IAMU
International Association of Maritime Universities

日本財団
THE NIPPON FOUNDATION

IAMU 2015 Research Project
(No. 20150202)

Development of a Methodology to Measure and Assess Ship Emissions

By

Australian Maritime College (AMC)

August 2016

IAMU
International Association of Maritime Universities

This report is published as part of the 2015 Research Project in the 2016 Capacity Building Project of International Association of Maritime Universities, which is fully supported by The Nippon Foundation.

The text of the paper in this volume was set by the author. Only minor corrections to the text pertaining to style and/or formatting may have been carried out by the editors.

Editorial

IAMU Academic Affairs Committee (AAC)

Head of Committee : Piotr JĘDRZEJOWICZ
Rector, Gdynia Maritime University (GMU)

Editorial committee : Bogumil LACZYNSKI (GMU)
Bill DAVIDSON (CSUMA)
NGUYEN Thanh Son (VMU)

Published by the International Association of Maritime Universities (IAMU) Secretariat
Meiwa Building 8F, 1-15-10 Toranomon, Minato-ku,
Tokyo 105-0001, JAPAN
TEL : 81-3-6257-1812 E-mail : info@iamu-edu.org URL : http://www.iamu-edu.org

ISBN978-4-907408-14-5

IAMU 2015 Research Project
(No. 20150202)

Development of a Methodology to Measure and Assess Ship Emissions

By

Australian Maritime College (AMC)

Contractor : Neil BOSE, Principal, AMC
Research Coordinator : Vikram GARANIYA, AMC
Research Partner : Faisal KHAN, AMC
Richard BROWN, (Queensland University of Technology)
Richard KIMBALL, MMA

Contents

Development of a Methodology to Measure and Assess Ship Emissions

Theme 2 - Marine Environmental Issues

Australian Maritime College

Dr Vikram GARANIYA

Course Coordinator - B.E (Marine & Offshore Engineering)

V.Garaniya@utas.edu.au

Abstract

Exhaust emissions from ships are one of the major sources of air pollutants. While it is evident that shipping emissions are of concern globally, the global effects tend to be more dispersed and less easily attributed to their original sources. Continued implementation of the amendments to the MARPOL Annex VI regulations is an attempt to reduce emissions on a global scale. In-port emissions account for a relatively small proportion of the total emissions due to shipping, yet they have some of the most significant health impacts on the surrounding population. It is commonly known that these emissions are linked to cardiopulmonary and cancer related health problems, with an estimated number of deaths due to SOx emissions from shipping alone during 2012 of approximately 87,000 worldwide. Regulated pollutants including SOx, NOx, PM and the hundreds of other constituents of exhaust emissions generated by the combustion of fuels depend on the quality of the fuel and the characteristics of combustion. This research project is led by the AMC in collaboration with QUT and MMA to develop in-vessel emission measurement systems and assess the fuel characteristics which provide a baseline for the fuels that can be compared to the in-vessel emission results. Data from on-board measurements and laboratory analysis is used to develop a model for emission factor estimation for ships operating in different conditions. MMA presented preliminary emissions data aboard their workboat to demonstrate the performance of the continuous monitoring system. Results showed that for vessel operations at berth, AE (Auxiliary Engine) emissions were found to be dominant over ME (Main Engine) emissions. It was also reported that some ship emissions were up to several orders of magnitude higher than the corresponding land-based diesel emission levels, and significant variations in emissions were credited to fuel sulphur content and the engine load. Furthermore, SOx emission factors at berth were also found to be higher than those of previous studies. Particle number size distributions were found to peak at 35-45 nm in diameter, and showed a significant decline at higher engine load conditions. While the vessel is manoeuvring and cruising, ME emissions were found to be much more significant due to the higher engine load. To conclude the study, the emission factors developed were benchmarked against 13 known emission inventory methodologies, and it was found that the US EPA method had the closest resemblance, predicting the overall primary emissions with a 19% average deviation from the on-board measurements.

Keyword: Ship emissions, emission inventories, real time emission monitoring, on board measurements

1. Introduction

1.1. Background

Exhaust emissions from ships are one of the major sources of air pollutants. While gaseous emissions have been extensively studied over several decades, diesel particulate emissions of PM2.5 and sub-micron nano-particles have recently emerged as a major health issue. Based on sufficient evidence in 2012 the International Agency for Research on Cancer (IARC), which is part of the World Health Organization (WHO), classified diesel engine exhaust as carcinogenic to humans (Group 1, same as asbestos). This research work focused on maritime environmental protection under the regulatory compliance of IMO MARPOL Annex VI addressing ship emissions (SOx, NOx and PM2.5). These regulated pollutants and the hundreds of other constituents of exhaust emissions generated by the combustion of fuels depend on the quality of the fuel and the characteristics of combustion. Therefore, Australia Maritime College (AMC) in collaboration with Queensland University of Technology (QUT) and Maine Maritime Academy (MMA) studied and developed? in-vessel emission measurement systems and emissions evaluation protocols to aid the industry in the characterisation of fuel emissions emitted in at-sea conditions.

1.2. Motivation

Ship emissions, which include gaseous particles and particulate matter (PM), have negative effects on both environmental and public health [1-4]. Viana et al [5] investigated and found that shipping related emissions are one of major contributors to global air pollution, especially in coastal areas. They cause an increase in the levels and composition of both particulate and gaseous pollutants and the formation of new particles in densely-populated regions [5, 6]. This is obvious as over 70% of ship emissions may spread 400 km inland and significantly contribute to air pollution in the vicinity of coastal areas and harbors [7]. As a result, Corbett et al [8] estimated that annually shipping-related PM2.5 emissions are the causes of approximately 60,000 deaths associated with cardiopulmonary and lung problems around the world. Most deaths occur in highly populated and PM concentration areas such as Asia and Europe, and the number of annual mortalities were predicted to increase 40% by 2012 [4]. Moreover, shipping activities significantly contribute to ocean acidification [9]. Therefore, quantitative and qualitative estimation of pollutant emissions from ships and their distribution are becoming more significant [3]. Another concern relating to shipping transportation is the fuel used. Heavy fuel oil (HFO), which contains many impure compositions such as sulphur and metals, are used by almost all ships owing to the economic benefit [2]. Corbett [10] has estimated that approximately 80% of fuel consumed by the world ship fleet is HFO. This calls for the need of research into ship emission related issues.

Emissions from ships are regulated by the International Maritime Organisation (IMO) through Annex VI of the International Convention for the Prevention of Pollution from Ships – the Marine Pollution Convention (MARPOL) [11]. Continued implementation of the amendments to the MARPOL Annex VI is an attempt to reduce ship emissions on a global scale [12-14]. Main regulations to limit sulphur content of any fuel oil used on board and NO_x emissions are being implemented. In European areas, regulations for ship emissions are more stringent than in other places. In particular, from January 1st 2010, European directive requires all ships at berth or anchorage in European harbours to use fuel oil with sulphur content of less than 0.1% by weight [15]. However, further regulation should be implemented because the fuel shift to low sulphur was insufficient to reduce small-sized PM emissions [16].

1.3. Objectives
This research aims to achieve three main objectives:

- Demonstrate real time in-vessel continuous emissions measurements (CEMS) of Particulate Matter (PM), NOx, SOx, CO2, and CO measurements using portable gas instrumentation including PM size distributions.
- Develop a relationship between fuel quality and emissions from ships operating in different conditions
- Develop a model for an emission factor estimation method and informed decision making framework for ships operating in different conditions (fuel, operation, engine type, engine size, region)

To achieve the above objectives, research work was carried out in two major campaigns to utilize the strengths of the research partners. The Port of Brisbane campaign aimed to demonstrate the use of online sampling techniques on board vessels while in port, transit and cruising. The emphasis of this campaign was to focus on ocean going vessels operating within the Port of Brisbane utilising heavy fuel oil (HFO). Emissions from the vessels were collected from the main, as well as auxiliary, engines. The MMA (Maine Maritime Academy) campaign expanded on this work and focused on continuous emissions measurements on-board vessels while underway. The MMA has a fleet of their own vessels that allowed these measurements to be made in a number of varying sea conditions.

1.4. Methodology
The in-vessel emission monitoring work comprised testing both in the port of Brisbane, on a commercial vessel, as well as at MMA's Marine Engine Testing and Emissions Laboratory (METEL). QUT has developed a unique, portable particle measurement systems (SMPS) and has a fully equipped combustion laboratory to conduct the necessary measurements. MMA's work vessel includes a portable FTIR gas analyser and PM measurement system installed on work boat engines which is fully instrumented for performance measurement allowing real time correlations between engine load and missions under at-sea conditions.

The fuel characterisation work was carried out in QUT's combustion laboratories and is used to provide baseline emissions profiles for the fuels that can be compared to the in-vessel emission results. Finally the data from the in-vessel tests and the laboratory analysis is used to develop the emission factor estimation method, whereby the in-vessel data will be used as validation of the methods results. The research program comprised the following steps:

- Review literature on emissions factor estimation. This includes emission factor (EF) calculation approaches used in different regions and different industries such as oil and gas industries, chemical industries, industrial hygiene and also marine industry.
- Collection of fuel samples, characterising them in the chemistry laboratory for tests related to combustion quality of the fuel.
- Collection and analysis of emission data under a range of conditions (fuel, operation, engine type, engine size, region, etc.) and analysing them.
- Development of a mathematical model to estimate emission factors (EF) earlier defined condition and collected data.
- Testing and validation of developed emission factors (EF) against experimental data and field data.

