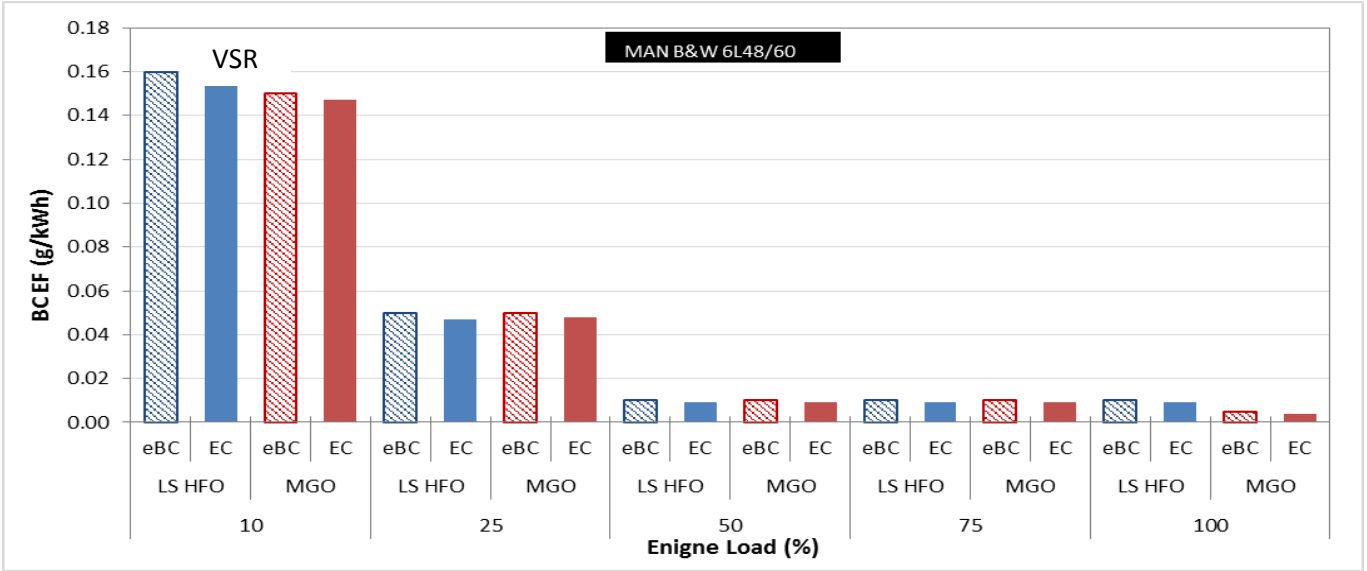


Figure 6-9 Comparison bsBC Emissions for LS HFO and MGO fuels

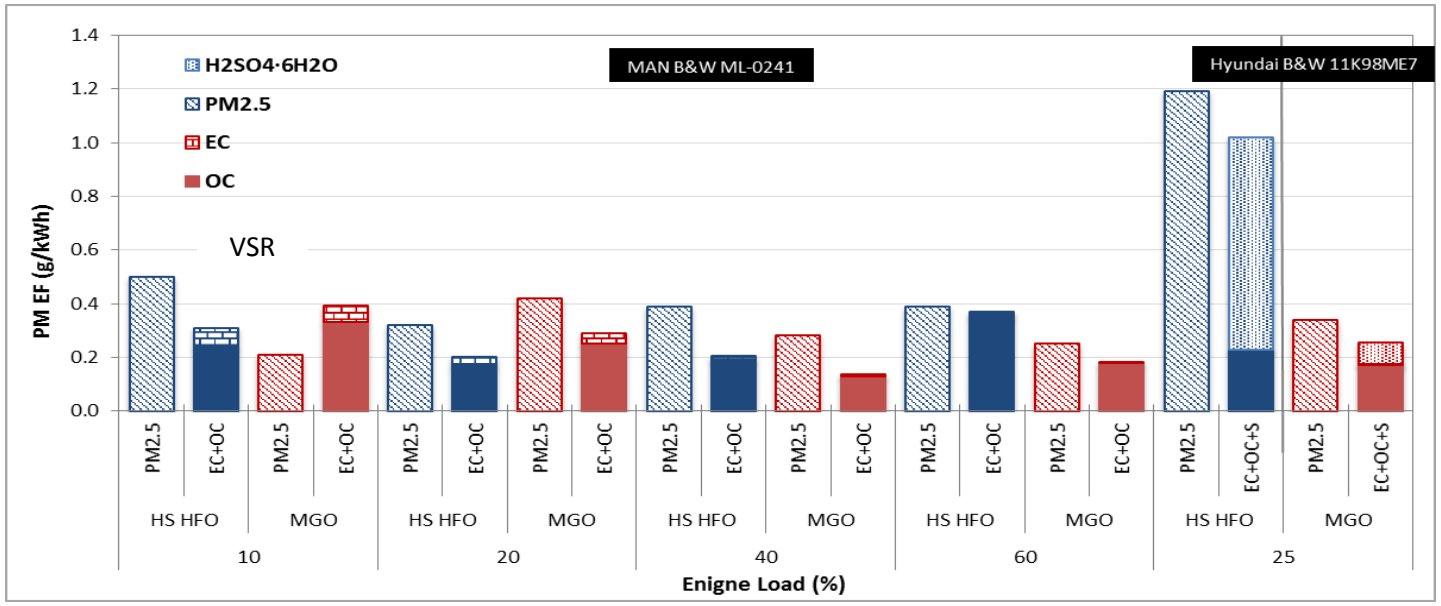


Figure 6-10 Comparison of bsPM Emissions for HS HFO and MGO fuels

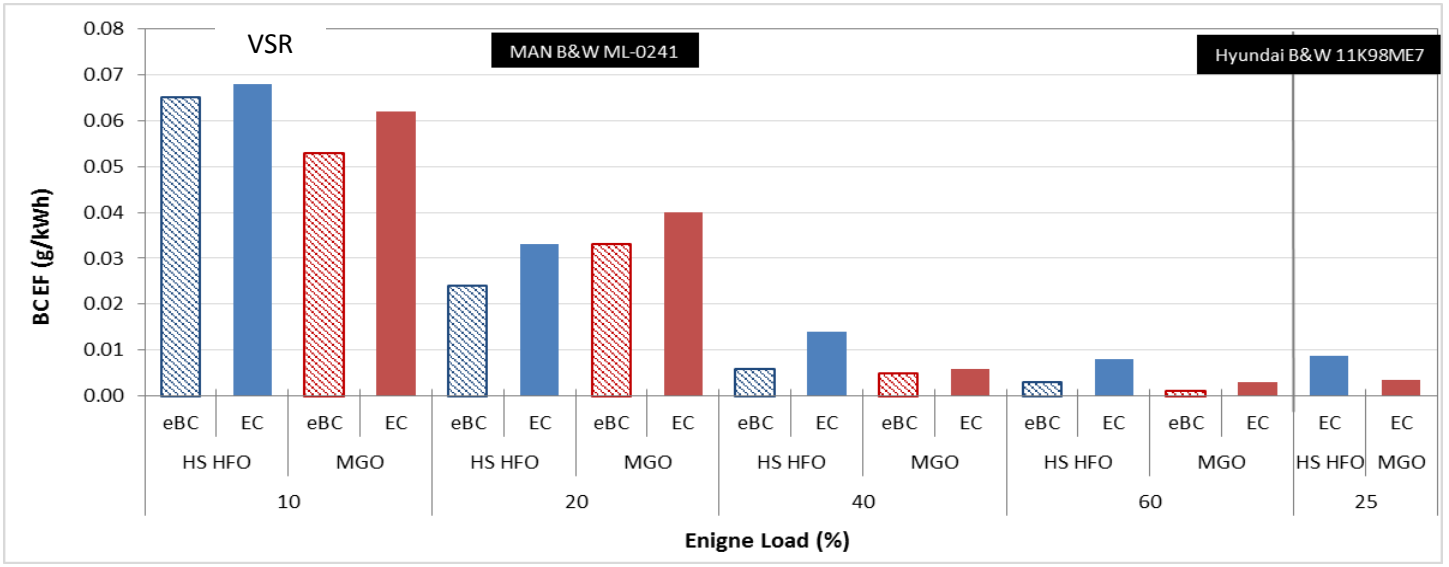


Figure 6-11 Comparison of bsBC Emissions for HS HFO and MGO fuels

Table 6-1 Summary of Comparison of Brake Specific BC and PM Emissions for HS HFO and MGO

Fuel Type	Engine Name/Rating	Vessel/Engine Name/Type	Load Points	EC g/kWhr	OC g/kWhr	tPM g/kWhr	eBC g/kWhr
LS HFO (<0.1% S)	Four-MAN B&W 6L48/60, 6.3 MW2-stroke	Very Large Crude/Main	100	0.009	0.39	0.34	0.01
			75	0.009	0.6	0.64	0.01
			50	0.009	0.79	0.79	0.01
			25	0.047	1.4	1.7	0.05
			10	0.154	2.98	3.5	0.16
MGO (<0.1% S)	Four-MAN B&W 6L48/60, 6.3 MW 2-stroke	Very Large Crude/Main	100	0.004	0.19	0.16	0.005
			75	0.009	0.18	0.17	0.01
			50	0.009	0.19	0.17	0.01
			25	0.048	0.43	0.52	0.05
			10	0.147	1.05	1.2	0.15
HS HFO (<0.9% S)	2000 MAN B&W ML-0241, 74.6 MW 2-stroke	Container 2600 TEU /Main	60	0.008	0.36	0.39	0.003
			40	0.014	0.19	0.39	0.006
			20	0.033	0.17	0.32	0.024
			10	0.068	0.24	0.5	0.065
MGO (<0.3% S)	2000 MAN B&W ML-0241, 74.6 MW 2-stroke	Container 2600 TEU /Main	60	0.003	0.18	0.25	0.001
			40	0.006	0.13	0.28	0.005
			20	0.04	0.25	0.42	0.033
			10	0.062	0.33	0.21	0.053
HS HFO (<2.4% S)	2010 Hyundai B&W 11K98ME7 68.530 MW 2-stroke	Post-Panamax Container	25	0.0087	0.22	1.19	
MGO (<0.17% S)	2010 Hyundai B&W 11K98ME7 68.530 MW 2-stroke	Post-Panamax Container	25	0.0034	0.17	0.34	

[1] Data sources are from UCRs previous test reports that vary

6.5 Hygroscopic growth

The hygroscopic growth of aerosol particles has an important influence on their residence time in the atmosphere, deposition efficiency in lung as well as their optical properties (i.e. visibility degradation). Thus the hygroscopicity of ambient particles has been a concern of previous research projects. As one of the main sources of ambient particles, soot emitted from engine emission is a focus of hygroscopicity study. Weingartner et al. (1995; 1997) reported that diesel combustion particles exhibit small hygroscopic growth (up to GF=1.025 at RH=95% for d0=51.5nm). Dua et al. (1999) also showed similar result: consistent trend at high relative humidity (RH >99%): the GF varies from 0.93 to 1.06 for diesel particles from 58 to 94nm.

Marine diesel engines emit particles at relatively high RH environment. Thus the characterization of hygroscopicity of marine engine combustion particles at relatively high RH appears to be particularly important. To reduce air pollution IMO considers to reduce sulfur content in the fuel. Currently some types of fuels for marine engine still contain high level of sulfur up to 3.5 wt. %. The sulfur content on the surface of emitted particles is thought to enhance the hygroscopic property of particles. Weingartner et al. (1997) found that the hygroscopicity of the diesel particles was increased to GF=1.04 at 95% for d0=51.5nm when the sulfur content of the fuel was increased to <0.25 wt. %. However, there is almost no research studying the hygroscopicity of particles emitted from engines using higher fuel sulfur content. In this study, the hygroscopic growth of particles from both low sulfur fuel (RMB-30, 0.001 wt. %S) and high sulfur fuel (RMG-380, 3.18 wt. %S) were measured and discussed.

The results show that the particles size grew by 15% with a change in relative humidity (RH) from 50% to 90% for the HFO-380 fuel. When the CS was used in the particle sample line, no particle growth was found for any of the fuels. These results suggest the sample conditioning system and fuels can be a significant factor in in determining hygroscopicity of diesel particles from ship engines.

7 Overall Conclusions

This research included the evaluation of a marine 2-stroke engine on a test stand while operating at several modes utilizing three fuels and several BC, PM and gaseous instruments (Task 1). Additionally, this research evaluated two ocean going vessels during at-sea conditions. This included the testing of an OGV with modern Tier 2 engine for BC emission factors over a full range of loads, including VSR operation under Task 2. For Task 3, an OGV with a PM equipped scrubber system on the main engine were tested while operating HS HFO fuels. The results of these tests and previous tests at UCR are summarized in this overall conclusion section.

7.1 Task observations

The main observations of the research are summarized in the three sub sections representing each task in the completed project.

7.1.1 Task 1

The laboratory engine testing conducted in Task 1 provided a controlled environment to develop baseline emission factors for marine engine types used on oceangoing vessels under representative fuels and operating loads. Testing was conducted on a 2-stroke, 7 liter, 210 Hp DDC 6-71N engine with three different marine fuels with varying sulfur content: RMG 380 (≤3.5 wt. % S); DMA (<0.1 wt. % S); and, RMB-30 (<0.1 wt. % S). A wide range of PM/BC measurement techniques were used to evaluate their measurement effectiveness. Testing was conducted in a bypass (BP) mode with and without the CS sampling conditioning.

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

- PM mass emissions were relatively similar on a g/kWh basis between the 25% and the 75% loads for the bypass mode measurements. The RMG-380 fuel showed the highest emissions, while the DMA fuel showed the lowest emissions for the 25% load. At the 75% load, the PM emissions for the RMG-380 and RMB-30 fuel were similar, with the DMA fuel providing the lowest emissions. Interestingly, the measurements made with the CS showed a slight trend of higher emissions at the 75% load point compared to the 25% and 50% load points, with generally smaller differences between fuels.
- The PSDs for the DMA and RMB-30 fuels at the 75% load point were similar for both BP and CS suggesting these particles are solid, consistent with the trend of higher levels of EC at the 75% load point. The solid nature of the particles is important for their possible control in marine engine PM control systems (such as a PM scrubber), as evaluated in Task 3.
- PM mass collected in the BP mode was largely organic and elemental carbon for the DMA and RMB-30 fuels, but had a considerable sulfate contribution for the RMG-380 fuel. For the DMA and the RMB-30 fuels, the PM mass was almost entirely organic carbon at the 25% load, but consists of nearly equal parts of organic and elemental carbon at the 75% load. Organic carbon and sulfate are largely eliminated going through the CS and leaving a PM mass that is more predominantly EC.
- BC emissions showed a trend of increasing emissions with increasing load. This trend is consistent with the prevalence of EC at the higher load point. The RMB-30 with the lowest sulfur, viscosity and residual carbon content showed the highest BC emissions factors (g/kWh) at both 25% and 75% load points, while the RMG-380 with the highest sulfur content showed a relatively comparable results with the DMA (distillate marine fuel).

- The BC emission rates varied from 0.09 g/kg fuel to 0.84 g/ kg fuel for the DMA fuel, from 0.26 g/ kg fuel to 1.84 g/ kg fuel for the RMB-30 fuel and from 0.05 g/kg fuel to 1.04 g/kg fuel for the RMG-380 fuel based on the measured results from MSS.
- For BC emissions, the CS measurements were generally below those of the corresponding BP measurements for individual test points, but not significantly lower. This suggests that the CS has some impact on the black carbon emissions in addition to the strong reductions seen for the organic carbon (OC) and sulfate.
- A smoke meter and LII system were the two methods that sampled from the raw exhaust and downstream of the sampling conditioning system. The Smoke Meter measurements were higher than those for the LII for corresponding tests conducted with the DMA fuel and for the RMB-30 for the 25% and 50% load points, with comparable results within the experimental variability at the 75% load point.
- A greater number of instruments were sampled via the primary dilution system at a dilution ratio of 14 to 1, including an MSS, LII, PAX, as well as EC and OC measured both from quartz filters in a batch mode and with a Semi-Continuous OC-EC Field analyzer. In general, the emission levels were comparable between the different instruments for the different test fuels, with a wider spread of emissions for the 75% test load point. The EC measured in batch mode and the Semi-Continuous OC-EC Field analyzer showed lower readings than those seen for the other real-time black carbon instruments.
- Two black carbon instruments, a MAAP and Aethalometer, were sampled at a higher dilution of 1400 to 1. The Aethalometer showed higher readings than the MAAP that were more similar to the instruments measuring in in the raw exhaust and at the lower dilution ratio. This was particularly evident at the 75% load point.
- The black carbon instruments all generally measured similar trends for the black carbon measurements, with BC increasing (going from 25 to 75% load). Regression analysis comparing the MSS with the other black carbon instruments showed a slope ranging from 0.62 to 1.47 for the BP mode testing and from 0.60 to 1.92 for the BP mode testing. The slopes of the regressions for the FSN and LII were above the 1 to 1 comparison line, while the slopes of the Aethalometer, batch and semi-continuous EC-OC, and MAAP were below the 1 to 1 comparison line, with the MAAP and the batch EC-OC methods showing the lowest BC values. Overall, the spread seen in the differences in the instruments was consistent with the values suggested by the EPA.
- The OC measurements showed decreasing emissions with increasing engine load. The OC measurements also showed that the OC is significantly reduced for measurements made with the CS, consistent with the idea that CS removes most of the OC PM.
- The hygroscopic growth of aerosol particles has an important influence on their residence time in the atmosphere, deposition efficiency in lung as well as their optical properties (i.e. visibility degradation), especially for marine diesel engines that operate in high RH environments and have complex fuels. The results show that the particles size grew by 15% with a change in relative humidity (RH) from 50% to 90% for the HFO-380 fuel. When the CS was used, no particle growth was found for any of the fuels. These results suggest the sample conditioning system and fuels can be a significant factor in the uncertainty of PM emissions from vessels and their contribution to the atmosphere.

7.1.2 Task 2

Testing was conducted at sea on an IMO Tier II certified diesel engine on a container vessel. This testing suggests modern Tier 2 engines may have low EFs which can range from 0.0023 g/kg-fuel to 0.069 g/kg-fuel. Another main highlight was all three BC measurement (EC, FSN, and PA) methods coincided with each other similar to what was reported in Task 1.

A summary of the results for the Tier 2 engine testing is as follows:

- The $PM_{2.5}$ emissions results ranged from 0.05 to 0.15 g/kWhr.
- The $PM_{2.5}$ was composed of primarily carbonaceous material, with the total carbon being dominated by OC emissions for all the test points, with no strong trend with engine load.
- BC emissions ranged from 0.00043 to 0.011 g/kWh for the different loads. The BC emissions measured on this engine were lower than those measured in any of UCR's previous studies. The fuel specific emissions varied from 0.0023 g/kg-fuel to 0.069 g/kg-fuel.
- The VSR BC emissions were less than the 25% load condition.
- The BC emissions at the 25% load point are significantly higher (3 to 13 times higher) on a per distance basis than the VSR and 50% loads, respectively. The significantly higher 25% load point suggests this load should not be utilized by the vessel. The vessel owner commented that the 25% load point is not utilized except to go between VSR and regular steaming (57% load).
- The instrument correlation to the MSS showed a good correlation (R^2 of 0.9 or higher) and a slope that varied from 1.2 (FSN) to 0.91 (EC)
- The post-hoc calibration improved the correlation slightly where the FSN slope improved to 1.09 and the EC slope improved to 1.05.

7.1.3 Task 3

Testing was conducted at sea on a diesel engine on a container vessel equipped with a retrofit scrubber system operating on Heavy Fuel Oil (RMG-380). The results in general showed that BC is reduced by a scrubber system by around 30%, the BC measurement methods varied significantly for the pre scrubber thermal optical method, and the total fuel sulfur PM balance may be higher for scrubber system as compared to fuel switching to MGO.

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

- $PM_{2.5}$ emissions ranged from about 0.9 to 1.4 g/kWhr. The $PM_{2.5}$ emissions did not show a strong trend with respect to load. The PM composition was predominantly sulfate.
- BC emissions ranged from 0.003 to 0.009 g/kWh over the different loads and pre- and post-EGCS for the ME and up to .063 g/kWh for the AE. On a fuel specific basis, the BC emission factors ranged from 0.01 to 0.1 g/kg-fuel.
- The BC emissions were only slightly reduced from the scrubber system (~30%).
- The EGCS provideed significant reductions in SO_2 gaseous emissions on the order of 96.7 to 98.4 percent. The reduction efficiency was sufficient in meeting fuel sulfur requirments for scrubber systems. The SO_2 emission levels ranged from 0.10 to 0.13 g/kWh which was similar or less than SO_2 emissions from the Tier 2 engine operated on MGO fuel.
- The organic PM reductions ranged from 41% to 13% with an ISO weighted reduction of 28%. The organic PM reductions appeared to be lower at higher loads and higher at lower loads which may suggest residence times impacts the performance of the scrubber system.
- The particle phase sulfur emissions varied from -6% (i.e., an increase in sulfate PM) to a 28.8% reduction. This was also found when testing other OGV equipped with scrubber systems. The ISO weighted sulfate PM pre scrubber emissions were 0.935 g/kWh and the post-scrubber sufate PM emissions were 0.888 g/kWh (a 5% ISO weighted PM reduction).
- The MSS, FSN, and EC measurements showed a weighted BC reduction across the scrubber that varied from 36% (EC and MSS) to 20% (FSN).
- The gas phase fuel sulfur percent was estimated at 0.029% at low load and 0.065% at high load, all of which are below the 0.1% ECA SO_x requirement.