1.5. Outputs

The research outcome of the current study includes:

- Research papers (including conference and journals)
  - *A journal article titled "Emissions inventories for shipping operations: Comparison with on-board measurements" is about to be submitted to the journal of Marine Pollution Bulletin.*
  - *A conference paper titled "Emissions from marine diesel engines using heavy fuel oil" has been accepted for the upcoming 10th Australasian Heat and Mass Transfer Conference, Brisbane, 14-15 July 2016*
  - *A conference paper titled "Particle emissions from ships at berth using heavy fuel oil" has been submitted for the upcoming 17^{th} International Association of Maritime Universities (IAMU) Annual General Assembly, Haiphong, Vietnam 26-29 October 2016*
  - *A conference publication titled "Real time emissions monitoring of diesel engines aboard marine vessels" presented at the 250^{th} National Meeting of the American Chemical Society, Boston, MA, USA, 16-20 August 2015.*
- Research reports (Chapters in Theses)
- Workshops/seminars with stakeholders to disseminate findings and identify shipping and port facility concerns.
  - A presentation was made to CSL Australia, on 7^{th} March 2016 and the client is keen to learn more about the findings.

1.6. Report outline

The report consists of a total of seven sections. Section one discusses the background, motivation and objectives of the project. It also briefly describes the on-board measurement campaign and contains the methodology and work carried out pertaining to the campaign. A summary of the output from the research project which includes the research papers submitted for publication is also presented.

Section two contains details of the on-board measurement campaign performed at the Port of Brisbane, which includes security clearances and approvals obtained and description of the pilot and main measurement campaign (test vessel, instrumentation setup and on-board measurements).

Section three onwards mainly provides publication outputs of this research in its original format. In particular, sections three and four describe assessment of gaseous emissions and particulate matters from a marine diesel engine using Heavy Fuel Oil (HFO) at berth. Section five describes detailed on-board measurement results and their comparisons with the existing emission inventories to find best emission estimation methods that can be applicable for ships at berth, manoeuvring and cruising.

Section six describes implementation of real time emissions monitoring systems of marine diesel engine while the final section (seven) provides the overall conclusions of the current research project and recommendations for future works to be carried out. Please note since sections 3 to 7 are publications in original format, there is some repetitive information. This information is maintained to ensure that the description for the flow of the paper remains uninterrupted.

2. On-board Measurement Campaign

2.1. The Port of Brisbane emission measurement campaign

Like many Australian ports, the Port of Brisbane lies in close proximity to a large urban centre. Consequently a large percentage of the emissions from ships both in transit to the berths and while at berth have the potential to directly impact the surrounding residents. With the likelihood of development of the Port of Brisbane (and many other Australian ports in the near future, to keep up with increasing industry, having a reliable method to quantify and estimate these emissions is becoming increasingly important. This section describes the procedure followed for data collection including all regulatory approvals.

Data collected from the Port of Brisbane comprises of a large component of the project. On-board emission measurements were taken from the running machinery on-board the vessels while at berth and at sea. To achieve this, a number of emissions samples were collected using an array of portable instrumentation. This equipment has been designed to be portable to allow it to be carried on board vessels with minimal disruption to the operations of the crew. On board measurements were to be made either from each individual engine at a sampling point off the exhaust manifold or alternatively from a common sampling point located either before or after the economizer. Fuel samples were collect from the vessels.

2.2. Security Clearances and Approvals

A number of approvals is required to undertake any work within ports or on-board vessels within Australia. Due to the number of stakeholders involved, understanding the complexities of these approvals is quite difficulty in itself. The following approvals have been obtained:

- Maritime Security Identification Cards (MSIC)
- Port of Brisbane General Induction
- Stevedore operation (AAT, Patricks, DP World) inductions
- Maritime Safety Queensland approval
- Stevedore operation approval
- Approval from vessel owner/operators

A large amount of the effort thus far was dedicated to receiving the required approvals to gain access to the restricted landside and waterside zones as shown in Fig. 2-1. In Australia, a Maritime Security Identification Card (MSIC) is required to access work in a maritime security zone. The introduction of MSIC cards was part of a larger system to secure the maritime transport sector. MSIC cards are nationally recognized and are required to be carried at all times while located within these areas. These were obtained for all team members involved in the study.

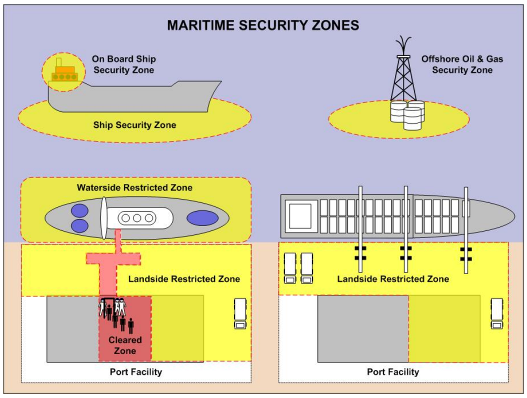


Fig. 2-1 Types of maritime security zones on Australian facilities

Approval has been given from both the Port of Brisbane as well as three of the stevedore operations (DP World, AAT, Patricks) on Fisherman Islands at the Port of Brisbane to conduct work within their facilities. In addition to the requirement of MSIC cards to access these areas of the Port, individual inductions were required to be completed for each facility for all involved in the project. Strong collaboration with the Port of Brisbane has meant they have agreed to provide adequate space for conducting required analysis at their offices. Obtaining all the required permits to gain access to the restricted Port areas has taken in excess of 2 months even with the assistance of the Port of Brisbane. It is evident that the restrictions in place severely hinder the progress of research and are no doubt partially accountable for the lack of other similar studies.

2.3. Pilot Campaign and Collaboration with QUT

A 5-day pilot campaign was conducted in collaboration with QUT in Brisbane during August 2015. The outcome of this campaign was to test the complete range of on-board measuring equipment instruments and assess the feasibility of using the equipment on-board vessels in port. The experimental apparatus is setup to induce the exhaust gas into a sampling bag contained within a rigid 200 litre ABS drum. By pre-charging a vacuum to the outside of the sampling bag (within the drum) the sampling bag can be taken on-board and emissions extracted from a sampling point without the need for electricity or compressed air on-board the vessel.

A 5-gas analyser is being utilised to measure the O_2, CO_2 and NOx emissions from the sampled gas. A portable Dust Trak analyser is being utilised to measure the PM size distributions from PM1.0 to PM2.5 and PM10. In addition to the bag sampling filters can be used to determine the composition of the particulate matter in particular focusing on the elemental and organic carbon.

To assess the emissions measuring equipment, the available apparatus was setup on-board the HMAS Diamantina at the Queensland Maritime Museum. Preliminary measurements were taken from a portable 4 stroke petrol generator. While measurements from a diesel engine were not able to be made, conducting the measurements on board the vessel still provided proof of concept in terms of the difficulties to be encountered on real vessels.

Fig. 2-2 Portable emissions measuring equipment setup on board the HMAS Diamantina.

2.4. Main Emission Measurement Campaign

2.4.1. Test Vessel

The measurements were taken in October and November 2015 on two large cargo ships at the Ports of Brisbane, Gladstone, and Newcastle. The first on-board measurement was performed on CSL vessel I (to ensure confidentially the identity of ship is suppressed) from 26th to 31st of October, 2015 when she was running from Port of Brisbane to Port of Gladstone. The second measurement was conducted on CSL vessel II from 3rd to 6th of November, 2015 on her voyage from Gladstone to Sydney. All measurements have been carried out on both the main and auxiliary engines of two ships for three ship operating conditions, which are at berth, manoeuvring, and at sea. Main information of ships and engines can be seen in Table 2-1.

Table 2-1 General information about two ships

	CSL Vessel I	CSL Vessel II
Ship's Owner	CSL Australia	CSL Australia
Ship's Type	General cargo	Bulk carrier
Classification Society	Lloyd's Register	Lloyd's Register
Flag	Australia	Barbados
Port of Registry	Sydney	Bridgetown
IMO Number	?	?
Build Year	1981, converted 2008	2002
Builder	Mitsui Engineering & Ship Building Co., Japan	Cosco Nantong Shipyard Nantong, China
Net Tonnage	11250 tonnes	16160 tonnes
Gross Tonnage	30909 tonnes	27198 tonnes
Deadweight	40876 metric tonnes	49502 metric tonnes
Length Overall	184.5m	187.5m
Breadth	32.2m	31.0m
Depth	15.32m	16.75m
Main Engine	Mitsui B&W 6L80GFCA 12080 kW x 102 RPM	Man B&W 6S50MC 6880 kW x 102 RPM
Auxiliary Engine	Daihatsu 6DK-20 960 kW @ 900 RPM	Wartsila 425 kW x 900 RPM

2.4.2. Experimental Setup

Measurement instruments were arranged at a deck high up in the machinery room and the exhaust gas was sampled and measured continuously from holes cut in the exhaust pipe after the economiser for CSL Vessel I and after the turbocharger of the main engine for CSL Vessel II. The schematic diagram of sampling setup is illustrated in Fig. 2-3. Photos of the exhaust sampling points on both the vessels can be seen in Fig. 2-4 and Fig. 2-5 respectively. At each sampling point, two holes were created for the measurement instrumentations: one for the Testo 350XL, and the other one for the DMS, Dust Trak, Horiba 5-gas analyser and Sable CO2 monitor.

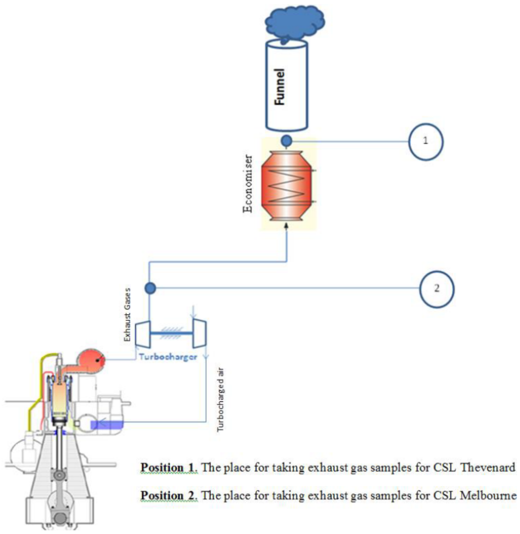


Fig. 2-3 Schematic diagram of sampling setup for two ships

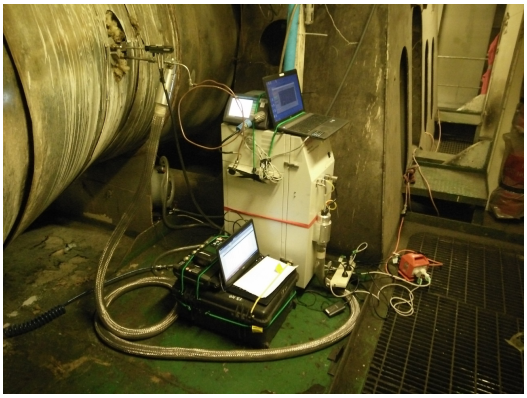


Fig. 2-4 Exhaust gas sampling point for CSL Vessel I

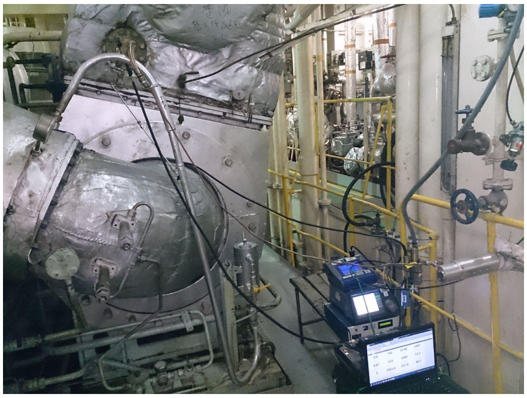


Fig. 2-5 exhaust gas sample point for CSL Vessel II

Data on engine power, engine revolution, fuel oil consumption, intercooled air temperature, scavenging air pressure, cooling fresh water and exhaust gas temperature were measured by the ship's instrumentation.

2.4.3. On-board Exhaust Measurements

Particle measurements

Particle number and mass distributions in the size range 5 nm – 2.5 μm were obtained with a time resolution of 10 Hz (0.1 s) by using DMS 500 MKII (Combustion). Besides, mass concentrations of PM 10, PM 2.5, PM 1.0 have been measured with Dust Trak^{TM} II Aerosol Monitor 8530 (TSI), which is a desktop battery-operated, data-logging, light-scattering laser photometer.

Gaseous phase measurements

The gaseous species, including sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide CO), carbon dioxide (CO_2), oxygen (O_2), and hydrocarbons (HCs), were measured by using Testo 350XL, Horiba 5-gas analyser. Further technical information of these measurement devices are given in Table 2-2.

Table 2-2 Main information of measurement instruments

Measurement Instruments	Types of exhaust gases	Range	Accuracy	Flow rate (L/min)
A Portable 5-Gas Analyser (The Horiba MEXA 584L)	HC CO CO_2 O_2 NO_x	0 – 60,000 ppm 0 – 10% 0 – 20% 0 – 25% 0 – 5000 ppm	60 ppm 0.03 % 0.03 % 0.01 % 25 ppm	
Testo 350XL	SO_2 CO CO_2 O_2 NO NO_2	0 – 5000 ppm 0 – 10,000 ppm 0 – CO_2 max 0 – 25% 0 – 3000 ppm 0 – 500 ppm	5% of mv 5% of mv - 0.8% of fv 5% of mv 5 ppm	1.2
Sable CA-10	CO_2	0 – 5% standard 0 – 10% optional	1%	5-500(x 10^{-3})
Dust Trak	PM_1 $PM_{2.5}$ PM_{10}	0.1 – 10 µm	5%	3.0
DMS 500	Fast particulate spectrometer	5 nm – 2.5 µm	-	8.0

The on-board measurement performed constitutes the basis of work carried out by the AMC and QUT.

3. Emissions from a marine auxiliary diesel engine at berth using heavy fuel oil

3.1. Abstract
This study presents an emission measurement campaign on commercial ships plying the east coast of Australia. Detailed investigation of engine performance and emissions from main and auxiliary marine diesel engines using heavy fuel were undertaken. Marine diesel engine gaseous (O_2, CO, CO_2, SO_2 and NO_x) and particle number and mass emissions were measured using research grade instrumentation. The measurements were performed in October and November 2015 on two large cargo ships at berth, manoeuvring and during travel between the ports of Brisbane, Gladstone and Newcastle. Detailed measurements on an auxiliary engine at berth are analysed in this paper, and include engine power and RPM, fuel oil consumption, exhaust gas temperature and exhaust particle and gaseous emissions. It was found that some ship emissions were up to several orders of magnitude higher than corresponding land-based diesel emission levels. Significant variations in emissions were also related to fuel sulphur content and engine load.

Key words: On-board ship emission measurement, heavy fuel oil, cold start state, stable working conditions.

3.2. Introduction
Increasing diesel engine brake power, and reducing brake specific fuel oil consumption, exhaust gas and noise emissions occur by turbocharging a diesel engine, which is popular in many applications, including road, non-road, marine and industry [17]. For land-based applications, turbocharging has been incorporated into the engine design carefully, so as not to adversely affect emissions because of the strict framework for emission control including EURO and TIER used in the EU and USA, respectively. However, for marine applications the main motivation for turbocharging has been reduction in fuel consumption alone. Consequently, marine diesel emissions are an emerging issue and have become of global concern over the past decade.

Ship emissions, including gases and particulate matter (PM), have negative effects on both the environment and public health [1, 2, 18-20]. Physical and chemical characteristics of diesel particulate matter (DPM), and its respiratory health effects have been investigated by Ristovski [19]. Particle number (PN) and mass from diesel engines using both diesel fuel and marine gas oil (MGO) have also been investigated and compared [21]. Corbett et al. (2007) estimated that shipping-related PM2.5 emissions are the cause of approximately 60,000 deaths per year associated with cardiopulmonary and lung problems around the world [20]. Therefore, quantitative and qualitative estimation of pollutant emissions from ships and their distribution are becoming more important [18]. However, only a limited number of on-board measurement studies [18, 22] investigated this problem.

Heavy fuel oil (HFO), which contains many impurities including sulphur and metal, is used by almost all medium and large ships owing to its cost-effectiveness [2]. Corbett (2003) has estimated that the yearly amount of fuel consumption was almost 290 million tonnes globally, of which approximately 80% of fuel consumed by the world ship fleet was HFO. HFO is the main fuel for 95% of 2-stroke low-speed main engines and 70% of 4-stroke medium-speed engines [10]. This makes ship emission-related issues more critical, especially in port environments [23]. This study aims to investigate heavy fuel oil auxiliary marine diesel engine emissions during constant revolution conditions and load acceptance.

3.3. Ship Emission On-Board Measurement Campaign

An 11-day measurement campaign was performed in October and November 2015 on two large cargo ships at the ports of Brisbane, Gladstone and Sydney. The work was a collaboration of the Australian Maritime College (AMC), Queensland University of Technology (QUT), and Maine Maritime Academy (MMA). The first on-board measurements were performed on CSL Vessel I from 26th to 31st of October, 2015 when she was running from Port of Brisbane to Port of Gladstone. The second measurements were conducted on CSL Vessel II from 3rd to 6th of November, 2015 in her voyage from Gladstone to Newcastle. All measurements have been carried out on both main and auxiliary engines of the two ships for different ship operating conditions, such as at at berth, manoeuvring, and at sea.

Measurements presented in this paper were performed on the auxiliary engine data from the CSL Vessel II while she was at berth. Instruments were arranged on a deck high up in the machinery room and the exhaust gas was sampled continuously from a hole cut in the exhaust pipe after the turbocharger of auxiliary engine No.1. The details of the measured engine can be seen in Table 3-1. At the sample point, one hole was created for the present measurements by a Testo 350XL and a DMS 500. The schematic diagram of sampling setup is shown in Fig. 3-1. Data on engine power, engine revolution, fuel oil consumption, and exhaust gas temperature were measured by the ship's instrumentation. Characteristics of HFO used are presented in
Table 3-2. The measurement procedure followed ISO 8178 standard [24, 25].

Table 3-1 Technical parameters of Main Diesel Generator.

MAIN DIESEL GENERATOR			
AUXILIARY DIESEL ENGINE		**GENERATOR**	
Type	Four-stroke, trunk piston type marine diesel engine with exhaust gas turbo charger and air cooler	Type	Protected drip proof type (FE 41A-8)
Output	425 kW	Output	531.25 kVA x 450V x 60 Hz x 3Φ
Revolution	900 RPM	Revolution	900 RPM
Max Combustion Press	165 bar		
Mean Effective Press	16.7 bar		
No. Cylinder	4		
Cylinder Bore x Stroke	200 x 280 mm		
Maker	Wartsila Diesel Mfg Co., Ltd	Maker	Taiyo Electric Co., Ltd

The Testo 350XL was calibrated on 10th, August 2015 by the Techrentals Company and was used to measure gaseous emissions. Particle number size distributions in the size range 5 nm – 1.0 µm in the hot exhaust gas were analysed with a time resolution of 10 Hz (0.1 s) using a DMS 500 MKII – Fast Particulate Spectrometer with heated sample line, and built in dilution system (combustion). All auxiliary engines used on board ships work at load characteristic. This means that a marine diesel engine is working at a constant speed while the torque load is varied. Engine load depends on electric loads of electric equipment of ship. In this case, we investigated exhaust emissions at different engine loads, including 0, 24, 35, 55, 70, 83, and 95% load by means of alternating the load between two auxiliary engines. This can be seen in Fig. 3-2.

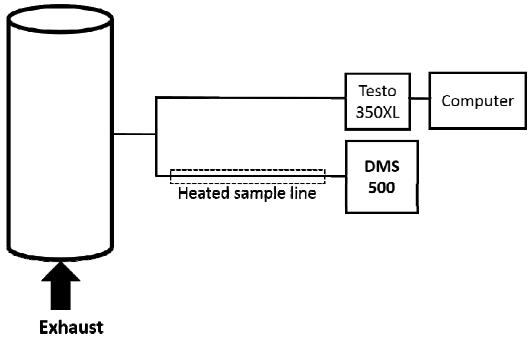


Fig. 3-1 Schematic diagram of exhaust emission sampling setup

Table 3-2 Main chemical composition and physical properties of HFO.