- The gas and particle phase fuel sulfur percent was estimated at 0.12% to 0.42% from low to high load, all of which are above the 0.1%. This suggests the low sulfur rule will result in lower PM emissions than a scrubber equivalent system.
- The NOx emissions ranged from about 14 to 17 g/kWh (ME) which are in good agreement for other OGVs tested.
- If the Task 1 post-hoc calibration was applied to the scrubber data, the correlation for the both the FSN and EC methods would result in a slope further from unity. The ME tests the post-hoc calibration causing the slope to move further from unity for the EC method (from 2.26 to 2.97), but the FSN the slope improved slightly (from 1.59 to 1.4).
- The post-hoc calibration improved the Task 2 results, but didn't for the Task 3 results where the correlation became very poor between the methods and showed biases up to 3 times. One differences observed between Task 3 and Task 1 and 2 is the BC/$PM_{2.5}$ ratio was less than 0.5% for the Task 3 ME tests (48%, 70%, and 85%) and greater than 5% (and up to 50%) for the other two Tasks. This suggest some possible complexities with correlations that changes with concentration and not just fuels alone. More data is needed to support this hypothesis.

7.2 Load Effects

Black carbon emissions on a g/kWh basis were found to decrease as the main engine load increases. In real-world operating conditions, the Task 2 and Task 3 results support the conclusion that for large, 2-stroke, slow speed marine diesel engines, BC emissions decrease as main engine load increases. This is consistent with UCR's findings in previous research projects (see Section 6.3) and the research of others. The Task 3 results coincide with previous tests, but the Task 2 (Tier 2 69.6 2-stroke engine) results, are significantly lower than all previously tested MEs. This is the first Tier 2 engine tested by UCR and there may be some combustion improvements for NOx control that also offer low BC emissions. More at-sea tests of Tier 2 engines are needed to corroborate these results.

The trends of BC emissions as a function of load for smaller engines show more mixed results, however. The Task 1 test stand engine showed an increasing BC EF as load increased. This trend is consistent with the prevalence of EC at the higher load point for this engine. This increasing trend was also found to be exponential in some cases, including for the CS mode, for the RMG-380 fuel under BP sampling conditions, and for the increase in load from 70-72% to 77-79%. These engine test stand results were also consistent with results from a previous study of a 3.2 MW AE engine.

7.3 VSR

Vessel speed reduction typically decreases BC emissions per unit distance, even though it usually increases BC emissions per unit energy (g/kWh). VSR operation for all the Tier 0 and Tier 1 MEs tested showed higher BC emissions compared to other loads on a work basis, except for the Tier 2 engine tested. The Tier 2 BC emissions were 0.0193 g/kg-fuel at VSR speeds compared to 0.0515 g/kg-fuel at 25% load. There is some speculation that the engine controls for the Tier 2 vessel may incorporate special design elements for VSR given its widespread use. This suggests significant improvement in BC emissions may be possible for BC emissions when newer vessel designs are developed. It is unclear what a BC regulation would do to the design of modern engines, but these results are encouraging.

7.4 Fuel Effects

The RMB-30 with the lowest sulfur, viscosity and residual carbon content showed the highest BC emissions factors (g/kWh) at both 25% and 75% load points. The DMA fuel showed the lowest

emissions at the 75% engine load under BP conditions. The BC emissions from the RMG-380 fuel tended to be similar to those from the DMA fuel, or slightly higher. At 25 and 50% load points, the BC emissions for the RMG-380 fuel were similar to those for the DMA fuel and both were lower than the BC emissions for the RMB-30 fuel.

Fuel Switching: Three fuel switching studies were evaluated and for each only minor BC emission factor changes were observed. They varied from a few percent to as much as 60% less BC with lower sulfur fuels. The highest BC reduction occurred when switching from a HFO (3.4% S) to MGO (0.02% S) fuel and lower reductions for a LS HFO fuel and a LS MGO fuel. These results coincide with other studies, but the magnitude in the other studies suggest factors of 10 lower BC emissions when going to MGO fuels. More research is needed to confirm these findings when switching to MGO fuels.

7.5 Exhaust Gas Cleaning Systems

A ~30% BC reduction was observed in tests on an OGV equipped with the scrubber system. This suggests that EGCS that are designed to reduce sulfur emissions may have some BC reduction co-benefits; however, more research is needed to validate this result.

7.6 Emissions Inventories

Overall, it appears that BC emission factors near the lower end of the 0.1 to 1.0 g/kg of fuel range found in the literature likely provide the best estimate for the more prevalent larger marine engines during at sea operation. For marine vessels, BC emission inventory guidelines for North American and Europe recommend application of speciation factors (typically for elemental carbon) to PM2.5 emission inventories. For the U.S. National Emissions Inventory, PM2.5 emissions for Category 3 vessels are developed using a single fuel-based emission factor of 7.563 grams/gallon (2.35 gram/kg fuel) for ECA-compliant fuel. This emission factor has been used by EPA for several years, dating back to the development of Tier 4 Category 3 standards finalized in 2008. The North American black carbon inventory guidelines published by the Commission for Environmental Coordination (CEC) in 2015, recommend this emission factor for ECA-compliance fuel and an emission factor of 23.735 grams/gallon (7.37 gram/kg fuel) for global residual marine fuel. For estimating black carbon, the guidelines then recommend application of a factor from EPA's SPECIATE database of 77% (by weight) for ECA-compliant fuel, and 6% for global residual fuel. These are based on elemental carbon, as the majority of speciation factors in SPECIATE are, because of lack of measurement of "true" black carbon.

In this context, the measurements presented in this report can be useful in several ways for improving PM2.5 and black carbon inventories. The variety of engines, fuels and technologies provide a finer level of detail for producing a bottom-up PM2.5 inventory if vessel fleet and activity data are available for specific engines and technologies. In particular, Tier 2 and scrubber-equipped engine data are a significant update to the emission factors currently used. For developing BC inventories, the use of speciation factors will be recommended in the foreseeable future in North America and Europe. Overall, this approach accounts for the likelihood that PM inventories are more robust than straight BC inventories. The data collected in this program would be immediately useful for updating speciation factors in EPA's SPECIATE database, accounting for important variations in technology and fuel.

Engine load, speed, and size seemed to be primary factors in explaining the wide range of BC values, with fuel type being a more secondary consideration. For the larger main engines operating at higher loads, the BC emissions factors were generally towards the lower end of the range, with values ranging from 0.01 to 0.1 for the older technology main engine tested in Task 3. Results tended to be somewhat higher for the smaller engines, including the engine tested in the laboratory study and the auxiliary

engine tested in Task 3, with values closer to the upper end of the range found in the literature for the laboratory engine tested at high load. On the other hand, emission factors for the lower loads for the laboratory engine were near the lower end of the range found in the literature. Testing of the Tier 2 engine suggests that these BC emissions will likely continue to decline with the implementation of more modern engines to levels in the range of 0.0023 g/kg-fuel to 0.069 g/kg-fuel.

From the conducted research project and past observations from other in-house testing (as presented in Section 6), BC emission factors are a function of the following (in the order of significance):

1. Slow-speed diesel engines (two stroke) vs medium-speed diesel engines (four stroke) vs high-speed diesel engines (four stroke)
2. Engine load
3. Engine displacement
4. Engine Tier
5. EGCS Systems
6. Fuel

7.7 Reduction Potentials

The use of newer (e.g. Tier II) engines: While existing engine standards were established to control NOx, the control strategies utilized may have black carbon cobenefits, although further research is recommended to confirm. Policies that promote the use of newer engines, for example through accelerating fleet turnover or vessel repowers, may serve to reduce BC emissions. Slow-steaming/vessel speed reduction (VSR): On a mass per unit distance basis, VSR was seen to reduce black carbon emissions compared to higher speed operations. In contrast, for the (Tier II) engine tested, intermediate speeds (e.g. 28% load point) was associated with higher emissions, suggesting that engine manufacturers may be able to calibrate their engines for lower emissions under typical operations. Further research into the emission impacts of reduced speeds and how existing and potential future policies may help ensure that lower speeds result in commensurate emission reductions is recommended. EGCS: The use of scrubbers to meet global or regional fuel sulfur limits may have black carbon benefits. At the same time, while scrubbers appear to allow compliance with regional (SECA) gaseous phase sulfur limits, they do not appear to control sulfur particulates. This finding, which holds implications for near ship and near port public health and the overall design of IMO's fuel sulfur limits, points to the need for better data on scrubber performance. Use of high quality distillate fuels: Overall, distillate fuels had the lowest black carbon emissions, followed by conventional HFO. The low sulfur residual fuel tested, however, had the highest BC EF of the fuels tested. This raises concerns about the potential impact of IMO's tightened global sulfur limit of 0.5% for marine fuels in 2020 on BC emissions if met primarily through the use of blended fuels.

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Weingartner, E., Baltensperger, U., & Burtscher, H., 1995. Growth and structural changes of combustion aerosols at high relative humidity. Journal of Aerosol Science, 26(12), S667–S668.

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Appendix A – ISO Sampling Method

ISO 8178-1[3] and ISO 8178-2[4] 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[5], 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 to accurate collection of a representative sample from the exhaust and subsequent analysis. ISO points out that particulate must be collected in either a full flow or partial flow dilution system and UCR chose the partial flow dilution system with single venturi as shown in Figure A-1.

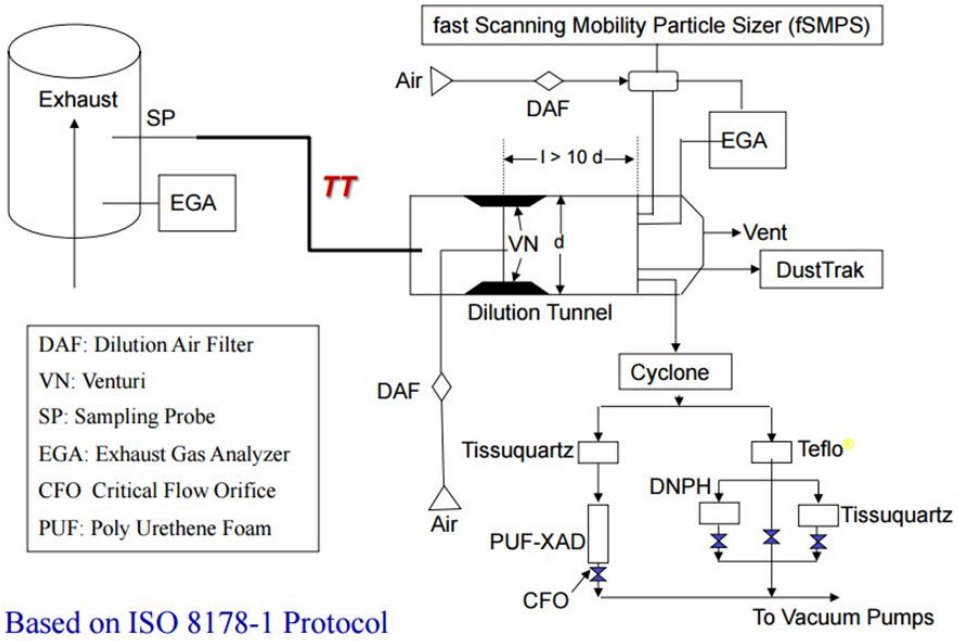


Figure A-1 Partial Flow Dilution System with Single Venturi

The flow in the dilution system eliminates water condensation in the dilution and sampling systems and maintains the temperature of the diluted exhaust gas at <52°C before the filters. ISO cautions the advantages of partial flow dilution systems can be lost to potential problems such as: losing particulates

[3] 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

[4] 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

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

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.

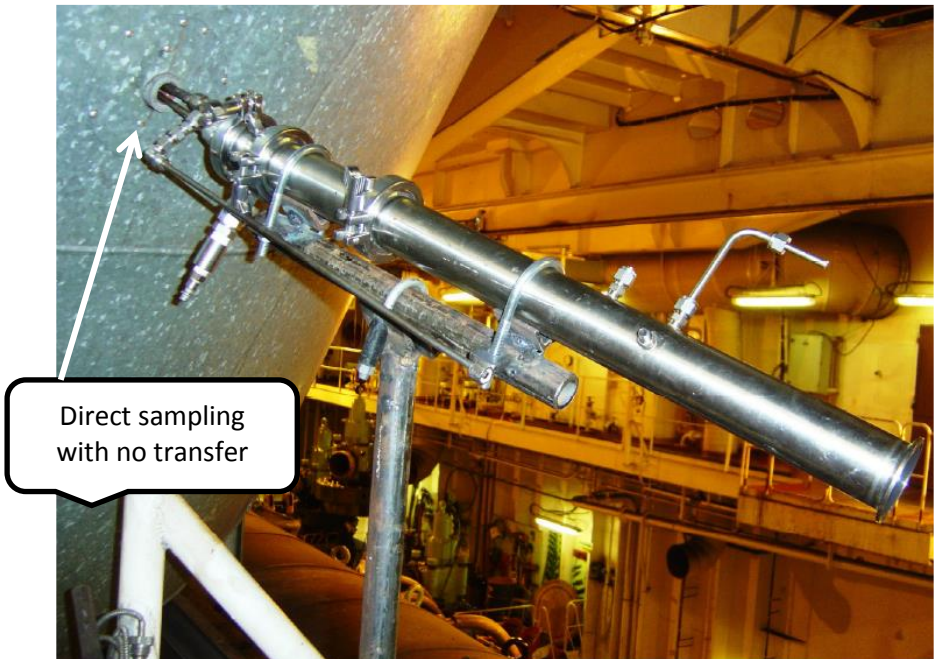


Figure A-2 measurement layout on an engine exhaust stack

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 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)	• should be of a sufficient length to cause complete mixing of the exhaust and dilution air under turbulent flow conditions; • should be at least 75 mm inside diameter (ID) for the fractional sampling type, constructed of stainless steel with a thickness of > 1.5 mm.	UCR uses fractional sampling; stainless steel tunnel has an ID of 50mm and thickness of 1.5mm.
Venturi (VN) --	The pressure drop across the venturi in the DT creates suction at the exit of the transfer tube TT and gas flow rate through TT is basically proportional to the flow rate of the dilution air and pressure drop.	Venturi proprietary design provided by MAN B&W; provides turbulent mixing.
Exhaust Gas Analyzers (EGA)	One or several analyzers may be used to determine the concentrations. Calibration and accuracy for the analyzers are like those for measuring the gaseous emissions.	UCR uses a 5-gas analyzer meeting IMO/ISO specs

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

Measuring Gaseous Emissions: ISO & IMO Criteria

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

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

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

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

ISO, IMO, 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 should be >95 % and will be evaluated prior to testing.

ISO requires measurement of the effects from 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.

Figure A-4 Gas analyzer setup with continuous data logging system

Details of the gases and the ranges for the Horiba instrument are shown in Table A-2. Note that the Horiba instrument measured 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 (NOx)	Heated Chemiluminescence Detector (HCLD)	0-25, 50, 100, 250, 500, 1000, & 2500 ppmv
Carbon Monoxide (CO)	Non dispersive Infrared Absorption (NDIR)	0-200, 500, 1000, 2000, & 5000 ppmv
Carbon Dioxide (CO_2)	Non dispersive Infrared Absorption (NDIR)	0-5, 10, & 20 vol%
Sulfur Dioxide (SO_2)	Non dispersive Infrared Absorption (NDIR)	0-200, 500, 1000, & 3000 ppmv
Oxygen	Zirconium oxide sensor	0-5, 10, & 25 vol%

For quality control, UCR carries out analyzer checks with calibration gases both before and after each test to check for drift. Because the instrument measures the concentration of five gases, the calibration gases are a blend of several gases (super-blend) made to within 1% specifications. Experience has shown that the drift is within manufacturer specifications of ±1% full scale per day shown in Table 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-250

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

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 CO2 per time Out… vol % CO2 * (grams exhaust/time * 1/density exhaust) → exhaust CO2 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 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 Gelman filter holder. One holder collects PM on a Teflon filter and the other collects PM on a quartz filter. UCR simultaneously collects PM on Teflon and quartz filters at each operating mode and analyzes them 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 Teflo filters and weighed using a Metler 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 Teflon filters provides a comparative check of PM mass measured by two independent methods for measuring PM mass.

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 as units of mg/m^3. As scattering per unit mass is a strong function of particle size and refractive index of the particle size distributions and as refractive indices in diesel exhaust strongly depend on the particular engine and operating condition, some 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.

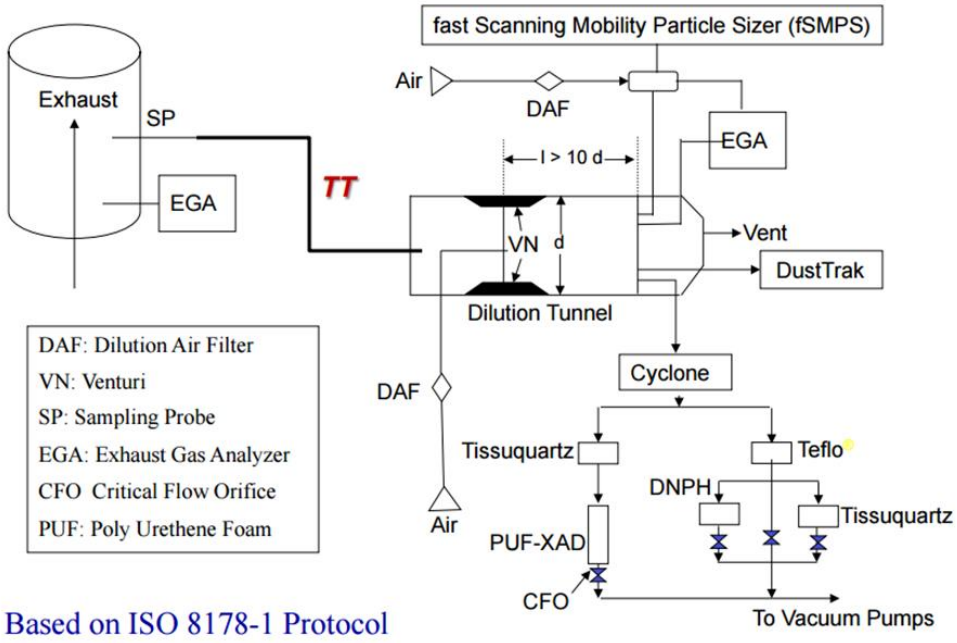


Figure A-5 Extended setup of the PFDS for non-regulated emissions

Appendix B – Quality Control

Pre-test calibrations

Prior to departing from UCR all systems were verified and cleaned for the testing campaign. This included all instruments used during this testing project. All systems were found to be within specifications and the systems were prepared for testing.

On-site calibrations

Pre- and post-test calibrations were performed on the gaseous analyzer using NIST traceable calibration bottles. Post-test dilution ratio was verified by removing the probe from the dilution tunnel and sampling from the raw exhaust. This method has been used in addition to operating two gas analyzers and has been shown to be reliable. Hourly zero checks were performed with each of the real time PM instruments. Leak checks were performed for the total $PM_{2.5}$ system prior to each sample point.

Post-test and data validation

Post-test evaluation includes verifying consistent dilution ratios between points, 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 with-in reason this suggests that the load and mass of emissions measured are reasonable and representative. Thus, this suggests the data collected for the test article are accurate and representative of a properly functioning system.

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 Example Chain of Custody Form

PRAXAIR.

Praxair Distribution, Inc.
5700 S. Alameda St.
Los Angeles, CA 90058
Tel: 323-585-2154
Fax: 714-542-6689

11/06/2012

UC RIVERSIDE
DIESEL LAB
1200 COLUMBIA AVE
RIVERSIDE, CA 925210000
Attention: LUCI PACOCHA 909-781-5791,

Work Order No. **21895565**
Customer Reference No.

Product Lot/Batch No. **109230503**
Product Part No. **NI CD12CNP18PAS**

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 (CMM)
Analyst: **Chas Manning**

Approved Signer: **Nelson Ma**

Figure B-2 Sample Protocol Gas Analysis

Appendix C – Marine Testing Load References

Test Cycles and Fuels for Different Engine Applications

Engines for off-road use are made in a much wider range of power output and used in a more applications than engines for on-road use. The objective of IS0 8178-4[6] 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 should 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 should be 60% of the rated speed. If the maximum torque speed is greater than 75% of the rated speed then the intermediate speed should be 75% of rated speed.

The intermediate speed will typically be between 60% and 70% of the maximum rated speed for engines not designed to operate over a speed range on the full-load torque curve at steady state conditions. Intermediate speeds for engines used to propel vessels with a fixed propeller are defined based on that application.

[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)

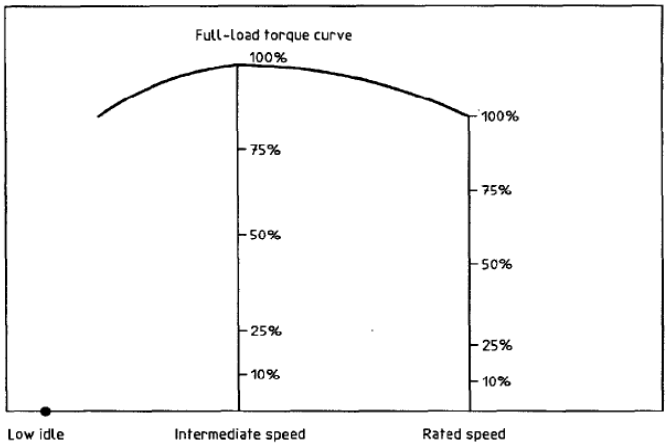


Figure C-1 Torque as a Function of Engine Speed

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.