Parameter	Units	Method	Bunker receipt	Laboratory
Density at 15^0 C	kg/m^3	ISO 3675	986.2	-
Viscosity at 50^0 C	mm^2/s	ISO 3140	377	-
Micro - carbon residue	% mass	ISO 10370	14.65	-
Sulphur (S)	% mass	ISO 2719	3.13	-
Carbon (C)	% mass	AR 2816	-	88.14
Hydrogen (H)	% mass	-	-	-
Nitrogen (N)	% mass	AR 2816	-	0.68
Ash	% mass	ISO 6245	0.064	-
Vanadium (V)	mg/kg	IP 501	141	-
Nickel (Ni)	mg/kg	IP 501	34	-
Asphaltenes	% mass	IP 143/D6560	7.42	-

3.4. Results and Discussion

The emission ratios (ERs) were calculated using the co-emitted CO_2 (g of emissions/g of CO_2) and used to express the emission data. Such an approach does not require the instantaneous engine fuel consumption to be known. This is particularly helpful for the auxiliary engine used in this case because the engine load could not be held perfectly constant. It should also be noted that ERs do not require knowledge of the fuel properties.

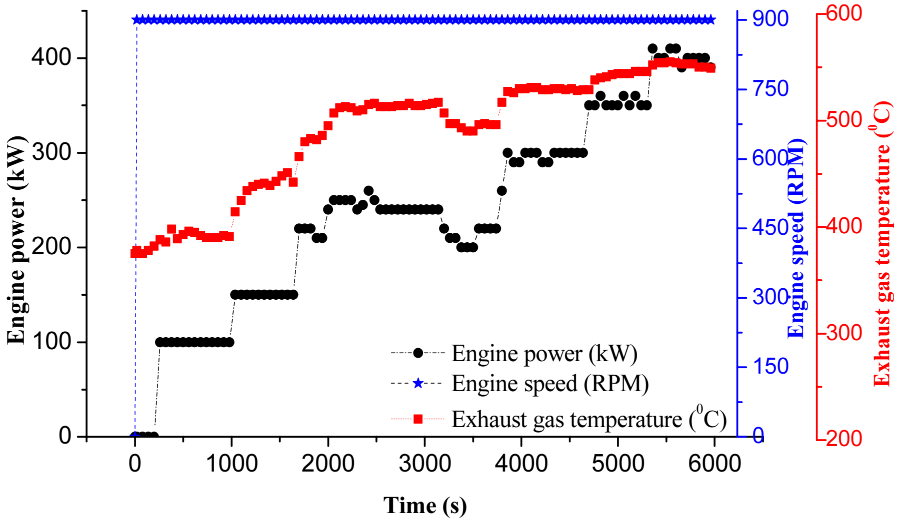
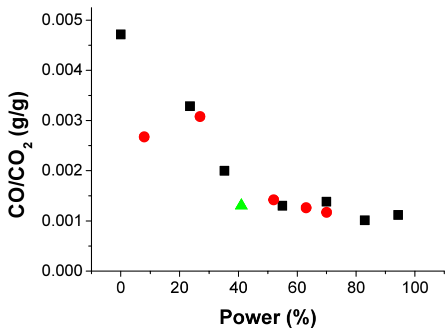


Fig. 3-2 Auxiliary engine (at berth) speed, power output and exhaust gas temperature with time

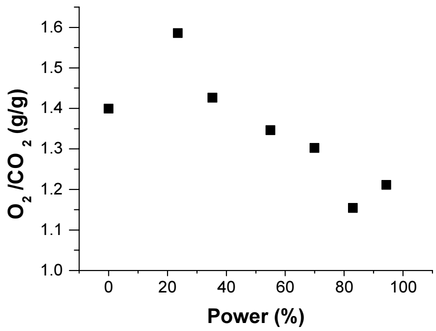
The relationship of gaseous ERs with engine power in percentage of full load is shown in Fig. 3-3a, Fig. 3-3b, Fig. 3-3c and Fig. 3-3d. Generally there is a significant relationship between the ERs and engine load, except for SO_2 emissions in Fig. 3-3c. This is because sulphur emissions are directly related to fuel sulphur levels which do not change during the operation of the engine. There was an initial peak in CO concentration at start-up in cold start period – which can be seen in Fig. 3-3a. This is due to the cold start of the engine and the low engine load condition, which leads to incomplete combustion and contributes to carbon monoxide reaching its highest level. CO concentration then significantly decreases and reached a stable value when the engine load was at a high level. If the engine test was repeated at warm up condition ERs of CO/CO_2 at 0 and 25% load would most likely be smaller than that in the cold start.

A decreasing trend of O_2 emissions with power was observed in Fig. 3-3b. This may be due to the engine's revolution being constant, which makes the amount of air stable while the engine load is increased. Thus, more fuel is required and a rich fuel-air mixture combustion condition is reached. The SO_2 and CO_2 emissions in Fig. 3-3c are generally proportional to the fuel carbon and sulphur content, and therefore the ER of SO_2/CO_2 seems to be constant, as was expected. The theoretical and measured curves of the ER of SO_2/CO_2 had a difference in value of 20 – 25%. This difference is likely to arise from a combination of combustion and measurement issues including not all the sulphur in the fuel being converted to SO_2 and the high levels of sulphur in the exhaust gas being at the far end of the Testo instrument range. Of most interest in this study is the ER of SO_2/CO_2 which is significantly higher than that in the research of Agrawal [22] and Cooper [26], as a result of higher sulphur content fuel used in this research (3.13 % mass). Their fuel sulphur contents were 2.05 and 2.2% by mass, respectively. The emission of NO_x will depend on the engine temperature, and thus the ER for NO_x presented in Fig. 3-3d shows a dependence on engine load in which high engine load produces the highest temperature and therefore the highest emission. However, the ER of NO_x/CO_2 was much lower than that of compared studies. This may be due to differences in engine types and working conditions.

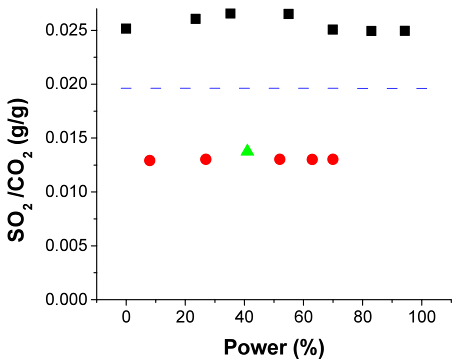
For particle emissions, PN and PM ERs in Fig. 3-3e and Fig. 3-3f were observed at a high level at low and medium engine load working conditions, especially at the cold start of the engine compared to the high load condition. However, these values then significantly dropped at higher engine loads. The ER of the PM in this study was significantly smaller than that of compared studies. Available data concerning PN is extremely limited to just a few papers as shown in Fig. 3-3.



(a)

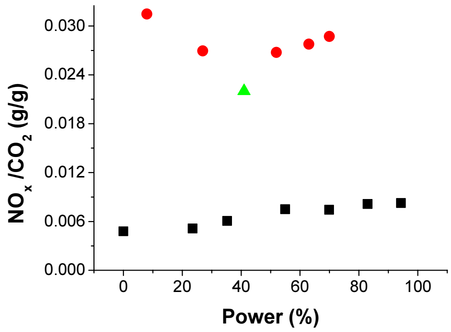


(b)

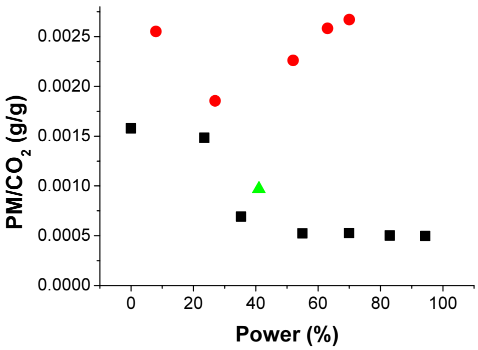


(c)

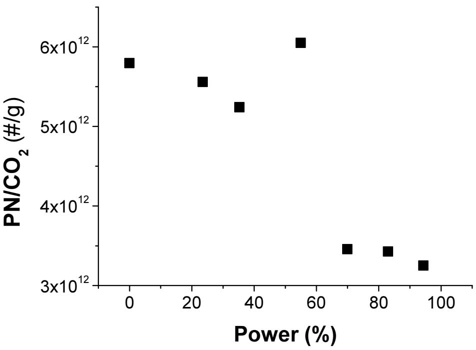
(AMC)



(d)



(e)



(f)

Fig. 3-3 Auxiliary engine at berth emission ratios of CO, O2, SO2, NOx, PM, and PN (g/g AND #/g CO2) with engine power. ■ this study, ● Agrawal 2008 [22], ▲ Cooper 2003 [26]. The dashed line in Fig. 3-3c illustrates the theoretical curve of gSO2 /gCO2 according to the fuel sulphur and carbon content.

3.5. Conclusion

To improve the limited knowledge regarding marine engine emissions, a measurement campaign on two commercial ships plying the east coast of Australia was conducted and has been described. Engine performance and emissions (gaseous and particle) of an auxiliary engine while in berth, were measured on-board the ship during actual harbour stopovers. The ERs (g of emissions/g of co-emitted CO_2) were used to present the emission data. From cold start exhaust emissions experienced a high level when compared to the stable working condition and were closely related to the fuel sulphur level.

3.6. Acknowledgement

The authors gratefully acknowledge the Port of Brisbane Corporation for their ongoing support in the project, Maritime Safety Queensland and stevedore operators (AAT, Patricks and DP World). The authors would like to acknowledge the outstanding support received from all employees and crew of CSL Group Inc. in coordinating this project. In addition, the materials and data in this publication have been obtained through the support of the International Association of Maritime Universities (IAMU) and the Nippon Foundation in Japan.