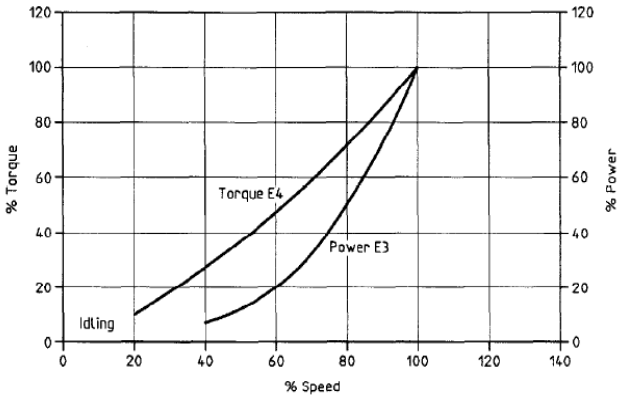


Figure C-2 Examples of Power Scales

Modes and Weighting Factors for Test Cycles

Most test cycles were derived from the 13-mode steady-state test cycle (UN-ECE R49). Apart from the test modes of cycles E3, E4 and E5, which are calculated from propeller curves, the test modes of the other cycles can be combined into a universal cycle with emissions values calculated using the appropriate weighting factors. Each test should 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 should be recorded and reported and the gaseous exhaust emission concentration values should 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

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 should 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 should be in accordance with the manufacturer's recommendations. The fuel temperature should be measured at the in-let 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 should 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

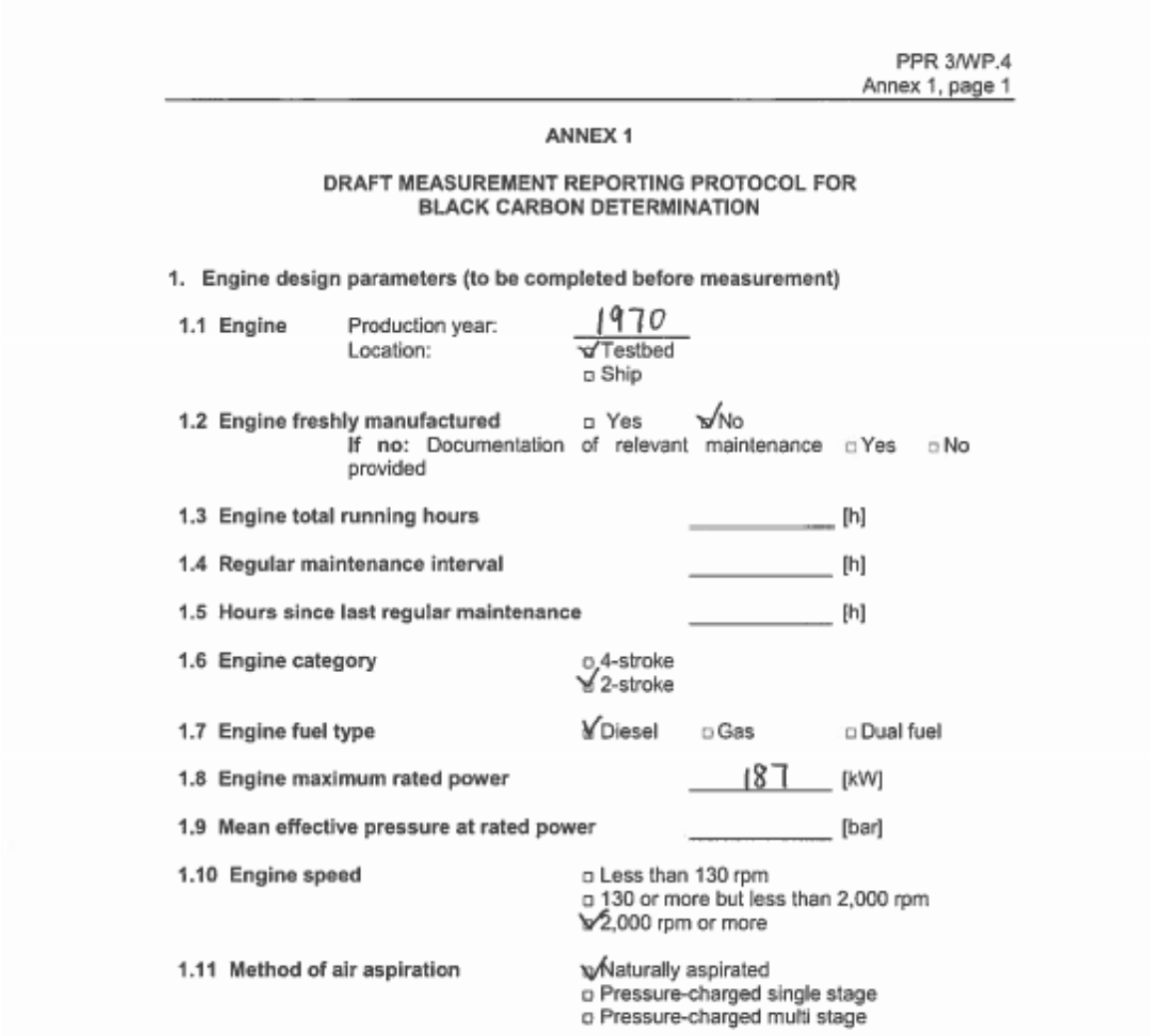
1) Customers and inspectors should note that the emission tests carried out using commercial fuel will not necessarily comply with limits specified when using reference fuels.

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 –EUROMOT Protocol

EUROMOT presented a draft reporting protocol for consideration by workshop participants that could be used in marine BC testing campaigns (see PPR 2 and PPR 3 for further detail). The protocol accounts for a variety of factors to be reported in BC emissions testing including, inter alia: engine design parameters, engine maintenance status, fuel type, detail on measurement instruments and calibration, and exhaust sample conditioning.

The protocol is provided in detail for the Task 1 test as listed in Figure D-1 through D-10 and summarized in the Table D-1 for all the tests performed.



PPR 3/WP.4
Annex 1, page 1

ANNEX 1

DRAFT MEASUREMENT REPORTING PROTOCOL FOR BLACK CARBON DETERMINATION

1. Engine design parameters (to be completed before measurement)

1.1 Engine Production year: 1970
Location: ☑ Testbed ☐ Ship

1.2 Engine freshly manufactured ☐ Yes ☑ No
If no: Documentation of relevant maintenance provided ☐ Yes ☐ No

1.3 Engine total running hours _____ [h]

1.4 Regular maintenance interval _____ [h]

1.5 Hours since last regular maintenance _____ [h]

1.6 Engine category ☐ 4-stroke ☑ 2-stroke

1.7 Engine fuel type ☑ Diesel ☐ Gas ☐ Dual fuel

1.8 Engine maximum rated power 187 [kW]

1.9 Mean effective pressure at rated power _____ [bar]

1.10 Engine speed
☐ Less than 130 rpm
☐ 130 or more but less than 2,000 rpm
☑ 2,000 rpm or more

1.11 Method of air aspiration
☑ Naturally aspirated
☐ Pressure-charged single stage
☐ Pressure-charged multi stage

Figure D-1 Protocol draft worksheet part 1 of 15

Table D-1 EUROMOT summary report for all tests by task and fuel used (some data is provided within the main report)

Project Detials		Engine design parameters																	
-	-	1.1		1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10	1.11	1.12	1.13	1.14	1.15.1	1.15.2	1.15.3	1.16
Project	Task	Engine		New	Run Hr	Maint Int.	Last	Category	Fuel Type	Max P	MEP	Eng Speed	Aspir.	Inj Sys.	Standard	Test Cycle	SLOC	CLL	IVSL	EGCS
name	#	year	type	n/a	hr	hr	hr	stroke	n/a	kW	bar	rpm	n/a	n/a	n/a	n/a	g/kWhr	g/hr	g/hr	n/a
ICCT	1	1970	stand	no	563	250	100	2	Diesel	187		>2000	natural	conv.	Tier 0	D2				no
ICCT	1	1970	stand	no	563	250	100	2	Diesel	187		>2000	natural	conv.	Tier 0	D2				no
ICCT	1	1970	stand	no	563	250	100	2	Diesel	187		>2000	natural	conv.	Tier 0	D2				no
ICCT	2	2011	ship	no	ME			2				< 130	multi	comn	Tier 2	E2				EGR
ICCT	2	2011	ship	no	AE			4				>130 <2000	multi	comn	Tier 2	D2				EGR
ICCT	3	1987	ship	no	ME			2				< 130	single	conv.	Tier 0	E2				scrubber
ICCT	3	1987	ship	no	AE			4				>130 <2000	single	conv.	Tier 0	D2				scrubber

Project Detials		Fuel					Lub Oil			Measurments						
-	-	2.1	2.3				3.1	3.2	3.3	4.1	4.2	4.3	4.4	4.5	4.6	
Project	Task	Type	Properties				Circulation	Cylinder	Valve Seat	BC measure	Principle	reported	values	ref cond	sample time	
name	#	Name	Viscosity	Density	Sulfphur	Carb. Resid	name	name	name	make/model	n/a	n/a	n/a	n/a	sec	repeats
ICCT	1	DMA	2.696	830.9	13	<0.1				see report	see report	see report	mg/kWhr	20C, 1 bar	>600	3
ICCT	1	RMA-12	13.73	858.6	8.2	<0.1				see report	see report	see report	mg/kWhr	20C, 1 bar	>600	3
ICCT	1	RMG-380	398.49	982.6	31,849	12.84				see report	see report	see report	mg/kWhr	20C, 1 bar	>600	3
ICCT	2	MGO								see report	see report	see report	mg/kWhr	20C, 1 bar	>600	3
ICCT	2	MGO								see report	see report	see report	mg/kWhr	20C, 1 bar	>600	3
ICCT	3	RMG-380								see report	see report	see report	mg/kWhr	20C, 1 bar	>600	3
ICCT	3	RMG-380								see report	see report	see report	mg/kWhr	20C, 1 bar	>600	3

1.12 Injection system

- ☐ Conventional
- ☐ Common rail

1.13 Applicable emission limit

- ☐ IMO Tier I
- ☐ IMO Tier II
- ☐ IMO Tier III
- ☑ Others: No Standar

1.14 Applicable test cycle

- ☐ C1 ☐ D2 ☐ E2 ☐ E3
- ☑ Others: 25% 50% and 75% Load points

1.15.1 Specific lubrication oil consumption

SLOC: _____ [g/kWh]

Breaking-in period:
- ☐ Finished
- ☐ Not finished
- ☐ Not applicable

1.15.2 Cylinder liner lubrication

- ☐ None
- ☐ Yes, active at

☐ 100%	Feed rate:	_____ [g/h]
☐ 75%	Feed rate:	_____ [g/h]
☐ 50%	Feed rate:	_____ [g/h]
☐ 25%	Feed rate:	_____ [g/h]
☐ 10%	Feed rate:	_____ [g/h]

Breaking-in period:
- ☐ Finished
- ☐ Not finished
- ☐ Not applicable

1.15.3 Inlet valve seat lubrication

- ☐ None
- ☐ Yes, active at

☐ 100%	Feed rate:	_____ [g/h]
☐ 75%	Feed rate:	_____ [g/h]
☐ 50%	Feed rate:	_____ [g/h]
☐ 25%	Feed rate:	_____ [g/h]
☐ 10%	Feed rate:	_____ [g/h]

1.16 Exhaust gas treatment device

- ☑ None ☐ Yes
- ☐ SCR
- ☐ Scrubber
- ☐ EGR
- ☐ Water injection
- ☐ Others: _____

Figure D-2 Protocol draft worksheet part 2 of 15

2. Fuel

2.1 Fuel in use

☐ ULSD ☐ DMX ☑ DMA ☐ DMZ ☐ DMB ☐ DMZ
☑ RMA ☐ RMB ☐ RMD ☐ RME ☑ RMG ☐ RMK

☐ Other: _____ acc.standard: _____

☐ Natural Gas

☐ Other gases acc. IGF:

☐ Liquid to gas fuel ratio as certified at mode point:

100% _____
75% _____
50% _____
25% _____
10% _____

Fuel properties and composition (in use during testing)

2.2 Gas

Please fill in as far as possible most important marked with *)

Property	Unit / Standard	Actual value	Remark
Methane number*)	[-] / DIN EN 16726		
Lower calorific value*)	[MJ/kg] / ISO 6976		
Higher calorific value	[MJ/kg] / ISO 6976		
Wobbe Indices Ws / Wi	[MJ/m³] / ISO 6976		
Density*)	[kg/m³] / ISO 6976		
Methane*)	wt.-% [kg/kg] / ISO 6974 or DIN 51894		
Ethane*)	wt.-% [kg/kg] / ISO 6974 or DIN 51894		
Propane*)	wt.-% [kg/kg] / DIN 51894		
Isobutane*)	wt.-% [kg/kg] / DIN 51894		
N-Butane*)	wt.-% [kg/kg] / DIN 51894		
Pentane	wt.-% [kg/kg] / DIN 51894		
Hexane	wt.-% [kg/kg] / DIN 51894		
Heptane	wt.-% [kg/kg] / DIN 51894		
Nitrogen	wt.-% [kg/kg] / ISO 6974		
Sulphur*)	wt.-% [kg/kg] / ISO 6326-5		
Hydrogen sulfide	wt.-% [kg/kg] / ISO 8819		
Carbon dioxide	wt.-% [kg/kg] / ISO 6974		

Figure D-3 Protocol draft worksheet part 3 of 15

Hydrogen	wt.-% [kg/kg] / DIN 51894		
Others			

2.3 Liquid fuel
DMA
Please fill in as far as possible most important marked with *) essential **)

Property	Unit / Standard	Actual value	Remark
Type of fuel	Grade / ISO 8217		DMA
Flash point*)	[°C] / ISO 2719		
Viscosity @ 40/50°C **)	[mm^2/s] / ISO 3104	2.696	cSt
Density @ 15°C *)	[kg/m^3] / ISO 3675 or 12185	830.9	
Net calorific value (Hu) *)	[J/g] / DIN 51900		
Sulphur content*)	ppm [mg/kg] / ISO 8754 or 14596	13	
Ash content*)	ppm [mg/kg] / ISO 6245		
Water content*)	ppm [mg/kg] / ISO 3733		
Carbon content*)	wt.-% [kg/kg] / ASTM D5291		
Hydrogen content*)	wt.-% [kg/kg] / ASTM D5291		
Nitrogen content*)	wt.-% [kg/kg] / DIN 51444		
Oxygen content*)	wt.-% [kg/kg] / DIN 51732		
Cetane index*)	ISO 4264		
CCAI*)			
FAME content*)	wt.-% [kg/kg] / EN 14078		
Mono aromatic compounds*)	wt.-% [kg/kg] / EN 12916		
Poly aromatic compounds*)	wt.-% [kg/kg] / EN 12916		
Di aromatic compounds	wt.-% [kg/kg] / EN 12916		
Tri aromatic compounds	wt.-% [kg/kg] / EN 12916		
Inorganic constituents (V)	ppm [mg/kg] / ISO 14597 or 8691		
Inorganic constituents (Ni)	ICP		
Carbon residues*)	wt.-% [kg/kg] / ASTM D4530	<0.1	
Others			

Figure D-4 Protocol draft worksheet part 4 of 14

2,3 Liquid fuel

Please fill in as far as possible most important marked with *) essential **)

Property	Unit / Standard	Actual value	Remark
Type of fuel	Grade / ISO 8217		RMB
Flash point*)	[°C] / ISO 2719		
Viscosity @ 40/50°C **)	[mm²/s] / ISO 3104	1373	5t
Density @ 15°C *)	[kg/m³] / ISO 3675 or 12185	858.6	
Net calorific value (Hu) *)	[J/g] / DIN 51900		
Sulphur content*)	ppm [mg/kg] / ISO 8754 or 14596	B.2	
Ash content*)	ppm [mg/kg] /ISO 6245		
Water content*)	ppm [mg/kg] /ISO 3733		
Carbon content*)	wt.-% [kg/kg] / ASTM D5291		
Hydrogen content*)	wt.-% [kg/kg] / ASTM D5291		
Nitrogen content*)	wt.-% [kg/kg] / DIN 51444		
Oxygen content*)	wt.-% [kg/kg] / DIN 51732		
Cetane index*)	ISO 4264		
CCAI*)			
FAME content*)	wt.-% [kg/kg] / EN 14078		
Mono aromatic compounds*)	wt.-% [kg/kg] / EN 12916		
Poly aromatic compounds*)	wt.-% [kg/kg] / EN 12916		
Di aromatic compounds	wt.-% [kg/kg] / EN 12916		
Tri aromatic compounds	wt.-% [kg/kg] / EN 12916		
Inorganic constituents (V)	ppm [mg/kg] / ISO 14597 or 8691		
Inorganic constituents (Ni)	ICP		
Carbon residues*)	wt.-% [kg/kg] / ASTM D4530	<0.1	
Others			

Figure D-5 Protocol draft worksheet part 5 of 15

2.3 Liquid fuel

Please fill in as far as possible most important marked with *) essential **)

Property	Unit / Standard	Actual value	Remark
Type of fuel	Grade / ISO 8217		RMG
Flash point*)	[°C] / ISO 2719		
Viscosity @ 40/50°C **)	[mm²/s] / ISO 3104	382.49	cSt
Density @ 15°C *)	[kg/m³] / ISO 3675 or 12185	982.6	
Net calorific value (Hu) *)	[J/g] / DIN 51900		
Sulphur content*)	ppm [mg/kg] / ISO 8754 or 14596	31849	
Ash content*)	ppm [mg/kg] / ISO 6245		
Water content*)	ppm [mg/kg] / ISO 3733		
Carbon content*)	wt.-% [kg/kg] / ASTM D5291		
Hydrogen content*)	wt.-% [kg/kg] / ASTM D5291		
Nitrogen content*)	wt.-% [kg/kg] / DIN 51444		
Oxygen content*)	wt.-% [kg/kg] / DIN 51732		
Cetane index*)	ISO 4264		
CCAI*)			
FAME content*)	wt.-% [kg/kg] / EN 14078		
Mono aromatic compounds*)	wt.-% [kg/kg] / EN 12916		
Poly aromatic compounds*)	wt.-% [kg/kg] / EN 12916		
Di aromatic compounds	wt.-% [kg/kg] / EN 12916		
Tri aromatic compounds	wt.-% [kg/kg] / EN 12916		
Inorganic constituents (V)	ppm [mg/kg] / ISO 14597 or 8691		
Inorganic constituents (Ni)	ICP		
Carbon residues*)	wt.-% [kg/kg] / ASTM D4530	12.84	
Others			

Figure D-6 Protocol draft worksheet part 6 of 15

3. Lube oil properties and composition
(in use during testing; Producers specification can be used)

3.1 Circulation lubrication oil please fill in as far as possible

Property	Unit / Standard	Actual value	Remark
Lube oil	Brand / Type		
Grade	Multi / Mono		
BN	mg KOH/g / ISO 3771		
Ash content	wt.-% [kg/kg] / ISO 6245		
Viscosity	[mm^2/s] / ASTM D7042		
Sulphur content	wt.-% [kg/kg] / ISO 20884		

3.2 Cylinder oil Please fill in as far as possible Please fill in if applicable

Property	Unit / Standard	Actual value	Remark
Lube oil	Brand / Type		
Grade	Multi / Mono		
BN	mg KOH/g / ISO 3771		
Ash content	wt.-% [kg/kg] / ISO 6245		
Viscosity	[mm^2/s] / ASTM D7042		
Sulphur content	wt.-% [kg/kg] / ISO 20884		

3.3 Valve seat lubrication oil Please fill in as far as possible Please fill in if applicable

Property	Unit / Standard	Actual value	Remark
Lube oil	Brand / Type		
Grade	Multi / Mono		
BN	mg KOH/g / ISO 3771		
Ash content	wt.-% [kg/kg] / ISO 6245		
Viscosity	[mm^2/s] / ASTM D7042		
Sulphur content	wt.-% [kg/kg] / ISO 20884		

Figure D-7 Protocol draft worksheet part 7 of 15

4. Measurement equipment information (to be completed before measurement) and parameters

Measurement instrument

4.1 Black Carbon measurement instrument information

Make: AVL Model: 483

4.2 Measurement principle

□ LII □ FSN ☑ PAS □ MAAP

□ Others: _____

4.3 Values reported as

□ EC (thermal) Protocol acc.: _____

□ rBC

☑ eBC

□ FSN

□ Others: _____

4.4 Values reported in unit

□ mg/m_n^3	(wet basis; act. O_2-concentration)	H_2O-conc.:	_____	[Vol.-%] (wet)
□ mg/m_n^3	(dry basis; act. O_2-concentration)			
□ mg/m_n^3	(dry basis; Ref. O_2-concentration)	O_2-conc.:	_____	[Vol.-%] (dry)
□ mg/kWh	refer to 5.			
□ FSN				
□ mg/kg fuel	refer to 5.			
□ Others:	_____			

4.5 Reference conditions
(only if 4.4 is referred to Norm-cubic meters [m_n^3])

Norm temperature: 15 [°C]

Norm pressure: 1.0 [mbar]

4.6 Sampling time / -number

Sampling time of each measurement: 600 [s]

If mean values are reported: Number of consecutive measurements at each mode point: 3 [-]

Acc. manufacturer specification: □ Yes □ No

Figure D-8 Protocol draft worksheet part 8 of 15

4.7 Black Carbon instrument parameter

Temperature inside measuring cell: 52.1 [°C]

Pressure inside measuring cell: 3.7 [mbar]

Wavelength(s) used: 850 [nm]

Mass absorption cross section(s) used: 3.10 ~~[m²/g]~~ $mV \cdot m^3/g$

Conversion equation(s) used: $[BC] = \sigma_{ap} \times MAC^{-1}$

Repeatability of the instrument used: _____

Reproducibility of the instrument used: _____

Acc. manufacturer specification: ☐ Yes ☐ No

Other parameters which could influence the measured values:

Parameter / Correction	Unit
Resonance frequency	Hz
Laser diode Temp.	°C

4.8 Black Carbon Instrument Calibration

Date of last calibration: _____ (dd.mm.yyyy)

Calibration procedure according manufacturer specification:
☐ Yes ☐ No ☐ Others: _____

Calibration including zero point: ☐ Yes ☐ No

Used medium for zero point calibration: _____

Used calibration standard:
- ☐ Synthetic flame soot
- ☐ Printex-U
- ☐ Graphite spark aerosol generator GfG soot
- ☐ Soot with inorganic coatings
- ☐ Soot without inorganic coatings
- ☐ Reflectance standards
- ☐ Others: _____

Remark _____

Leakage test performed before or after calibration:
☐ Yes ☐ No ☐ Not applicable

4.9 Sample gas pre-treatment
Please fill in if applicable

Exhaust gas dilution: ☒ Yes ☐ No

If yes, dilution ratio (1:x)	at mode point:	[%]
1:14		25% 50% 75%
1:400		: : :

Figure D-9 Protocol draft worksheet part 9 of 15

Dilution medium: ☑ Ambient air ☐ Exhaust gas
☐ Others: _____

Filtration of the dilution medium before dilution: ☑ Yes ☐ No

Temperature of the dilution medium: 20 [°C]

Temperature of the diluted exhaust gas: 20 [°C]

Evaporation tube ☑ Yes ☐ No
Temperature _____ [°C] acc. manufacturer spec. ☐ Yes ☐ No

Catalytic stripper ☑ Yes ☐ No
Temperature 400 [°C] acc. manufacturer spec. ☐ Yes ☐ No

Thermo-denuder ☑ Yes ☐ No
Temperature 20 [°C] acc. manufacturer spec. ☐ Yes ☐ No

Others: _____

4.10 Sample flow rate/volume

Acc. manufacturer specification: ☐ Yes ☐ No

Sample flow rate of the raw exhaust gas: ~~7480 1560~~ [l/min]

Sample flow rate of the diluted exhaust gas: 1.9 [l/min]

Sample volume of the raw exhaust gas: ~~40 L/min~~ [l]

Sample volume of the diluted exhaust gas: _____ [l]

☐ Subkinetic ☐ Isokinetic ☐ Superkinetic ☐ Not applicable

Sample line and probe

4.11 Sample/transfer line
Please fill in if applicable

Use of a sample line: ☑ Yes ☐ No (in situ,...)

Acc. manufacturer specification: ☐ Yes ☐ No

Length of the sample line: 1.5 [m]

Heated sample line: ☐ Yes ☑ No Temperature: _____ [°C]

Sample line material: Stainless / Copper

Inner diameter of the sample line: 9.4 [mm]

Isolated or heated connections between sample line, measurement instrument and probe: ☑ Yes ☐ No

Electrical conductive (sample line material): ☑ Yes ☐ No

Grounded: ☑ Yes ☐ No

Figure D-10 Protocol draft worksheet part 10 of 15

Grounding method: Metal Rack

Backflushing sample line between measurements: ☐ Yes ☐ No

4.12 Sample probe
Please fill in if applicable

Use of sample probe: ☑ Yes ☐ No (in situ,...)

Acc. manufacturer specification: ☐ Yes ☐ No

Material: ☐ Stainless steel ☑ Others: Stainless

Type/design:

☐ Probe with single hole at the end (pipe)

☐ Probe with single hole at the end (45° bevelled)

☐ Multi-hole

☐ L-shaped pipe with single hole, opening shielded with preclassifier (e.g. hat)

☐ Others: _____

Direction of the probe opening relative to the exhaust gas flow:

☐ With flow ☐ Against flow

☐ Others: _____

Effective cross section of sample hole opening(s) _____ [mm²]

Backflushing sample probe between measurements: ☐ Yes ☐ No

Figure D-11 Protocol draft worksheet part 11 of 15

Sampling point and probe location

4.13 Sample point and probe location

- ☐ Engine Outlet
- ☐ Downstream of heat exchanger
- ☐ Downstream of exhaust gas treatment device
  Treatment device active during measurement: ☐ Yes ☐ No
- ☑ Others: Downstream of Catalyst Stripper

Distance between engine outlet and sampling point: 2 [m]

Diameter of the exhaust gas pipe: 0.037 [m] inch

Type of exhaust gas pipe where the sample probe is located:

- ☑ Straight part of the exhaust gas pipe
- ☐ Bent part of the exhaust gas pipe

Immersion depth of the sample probe: 0 [m]

Orientation of the exhaust gas pipe where the sample probe is located:

☐ Horizontal ☑ Vertical ☐ Others: _____

Length of straight part of the exhaust gas pipe, if sample probe is located at straight part of the exhaust gas pipe:

Upstream sample probe: 1.5 [m]
Downstream sample probe: 3 [m]

Exhaust gas pulsation at the sampling point during measurement:

☐ No ☑ Yes _____ [mbar]

Figure D-12 Protocol draft worksheet part 12 of 15

5. Determination of engine load, exhaust gas flow, exhaust water content, fuel mass flow, O_2 and CO_2 (if applicable)

5.1 Determination of values, instrument performance and calibration shall be in accordance with the requirements of NOx Technical Code 2008 (NTC 2008) and its applicable appendices

5.2.1 Method of load determination	GE electrical Motor	
5.2.2 Estimated accuracy of engine load determination	+/- _____	[%] of reading
5.3.1 Method of exhaust gas flow determination	Fuel rate. / Air Pump	
5.3.2 Estimated accuracy of exhaust gas flow determination	+/- _____	[%] of reading
5.4.1 Method of exhaust water content determination	_____	
5.4.2 Estimated accuracy of exhaust water content determination	+/- _____	[%] of reading
5.5.1 Method of fuel mass flow determination	_____	
5.5.2 Estimated accuracy of fuel mass flow determination	+/- _____	[%] of reading
5.6.1 Method of O_2 and CO_2 determination	Horiba PG-350 / PG-250	
5.6.2 Estimated accuracy of O_2 and CO_2 determination	+/- _____	[%] of reading

Figure D-13 Protocol draft worksheet part 13 of 15

6. Measured values for Black Carbon determination
(to be completed during measurement; measured values)

Date of measurement (dd.mm.yyyy)						
Engine parameters						
Measurement at mode points:						[%]
	↓	↓	↓	↓	↓	
6.1 Stabilized mode point						
Actual Speed						[rpm]
Speed variation during measuring						+/- [%]
Actual Load						[kW]
Load variation during measuring						+/- [%]
6.2 Charge air temperature						[°C]
6.3 Charge air pressure						[mbar]
6.4 Exhaust gas temp. at engine outlet						[°C]
6.5 Exhaust gas temp. at sampling point (only if there is a significant difference to the exhaust gas temperature at the engine outlet)						[°C]
6.6 Exhaust gas back pressure						[mbar]
6.7 Exhaust gas mass flow						[kg/h]
Ambient conditions						
6.8 Ambient temp. at engine inlet						[°C]
6.9 Ambient pressure at engine inlet						[mbar]
6.10 Absolute humidity of ambient air						[g/kg]

Figure D-14 Protocol draft worksheet part 14 of 15

7. Black Carbon	Reported as (see 4.3):			Unit (see 4.4):		
7.1 Estimated accuracy of measured value						+/- [%]
7.2 Black Carbon emission						
	Remark:					
8. Measurement repeatability Indicators						
8.1 95% confidence interval (+/- unit measured)						
8.2 Variance						
8.3 Sample size (number of measurements taken						

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Figure D-15 Protocol draft worksheet part 15 of 15

Appendix E –Test log details

Table E-1 Emissions data log (Task 1)

		Filter Media Sample Time			Smoke Meter Sample Time										
ID	Date	Start Time	Duration	Stop Time	Start Time	Duration	Stop Time	Test	Sample Position	Test Condition	UCR Comments	Dyno Power	Dyno Current	Percent Max	Engine Power	Engine Speed
		hh:mm:ss	Min	hh:mm:ss	hh:mm:ss	Min	hh:mm:ss		n/a	n/a		volts	amps	%	kW	RPM
1	12/4/2015	10:17:00	5	10:22:00	10:14:00	3	10:17:00	Zero	BP	Cast						
2	12/4/2015	10:31:00	10	10:41:00	10:28:00	3	10:31:00	Span1	BP	Cast						1100
3	12/4/2015	10:45:00	10	10:55:00	10:42:00	3	10:45:00	Span 2	BP	Cast						1100
4	12/4/2015	10:58:00	10	11:08:00	10:55:00	3	10:58:00	Span 3	BP	Cast	Study how Smoke Meter work					1100
5	12/4/2015	16:48:00	5	16:53:00	16:45:00	3	16:48:00	Zero	BP	Cast						1100
6	12/4/2015	17:09:00	10	17:19:00	17:06:00	3	17:09:00	Span1	BP	Cast_2mg/m3	Calibration					1100
7	12/4/2015	17:36:00	10	17:46:00	17:33:00	3	17:36:00	Span 2	BP	Cast_0.2mg/m3						1100
8	12/4/2015	18:00:00	5	18:05:00	17:57:00	3	18:00:00	Zero	CS	Cast						1100
9	12/4/2015	18:24:00	10	18:34:00	18:21:00	3	18:24:00	Span1	CS	Cast_2mg/m3						1100
10	12/4/2015	18:48:00	10	18:58:00	18:45:00	3	18:48:00	Span 2	CS	Cast_0.2mg/m3						1100
11	12/5/2015	10:58:00	10	11:08:00	10:55:00	3	10:58:00	DMA	CS	25%	SP2 and MSS lost power @10:05	258	-96	26%	28.8	1100
12	12/5/2015	11:10:00	10	11:20:00	11:07:00	3	11:10:00	DMA	CS	25%		258	-98	27%	25.3	1100
13	12/5/2015	11:35:00	10	11:45:00	11:32:00	3	11:35:00	DMA	CS	25%		258	-100	27%	25.8	1100
14	12/5/2015	12:01:00	10	12:11:00	11:58:00	3	12:01:00	DMA	BP	25%	Switch BP @ 11:47	258	-100	27%	25.8	1100
15	12/5/2015	12:28:00	10	12:38:00	12:25:00	3	12:28:00	DMA	BP	25%		259	-100	27%	25.9	1100
16	12/5/2015	13:02:00	10	13:12:00	12:59:00	3	13:02:00	DMA	CS	50%		259	-180	49%	46.6	1100
17	12/5/2015	13:26:00	10	13:36:00	13:23:00	3	13:26:00	DMA	CS	50%		259	-180	49%	46.6	1100
18	12/5/2015	14:00:00	10	14:10:00	13:57:00	3	14:00:00	DMA	CS	75%	Switch 75% @ 13:41	260	-262	71%	68.1	1100
19	12/5/2015	14:33:00	10	14:43:00	14:30:00	3	14:33:00	DMA	CS	75%		260	-262	71%	68.1	1100
20	12/5/2015	14:55:00	10	15:05:00	14:52:00	3	14:55:00	DMA	CS	75%	Semi-EC/OC lost cable connection @ 14:57	260	-260	70%	67.6	1100
21	12/5/2015	15:21:00	10	15:31:00	15:18:00	3	15:21:00	DMA	BP	75%	Switch BP @ 15:08 NTK stopped working @ 15:	260	-260	70%	67.6	1100
22	12/5/2015	15:40:00	10	15:50:00	15:37:00	3	15:40:00	DMA	BP	75%	Switch CS @ 15:55	260	-260	70%	67.6	1100
23	12/6/2015	8:35:00	10	8:45:00	8:32:00	3	8:35:00	RMA-12	CS	25%	Engine started warm up @ 07:34	259	-95	26%	24.6	1100
24	12/6/2015	9:00:00	10	9:10:00	8:57:00	3	9:00:00	RMA-12	CS	25%	CPC and SP2 showed peaks Aethelomater touc	259	-95	26%	24.6	1100
25	12/6/2015	9:20:00	10	9:30:00	9:17:00	3	9:20:00	RMA-12	CS	25%	AMS port open	259	-97	26%	25.1	1100
26	12/6/2015	9:50:00	10	10:00:00	9:47:00	3	9:50:00	RMA-12	BP	25%	Switch BP @ 09:40	259	-96	26%	24.9	1100
27	12/6/2015	10:10:00	10	10:20:00	10:07:00	3	10:10:00	RMA-12	BP	25%	AMS port fixed, CPC still showed peaks	259	-96	26%	24.9	1100
28	12/6/2015	10:45:00	10	10:55:00	10:42:00	3	10:45:00	RMA-12	CS	50%	Switch CS @ 10:25	259	-193	52%	50.0	1100
29	12/6/2015	11:05:00	10	11:15:00	11:02:00	3	11:05:00	RMA-12	CS	50%		259	-194	53%	50.2	1100
30	12/6/2015	11:40:00	10	11:50:00	11:37:00	3	11:40:00	RMA-12	CS	75%	Switch 75% @ 11:22	260	-260	70%	67.6	1100
31	12/6/2015	12:00:00	10	12:10:00	11:57:00	3	12:00:00	RMA-12	CS	75%		260	-260	70%	67.6	1100
32	12/6/2015	12:20:00	10	12:30:00	12:17:00	3	12:20:00	RMA-12	CS	75%	NTK stopped working	260	-260	70%	67.6	1100
33	12/6/2015	12:45:00	10	12:55:00	12:42:00	3	12:45:00	RMA-12	CS	75%	RDD maybe sample from ambient	260	-260	70%	67.6	1100
34	12/6/2015	13:10:00	10	13:20:00	13:07:00	3	13:10:00	RMA-12	BP	75%	Switch BP @ 13:00	260	-261	71%	67.9	1100
35	12/6/2015	13:30:00	10	13:40:00	13:27:00	3	13:30:00	RMA-12	BP	75%		260	-260	70%	67.6	1100
36	12/6/2015	13:50:00	10	14:00:00	13:47:00	3	13:50:00	RMA-12	BP	75%		260	-260	70%	67.6	1100
37	12/7/2015	8:45:00	5	8:50:00	8:42:00	3	8:45:00	RMG-380	CS	50%	MSS warm-up issue, flow rate was too low	259	-175	47%	45.3	1100
38	12/7/2015	9:05:00	5	9:10:00	9:02:00	3	9:05:00	RMG-380	CS	50%	MSS showed peak, but not 1000:1 instuments	259	-175	47%	45.3	1100
~~39~~	~~12/7/2015~~	~~9:35:00~~	~~5~~	~~9:40:00~~	~~9:32:00~~	~~3~~	~~9:35:00~~	~~RMG-380~~	~~CS~~	~~75%~~	~~Switch 75% @ 09:21 Fuel Press was too low, sw~~	~~259~~	~~-175~~	~~47%~~	~~45.3~~	~~1100~~
40	12/7/2015	10:00:00	5	10:05:00	9:57:00	3	10:00:00	RMG-380	CS	75%	Switch 75% @ 09:26	260	-284	77%	73.8	1100
~~41~~	~~12/7/2015~~	~~10:15:00~~	~~5~~	~~10:20:00~~	~~10:12:00~~	~~3~~	~~10:15:00~~	~~RMG-380~~	~~BP~~	~~75%~~	~~Overheated Aborted Early~~	~~260~~	~~-270~~	~~73%~~	~~70.2~~	~~1100~~
42	12/7/2015	10:50:00	5	10:55:00	10:47:00	3	10:50:00	RMG-380	BP	75%	Enigne re-start @ 10:31	260	-292	79%	75.9	1100
43	12/7/2015	11:10:00	5	11:15:00	11:07:00	3	11:10:00	RMG-380	BP	25%	25% @ 10:55	260	-91	25%	23.7	1100
44	12/7/2015	11:25:00	5	11:30:00	11:22:00	3	11:25:00	RMG-380	CS	25%		260	-91	25%	23.7	1100
45	12/7/2015	11:45:00	5	11:50:00	11:42:00	3	11:45:00	RMG-380	CS	75%	Switch 75% @ 11:35 till 11:50	260	-263	71%	68.4	1100
46	12/7/2015	12:00:00	5	12:05:00	11:57:00	3	12:00:00	RMG-380	CS	25%	CPC and SP2 lost signal @ 11:56 RDD stopped w	261	-97	26%	25.3	1100
47	12/7/2015	14:25:00	5	14:30:00	14:22:00	3	14:25:00	RMG-380	CS	25%	14 :00 re-start engine	260	-101	27%	26.3	1100
48	12/7/2015	14:40:00	5	14:45:00	14:37:00	3	14:40:00	RMG-380	BP	25%		206	-104	28%	21.4	1100
49	12/7/2015	15:05:00	5	15:10:00	15:02:00	3	15:05:00	RMG-380	BP	75%	Switch 75% BP @ 15:00 till 15:12	261	-265	72%	69.2	1100
50	12/7/2015	15:18:00	5	15:23:00	15:15:00	3	15:18:00	RMG-380	CS	75%	Switch 75% CS @ 15:12 till 15:20	261	-264	72%	68.9	1100

Table E-2 Emissions on a g/kWh basis (Task 2)

					On Stack Dilution 1:1 (g/kWhr)				Dilution 1:1 (g/g/kWhr)				Dilution 14:1 (g/g/kWhr)											Dilution 1400:1 (g/g/kWhr)			
ID	Test	Sample Position	Percent Max	Engine Power	FSN_1	LII	NTK		FSN_2	LII	PG-350		MSS	Batched			Teflon	Sulfate	Dustrak	Pax	SemiCont			LII	MAAP	Aethalometer		CPC
			%	Kw			NOx	PM			NOX	CO2		EC	OC	EC+1.4OC					EC	OC	EC+1.4OC			880 nm	C370 nm	#/kWhr
11	DMA	CS	26%	24.8	0.06	0.03	28.5	0.19	0.03	0.02			0.02	0.12	0.15	0.33	0.23		0.03	0.03					0.05	0.07	0.08	3.84E+11
12	DMA	CS	27%	25.3	0.06	0.03	29.7	0.20	0.03	0.02			0.02	0.04	0.09	0.16	0.11		0.03	0.03	0.02	0.00	0.02		0.05	0.07	0.08	3.70E+11
13	DMA	CS	27%	25.8	0.06	0.03	30.3	0.20	0.03	0.02	29.8	1301	0.02	0.02	0.03	0.07	0.04		0.03	0.04	0.02	0.00	0.02		0.05	0.08	0.08	3.74E+11
14	DMA	BP	27%	25.8	0.05	0.03	27.2	0.17	0.04	0.02	27.4	1301	0.04	0.03	0.32	0.48	0.35		0.18	0.07	0.03	0.13	0.21		0.10	0.13	0.13	8.63E+12
15	DMA	BP	27%	25.9	0.05	0.03	27.0	0.17	0.05	0.02	26.6	1301	0.04	0.03	0.31	0.47	0.34		0.18	0.07	0.03	0.13	0.21		0.10	0.10	0.11	8.46E+12
16	DMA	CS	49%	46.6	0.10	0.07	24.7	0.09	0.06	0.04	19.2	1144	0.05	0.04	0.05	0.11	0.07		0.07	0.08	0.04	0.01	0.05		0.09	0.11	0.10	2.08E+11
17	DMA	CS	49%	46.6	0.10	0.07	24.7	0.09	0.06	0.04	19.6	1144	0.05	0.04	0.04	0.09	0.07		0.06	0.07	0.04	0.01	0.05		0.10	0.10	0.09	2.04E+11
18	DMA	CS	71%	68.1																								
19	DMA	CS	71%	68.1	0.32	0.19	21.5	0.08	0.23	0.26	18.0	1054	0.18	0.16	0.04	0.21	0.21		0.23	0.26					0.10	0.23	0.20	2.47E+11
20	DMA	CS	70%	67.6	0.32	0.18	21.8	0.08	0.23	0.27	22.9	1055	0.18	0.15	0.04	0.20	0.21		0.23	0.25	0.16	0.01	0.17		0.10	0.21	0.17	2.59E+11
21	DMA	BP	70%	67.6	0.34	0.17	21.8	0.07	0.31	0.33	22.0	1055	0.27	0.20	0.18	0.45	0.44		0.66	0.39					0.18	0.39	0.34	
22	DMA	BP	70%	67.6	0.33	0.16	21.8		0.32	0.34	21.8	1055	0.29	0.22	0.18	0.48	0.45		0.65	0.40	0.26	0.10	0.40		0.18	0.37	0.30	
23	RMA-12	CS	26%	24.6	0.14			0.21	0.08	0.04	19.0	1316	0.08	0.07	0.04	0.13	0.11		0.10	0.13	0.07	0.02	0.10	0.11	0.08	0.09	0.09	5.03E+11
24	RMA-12	CS	26%	24.6	0.12		24.5	0.22	0.08	0.04	19.3	1316	0.08	0.07	0.04	0.12	0.11		0.10	0.13	0.07	0.01	0.08	0.11	0.08	0.11	0.10	7.72E+11
25	RMA-12	CS	26%	25.1	0.13		24.3	0.22	0.07	0.04	18.9	1310	0.08	0.06	0.04	0.11	0.09		0.10	0.12	0.07	0.01	0.07	0.11	0.08	0.11	0.11	6.57E+11
26	RMA-12	BP	26%	24.9	0.11		24.8	0.22	0.10	0.04	25.2	1313	0.11	0.09	0.76	1.15	0.95		0.82	0.23	0.09	0.36	0.60	0.10	0.17	0.14	0.15	2.92E+12
27	RMA-12	BP	26%	24.9	0.11		23.8	0.22	0.10	0.04	24.4	1313	0.10	0.08	0.76	1.15	0.95		0.78	0.22	0.08	0.36	0.59	0.09	0.16	0.12	0.13	2.85E+12
28	RMA-12	CS	52%	50.0	0.22		24.0	0.12	0.17	0.14	19.5	1127	0.15	0.12	0.07	0.22	0.20		0.20	0.22	0.11	0.02	0.13	0.21	0.16	0.18	0.14	3.30E+11
29	RMA-12	CS	53%	50.2	0.23		23.4	0.11	0.18	0.15	20.1	1125	0.15	0.12	0.05	0.19	0.18		0.19	0.21	0.11	0.01	0.13	0.20	0.16	0.15	0.12	2.51E+11
30	RMA-12	CS	70%	67.6	0.67		20.1	0.19	0.53	0.63	17.4	1055	0.44	0.34	0.09	0.46	0.49		0.60	0.58				0.67	0.23	0.34	0.29	2.61E+11
31	RMA-12	CS	70%	67.6	0.69		19.8	0.18	0.53	0.64	17.4	1055	0.45	0.33	0.10	0.47	0.50		0.61	0.57	0.37	0.03	0.41	0.68	0.21	0.26	0.20	2.57E+11
32	RMA-12	CS	70%	67.6	0.72		20.0		0.58	0.63	17.4	1055	0.46	0.35	0.09	0.47	0.51		0.62	0.56	0.40	0.03	0.43	0.69	0.25	0.33	0.28	2.58E+11
33	RMA-12	CS	70%	67.6	0.71		20.1		0.55	0.62	17.1	1055	0.46	0.34	0.10	0.48	0.51		0.63	0.56	0.40	0.03	0.44	0.69	0.31	0.40	0.30	3.42E+11
34	RMA-12	BP	71%	67.9	0.76		19.9		0.77	0.75	20.6	1054	0.63	0.37	0.41	0.95	0.91		1.46	0.75	0.56	0.22	0.86	0.83	0.37	0.62	0.49	5.41E+11
35	RMA-12	BP	70%	67.6	0.73		20.3		0.79	0.78	20.3	1055	0.58	0.38	0.32	0.83	0.78		1.11	0.70	0.53	0.15	0.74	0.82	0.39	0.48	0.36	4.93E+11
36	RMA-12	BP	70%	67.6	0.73		20.2		0.77	0.77	20.2	1055	0.62	0.38	0.33	0.84	0.84		1.13	0.70	0.55	0.14	0.75	0.85	0.42	0.62	0.50	5.11E+11
37	RMG-380	CS	47%	45.3	0.09		18.4	0.35	0.07	0.03	19.1	918	0.06	0.03	0.06	0.11	0.19	0.03	0.08	0.07	0.05	0.01	0.07	0.06	0.16	0.07	0.08	9.07E+11
38	RMG-380	CS	47%	45.3	0.09		20.7	0.39	0.06	0.03	18.4	918	0.05	0.03	0.05	0.10	0.16	0.03	0.07	0.07	0.04	0.01	0.06	0.05	0.12	0.09	0.10	1.01E+12
39	RMG-380	CS	47%	45.3																								
40	RMG-380	CS	77%	73.8	0.54		11.8	0.19	0.36	0.48	12.9	826	0.32	0.22	0.04	0.28	0.38	0.00	0.45	0.32	0.25	0.01	0.26	0.44	0.20	0.23	0.17	2.40E+11
41	RMG-380	BP	73%	70.2																								
42	RMG-380	BP	79%	75.9	0.67		12.2	0.19	0.63	0.53	16.1	821	0.48	0.34	0.16	0.57	0.85	0.63	0.97	0.47	0.42	0.07	0.51	0.53	0.28	0.38	0.28	8.10E+11
43	RMG-380	BP	25%	23.7	0.05		22.4		0.04	0.01																		
44	RMG-380	CS	25%	23.7	0.04		22.2	0.61	0.02	0.01	17.7	1060	0.01	0.01	0.09	0.13	0.11	0.04	0.02	0.03	0.01	0.02	0.05	0.01	0.02	0.02	0.04	1.52E+12
45	RMG-380	CS	71%	68.4	0.34		13.1	0.19	0.24	0.28	10.2	840	0.17	0.12	0.06	0.21	0.24	0.01	0.23	0.18	0.15	0.02	0.17	0.21	0.16	0.13	0.09	2.87E+11
46	RMG-380	CS	26%	25.3	0.04		22.1	0.57	0.03	0.01	21.0	1045	0.01	0.01	0.06	0.09	0.10	0.04	0.02	0.02	0.03	0.01	0.05	0.01	0.03	0.02	0.02	1.08E+11
47	RMG-380	CS	27%	26.3	0.04		21.0	0.54	0.03	0.01		1036	0.01	0.01	0.06	0.10	0.11	0.06	0.02	0.03	0.01	0.01	0.03	0.01	0.14	0.04	0.06	1.35E+12
48	RMG-380	BP	28%	21.4	0.05		26.2	0.66	0.04	0.01		1160	0.02	0.02	0.41	0.59	1.13	1.80	0.10	0.04	0.01	0.23	0.34	0.01	0.09	0.07	0.11	6.25E+12
49	RMG-380	BP	72%	69.2	0.37		12.5	0.20	0.36	0.29			0.20	0.15	0.14	0.34	0.62	0.84	0.72	0.22	0.15	0.14	0.35	0.19		0.31	0.24	1.06E+12
50	RMG-380	CS	72%	68.9	0.45		12.7	0.20	0.29	0.35			0.14		0.01	0.01	0.03		0.26	0.14	0.11	0.01	0.13	0.17				2.60E+11