4. Particle emissions from ships at berth using heavy fuel oil

4.1. Abstract

The composition of exhaust from a marine diesel auxiliary engine running on Heavy Fuel Oil (HFO) was investigated on-board a large cargo vessel. Engine particle emissions were measured using a DMS 500 for particle number size distributions in the size range of 5-1000 nm and measurements for gaseous emissions were carried out using Testo 350XL for O_2, CO, CO_2, SO_2 and NO_x. The measurements were performed in October and November 2015 on two large cargo ships at berth and during travel. Measurements were also carried out on auxiliary engines of two ships when she was at berth. Data on engine power, engine revolution, fuel oil consumption, intercooled air temperature, scavenging air pressure, cooling fresh water and exhaust gas temperature were measured using instrumentation of the ship. Results showed that emission factors (g/kWh) are higher than that of previous studies for SO_2. This may be due to the high sulphur content of fuel used. Particle number size distribution was observed to be the highest around 35 - 45 nm in diameter, and the particle number remarkably decreased during higher engine load conditions.

Key words: On-board ship emission measurement, heavy fuel oil, fuel sulphur content, particle number emission factor, particulate matter emission factor, HFO composition.

4.2. Introduction

Exhaust emissions from ships have negative effects on both the environment and public health [1, 2, 18-20, 27]. Based on sufficient evidence in 2012, the International Agency for Research on Cancer (IARC), which is part of the World Health Organization (WHO), classified diesel engine exhaust as carcinogenic to human health (Group 1, same as asbestos). According to Viana et al. [5], shipping-related emissions are one of the major contributors to global air pollution, especially in coastal areas. This is obvious because over 70% of ship emissions may spread up to 400 km inland and significantly contribute to air pollution in the vicinity of harbors [7]. They may cause an increase in the levels and composition of both particulate and gaseous pollutants and the formation of new particles in densely-populated regions [5, 6]. As a result, Corbett et al. [20] estimated that shipping-related $PM_{2.5}$ emissions are the cause globally of approximately 60,000 deaths annually associated with cardiopulmonary and lung problems. Continued implementation of the amendments to the Maritime Pollution Convention (MARPOL) Annex VI regulations are a good way to reduce ship emissions, however, further regulation should be implemented because a fuel shift to low sulphur alone seems to be insufficient to reduce fine and nano-particle emissions [16]. Quantitative and qualitative estimation of pollutant emissions from ships and their dispersion thus are becoming more important [18]. However, from the literature, a very limited number of on-board measurement studies have been carried out [18, 22].

Heavy Fuel Oil (HFO), which contains many impurities including sulphur, ash, vanadium, and nickel, is the main fuel for up to 95% of 2-stroke low-speed main engines and around 70% of 4-stroke medium-speed auxiliary engines [10] because of to its economic benefit [2]. Different compounds like particulate sulphate, black carbon (BC), ash and heavy metals in emitted particles are associated with HFO combustion [28, 29]. In practice, while gaseous emissions have been extensively studied over several decades, diesel engine fine and nano-particles have recently emerged as a major health concern and received more attention from researchers.

The aim of this study is to investigate the particle emissions with respect to number, concentration and size distribution, from an auxiliary marine engine using HFO (3.13 wt % S) when the ship is at berth. The engine operates at a constant speed, with different engine load conditions.

4.3. Ship Emission On-board Measurement Campaign

The measurements were performed in October and November 2015 on two large cargo ships at the Ports of Brisbane, Gladstone, and Sydney. The work was a collaboration of the Australian Maritime College (AMC), Queensland University of Technology (QUT), and Maine Maritime Academy (MMA). The first on-board measurement was performed on CSL Vessel I from 26th to 31st of October, 2015 when she was running from Port of Brisbane to Port of Gladstone. The second measurement was conducted on CSL Vessel II from 3rd ^{to} 6th November, 2015 on her voyage from Gladstone to Newcastle. All measurements have been carried out on both main and auxiliary engines of the two ships for different operating ship conditions, such as at at berth, manoeuvring, and at sea.

The on-board measurement presented in this paper was performed on the auxiliary engine of the CSL Vessel II. Instruments were arranged on a deck high up in the machinery room and the exhaust gas was sampled, and measured continuously from a hole cut in the exhaust pipe after turbocharger of auxiliary engine No.1. The details of the measured engine can be seen in Table 4-1. At the sample point, one hole was created for the present measurement by a Testo 350XL and a DMS 500. Data on engine power, engine revolution, fuel oil consumption, and exhaust gas temperature were measured by the ship's instrumentation. The measurement procedure is in line with the ISO 8178 standard [24, 25].

Table 4-1 Technical parameters of Main Generator (Auxiliary Engine)

MAIN DIESEL GENERATOR			
AUXILIARY DIESEL ENGINE		**GENERATOR**	
Type	Four-stroke, trunk piston type marine diesel engine with exhaust gas turbo charger and air cooler	Type	Protected drip proof type (FE 41A-8)
Output	425 kW	Output	531.25 kVA x 450V x 60 Hz x 3Φ
Revolution	900 RPM	Revolution	900 RPM
Max Combustion Press	165 bar		
Mean Effective Press	16.7 bar		
No. Cylinder	4		
Cylinder Bore x Stroke	200 x 280 mm		
Maker	Wartsila Diesel Mfg Co., Ltd	Maker	Taiyo Electric Co., Ltd

The specifications of the fuel used are presented in Table 4-2. Regarding engine type, all auxiliary engines used on board ships work at load characteristic. This means that a marine diesel engine is working at a constant speed while the torque load is varied. Engine load depends on electric loads of electric equipment of a ship. In this study, we investigated exhaust emissions at different engine loads, including 0, 24, 35, 55, 70, 83, and 95% of the maximum continuous rating (MCR) by means of alternating the load between two auxiliary engines. (What does the word it represent?)It is shown in Fig. 4-1c.

Table 4-2 Fuel characteristics of HFO (from Bunker Delivery Receipt)

Parameter	Units	Method	Result	Parameter	Units	Method	Result
Density at 15^0 C	kg/m^3	ISO 3675	986.2	Silicon	mg/kg	IP 501	9
Viscosity at 50^0 C	mm^2/s	ISO 3140	377	Aluminium	mg/kg	IP 501	6
Flash point	^0C	ISO 2719	118.5	Vanadium	mg/kg	IP 501	141
Water	% Vol	ISO 3733	0.2	Sodium	mg/kg	IP 501	41
Sulphur	% mass	ISO 2719	3.13	Iron	mg/kg	IP 501	14
Ash	% mass	ISO 6245	0.064	Lead	mg/kg	IP 501	0
Carbon residue	% mass	ISO 10370	14.65	Nickel	mg/kg	IP 501	34
Total sediment	% mass	ISO 10307	0.03	Calcium	mg/kg	IP 501	10
Calorific value	MJ/kg	IP 501	40.22	Zinc	mg/kg	IP 501	1
Asphaltenes	% mass	IP 143	7.42	Potassium	mg/kg	ASTM	0.8

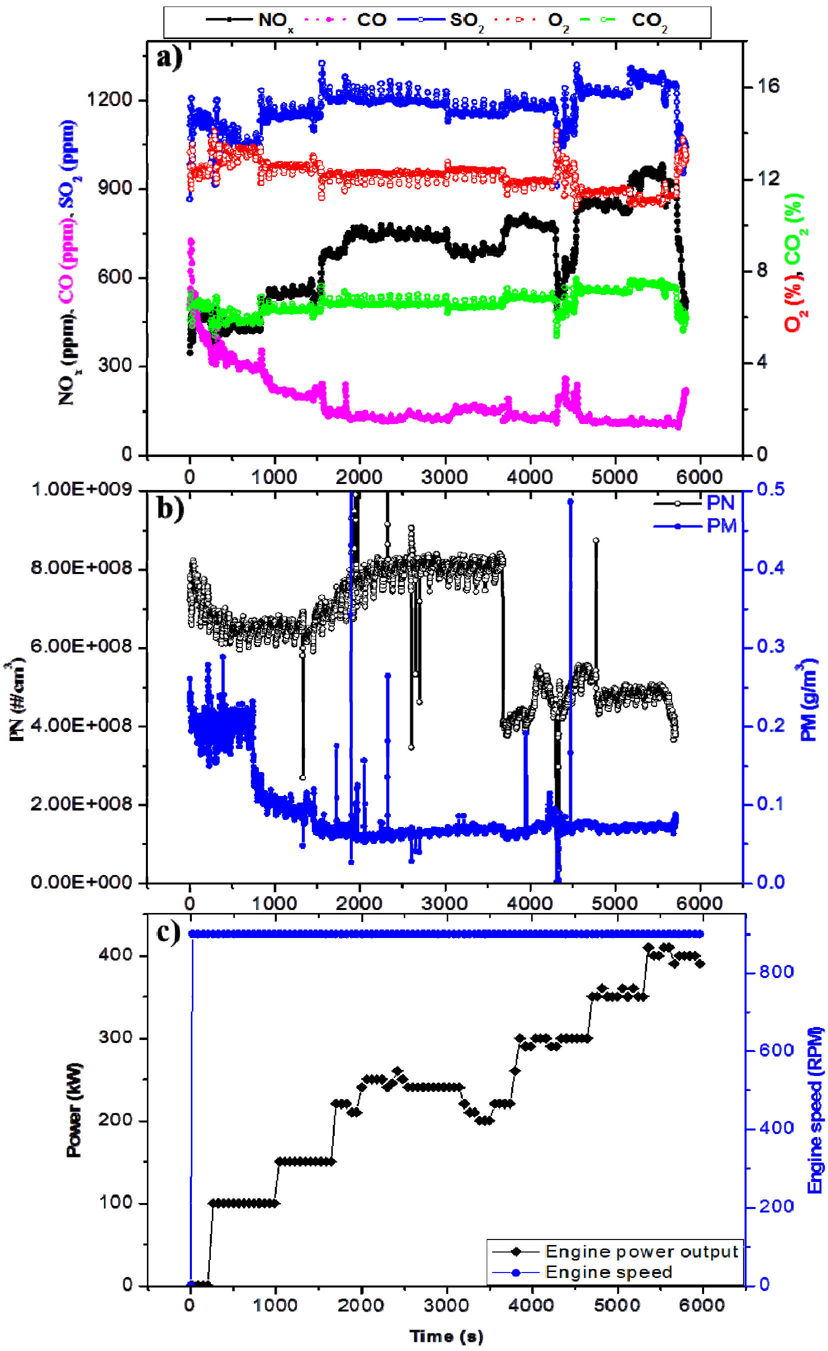


Fig. 4-1 (a) Gaseous concentrations measured NOx (solid line with filled black circles), CO (dotted line with filled pink circles), SO2 (solid line with open circles), O2 (dotted line with open circles), and CO2 (dashed line with open circles). (b) Number (solid line with open circles) and mass (solid line with filled blue circles) of particles. (c) The relationship between engine speed, engine power with period of measurement time.

Emission factors for emitted gas-phase species and number/mass of particles were calculated following ISO 8178 [24, 25], using specific fuel consumption and formed CO_2 to obtain the exhaust gas flow rate (equation (1)). These calculations assume that all carbon in the fuel is converted completely into CO_2.

$$\boldsymbol{Exhaust\ gas\ flow} = \frac{\boldsymbol{Fuel\ consumption}\left(\frac{kg}{hr}\right) \times \boldsymbol{Fuel\ oil\ carbon\ content}\ (\%) \times (\boldsymbol{44}/\boldsymbol{12})}{\boldsymbol{Density\ of\ CO_2}\left(\frac{kg}{m^3}\right) \times (C_{CO2,exh} - C_{CO2,air})} \tag{1}$$

$$\boldsymbol{EF_{PM}} = \frac{\boldsymbol{Exhaust\ gas\ flow \times PM}}{\boldsymbol{Engine\ power}} \tag{2}$$

$$\boldsymbol{EF_{PN}} = \frac{\boldsymbol{Exhaust\ gas\ flow \times PN}}{\boldsymbol{Engine\ power}} \tag{3}$$

Where $C_{CO2,\ exh}$ and $C_{CO2,\ air}$ are the CO_2 concentration in v/v % in the exhaust gas and in the air, respectively. Data on fuel consumption and engine power were obtained from the ship's instruments.

The emission factors of both gases and particulate matter are presented as mass or number per kWh of engine work (g/kWh, #/kWh), and normalised to standard conditions regarding temperature of 273.15 K and pressure of 101.325 kPa.

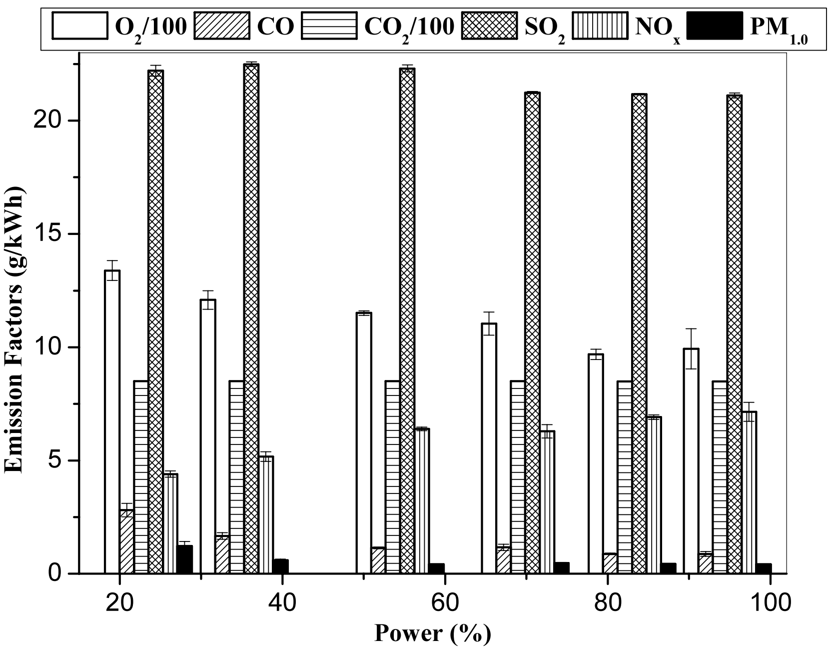


Fig. 4-2 Specific emissions against engine load. (A 95% CI for each mean value is shown as the mean ± X)

4.4. Results and Discussion

The major gaseous emissions of interest in the engine exhaust were NO_x, CO, SO_2, O_2, and CO_2. The real-time on-board measurement of these gases can be seen in Fig. 4-1a. Fig. 4-1 demonstrates the relationship between the changes of emissions with time and engine power output while engine speed is kept at constant value. The results of gas-phase emission factors for O_2, CO, CO_2, SO_2, and NO_x in terms of g/kWh are presented in Fig. 4-2. There was an initial peak in CO concentration at start-up in cold start period - this can be seen in Fig. 4-1a and Fig. 4-2. This is due to the cold start of the engine and the low engine load condition, which leads to incomplete combustion and aids carbon monoxide to gain the highest level. CO concentration then significantly decreased and gained a stable value when the engine load was at a high level.

Table 4-3 Comparison of gaseous emissions between this study and previous studies.

Study	Engine Type	Fuel (% S)	Engine Load (%)	O_2 (g/kWh)	CO (g/kWh)	CO_2 (g/kWh)	SO_2 (g/kWh)	NO_x (g/kWh)
Moldanová et al. [30]	4-stroke, medium speed, main engine, 4440 kW	HFO (1.0)	30 80	1127 1054	1.82 1.17	617 678	3.24 3.65	9.6 9.6
Khan et al. [31]	2-stroke, low speed, main engine, 36740 kW	HFO (3.14)	29 52 73 81	- - - -	0.57 0.41 0.36 0.35	577 555 561 576	11.4 10.9 11.0 11.3	19.5 18.5 19.5 19.1
Winnes and Fridell [16]	4-stroke, medium speed, main engine, 4500 kW	HFO (1.6)	50 70 90	- - -	1.05 0.74 0.3	620 603 607	4.62 4.62 4.57	7.49 8.49 10.71
Agrawal et al. [32]	2-stroke, low speed, main engine, 15750 kW	HFO (2.85)	13 25 50 75 85	- - - - -	2.5 1.5 1.0 0.8 0.5	~1200 640 620 670 680	13 12 10.5 10 10	22 17 18 21 20.5
Cooper [26]	4-stroke, medium speed, auxiliary engine, 1270 kW	HFO (0.53)	47-58	-	1.06 - 1.71	763-803	2.5-2.7	13.3 - 17.5
	4-stroke, medium speed, auxiliary engine, 2675 kW	HFO (2.2)	41	-	0.90	691	9.5	15.2
	4-stroke, medium speed, auxiliary engine, 2005 kW	HFO (2.2)	39	-	0.77	697	9.6	12.9
This study	4-stroke, medium speed, auxiliary engine, 425 kW	HFO (3.13)	24 35 55 70 83 95	1338 1208 1150 1104 969 992	2.81 1.66 1.14 1.16 0.88 0.87	850 850 849 849 849 849	22.20 22.49 22.30 21.24 21.17 21.11	4.40 5.17 6.40 6.30 6.91 7.14

A significantly decreasing trend of O_2 emissions with power was observed in Fig. 4-1a and Fig. 4-2. This may be due to the engine revolution being constant, which makes the amount of air stable while the engine load is increased. Thus, more fuel is required and a rich fuel-air mixture combustion condition is reached. The fuel-dependent specific emissions of SO_2 and CO_2 in Fig. 4-1a are generally proportional to the fuel carbon and sulphur content, and therefore these emission factors of SO_2 and CO_2 seem to be constant as was expected. Of most interest in this study is that emission factor of SO_2 was much higher than that of comparable studies (Table 4-3), as a result of higher sulphur content fuel used in this research. The theoretical value of SO_2 emission factor calculated in this study was around 16.6 g/kWh, which was significantly less than measured cases. The emission of NO_x will depend on the engine temperature, and thus the emission of NO_x presented in Fig. 4-1a and Fig. 4-2 shows a dependence on engine load in which high engine load produces the highest emission. As shown in Table 4-3, the value of NO_x emission in the present research was much lower than that of previous studies, this may be due to differences in engine types and working conditions.

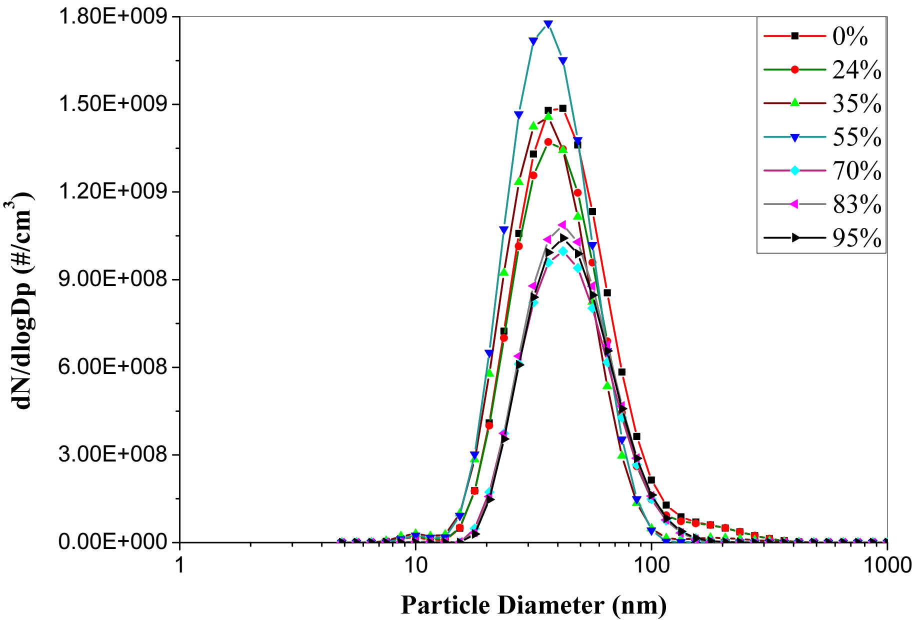


Fig. 4-3 Number size distributions of measured particles (5-1000 nm) for idle, 24%, 35%, 55%, 70%, 83%, and 95% load.