Table E-3 Emissions on a g/hr basis (Task 3)

					On Stack Dilution 1:1 (g/hr)				Dilution 1:1 (g/hr)				Dilution 14:1 (g/hr)												Dilution 1400:1 (g/hr)			
ID	Test	Sample Position	Percent Max	Duration	FSN_1	LII	NTK		FSN_2	LII	PG-350		MSS	Batched			Teflon	Sulfate	Dustrak	Pax	SemiCont			LII	MAAP	Aethalometer		CPC
			%	Min			NOx	PM			NOX	CO2		EC	OC	EC+1.4OC					EC	OC	EC+1.4OC			880 nm	C370 nm	#/hr
11	DMA	CS	26%	1.69	1.55	0.70	706	4.77	0.84	0.43			0.53	3.08	3.69	8.24	5.77		0.78	0.86					1.12	1.73	1.97	9.52E+13
12	DMA	CS	27%	1.48	1.41	0.77	751	5.00	0.73	0.49			0.55	1.00	2.25	4.15	2.83		0.79	0.86	0.50	0.09	0.62		1.27	1.83	2.01	9.35E+13
13	DMA	CS	27%	8.78	1.57	0.86	782	5.05	0.82	0.55	770	33565	0.61	0.55	0.83	1.71	1.02		0.89	0.96	0.51	0.09	0.63		1.26	2.13	2.14	9.64E+13
14	DMA	BP	27%	9.49	1.25	0.76	703	4.48	1.13	0.61	707	33565	0.93	0.76	8.26	12.33	9.04		4.71	1.80	0.83	3.37	5.55		2.62	3.36	3.47	2.23E+15
15	DMA	BP	27%	10.00	1.25	0.80	698	4.53	1.18	0.63	688	33696	0.98	0.74	8.11	12.09	8.85		4.77	1.82	0.85	3.29	5.47		2.51	2.69	2.82	2.19E+15
16	DMA	CS	49%	10.00	4.65	3.13	1151	4.17	2.70	1.95	896	53326	2.18	1.81	2.42	5.20	3.12		3.12	3.52	1.81	0.30	2.22		4.23	5.04	4.84	9.70E+13
17	DMA	CS	49%	10.00	4.51	3.05	1153	4.13	2.75	1.86	914	53326	2.14	1.71	1.84	4.28	3.22		2.98	3.29	1.78	0.24	2.13		4.70	4.80	4.41	9.51E+13
18	DMA	CS	71%	10.00																								
19	DMA	CS	71%	10.00	21.51	12.63	1465	5.58	15.55	17.62	1228	71769	12.09	10.65	2.84	14.63	14.10		15.63	17.45					6.73	15.95	13.62	1.68E+14
20	DMA	CS	70%	10.00	21.58	12.36	1474	5.62	15.82	18.53	1550	71341	11.92	10.08	2.57	13.67	13.89		15.33	16.95	10.49	0.78	11.58		6.44	14.31	11.56	1.75E+14
21	DMA	BP	70%	9.89	22.81	11.37	1471	5.04	21.23	22.51	1490	71341	18.36	13.66	11.86	30.27	29.60		44.34	26.10					12.25	26.19	23.11	
22	DMA	BP	70%	10.00	22.57	11.12	1471		21.89	22.83	1473	71341	19.52	15.08	12.24	32.22	30.24		44.17	27.38	17.35	6.68	26.71		11.85	24.97	20.42	
23	RMA-12	CS	26%	10.00	3.46		183	5.10	1.97	1.06	468	32372	2.06	1.61	1.10	3.15	2.65		2.38	3.15	1.66	0.50	2.36	2.79	1.92	2.27	2.23	1.24E+14
24	RMA-12	CS	26%	10.00	2.89		603	5.36	1.90	0.99	475	32372	2.02	1.67	0.98	3.03	2.73		2.47	3.10	1.68	0.13	1.87	2.74	1.97	2.79	2.34	1.90E+14
25	RMA-12	CS	26%	10.00	3.20		611	5.61	1.79	0.99	475	32903	1.95	1.59	0.92	2.87	2.37		2.44	2.96	1.67	0.14	1.87	2.64	2.04	2.85	2.83	1.65E+14
26	RMA-12	BP	26%	10.00	2.77		617	5.52	2.54	1.03	626	32638	2.72	2.14	18.94	28.65	23.59		20.37	5.65	2.15	9.07	14.85	2.45	4.24	3.43	3.69	7.25E+14
27	RMA-12	BP	26%	10.00	2.76		591	5.42	2.52	1.02	607	32638	2.58	2.03	18.97	28.59	23.65		19.43	5.41	2.10	9.02	14.72	2.31	4.07	3.00	3.14	7.08E+14
28	RMA-12	CS	52%	10.00	10.96		1201	5.78	8.51	7.17	977	56311	7.45	6.03	3.56	11.01	9.99		10.00	10.84	5.47	0.85	6.65	10.31	8.16	8.87	7.13	1.65E+14
29	RMA-12	CS	53%	10.00	11.35		1175	5.59	8.93	7.41	1011	56539	7.31	5.89	2.70	9.66	8.98		9.63	10.41	5.71	0.66	6.63	10.26	7.95	7.31	6.28	1.26E+14
30	RMA-12	CS	70%	10.00	45.06		1360	12.52	35.80	42.46	1176	71341	30.02	22.68	6.18	31.34	33.38		40.84	38.95	0.00	0.00	0.00	45.55	15.42	23.31	19.54	1.77E+14
31	RMA-12	CS	70%	10.00	46.90		1338	12.11	36.06	43.26	1174	71341	30.17	22.49	6.44	31.52	33.83		41.06	38.20	24.92	1.79	27.43	45.72	14.30	17.39	13.36	1.74E+14
32	RMA-12	CS	70%	10.00	48.44		1355		38.89	42.88	1173	71341	30.77	23.66	5.88	31.89	34.35		42.08	38.19	26.78	1.86	29.38	46.59	16.57	22.55	19.06	1.74E+14
33	RMA-12	CS	70%	10.00	48.04		1357		36.99	41.69	1153	71341	31.07	23.17	6.61	32.42	34.27		42.29	37.60	26.96	1.80	29.48	46.87	20.65	27.26	20.46	2.31E+14
34	RMA-12	BP	71%	10.00	51.33		1353		52.21	50.70	1401	71555	42.61	25.21	27.95	64.34	61.96		98.79	51.21	37.89	14.70	58.47	56.31	24.78	42.28	33.36	3.67E+14
35	RMA-12	BP	70%	9.89	49.15		1372		53.47	52.96	1373	71341	39.52	25.76	21.67	56.10	52.91		75.19	47.36	36.15	10.06	50.24	55.18	26.15	32.76	24.17	3.34E+14
36	RMA-12	BP	70%	10.00	49.23		1363		51.94	52.07	1363	71341	41.76	25.88	22.16	56.91	56.81		76.31	47.49	37.23	9.51	50.54	57.69	28.06	41.60	34.06	3.46E+14
37	RMG-380	CS	47%	4.71	3.93		836	15.77	3.00	1.37	864	41626	2.50	1.42	2.52	4.95	8.51	1.50	3.74	3.36	2.22	0.59	3.05	2.57	7.19	3.02	3.70	4.11E+14
38	RMG-380	CS	47%	5.00	4.16		938	17.89	2.82	1.43	836	41629	2.20	1.23	2.30	4.45	7.11	1.52	3.25	3.15	2.03	0.62	2.90	2.21	5.42	3.88	4.73	4.57E+14
39	RMG-380	CS	47%	5.00																								
40	RMG-380	CS	77%	5.00	40.09		874	14.01	26.70	35.70	950	61001	23.80	16.23	3.22	20.74	28.06	0.32	33.32	23.70	18.37	0.69	19.34	32.48	14.71	16.97	12.70	1.77E+14
41	RMG-380	BP	73%	5.00																								
42	RMG-380	BP	79%	3.85	51.19		927	14.77	47.71	40.07	1224	62333	36.42	26.17	12.46	43.62	64.87	47.81	73.59	35.55	31.65	5.03	38.68	40.60	21.58	28.68	21.03	6.15E+14
43	RMG-380	BP	25%	5.00	1.22		529	14.49	0.89	0.19			0.45	0.33	8.15	11.73	20.47	29.06	2.17	0.84					10.38	0.91	1.65	1.42E+15
44	RMG-380	CS	25%	5.00	1.06		524	14.43	0.56	0.15	418	25073	0.28	0.14	2.08	3.05	2.66	0.91	0.43	0.69	0.35	0.53	1.08	0.18	0.53	0.46	0.97	3.61E+14
45	RMG-380	CS	71%	3.95	23.29		897	13.09	16.20	19.34	700	57445	11.33	8.47	4.34	14.54	16.36	0.47	16.02	12.03	9.93	1.03	11.37	14.62	11.13	8.95	6.44	1.96E+14
46	RMG-380	CS	26%	5.00	1.01		559	14.48	0.71	0.17	531	26461	0.32	0.16	1.54	2.33	2.44	0.98	0.52	0.54	0.64	0.37	1.16	0.23	0.83	0.53	0.49	2.74E+13
47	RMG-380	CS	27%	5.00	1.06		551	14.26	0.69	0.19		27203	0.36	0.17	1.67	2.50	2.95	1.45	0.53	0.69	0.26	0.37	0.78	0.26	3.77	1.03	1.47	3.54E+14
48	RMG-380	BP	28%	5.00	1.00		561	14.23	0.90	0.20			0.47	0.41	8.78	12.71	24.23	38.48	2.14	0.81	0.25	5.03	7.29	0.21	1.90	1.45	2.33	1.34E+15
49	RMG-380	BP	72%	3.95	25.56		866	13.79	24.72	20.37			13.50	10.48	9.52	23.81	42.65	57.87	49.90	15.22	10.19	9.95	24.11	12.82		21.15	16.44	7.35E+14
50	RMG-380	CS	72%	2.52	31.24		875	14.00	20.01	23.87			9.75		0.70	0.98	1.99		18.19	9.83	7.83	0.76	8.89	11.88				1.79E+14

Table E-4 Emissions on a g/kg fuel basis (Task 4)

ID	Test	Sample Position	Percent Max	Fuel rate	On Stack Dilution 1:1 (g/kg fuel)				Dilution 1:1 (g/kg fuel)				Dilution 14:1 (g/kg fuel)												Dilution 1400:1 (g/kg fuel)			
					FSN_1	LII	NTK		FSN_2	LII	PG-350		MSS	Batched			Teflon	Sulfate	Dustrak	Pax	SemiCont			LII	MAAP	Aethalometer		CPC
			%	kg/hr			NOx	PM			NOX	CO2		EC	OC	EC+1.4OC					EC	OC	EC+1.4OC			880 nm	C370 nm	#/kg fuel
11	DMA	CS	26%	8.16	0.15	0.07	69.01	0.47	0.08	0.04			0.05	0.30	0.36	0.81	0.56		0.08	0.08					0.11	0.17	0.19	9.30E+12
12	DMA	CS	27%	8.29	0.14	0.07	72.34	0.48	0.07	0.05			0.05	0.10	0.22	0.40	0.27		0.08	0.08	0.05	0.01	0.06		0.12	0.18	0.19	9.01E+12
13	DMA	CS	27%	8.42	0.15	0.08	74.12	0.48	0.08	0.05	72.96	3182	0.06	0.05	0.08	0.16	0.10		0.08	0.09	0.05	0.01	0.06		0.12	0.20	0.20	9.14E+12
14	DMA	BP	27%	8.42	0.12	0.07	66.61	0.42	0.11	0.06	67.00	3182	0.09	0.07	0.78	1.17	0.86		0.45	0.17	0.08	0.32	0.53		0.25	0.32	0.33	2.11E+14
15	DMA	BP	27%	8.45	0.12	0.08	65.92	0.43	0.11	0.06	64.98	3182	0.09	0.07	0.77	1.14	0.84		0.45	0.17	0.08	0.31	0.52		0.24	0.25	0.27	2.07E+14
16	DMA	CS	49%	13.37	0.28	0.19	68.67	0.25	0.16	0.12	53.45	3182	0.13	0.11	0.14	0.31	0.19		0.19	0.21	0.11	0.02	0.13		0.25	0.30	0.29	5.79E+12
17	DMA	CS	49%	13.37	0.27	0.18	68.83	0.25	0.16	0.11	54.53	3182	0.13	0.10	0.11	0.26	0.19		0.18	0.20	0.11	0.01	0.13		0.28	0.29	0.26	5.67E+12
18	DMA	CS	71%																									
19	DMA	CS	71%	18.00	0.95	0.56	64.96	0.25	0.69	0.78	54.45	3182	0.54	0.47	0.13	0.65	0.62		0.69	0.77					0.30	0.71	0.60	7.47E+12
20	DMA	CS	70%	17.89	0.96	0.55	65.75	0.25	0.71	0.83	69.14	3182	0.53	0.45	0.11	0.61	0.62		0.68	0.76	0.47	0.03	0.52		0.29	0.64	0.52	7.80E+12
21	DMA	BP	70%	17.89	1.02	0.51	65.62	0.22	0.95	1.00	66.46	3182	0.82	0.61	0.53	1.35	1.32		1.98	1.16					0.55	1.17	1.03	
22	DMA	BP	70%	17.89	1.01	0.50	65.62		0.98	1.02	65.70	3182	0.87	0.67	0.55	1.44	1.35		1.97	1.22	0.77	0.30	1.19		0.53	1.11	0.91	
23	RMA-12	CS	26%	8.12	0.34		18.02	0.50	0.19	0.10	45.97	3182	0.20	0.16	0.11	0.31	0.26		0.23	0.31	0.16	0.05	0.23	0.27	0.19	0.22	0.22	1.22E+13
24	RMA-12	CS	26%	8.12	0.28		59.27	0.53	0.19	0.10	46.65	3182	0.20	0.16	0.10	0.30	0.27		0.24	0.30	0.17	0.01	0.18	0.27	0.19	0.27	0.23	1.87E+13
25	RMA-12	CS	26%	8.25	0.31		59.06	0.54	0.17	0.10	45.92	3182	0.19	0.15	0.09	0.28	0.23		0.24	0.29	0.16	0.01	0.18	0.26	0.20	0.28	0.27	1.60E+13
26	RMA-12	BP	26%	8.19	0.27		60.13	0.54	0.25	0.10	61.04	3182	0.27	0.21	1.85	2.79	2.30		1.99	0.55	0.21	0.88	1.45	0.24	0.41	0.33	0.36	7.07E+13
27	RMA-12	BP	26%	8.19	0.27		57.62	0.53	0.25	0.10	59.16	3182	0.25	0.20	1.85	2.79	2.31		1.89	0.53	0.20	0.88	1.44	0.23	0.40	0.29	0.31	6.90E+13
28	RMA-12	CS	52%	14.12	0.62		67.86	0.33	0.48	0.41	55.20	3182	0.42	0.34	0.20	0.62	0.56		0.57	0.61	0.31	0.05	0.38	0.58	0.46	0.50	0.40	9.32E+12
29	RMA-12	CS	53%	14.18	0.64		66.14	0.31	0.50	0.42	56.92	3182	0.41	0.33	0.15	0.54	0.51		0.54	0.59	0.32	0.04	0.37	0.58	0.45	0.41	0.35	7.10E+12
30	RMA-12	CS	70%	17.89	2.01		60.65	0.56	1.60	1.89	52.46	3182	1.34	1.01	0.28	1.40	1.49		1.82	1.74				2.03	0.69	1.04	0.87	7.87E+12
31	RMA-12	CS	70%	17.89	2.09		59.70	0.54	1.61	1.93	52.35	3182	1.35	1.00	0.29	1.41	1.51		1.83	1.70	1.11	0.08	1.22	2.04	0.64	0.78	0.60	7.74E+12
32	RMA-12	CS	70%	17.89	2.16		60.43		1.73	1.91	52.32	3182	1.37	1.06	0.26	1.42	1.53		1.88	1.70	1.19	0.08	1.31	2.08	0.74	1.01	0.85	7.77E+12
33	RMA-12	CS	70%	17.89	2.14		60.52		1.65	1.86	51.44	3182	1.39	1.03	0.29	1.45	1.53		1.89	1.68	1.20	0.08	1.31	2.09	0.92	1.22	0.91	1.03E+13
34	RMA-12	BP	71%	17.95	2.28		60.17		2.32	2.25	62.28	3182	1.89	1.12	1.24	2.86	2.76		4.39	2.28	1.68	0.65	2.60	2.50	1.10	1.88	1.48	1.63E+13
35	RMA-12	BP	70%	17.89	2.19		61.18		2.38	2.36	61.21	3182	1.76	1.15	0.97	2.50	2.36		3.35	2.11	1.61	0.45	2.24	2.46	1.17	1.46	1.08	1.49E+13
36	RMA-12	BP	70%	17.89	2.20		60.80		2.32	2.32	60.80	3182	1.86	1.15	0.99	2.54	2.53		3.40	2.12	1.66	0.42	2.25	2.57	1.25	1.86	1.52	1.54E+13
37	RMG-380	CS	47%	13.08	0.24		50.97	0.96	0.18	0.08	52.72	2539	0.15	0.09	0.15	0.30	0.52	0.09	0.23	0.20	0.14	0.04	0.19	0.16	0.44	0.18	0.23	2.51E+13
38	RMG-380	CS	47%	13.08	0.25		57.22	1.09	0.17	0.09	50.99	2539	0.13	0.08	0.14	0.27	0.43	0.09	0.20	0.19	0.12	0.04	0.18	0.14	0.33	0.24	0.29	2.79E+13
39	RMG-380	CS	47%																									
40	RMG-380	CS	77%	19.17	1.67		36.38	0.58	1.11	1.49	39.56	2539	0.99	0.68	0.13	0.86	1.17	0.01	1.39	0.99	0.76	0.03	0.81	1.35	0.61	0.71	0.53	7.39E+12
41	RMG-380	BP	73%																									
42	RMG-380	BP	79%	19.59	2.09		37.78	0.60	1.94	1.63	49.87	2539	1.48	1.07	0.51	1.78	2.64	1.95	3.00	1.45	1.29	0.20	1.58	1.65	0.88	1.17	0.86	2.51E+13
43	RMG-380	BP	25%	7.88	0.12		53.58	1.47	0.09	0.02	0.00		0.05	0.03	0.82	1.19	2.07	2.94	0.22	0.09						0.09	0.17	1.44E+14
44	RMG-380	CS	25%	7.88	0.11		53.07	1.46	0.06	0.01	42.30	2539	0.03	0.01	0.21	0.31	0.27	0.09	0.04	0.07	0.04	0.05	0.11	0.02	0.05	0.05	0.10	3.65E+13
45	RMG-380	CS	71%	18.05	1.03		39.66	0.58	0.72	0.85	30.92	2539	0.50	0.37	0.19	0.64	0.72	0.02	0.71	0.53	0.44	0.05	0.50	0.65	0.49	0.40	0.28	8.67E+12
46	RMG-380	CS	26%	8.32	0.10		53.60	1.39	0.07	0.02	50.92	2539	0.03	0.02	0.15	0.22	0.23	0.09	0.05	0.05	0.06	0.04	0.11	0.02	0.08	0.05	0.05	2.63E+12
47	RMG-380	CS	27%	8.55	0.10		51.45	1.33	0.06	0.02		2539	0.03	0.02	0.16	0.23	0.28	0.14	0.05	0.06	0.02	0.03	0.07	0.02	0.35	0.10	0.14	3.30E+13
48	RMG-380	BP	28%	6.93	0.11		64.60	1.64	0.10	0.02			0.05	0.05	1.01	1.46	2.79	4.43	0.25	0.09	0.03	0.58	0.84	0.02	0.22	0.17	0.27	1.54E+14
49	RMG-380	BP	72%	18.23	1.12		37.89	0.60	1.08	0.89			0.59	0.46	0.42	1.04	1.87	2.53	2.18	0.67	0.45	0.44	1.06	0.56		0.93	0.72	3.22E+13
50	RMG-380	CS	72%	18.18	1.37		38.43	0.61	0.88	1.05			0.43		0.03	0.04	0.09		0.80	0.43	0.34	0.03	0.39	0.52				7.86E+12