For particle emissions presented in Fig. 4-1b, there is a general pattern in the emitted nanoparticles with an initial peak both in mass and number concentration at engine start-up in cold start period before reaching the constant value or significantly decreasing to low level at higher engine load working condition. This can be seen clearly in PN case, with a significant difference in particle number concentrations observed between low and medium engine load of 0, 24, 35 and 55% with 70, 83 and 95% of engine load working conditions, as illustrated in Fig. 4-1b and Fig. 4-3. This may be due to low temperature inside the engine combustion chamber at low loads, which caused more particles to be created [27]. Fig. 4-3 indicated that the number size distributions were dominated by nano-particles at around 35 – 45 nm for all engine load working conditions. Particle mass emission factor (PM) was calculated from the number of concentrations measured with the DMS 500 (5.0 – 1000 nm) assuming spherical particles with unit densities for nucleation and accommodation mode. A 95% confidence interval (CI) to each mean value in Table 4-4 was calculated.

Table 4-4 Comparison of PM and PN between this study and previous studies. (A 95% CI for each mean value is shown as the mean ± X)

Study	Engine Type	Fuel (% S)	Engine Load (%)	PN (10^{16} #/kWh)	PM (g/kWh)		
					PM_{10}	$PM_{2.5}$	$PM_{1.0}$
Moldanová et al. [30]	4-stroke, medium speed, main engine, 4440 kW	HFO (1.0)	30 80	-	0.35 0.41	-	0.27 0.41
Khan et al. [31]	2-stroke, low speed, main engine, 36740 kW	HFO (3.14)	29 52 73 81	-	-	1.19 1.44 2.14 2.19	-
Hallquist et al. [33]	4-stroke, medium speed, SCR-equipped main engine, 12600 kW	HFO (0.49)	75	2.05 ± 0.27	-	-	0.13 ± 0.02
Anderson et al. [27]	Test-bed engine, 4-stroke, 5-cylinder, high speed, 81 kW	HFO (0.12)	10 25 35	12 ± 0.04 17 ± 0.059 0.17 ± 0.003	-	-	0.45±0.025 0.71±0.11 0.65±0.03
This study	4-stroke, medium speed, auxiliary engine, 425 kW	HFO (3.13)	24 35 55 70 83 95	0.468 ± 0.013 0.450 ± 0.009 0.501 ± 0.025 0.310 ± 0.013 0.290 ± 0.011 0.281 ± 0.012	-	-	1.221 ± 0.198 0.585 ± 0.064 0.423 ± 0.009 0.473 ± 0.020 0.424 ± 0.013 0.421 ± 0.011

In comparison with the literature which can be seen in Table 4-4, there is a large variation of particle number emission factors, which may be due to the fact that there is not much available data on PN and a difference in fuel used, engine models, working conditions, and instruments used for PN measurement [33]. A decreasing trend of both PN and PM emission factors was observed clearly as engine output power increased in this study. A similar trend was also observed in the study of Anderson et al. [27], but particle number emissions at 10 and 25% load in their study (HFO, 0.12 wt % S) were much higher than that of present study (HFO, 3.13 wt % S). This shows that a fuel shift to low sulphur content fuel would not result in decreasing small size particle number concentrations. This can be supported by previous studies [16, 34]. Magnitude of PM emission factor in this study was similar to that of previous studies.

4.5. Conclusion

Although in-port auxiliary engine emissions account for a relatively small proportion of the total emissions from shipping compared to main engine emissions, they have some of the most significant health effects on the surrounding population [26]. To improve the limited knowledge regarding marine engine emissions [33], especially on particle number size distribution, a measurement campaign on two commercial ships plying the east coast of Australia was conducted and has been described. Engine performance and emissions of an auxiliary engine while in berth, were measured on-board the ship during actual harbour stopovers. The focus was directed toward characteristics of particle emissions. Gaseous and particle emission factors were presented in g/kWh or #/kWh, and investigated at different engine loads while engine speed as kept at constant value. The particle number size distribution peaked at around 35 – 45 nm and dominated by nano-particles, which have a negative impact on human health and climate.

4.6. Acknowledgement

The authors gratefully acknowledge the Port of Brisbane Corporation for their ongoing support in the project, Maritime Safety Queensland and stevedore operators (AAT, Patricks and DP World). The authors would like to acknowledge the outstanding support received from all employees and crew of CSL Group Inc. in coordinating this project. In addition, the materials and data in this publication have been obtained through the support of the International Association of Maritime Universities (IAMU) and the Nippon Foundation in Japan.

5. Emission inventories for shipping operations: Comparison with on-board measurements

5.1. Abstract

Maritime transportation has been a popular mode of transport for many years due to its cost efficiency, overall safety and relatively environmentally friendly operations. This trend is predicted to increase with the number of global fleet of vessels forecast to continue increasing. However, unlike land-based transportation which is strictly governed by stringent rules and regulations, the shipping regulators are still continuously amending their legislation to regulate the associated emissions. Considering the harmful effects of shipping emissions on human health and the environment, and uncertainty associated with different emission inventory methodologies, this study initiates a need to determine a suitable methodology that is able to consider and estimate emissions from ocean going ships. For this study, emission measurements on-board a 27198 GRT bulk carrier during its operation was carried out. Emissions were measured from a Slow Speed Diesel (SSD) Main Engine (ME) with 6880 kW output whilst the ship was at berth, manoeuvring, and cruising. Emissions from a Medium Speed Diesel (MSD) Auxiliary Engine (AE) of 465 kW output is also considered. Analysis was carried out to develop a methodology that provides the best overall prediction of the primary gaseous emissions and particulate matters. Total 13 emission inventory methodologies were studied considering factors such as ship's specifications, operating modes, geographical location and duration of travel. Results of these methodologies were compared with the on-board measurement of a bulk carrier. It was found that for vessels while at berth, EMS and US EPA methods has the best overall predictions of emission for the ME and AE respectively. However, for ME operations during manoeuvring and cruising, the US EPA method gave the closest estimate. Finally, for the total voyage, considering all three operation modes, the US EPA most closely resembled the results obtained from the on-board measurements.

Keywords: *Ship transport, Emission inventory, On-board measurement, accurate estimation*

5.2. Introduction

Transportation of cargo and crude oil by ships dates back many years and has played a vital role especially in transferring oil from the Middle East all over the world [35]. Today, maritime transport is still recognized as the most preferred mode of global transport for goods transfer [36]. Several reasons have contributed to its long lasting popularity, including transportation via ship, recognised to be a cost effective option in comparison to other modes of transport due to the large payload it can carry [37]. In addition, shipping is also a relatively safe transport option [38] and is regarded as one of the most environmentally friendly modes of transportation producing less emissions in comparison to road and rail transport [39]. With its current popularity, the number of sea-going vessels are forecast to grow continuously over the years [40].

With the increase in vessel operations arises the significance of pollution due to shipping operations spawned by the tendency to consume low quality fuel oil [37]. Hence, it is vital to track the emissions and understand their potential effect on the surrounding environment. However, unlike land-based emissions which are monitored by stringent rules and regulations, the shipping sector still lacks reliable approaches to monitor and estimate shipping emissions a factor crucial in improving environmental performance [8, 41, 42]. Shipping operations are known to release large amounts of primary pollutants in atmosphere including Carbon Dioxide (CO_2), Carbon Monoxide (CO), Nitrogen Oxides (NOx), Sulphur Oxides (SOx), Particulate Matters (PM) and Volatile Organic Compounds

(VOC) [43]. Concerns have been sparked over these shipping emissions that are associated with adverse effects on human health and the surrounding environment. For example, NO_2 and CO emissions result in flu like symptoms, while SOx-emissions cause breathing issues and premature births. Many statistics have also revealed asthma cases, heart related diseases and premature deaths [44, 45]. In addition, researchers [8] reported lung cancer deaths and heart attacks that have been recorded worldwide due to PM emissions in the port areas of Europe, East Asia and South Asia. Considering their alarming health risks to both the ecological entities and humans residing in the surrounding port areas, it is highly important to address the situation and implement solutions that are able to consider and measure shipping emissions precisely. Hence a guideline to regulate these primary emissions must be developed.

Many studies [46-48] reviewed shipping emissions and their impacts based on several methodologies on different scales, namely in different ports and countries. Researchers [10; 16; 17] reported that ocean-going vessels account for 14-31 % global emissions of NOx, 4-9% SOx and 3% CO_2 worldwide. A previous study [48] also reported that CO_2 from shipping emissions are responsible for approximately 2-3% of global emissions which is higher than the amount of non-GHG emissions; while SOx and NOx are responsible for 5-10 % and 17-31% respectively. A detailed study carried out on shipping emissions [18] also reported similar results. With the increase in the global fleet of vessels in operation, these emissions are forecast to largely increase over the coming years. It is predicted that primary emissions will increase about four times with ship numbers tripling by 2050 [10]. Recently, it has also anticipated that CO_2 could increase by 50% and 250% of the current emissions by the year 2050 [19]. Hence, estimating and evaluating the shipping emissions has become an increasing concern.