Task 2 Results for the Task 2 Modern Engine System

Task 2 test data reports in g/hr, g/kWhr, and g/kg-fuel

																		Calc Dry Exh. Flow Rate				Selected
Date	Project Name	Fuel	ATS	Location	Test Mode	Start Time	Load			Fuel Rate Meas.	cor. Factor	cor. Fuel Rate	Sample Duration	DR	Exh Temp	Filter Temp	Stack Pres	Exh Flow I		Exh Flow II		Exh Flow
mm/dd/yyyy	name					hh:mm:ss	MW	% MCR	% NCR	kg/hr	n/a	kg/hr	min	n/a	C	C	mbar	(scfm)	(m3/hr)	(scfm)	(m3/hr)	m3/hr
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	15:30:00	5.60	8%	10%	6246	1.00	6246	20.0	7.7	120.1	36.2	-6.8	202,879	429,876	37682	79845	79845
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	16:00:00	6.18	9%	12%	6333	1.00	6333	30.0	6.9	130.1	36.7	-6.7	192,445	407,769	39167	82990	82990
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	17:00:00	6.86	10%	13%	6430	1.00	6430	30.0	8.7	144.3	37.4	-6.9	159,695	338,374	35069	74308	74308
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	23:40:00	19.63	28%	37%	6610	1.00	6610	20.0	10.0	181.3	37.4	-5.6	116,018	245,828	66660	141244	141244
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	0:10:00	19.73	28%	37%	6652	1.00	6652	20.0	11.9	179.2	37.1	-4.4	117,784	249,571	67581	143197	143197
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	0:40:00	19.83	28%	37%	6629	1.00	6629	20.0	12.3	176.8	37.0	-3.5	119,486	253,177	68121	144341	144341
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	2:00:00	28.45	41%	53%	6791	1.00	6791	20.0	12.7	159.6	36.6	-2.3	130,004	275,463	103386	219064	219064
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	2:40:00	28.41	41%	53%	6838	1.00	6838	20.0	12.6	158.6	35.7	-2.2	132,815	281,419	101850	215809	215809
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	3:10:00	28.45	41%	53%	6775	1.00	6775	20.0	12.8	157.5	35.4	-2.0	133,192	282,217	103476	219253	219253
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	4:20:00	39.74	57%	75%	7100	1.00	7100	20.0	8.9	159.3	39.0	-4.1	139,929	296,492	144142	305419	305419
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	4:50:00	39.63	57%	74%	7071	1.00	7071	20.0	9.2	157.9	38.5	-4.0	139,023	294,573	144402	305971	305971
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	5:20:00	40.00	57%	75%	7043	1.00	7043	20.0	9.1	157.6	38.2	-3.9	139,490	295,563	144049	305222	305222

Date	Project Name	Fuel	ATS	Location	Test Mode	Start Time	g/hr															
mm/dd/yyyy	name					hh:mm:ss	NOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	Fuel Rate Carb. Kg/hr	PM soot	PM FSN	Dustrak
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	15:30:00	161,106	1,643	3,514,932	207	-	455.4	19.2	424.3	-	443.5	509.2	528.4	1,106	21.01512	28.5844	135.6
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	16:00:00	177,011	1,728	3,917,562	215	-	844.1	20.9	694.6	-	715.5	833.5	854.4	1,232	20.97749	31.06202	120.1
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	17:00:00	196,739	1,791	4,328,598	192	-	941.4	27.4	748.5	-	776.0	898.2	925.7	1,362	29.63126	33.6509	109.9
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	23:40:00	380,569	7,222	11,771,528	365	-	2,360.1	187.6	1,662.0	-	1,849.6	1,994.5	2,182.0	3,704	206.9106	219.2104	481.2
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	0:10:00	367,791	7,444	11,827,033	370	-	1,566.3	178.2	1,260.5	-	1,438.7	1,512.6	1,690.8	3,722	197.1118	234.2697	543.5
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	0:40:00	350,469	9,577	11,705,345	373	-	995.3	143.2	924.7	-	1,067.8	1,109.6	1,252.8	3,684	168.0096	249.1327	445.2
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	2:00:00	480,255	8,001	16,698,531	567	-	1,553.9	48.2	1,544.2	-	1,592.4	1,853.0	1,901.2	5,253	48.25218	96.82608	167.5
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	2:40:00	470,789	7,383	16,208,001	558	-	1,263.6	43.8	1,395.7	-	1,439.5	1,674.9	1,718.6	5,099	44.96134	89.34491	162.7
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	3:10:00	466,861	7,127	16,261,432	567	-	1,220.9	44.2	1,399.3	-	1,443.5	1,679.1	1,723.3	5,116	44.65239	89.0169	168.7
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	4:20:00	578,881	10,299	22,594,902	790	-	4,094.7	26.7	3,448.8	-	3,475.5	4,138.6	4,165.2	7,108	19.42523	41.23155	218.3
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	4:50:00	585,434	10,020	22,693,052	792	-	3,694.3	20.8	3,281.9	-	3,302.7	3,938.3	3,959.1	7,139	16.12102	34.26877	168.3
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	5:20:00	592,240	9,847	22,466,050	790	-	3,470.3	18.7	3,079.1	-	3,097.8	3,694.9	3,713.6	7,067	15.31166	34.79533	166.7

Date	Project Name	Fuel	ATS	Location	Test Mode	Start Time	g/kWhr														
mm/dd/yyyy	name					hh:mm:ss	NOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	bsFC Carb.	PM soot	PM FSN	Dustrak
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	15:30:00	28.79	0.29	628	0.04	-	0.081	0.003	0.076	-	0.079	0.091	0.094	198	0.003755	0.005108	0.024
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	16:00:00	28.66	0.28	634	0.03	-	0.137	0.003	0.112	-	0.116	0.135	0.138	200	0.003397	0.00503	0.019
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	17:00:00	28.68	0.26	631	0.03	-	0.137	0.004	0.109	-	0.113	0.131	0.135	199	0.00432	0.004906	0.016
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	23:40:00	19.38	0.37	600	0.02	-	0.120	0.010	0.085	-	0.094	0.102	0.111	189	0.010539	0.011165	0.025
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	0:10:00	18.64	0.38	599	0.02	-	0.079	0.009	0.064	-	0.073	0.077	0.086	189	0.009989	0.011872	0.028
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	0:40:00	17.67	0.48	590	0.02	-	0.050	0.007	0.047	-	0.054	0.056	0.063	186	0.008471	0.012561	0.022
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	2:00:00	16.88	0.28	587	0.02	-	0.055	0.002	0.054	-	0.056	0.065	0.067	185	0.001696	0.003403	0.006
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	2:40:00	16.57	0.26	571	0.02	-	0.044	0.002	0.049	-	0.051	0.059	0.060	179	0.001583	0.003145	0.006
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	3:10:00	16.41	0.25	572	0.02	-	0.043	0.002	0.049	-	0.051	0.059	0.061	180	0.001569	0.003129	0.006
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	4:20:00	14.57	0.26	569	0.02	-	0.103	0.001	0.087	-	0.087	0.104	0.105	179	0.000489	0.001038	0.005
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	4:50:00	14.77	0.25	573	0.02	-	0.093	0.001	0.083	-	0.083	0.099	0.100	180	0.000407	0.000865	0.004
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	5:20:00	14.81	0.25	562	0.02	-	0.087	0.000	0.077	-	0.077	0.092	0.093	177	0.000383	0.00087	0.004

Date	Project Name	Fuel	ATS	Location	Test Mode	Start Time	g/kg-fuel														
mm/dd/yyyy	name					hh:mm:ss	NOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	bsFC Carb.	PM soot	PM FSN	Dustrak
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	15:30:00	145.69	1.49	3178.7	0.1868	-	0.4118	0.0173	0.3837	-	0.4011	0.4605	0.4778	-	0.0190	0.0259	0.1226
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	16:00:00	143.63	1.40	3178.8	0.1742	-	0.6850	0.0169	0.5636	-	0.5806	0.6763	0.6933	-	0.0170	0.0252	0.0975
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	17:00:00	144.49	1.32	3179.0	0.1412	-	0.6914	0.0201	0.5497	-	0.5699	0.6597	0.6798	-	0.0218	0.0247	0.0807
5/22/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	23:40:00	102.74	1.95	3178.0	0.0986	-	0.6371	0.0506	0.4487	-	0.4993	0.5384	0.5891	-	0.0559	0.0592	0.1299
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	0:10:00	98.82	2.00	3177.9	0.0995	-	0.4208	0.0479	0.3387	-	0.3866	0.4064	0.4543	-	0.0530	0.0629	0.1460
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	0:40:00	95.12	2.60	3176.9	0.1013	-	0.2701	0.0389	0.2510	-	0.2898	0.3012	0.3400	-	0.0456	0.0676	0.1208
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	2:00:00	91.42	1.52	3178.6	0.1079	-	0.2958	0.0092	0.2939	-	0.3031	0.3527	0.3619	-	0.0092	0.0184	0.0319
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	2:40:00	92.33	1.45	3178.8	0.1095	-	0.2478	0.0086	0.2737	-	0.2823	0.3285	0.3371	-	0.0088	0.0175	0.0319
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	3:10:00	91.26	1.39	3178.8	0.1109	-	0.2387	0.0086	0.2735	-	0.2822	0.3282	0.3369	-	0.0087	0.0174	0.0330
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	1	4:20:00	81.44	1.45	3178.8	0.1112	-	0.5761	0.0038	0.4852	-	0.4889	0.5822	0.5860	-	0.0027	0.0058	0.0307
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	2	4:50:00	82.01	1.40	3178.8	0.1109	-	0.5175	0.0029	0.4597	-	0.4626	0.5517	0.5546	-	0.0023	0.0048	0.0236
5/23/2016	Tier 2 Engine	MGO	n/a	Post Economizer	3	5:20:00	83.80	1.39	3178.8	0.1117	-	0.4910	0.0026	0.4357	-	0.4383	0.5228	0.5255	-	0.0022	0.0049	0.0236

Task 3 Results for the Task 3 PM Scrubber Control System

The summary results in this Appendix include real time figures to show measurement stability followed by a full data set of measured parameters.

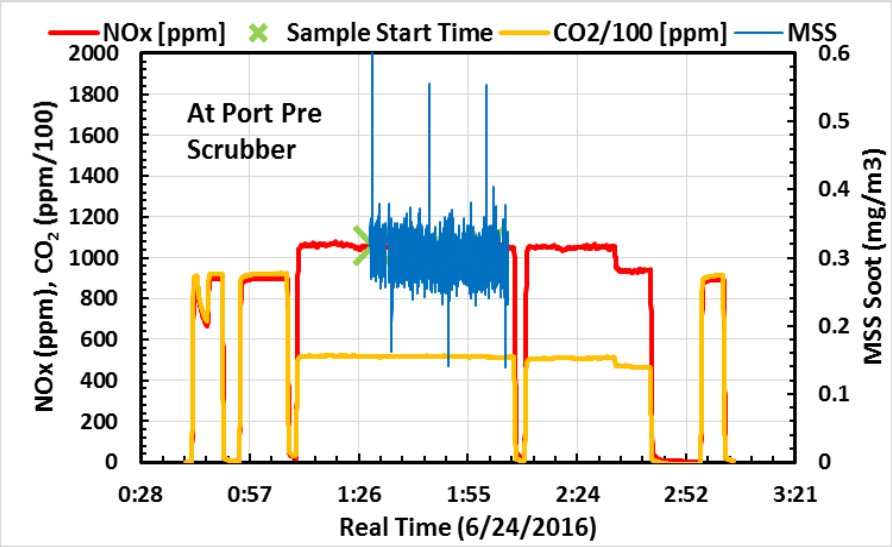


Figure E-Task3-1 Real time information for scrubber test 1 of 5

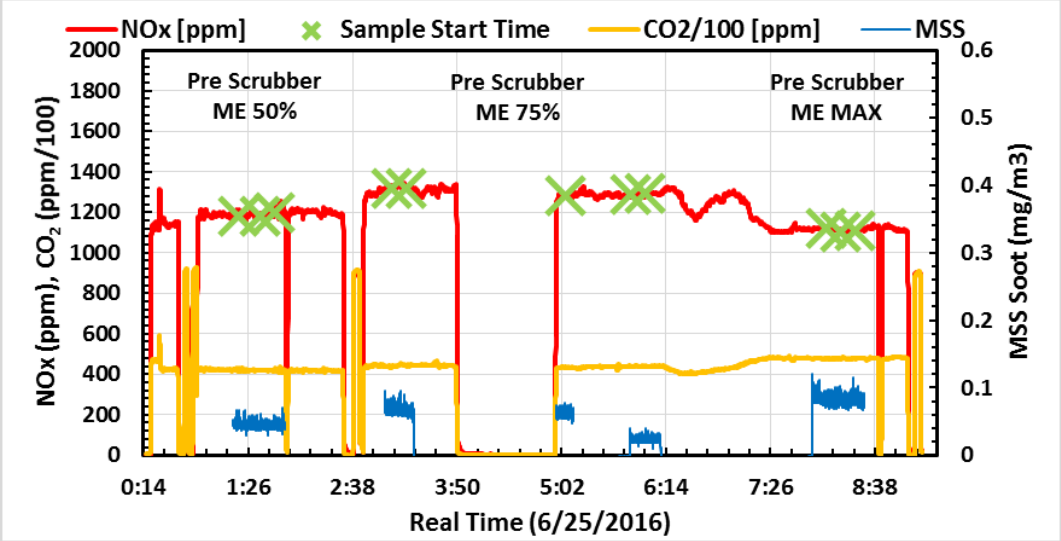


Figure E-Task3-2 Real time information for scrubber test 2 of 5

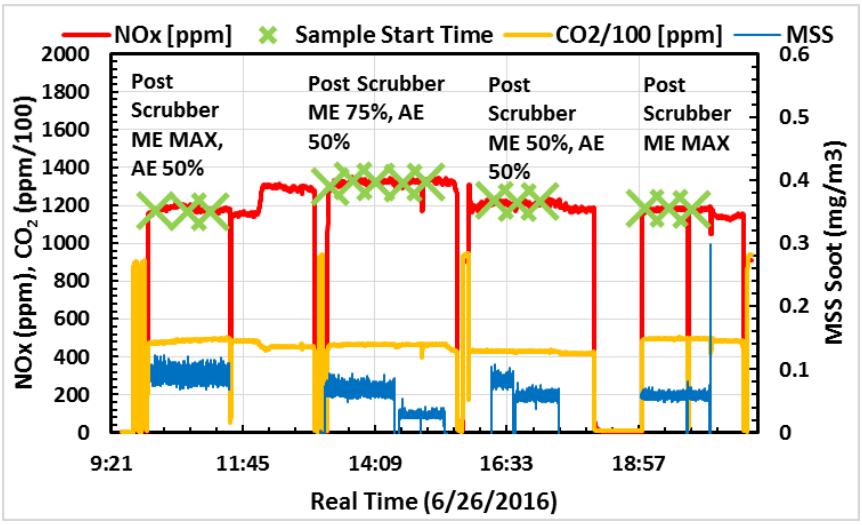


Figure E-Task3-3 Real time information for scrubber test 3 of 5

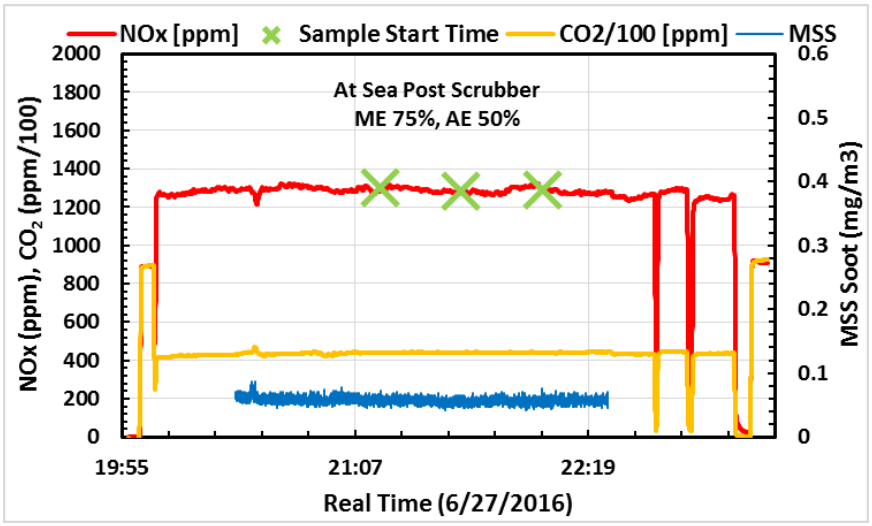


Figure E-Task3-4 Real time information for scrubber test 4 of 5

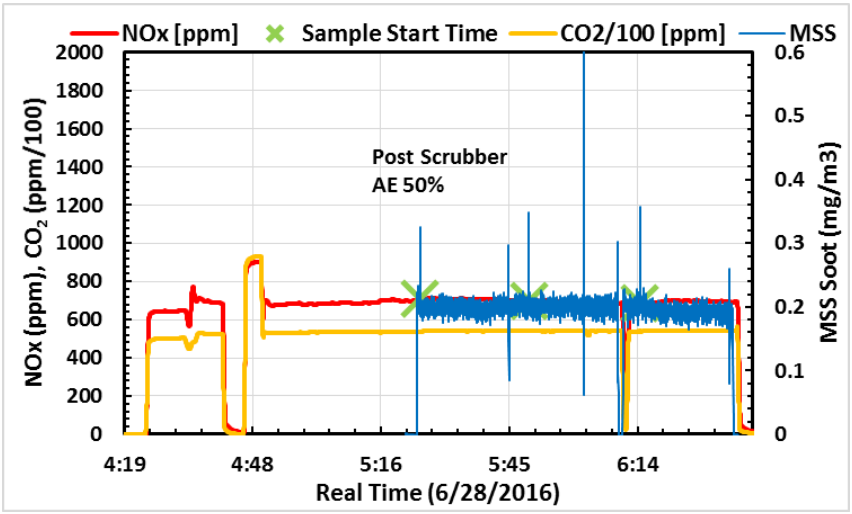


Figure E-Task3-5 Real time information for scrubber test 5 of 5

Table E- Task 3 emission factor results (g/kWhr)

Mode	Location [1]	DR	Exh Flow	Engine Load		Total Average Emissions Measured (g/kWhr) - triplicate													Weight (g/kWhr)	
			m3/hr	ME	AE	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	MSS	FSN	S_PM	S_gas
1	pre	6	50,252	15.56	0.62	13.8	0.263	623.4	3.946	1.22	0.013	0.079	0.914	1.006	0.095	1.021	0.0052	0.0064	0.135	1.97
2	pre	8	41,599	12.29	0.62	16.8	0.283	601.6	4.295	1.43	0.013	0.103	1.049	1.165	0.123	1.185	0.0060	0.0072	0.154	2.15
3	pre	12	29,258	8.50	0.62	15.6	0.278	587.8	4.650	1.16	0.011	0.114	0.787	0.913	0.137	0.936	0.0071	0.0086	0.116	2.33
4	pre	20	2,297	0.00	0.62	15.0	1.341	763.1	6.612	0.90	0.063	0.172	0.468	0.704	0.207	0.739	0.0473	0.0414	0.069	3.31
1	post	6	51,975	14.99	1.20	14.4	0.238	620.5	0.132	1.24	0.006	0.065	0.937	1.009	0.078	1.022	0.0037	0.0058	0.138	0.07
2	post	8	45,671	12.75	1.18	16.6	0.217	607.4	0.132	1.22	0.007	0.068	0.942	1.017	0.082	1.031	0.0037	0.0059	0.139	0.07
3	post	11	33,530	8.07	1.19	16.9	0.225	621.3	0.142	1.11	0.012	0.080	0.837	0.929	0.096	0.945	0.0053	0.0074	0.123	0.07
4	post	20	3,098	0.00	0.96	8.6	0.634	694.4	0.103	0.56	0.033	0.101	0.334	0.468	0.122	0.488	0.0270	0.0262	0.049	0.05
ISO Weighted	pre	9	38,946	11.60	0.62	15.8	0.330	611.6	4.409	1.30	0.015	0.103	0.935	1.054	0.124	1.075	0.0081	0.0090	0.138	2.21
ISO Weighted	post	9	42,380	11.62	1.17	15.8	0.244	617.6	0.133	1.17	0.009	0.072	0.888	0.969	0.086	0.984	0.0052	0.0072	0.131	0.07

Table E- Task 3 emission factor results (g/kg fuel)

Mode	Location [1]	DR	Exh Flow	Engine Load		Total Average Emissions Measured (g/kgfuel) - triplicate														
			m3/hr	ME	AE	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	MSS	FSN	S_PM	S_gas
1	pre	6	50,252	15.56	0.62	68.9	1.27	3106	19.58	6.09	0.061	0.39	4.58	5.03	0.47	5.11	0.024	0.030	0.674	9.80
2	pre	8	41,599	12.29	0.62	87.0	1.40	3099	22.05	7.42	0.064	0.53	5.46	6.05	0.63	6.15	0.028	0.035	0.803	11.04
3	pre	12	29,258	8.50	0.62	83.0	1.37	3096	24.45	6.19	0.055	0.60	4.20	4.86	0.72	4.98	0.033	0.042	0.618	12.24
4	pre	20	2,297	0.00	0.62	61.0	5.47	3111	26.96	3.65	0.258	0.70	1.91	2.87	0.84	3.01	0.193	0.169	0.281	13.49
1	post	6	51,975	14.99	1.20	71.5	1.39	3106	1.87	6.11	0.040	0.34	4.56	4.95	0.41	5.02	0.027	0.036	0.672	0.94
2	post	8	45,671	12.75	1.18	83.3	1.34	3104	2.06	6.10	0.049	0.37	4.66	5.07	0.44	5.15	0.028	0.037	0.686	1.03
3	post	11	33,530	8.07	1.19	82.9	1.44	3106	2.65	5.42	0.073	0.42	4.01	4.51	0.51	4.59	0.039	0.046	0.591	1.33
4	post	20	3,098	0.00	0.96	61.0	5.47	3111	26.96	3.65	0.258	0.70	1.91	2.87	0.84	3.01	0.193	0.169	0.281	13.49
ISO Weighted	pre	9	38,946	11.60	0.62	80.9	1.57	3101	22.26	6.68	0.071	0.52	4.82	5.42	0.62	5.52	0.037	0.042	0.710	11.14
ISO Weighted	post	9	42,380	11.62	1.17	79.5	1.58	3105	3.39	5.84	0.063	0.39	4.36	4.82	0.47	4.90	0.038	0.045	0.642	1.69

Table of combined emission reductions across the scrubber (with AE)

Mode	DR	Exh Flow	Engine Load		Total Percent Change from baseline (pre-scrubber) sample location												
		m3/hr	ME	AE	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	MSS	FSN
1	6	51,114	15.3	0.91	-4.2%	9.4%	0.5%	96.7%	-2.2%	53.3%	17.3%	-2.6%	-0.3%	17.3%	0.0%	29.4%	8.1%
2	8	43,635	12.5	0.90	1.6%	23.3%	-1.0%	96.9%	14.5%	43.3%	33.8%	10.2%	12.7%	33.8%	13.0%	37.6%	17.8%
3	12	31,394	8.28	0.90	-8.2%	19.2%	-5.7%	96.9%	4.0%	-2.9%	30.0%	-6.3%	-1.7%	30.0%	-0.9%	24.8%	14.1%
4	20	2,698	0.00	0.79	42.2%	52.7%	9.0%	98.4%	36.9%	48.5%	41.2%	28.8%	33.6%	41.2%	34.0%	42.9%	36.6%
ISO Wt	9	40,663	11.61	0.90	0.4%	26.1%	-1.0%	97.0%	9.9%	38.9%	30.7%	5.0%	8.0%	30.7%	8.5%	35.6%	19.9%

Table of combined emission reductions across the scrubber (without the AE)

Mode	DR	Exh Flow	Engine Load		Total Percent Change from baseline (pre-scrubber) sample location												
		m3/hr	ME	AE	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	MSS	FSN
1	6	51,114	15.3	0.91	-4.2%	9.4%	0.5%	96.7%	-2.2%	53.3%	17.3%	-2.6%	-0.3%	17.3%	0.0%	29.4%	8.1%
2	8	43,635	12.5	0.90	1.6%	23.3%	-1.0%	96.9%	14.5%	43.3%	33.8%	10.2%	12.7%	33.8%	13.0%	37.6%	17.8%
3	12	31,394	8.28	0.90	-8.2%	19.2%	-5.7%	96.9%	4.0%	-2.9%	30.0%	-6.3%	-1.7%	30.0%	-0.9%	24.8%	14.1%
ISO Wt	8	40,528	11.61	0.86	-1.7%	19.4%	-1.6%	96.9%	8.9%	36.4%	29.8%	4.4%	7.2%	29.8%	7.6%	32.7%	14.9%

Table of Direct comparisons ME at Maximum allowed load and no AEs

Mode	Location	DR	Exh Flow	Engine Load (MW)		Total Average Emissions Measured (g/kWhr) - triplicate												
			m3/hr	ME	AE	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	MSS	FSN
1	pre	6	50,252	15.56	0.00	13.8	0.21	617.0	3.82	1.23	0.0104	0.075	0.934	1.02	0.090	1.034	0.0033	0.0048
1	post	6	48,257	15.44	0.00	14.2	0.22	617.8	0.11	1.25	0.0055	0.058	0.923	0.99	0.070	0.998	0.0023	0.0045
Percent Change		0%	-4%	-1%	n/a	3%	1%	0%	-97%	2%	-47%	-22%	-1%	-3%	-22%	-4%	-31%	-5%

Table of Direct comparisons at two dilution ratios

Mode	Location	DR	Exh Flow	Engine Load (MW)		Total Average Emissions Measured (g/kWhr) - triplicate												
			m3/hr	ME	AE	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	MSS	FSN-raw
2	pre	8	41,599	12.29	0.00	16.9	0.22	592.7	4.17	1.46	0.0103	0.099	1.081	1.19	0.118	1.210	0.0037	0.0053
2	pre	20	43,437	12.83	0.00	16.7	0.22	592.3	3.83	1.53	0.0062	0.111	1.179	1.30	0.133	1.318	0.0033	0.0053
2	post	8	45,671	12.75	1.18	16.6	0.22	607.4	0.13	1.22	0.0074	0.068	0.942	1.02	0.082	1.031	0.0037	0.0059
2	post	20	45,588	12.77	1.18	16.6	0.22	605.9	0.13	1.19	0.0080	0.076	0.919	1.00	0.091	1.018	0.0038	0.0059
Percent Change Pre		150%	4%	4%	n/a	-1%	-2%	0%	-8%	5%	-40%	12%	9%	9%	12%	9%	-11%	0%
Percent Change Post		150%	0%	0%	0%	0%	0%	0%	-3%	-2%	8%	11%	-2%	-1%	11%	-1%	1%	0%

Table Direct comparisons for open loop vs closed loop

Mode	Location	Mode	Exh Flow	Engine Load (MW)		Total Average Emissions Measured (g/kWhr) - triplicate												
			m3/hr	ME	AE	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	MSS	FSN
2	post	OL	45,671	12.75	1.18	16.6	0.22	607.4	0.13	1.22	0.0074	0.068	0.942	1.02	0.082	1.031	0.0037	0.0059
2	post	CL	46,827	12.50	1.09	17.1	0.23	606.6	0.12	1.25	0.0092	0.071	0.941	1.02	0.086	1.036	0.0033	0.0078
Percent Change			3%	-2%	-8%	3%	8%	0%	-12%	3%	24%	5%	0%	0%	5%	1%	-12%	33%

Table Percent AE has on the total measured exhaust flow

Mode	Location	DR	Exh Flow		
			ME	AE	AE%
1	post	6	47,686	4,290	8%
2	post	8	41,265	4,406	10%
3	post	11	28,765	4,765	14%
4	post	20	0	3,098	100%

Table of estimates of the AE emission factors from measured results

Location	Meas. Or	DR	AE			Total Average Emissions Measured (g/kWhr) - triplicate												
	Est.		ExhFlow	Load Mw	Load %	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	MSS	FSN
pre	meas	20	2,297	0.62	29.4%	15.0	1.34	763.1	6.61	0.90	0.0633	0.172	0.468	0.70	0.207	0.739	0.0473	0.0414
post	est	20	4,290	1.19	56.3%	17.7	0.54	680.1	0.41	1.18	0.0123	0.161	1.165	1.34	0.193	1.371	0.0223	0.0234
post	meas	20	3,098	0.96	45.7%	8.6	0.63	694.4	0.10	0.56	0.0326	0.101	0.334	0.47	0.122	0.488	0.0270	0.0262

Table Total EF (g/kWhr) coefficient of variation (COV) for the triplicate measurements

Mode	Location	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	MSS	FSN
1	pre	0.8%	8.7%	0.3%	2.1%	1.4%	10.9%	3.0%	2.6%	2.2%	3.0%	2.2%	1.3%	0.2%
2	pre	0.8%	14.7%	1.0%	2.2%	5.2%	3.5%	5.1%	3.3%	3.2%	5.1%	3.2%	3.1%	2.1%
3	pre	5.8%	5.0%	5.5%	5.4%	7.8%	1.1%	5.8%	6.4%	6.2%	5.8%	6.2%	4.1%	5.4%
4	pre	1.2%	3.9%	0.0%	0.8%	14.3%	7.4%	5.0%	2.0%	3.1%	5.0%	3.1%	2.8%	0.7%
1	post	3.0%	1.6%	0.8%	10.2%	3.5%	4.4%	5.3%	3.8%	3.9%	5.3%	3.9%	3.8%	2.7%
2	post	1.0%	9.0%	1.6%	6.2%	2.0%	3.3%	5.3%	2.9%	3.0%	5.3%	3.1%	2.8%	2.2%
3	post	0.4%	2.2%	0.5%	0.4%	1.6%	7.4%	1.0%	2.0%	1.9%	1.0%	1.9%	0.5%	0.1%
4	post	1.7%	0.5%	0.0%	9.9%	2.2%	8.8%	8.3%	0.9%	2.7%	8.3%	2.9%	2.0%	0.1%
2.1	pre-hDR	0.3%	3.9%	0.8%	0.7%	1.5%	40.3%	7.3%	0.2%	0.6%	7.3%	0.7%	1.8%	0.0%
2.1	post-hDR	1.6%	1.1%	1.4%	1.8%	0.0%	4.0%	1.6%	0.7%	0.8%	1.6%	0.8%	1.5%	1.8%
1.1	post_ME_only	0.6%	3.8%	0.2%	8.9%	1.8%	6.4%	0.2%	5.1%	4.8%	0.2%	4.7%	0.8%	0.2%
2.2	post_CL	1.1%	2.5%	0.1%	0.3%	0.2%	4.9%	2.2%	0.5%	0.6%	2.2%	0.6%	1.6%	0.3%
COV less than 6%		136	87%											
COV >6% and <10%		15	10%											
COV >10% and <15%		4	3%											
COV > 15%		1	1%	large because of only two samples and very low values (0.004 and 0.008 g/kWhr)										
		156												

Appendix F –Task 1 Catalytic Stripper and Sulfur Adsorber

Catalytic stripper and sulfur absorber system

A 40 L/min catalytic stripper (CS) and two sulfur adsorbers were used in the ICCT sponsored project focused on understanding instrument performance and variability when measuring marine black carbon emissions, designed, constructed, and delivered by Kent Johnson of UC Riverside. The CSs consist of three heated flow-through ceramic monoliths that have a platinum and palladium-based washcoat. The design temperature range is 350°C - 400°C and the maximum operating flowrate is 40 L/min. Lower flowrates will increase the removal of semi-volatile material and increase particle loss. In the middle of the CS construction process, a technical project meeting highlighted the need for additional sulfur removal capability (beyond the removal due to the "poisoning" effect in which sulfur reversibly adsorbs to the precious metals in the CS). To meet this need, two "sulfur adsorbers," consisting of flow-through ceramic monoliths, containing barium were constructed. They are designed to capture gaseous SO_3 molecules resulting from the oxidation of SO_2 to SO_3 in the CS, and therefore they should be located downstream of the CS. Their design temperature range is 250°C - 300°C. Periodic regeneration of the adsorbers are typically required. This, includes bringing the adsorber section up to 350°C for thirty minutes with a flow of at least 1 slpm.

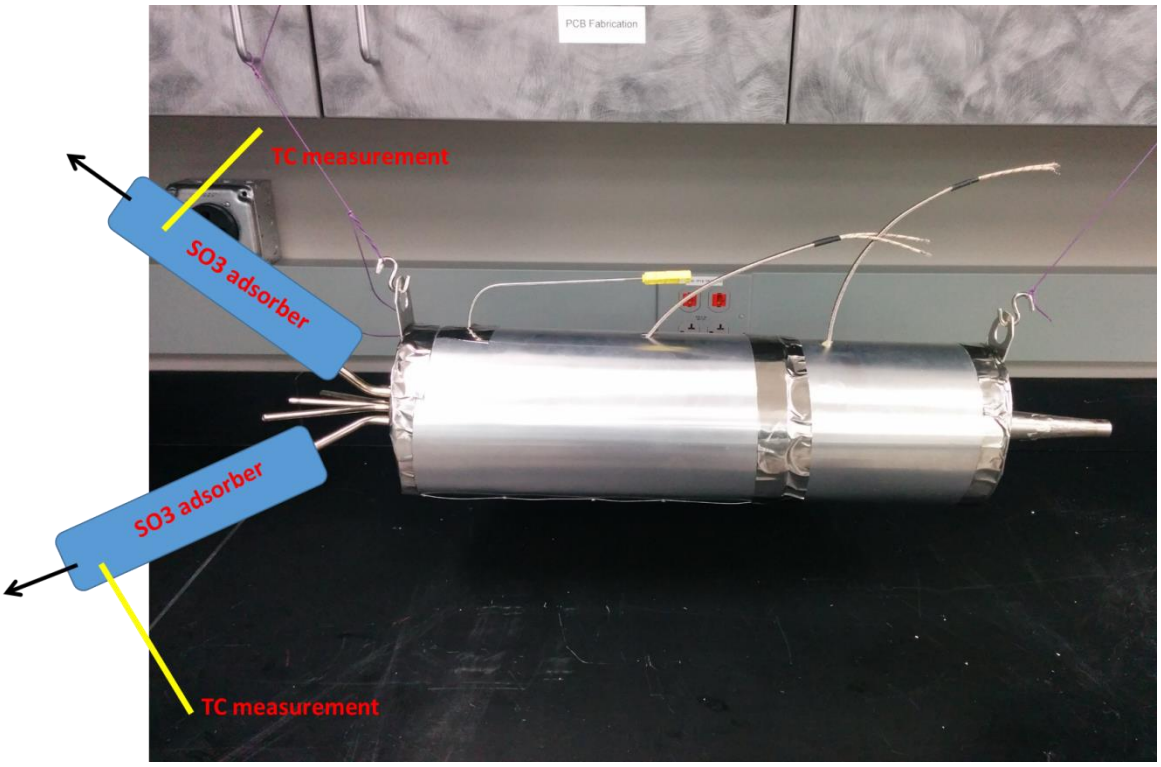


Figure F-1 Sample conditioning system (Catalytic stripper + sulfur absorbers)

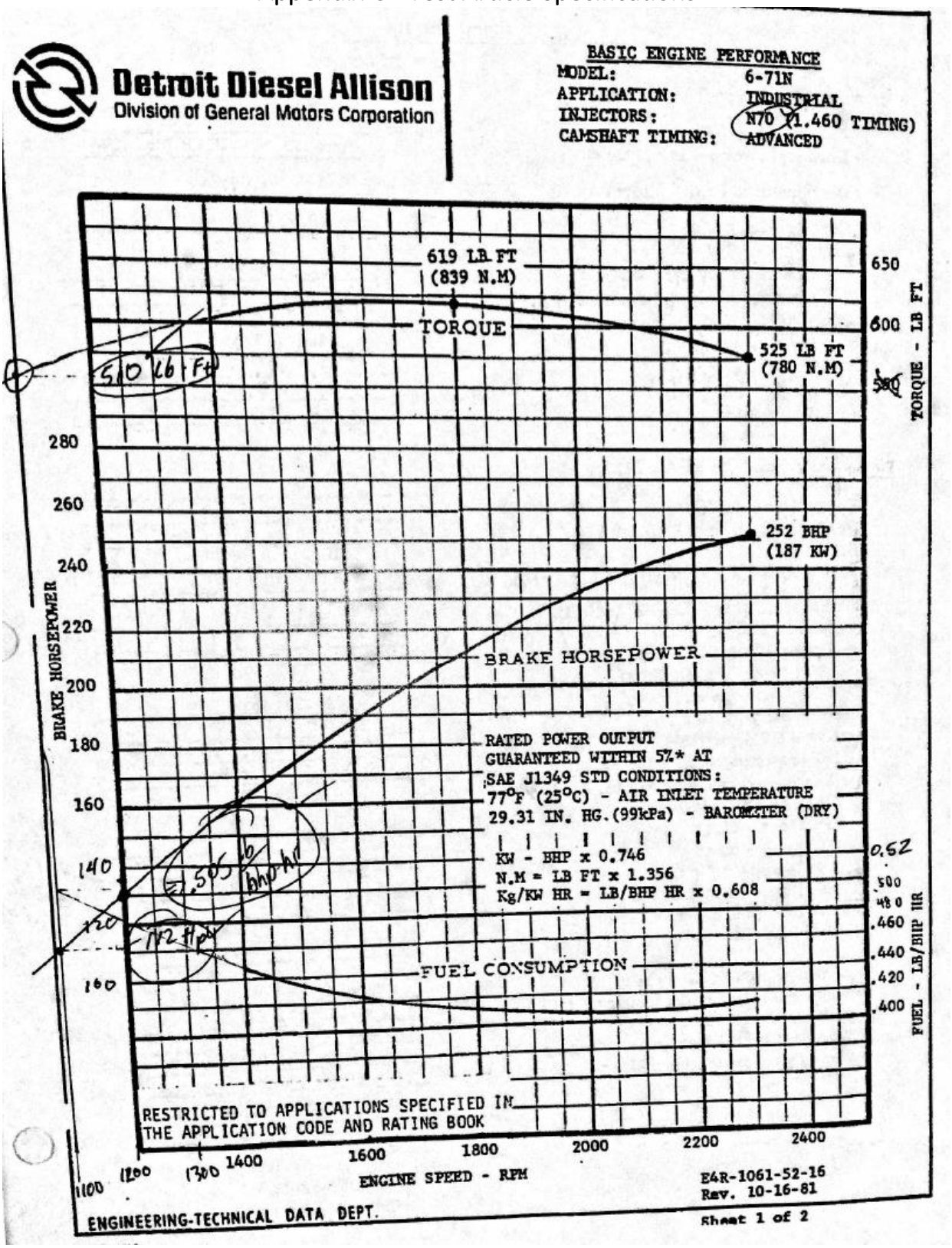


Figure G-1 Engine 6-71 performance map ranged from 1200 to 2200 RPM, N70 injector (Task 1)

ENGINE SPECIFICATION

General Engine Description:	
Model	6-71N
Number of cylinders	6
Bore and stroke – in. (mm)	4.25 x 5.0 (108 x 127)
Displacement – in.^{3} (liters)	426 (6.99)
Compression ratio	18.7:1
Firing order	
Clockwise rotation (RH)	1-5-3-6-2-4
Counter clockwise rotation (LH)	1-4-2-6-3-5
Dimensions & weight (approx.)	
Length – in. (mm)	54.0 (1372)
Width – in. (mm)	29.0 (737)
Height – in. (mm)	39.0 (991)
Weight – lbs. (kg)	2190 (993)
Technical Engine Specifications:	
Injector	N70
Engine speed – RPM	2300
Brake horsepower – BHP (kW)	252 (187)
BMEP – PSI (kPa)	93.0 (641)
Peak torque LB FT (N·m) @ RPM – 1800	619 (839)
Fuel consumption – LB/HR (kg/HR)	104.0 (47.17)
Specific fuel cons. – LB/BHP HR (g/kW HR)	.413 (251)
Fuel pump suction at pump inlet	
Maximum – in. Hg (kPa)	
Clean system	6 (20.3)
Dirty system	12 (40.6)
Airflow – CFM (m^3/min.)	715 (20.25)
Airbox pressure, Min. – in. Hg (kPa)	5.0 (16.93)
Air intake restriction, max. in. H_2O (kPa)	
(Dry type air cleaner)	
Full load – dirty	25.0 (6.22)
– clean	12.4 (3.09)
Exhaust temp. – °F (°C)	980 (527)
Exhaust flow – CFM (m^3/min.)	1915 (54.23)
Exhaust back press., max. in Hg (kPa)	
Full load	4.0 (13.54)
Coolant flow – GPM (liter/min.)	80.0 (303)
Coolant normal operating temp. °F (°C)	160-185 (71-85)
Heat rejection – BTU/Min. (W)	7860 (138255)
Coolant inlet restriction, max. – in. Hg (kPa)	3.0 (10.2)
Lubricating oil press. normal – psi (kPa)	40-60 (276-414)
Lubricating oil temp., in-pan °F (°C)	200-235 (93-113)

Figure G-2 Engine Specification sheet 6-71N (Task 1)

Fuel Grade: MGO

Quantity Measurement

	Volume @15C (m^3)	Density @15C (g/ml)	Weight Factor	Weight (M tons)
BDN Figures	405.43	0.8666	0.8655	350.900
Barge Delivered	416.12	0.8666	0.8655	360.149
Difference:	10.69	-	-	9.249
Vessel Received:	-	-	-	350.616

Bunker Fuels Information*

Density @15C (g/ml):	0.8666	Viscosity @40 C, cSt:	3.5
Water, vol. %:		Flash Point, C.	70
Sulfur, wt. %:	0.03	Fuel Temp., C	18.0
Nomination Quantity (M tons):	360		
Surveyor Density Tested (g/ml):	0.8565		

**Bunker Fuels Information Recorded on Bunker Delivery Note*

Delivery Comments

After the completion of pumping, delivery quantity submitted by cargo officer was initially stated as 360.149 M/Tons in the BDN. C/Eng refused to sign this BDN.
Finally, C/Eng signed the BDN in which the delivery quantity was agreed by both sides to amend as 350.900 M/Tons.

Seal Number of Tested Sample: 0001566 — **MGO Quality Test**

#	Quality Test	Result	MGO ISO Spec.	#	Quality Test	Result	MGO ISO Spec.
1	Density @ 15C.	0.8565	Max 0.89	6	Pour Point, C	-15	Max 0
2	Viscosity @ 40C	3.7	Max 6.00	7	Micro Carbon Residue, Bot 10%	0.10	Max 0.30
3	Flash point, PMCC, C.	70	Min 60.00	8	Ash	0.00	Max 0.01
4	Water %	0.0	Max 0.0	9	Cetane	48.88	Min 40.00
5	Sulfur Weight %	0.03	Max 1.50	10	Appearance	B&C	

Sample Information*

Vessel's Sample Seal: 0001564 (barge) **Marpol's Sample Seal:** 0001565 (barge) **Barge's Sample Seal:** 0001567 (barge)

Surveyor Sample Seal: 0001566 (barge) **Vessel's Analysis Seal:** nil

Sample Statment: Sample was taken on the Barge using Continuous Drip and was witnessed by C/E or representative. Chief Engineer and supplier agreed

Southwest Research Institute
Test Summary Report
for
University of California
Riverside, CA

SwRI Work Order # 75230
August 11, 2016

FS16001 dated 5/23/16

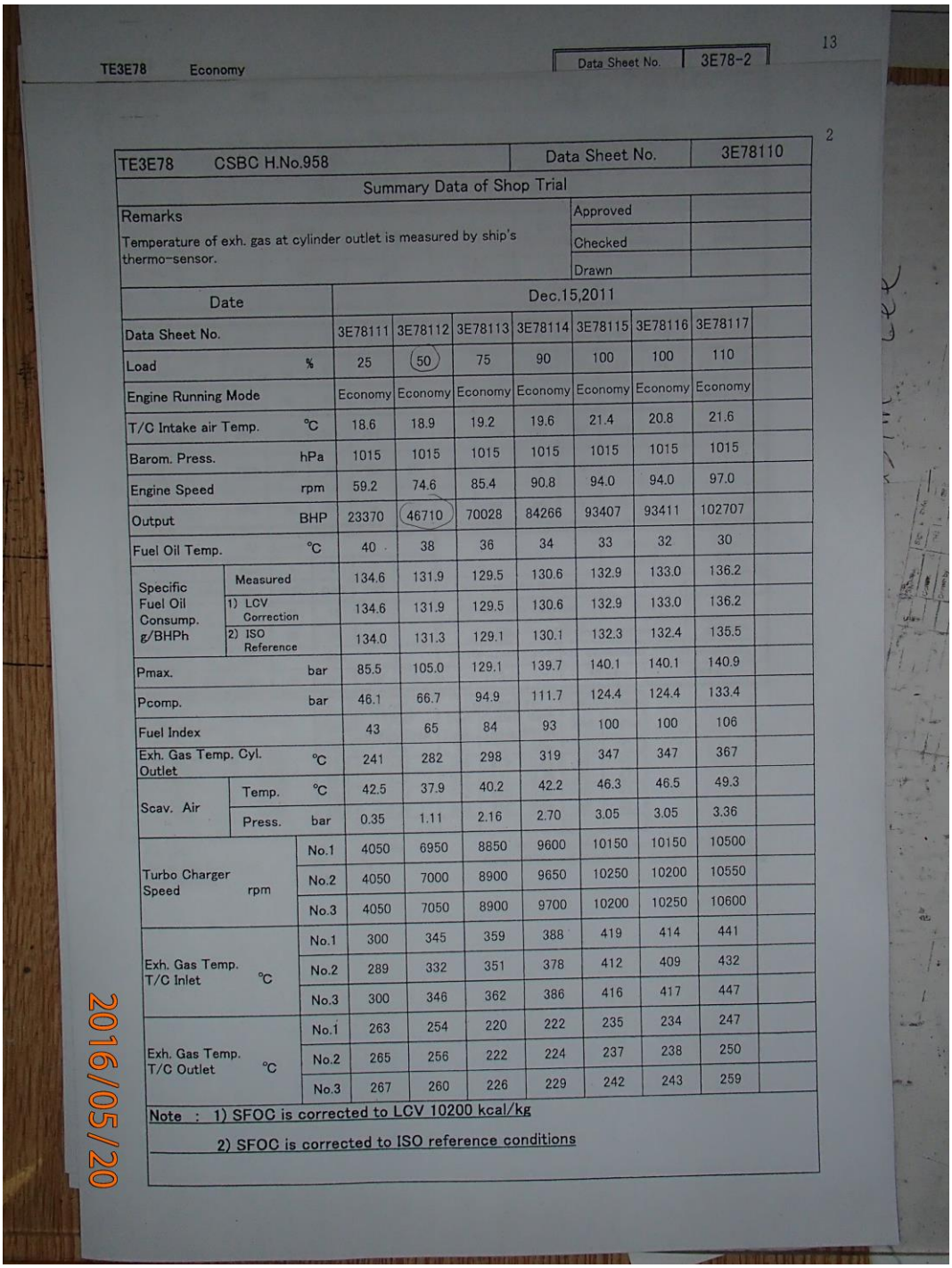
ASTM D4294
Sulfur by Energy Dispersive X-ray Fluorescence Spectrometry
Sulfur, (ppm) ..... <100

ASTM D4052
Density, Relative Density, and API Gravity by Digital Density Meter
API Gravity 37.8
Specific Gravity 0.8360
Density at 15°C (g/mL) 0.8356

ASTM D445
Kinematic Viscosity of Transparent and Opaque Liquids
Viscosity at 50°C (cSt) 2.39

ASTM D4530
Determination of Carbon Residue (Micro Method)
Carbon Residue (m/m) 0.07

Figure G-3 Bunker Report and UCR analysis of the MGO test fuel (Task 2)



TE3E78 Economy

Data Sheet No. 3E78-2

13

2

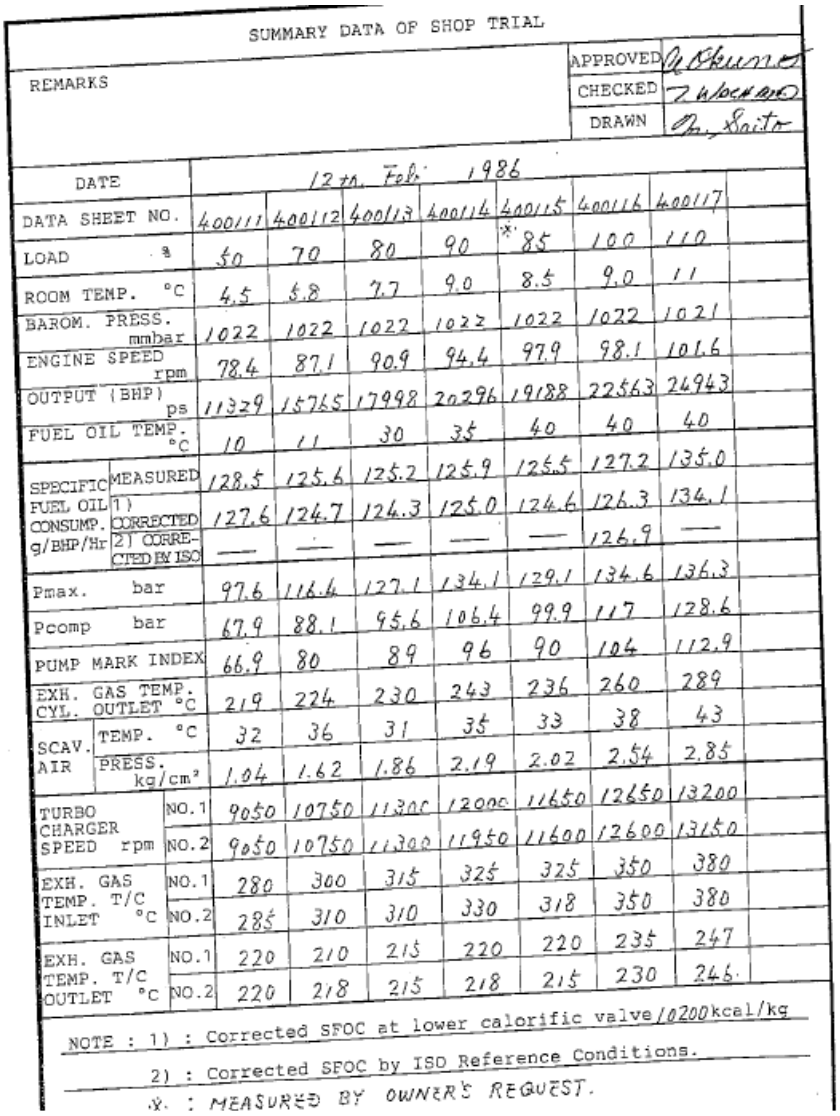
TE3E78 CSBC H.No.958								Data Sheet No.	3E78110
Summary Data of Shop Trial									
Remarks Temperature of exh. gas at cylinder outlet is measured by ship's thermo-sensor.								Approved	
								Checked	
								Drawn	
Date			Dec.15,2011						
Data Sheet No.			3E78111	3E78112	3E78113	3E78114	3E78115	3E78116	3E78117
Load		%	25	50	75	90	100	100	110
Engine Running Mode			Economy	Economy	Economy	Economy	Economy	Economy	Economy
T/C Intake air Temp.		℃	18.6	18.9	19.2	19.6	21.4	20.8	21.6
Barom. Press.		hPa	1015	1015	1015	1015	1015	1015	1015
Engine Speed		rpm	59.2	74.6	85.4	90.8	94.0	94.0	97.0
Output		BHP	23370	46710	70028	84266	93407	93411	102707
Fuel Oil Temp.		℃	40	38	36	34	33	32	30
Specific Fuel Oil Consump. g/BHPh	Measured		134.6	131.9	129.5	130.6	132.9	133.0	136.2
	1) LCV Correction		134.6	131.9	129.5	130.6	132.9	133.0	136.2
	2) ISO Reference		134.0	131.3	129.1	130.1	132.3	132.4	135.5
Pmax.		bar	85.5	105.0	129.1	139.7	140.1	140.1	140.9
Pcomp.		bar	46.1	66.7	94.9	111.7	124.4	124.4	133.4
Fuel Index			43	65	84	93	100	100	106
Exh. Gas Temp. Cyl. Outlet		℃	241	282	298	319	347	347	367
Scav. Air	Temp.	℃	42.5	37.9	40.2	42.2	46.3	46.5	49.3
	Press.	bar	0.35	1.11	2.16	2.70	3.05	3.05	3.36
Turbo Charger Speed		rpm	No.1	4050	6950	8850	9600	10150	10150	10500
			No.2	4050	7000	8900	9650	10250	10200	10550
			No.3	4050	7050	8900	9700	10200	10250	10600
Exh. Gas Temp. T/C Inlet		℃	No.1	300	345	359	388	419	414	441
			No.2	289	332	351	378	412	409	432
			No.3	300	346	362	386	416	417	447
Exh. Gas Temp. T/C Outlet		℃	No.1	263	254	220	222	235	234	247
			No.2	265	256	222	224	237	238	250
			No.3	267	260	226	229	242	243	259

Note : 1) SFOC is corrected to LCV 10200 kcal/kg

2) SFOC is corrected to ISO reference conditions

2016/05/20

Figure G-4 Shop trial data sheet for the Tier 2 engine tested (Task 2)



SUMMARY DATA OF SHOP TRIAL

REMARKS

APPROVED
CHECKED
DRAWN

DATE		12th. Feb. 1986						
DATA SHEET NO.		400111	400112	400113	400114	400115	400116	400117
LOAD %		50	70	80	90	*85	100	110
ROOM TEMP. °C		4.5	5.8	7.7	9.0	8.5	9.0	11
BAROM. PRESS. mmbar		1022	1022	1022	1022	1022	1022	1021
ENGINE SPEED rpm		78.4	87.1	90.9	94.4	97.9	98.1	101.6
OUTPUT (BHP) ps		11329	15765	17998	20296	19188	22563	24943
FUEL OIL TEMP. °C		10	11	30	35	40	40	40
SPECIFIC FUEL OIL CONSUMP. g/BHP/Hr	MEASURED	128.5	125.6	125.2	125.9	125.5	127.2	135.0
	1) CORRECTED	127.6	124.7	124.3	125.0	124.6	126.3	134.1
	2) CORRECTED BY ISO	—	—	—	—	—	126.9	—
Pmax. bar		97.6	116.4	127.1	134.1	129.1	134.6	136.3
Pcomp bar		67.9	88.1	95.6	106.4	99.9	117	128.6
PUMP MARK INDEX		66.9	80	89	96	90	104	112.9
EXH. GAS TEMP. CYL. OUTLET °C		219	224	230	243	236	260	289
SCAV. AIR	TEMP. °C	32	36	31	35	33	38	43
	PRESS. kg/cm²	1.04	1.62	1.86	2.19	2.02	2.54	2.85
TURBO CHARGER SPEED rpm	NO.1	9050	10750	11300	12000	11650	12650	13200
	NO.2	9050	10750	11300	11950	11600	12600	13150
EXH. GAS TEMP. T/C INLET °C	NO.1	280	300	315	325	325	350	380
	NO.2	285	310	310	330	318	350	380
EXH. GAS TEMP. T/C OUTLET °C	NO.1	220	210	215	220	220	235	247
	NO.2	220	218	215	218	215	230	246

NOTE : 1) : Corrected SFOC at lower calorific valve 10200 kcal/kg

2) : Corrected SFOC by ISO Reference Conditions.

*: MEASURED BY OWNER'S REQUEST.

Figure G-5 Shop trial data sheet for the Scrubber engine tested (Task 3)

Figure G-6 Fuel bunker r

T16168001

Oiltest Marine Testing Services - Marine Fuels Analysis Report

Vessel Name	
Attn :	
Port Bunkered	
Date Bunkered	6/14/2016
Sample Location	Bunker Line
Seal Number	36580206
Suppliers Name	PHILLIPS 66
Received By Lab	6/16/2016 10:21:00 AM
Sample Number	T16168001
Grade	Horizon HFO Spec - LS
Suppliers Density:	991.0 /Vis 310.0
BunkerReceipt:	1000 MT

	Result	Specification	
Density, kg/m3 @ 15C	989.3	991.0	Max
Viscosity cst @ 50C	306.6	500.0	Max
Viscosity cst @ 80C	67.8	75.0	Max
Flash Point, Deg C	73.3	60.0	Min
Pour Point, Deg C	0	20	Max
MCR, % m/m	12.59	22.00	Max
Ash, % m/m	0.052	0.200	Max
Water, % v/v	0.10	1.00	Max
Sulphur, %m/m	1.89	2.00	Max
Compatibility, Spot#	1	2	Max
Asphaltenes, % m/m:	3.9		
Vanadium, mg/kg	88	500	Max
Sodium, mg/kg	22	300	Max
Silicon, mg/kg	23		
Aluminum, mg/kg	18		
Al & Si, mg/kg	41	80	Max
Used Lubricated Oil:			
Zn, mg/kg:	1	15	Max
P , mg/kg:	1	15	Max
Ca, mg/kg:	7	30	Max
Total Sed, Pot., % m/m	0.04	0.10	Max
Net Cal, Val, MJ/Kg	40.54		
CCAI, Index#	852		
Injection Temp 10cst, C	145		
Injection Temp 13cst, C	133		
Injection Temp 15cst, C	127		

Comments based on above analysis results.
Specification : Met

eport #1

Task 3

Test Fuel

T16116001

Oiltest Marine Testing Services - Marine Fuels Analysis Report

Vessel Name	
Attn :	
Port Bunkered	
Date Bunkered	4/22/2016
Sample Location	Bunker Line
Seal Number	36580910
Suppliers Name	PHILLIPS 66
Received By Lab	4/25/2016 9:39:00 AM
Sample Number	T16116001
Grade	Horizon HFO Spec
Suppliers Density:	977.3/Vis 209.0

	Result	Specification	
Density, kg/m3 @ 15C	976.2	1010.0	Max
Viscosity cst @ 50C	212.3	380.0	Max
Viscosity cst @ 80C	51.3	75.0	Max
Flash Point, Deg C	85	60.0	Min
Pour Point, Deg C	-18	20	Max
MCR, % m/m	12.74	22.00	Max
Ash, % m/m	0.050	0.200	Max
Water, % v/v	0.05	1.00	Max
Sulphur, %m/m	1.88	2.00	Max
Compatibility, Spot#	1	2	Max
Vanadium, mg/kg	71	500	Max
Sodium, mg/kg	22	300	Max
Silicon, mg/kg	22		
Aluminum, mg/kg	17		
Al & Si, mg/kg	39	80	Max
Used Lubricated Oil:			
Zn, mg/kg:	0	15	Max
P , mg/kg:	5	15	Max
Ca, mg/kg:	8	30	Max
Asphaltenes, % m/m:	3.9	6.0	Max
Total Sed, Pot., % m/m	0.05	0.15	Max
Net Cal, Val, MJ/Kg	40.76		
CCAI, Index#	843		
Injection Temp 10cst, C	137		
Injection Temp 13cst, C	125		
Injection Temp 15cst, C	119		

Comments based on above analysis results.
Specification : Met

Figure G-6 Fuel bunker report #2 (Task 3)

Appendix H –Original Task 1 Scope of Work

This appendix describes the scope of work originally proposed by UCR. Modifications were made based on feedback from Utrecht workshop and a desire to see sample conditioning done.

> *The goal of this project is to develop baseline emission factors for key engine types used on oceangoing vessels under operating loads with representative fuels and to compare BC values measured with multiple instruments.*

Approach… There are two key elements outlined in the RFP by completing this task. First, setting up a test stand to provide steady-state emissions with various fuels at selected loads, and second, measuring the BC with multiple analytical methods. In addition to the two areas mentioned in the RFP, UCR recognized the unique opportunity to explore other parameters to add a deeper knowledge of the nature of marine diesel exhaust and the atmosphere that surrounds the black carbon. Accordingly, UCR proposes to add additional analytical measurements with instruments rarely used out of the lab.

Setting up the dyno…. For over twenty years UCR has built, maintained, and operated both engine and chassis dynamometers for light duty and heavy duty engines. UCR has tested marine engines on engine stands during some of their past research projects as listed in the Qualifications section (ref # 13). Based on the RFP, UCR plans to set up a marine diesel engine that can run on both HFO and distillate fuels. UCR has plans on using a Detroit Diesel straight 6-71 series of 2-stroke engine with mechanical fuel injection with Tier 0 emissions rating. This engine will be directly mounted to UCR's engine dynamometer rated at 600hp (see Appendix D for details). UCR has also tested marine engines on a nearby Caterpillar dealer dynamometer that can handle engines up to 1,000 horsepower and is also currently negotiating the transfer of a larger two-stroke, marine engine from a government entity that would need to operate on the larger dyno. A fueling system capable of delivering HFO to the engine and selecting the appropriate properties for the injectors would also be important. The local Detroit Diesel Technical Office (which supports west and east coast marine HFO systems) has offered their expertise and assistance in establishing operation with HFO fueling.

Operating test matrix…With an engine mounted to a dynamometer it is ready for steady state operation at selected loads. UCR proposes operating the engine at the modes specified for certification, identified as ISO 8178 E-3. Another test mode to be incorporated into the test schedule is operation at near 10% power as these levels are typical of when a vessel is slow steaming and in the VSR zones.

Table H-1 Engine Operating Conditions for the ISO 8178 E-3 Cycle

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

Fuels Matrix… A number of marine fuels are in the commercial use, such as:

- **MGO (Marine gas oil)** – roughly equivalent to No. 2 fuel oil, made from distillate only
- **MDO (Marine diesel oil)** – Blend of heavy gasoil with very small amounts of black oil. MDO has a viscosity <12 cSt**/**40^{0}C so used directly in IC engines.
- **IFO (Intermediate fuel oil)** – Blend of gasoil and heavy fuel oil (less gasoil than MDO)
- **HFO (Heavy fuel oil)** – Pure, or nearly pure, residual oil, equivalent to No. 6 fuel oil

The UCR team proposes to test three fuels with a range of properties. A number of parameters are normally mentioned in specifying fuel properties including: maximum sulfur content, density, maximum viscosity, pour point, etc…. However, these properties say less about fuel quality and today more focus is on the Calculated Carbon Aromaticity Index (CCAI) and the Calculated Ignition Index (CII), which describe the ignition quality of residual fuel oil. With a value for CCAI, it is possible to obtain an indication of the ignitability of the fuel and to rank ignition quality, similar to the cetane index for distillate fuel. Thus the question, 'is CCAI related to the amount of BC?' arises. The proposed fuels matrix in this research reflect a range of sulfur contents, viscosity and CCAI levels.

1. MGO with <0.1 weight percent sulfur content; thus meeting the ECA limits.
2. HFO with high sulfur content and a CAII to match the diesel engine.
3. HFO with <0.1 weight percent; thus meeting the ECA limits

The UCR team proposes running each of the three fuels at the four E-3 modes and 10%/VSR power levels as identified in the test matrix.