Currently, several methods for estimating the emissions from ocean going ships exist. Online monitoring of ship emissions is one of these methods. It may provide on-board data on a continuous real time basis; however, this method suffers from the lack of appropriate instrumentation and reliability [49]. The other approach is ship plumes based measurements, which is an on-board measurement carried out on a specific vessel. It provides real time emissions data of the vessel. However this approach is costly in time and human resources, and it is also challenging trying to engage the vessel owners to install the necessary measurement instrumentation [50, 51]. Many previous studies reviewed on-board measurement [50, 52-64]. Petzold et al. [61] worked on a 4-stroke engine type, while Kasper et al. [55] put the focus on PM emissions of a 2-stroke marine engine type. Lloyds [54, 63], and Corbett et al. [65] considered different emissions in various engine types. Researchers [26, 56, 58] studied the emissions from the MEs and AEs of ferries. Some studies [55, 59-61, 63, 64, 66] reported their findings on SSD and MSD engines on test rigs. Many factors affect ship emissions such as; type of ship, type of engine, operations etc. However, it is not always possible to investigate the effect and variation of these factors on the final emissions as this can be costly in time and requires human resources. Therefore, the emission inventories are the most commonly applied method to estimate ship emissions [53, 67, 68]. Numerous considerations are taken into account in creating these emission inventories, such as the region of study, the vessel characteristics, engine specifications, ship modes, etc.

To advocate for accurate estimation of total emissions due to shipping activities, several available methodologies are developed by different researchers. In this study, a total of 13 inventory methodologies are reviewed which includes; the Tier I-III (named after IMO NOx Technical Code) [69], the methodology applied by Corbett et al., ENTEC (one of the UK's largest environmental and engineering consultancies) [70], Methodology for calculating Transport Emissions and Energy consumption (MEET) [71], Ship Traffic Emission Assessment Model (STEAM) [72], Monitoring Programme on Air Pollution from Sea-going Vessels (MOPSEA) [73], International Maritime Organisation (IMO) [74], Swedish Methodology for Environmental Data (SMED) [75], Emission Registration and Monitoring Shipping (EMS) [76], US Environmental Protection Agency (US EPA) [77], and National Environmental Research Institute (NERI) [78]. These methodologies can be summarised and categorised into three groups, namely a full bottom-up approach, a full top-down approach, or a combination of both, as suggested by Miola et al. [79]. These approaches are characterised based on the emissions evaluation and the geographical characterisation. A full bottom-up approach evaluates the emissions by a single ship, considering vessel characteristics (i.e. ship type, building date, engine load and power, specific fuel oil consumption) at a specific position [47]. This approach allows the primary contributors of the emissions to be detected and assessed, thus providing a clear understanding of the effects on the primary emissions. Corbett et al., ENTEC, STEAM, MOPSEA, NERI, EMS, US EPA, and SMED alos fall into this category. On the other hand, a fully top-down approach considers the emissions from a more global scale, employing generalized factors such as fuel usage statistics of different fuel types and engine types installed on specific vessels as indicators of emissions [79]. While none of the discussed methodologies in this paper considered a full top-down approach, Tier I-III are top-down in terms of emission inventory, and bottom-up in terms of geographical distribution. Meanwhile MEET and IMO estimate emissions based on a bottom-up emission inventory and top-down based on the geographical distribution. Ultimately, each of these methodologies have reported a set of emission factors that are used as the key element in the calculation of the pollutants emitted for the comparative analysis. Most of these methodologies comprised inconsistent factors and assumptions including fuel consumption, navigation areas, ship modes, engine and vessel specifications which cause different variability in emission. Hence, it is necessary to find the most appropriate emission inventory methodology in terms of considered factors and assumptions.

In this study, emissions measured from an on-board measurement campaign on a bulk carrier is applied as baseline for the comparison with above mentioned inventories This study also investigates the methodology that has the best overall prediction of the primary emissions for a bulk carrier in different modes of operations.

5.3. Methodology

5.3.1. On-board measurement campaign

On-board measurement was carried out on a bulk carrier, on her voyage from Gladstone to Newcastle, Australia. The vessel was built in 2002, is 187.5m long, and has a tonnage of 27198 GRT and an average steaming speed of 11.6 knots. The vessel is propelled by a 6880 kW 2-stroke SSD engine (ME) operating on HFO. Whereas the AE is a 465 kW 4-stroke MSD diesel engine running on HFO. The technical parameters of the engines are provided in Table 5-1.

Table 5-1 Technical parameters of the ME and AE in this study

	Main Engine (ME)	Auxiliary Engine (AE)
Maker/Model	MAN B&W 6S50MC MkVI	Wartsila Diesel Mfg Co., Ltd
Type	Two stroke cycle single acting, cross head, direct reversible, marine diesel engine equipped with exhaust gas turbo charger and electric auxiliary blowers	Four stroke cycle, trunk piston type marine diesel engine with exhaust gas turbo charger and air cooler
Output	Normal - 6190 kW	460 kW
	Max Cont - 6880 kW	
Revolution	Normal - 98 rpm	900 rpm
	Max Cont - 102 rpm	
Mean Effective Pressure	18 bar	16.7 bar
No. of Cylinder	6	4
Cylinder Bore x Stroke	500mm x 1910mm	200 x 280mm

On-board emission measurements were carried out in accordance with procedures explained in ISO8178-1:2006 [80] and ISO8178-2:2008 [81] standards. Emissions vary across various operation stages of the vessel, hence the study is comprised of three main operating conditions of the voyage, listed as follows:

- Vessel while at berth (ME and AE)
- Vessel during manoeuvring (ME)
- Vessel during cruising (ME)

5.3.2. Measurement setup

The measurement instruments were arranged on a deck high up in the machinery room and the gases and particles from the exhaust gas were sampled continuously from probe holes located after the turbocharger of the ME. An illustration of the setup is provided in Fig 5-1. Two probe holes of 110 mm were created at the sampling point for the instruments; one for the main gas analyser Testo 350 XL, and another for Dust Trak Aerosol Monitor 8530 (TSI), Horiba MEXA 584L 5-gas analyser and Sable CA-10 CO_2 monitor. Further details of the measurement procedures by these instruments can be found in the literature [26, 35, 64, 82]

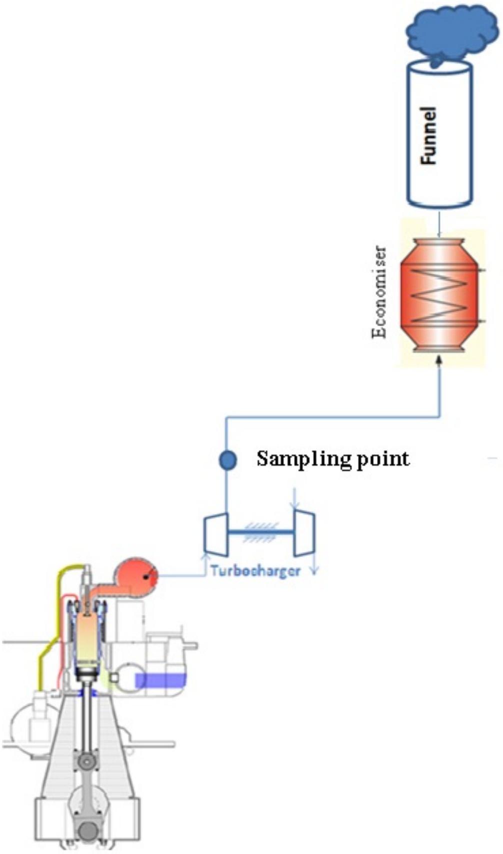


Fig 5-1 Sampling point of the experimental setup

In order to meet the working requirements of the measurement instruments, the hot exhaust gas is cooled to an ambient temperature by means of dilution with air. The CO_2 was used as a tracer gas to determine the dilution ratio. The dilution ratio was applied to correct the average concentration of PM in its corresponding operation mode. The measurements of CO_2 in both raw exhaust gas (Testo 350 XL) and after the dilution with air (Sable CA-10) were used to obtain the dilution ratio (DR), given as:

$$DR = \frac{CO_2(Raw) - CO_2(Background)}{CO_2(Diluted) - CO_2(Background)} \quad (1)$$

The concentration of each primary gaseous emission was measured using Testo 350 XL and Horiba gas analysers, while mass concentrations of PM (PM_{10}, $PM_{2.5}$ and PM_1) were measured with the Dust Trak data logging light-scattering laser photometer. A technical description on the measurement instruments used in the on-board measurements is summarized in Table 5-2.

Table 5-2 Instrumentation used for the on-board measurement

Instrument	Measurement	Range	Accuracy
Testo 350 XL (main gas analyser)	SOx	0 to 5000 ppm	5% of mv
	CO	0 to 10,000 ppm	5% of mv
	CO_2	0 to 50 Vol. %	0.3 Vol. % CO2 +1% of mv
	O_2	0 to 25 Vol. %	0.8% of fsv
	NO	0 to 4000 ppm	5% of mv
	NO_2	0 to 500 ppm	5ppm
Horiba 5 gas analyser	HC	0 to 60,000 ppm	60 ppm
	CO	0 to 10 Vol. %	0.03%
	CO_2	0 to 20 Vol. %	0.03%
	O_2	0 to 25 Vol. %	0.01%
	NO_x	0 to 5000 ppm	25 ppm
Sable CA-10	CO_2	0 – 5% standard 0 – 10% optional	1%
Dust Trak Aerosol Monitor 8530 (TSI)	PM_1	0.1 – 10 µm	5%
	$PM_{2.5}$		
	PM_{10}		

The data on engine power, engine revolution, fuel oil consumption and several other vessel parameters for each operating mode were obtained directly from the ship's instrumentation during the voyage. Using the average fuel consumption and engine power data, the specific fuel oil consumption (SFOC) of the ME during cruising was calculated. Due to unavailability of the data for the vessel while at berth and manoeuvring, their corresponding SFOC were estimated from the second degree polynomial equation for the relative SFOC based on the former, as follows [81]:

$$SFOC = SFOC_{relative} \times SFOC_{base} \tag{2}$$

Where,

$SFOC_{relative}$ = 0.455LF2-0.71LF+1.28

LF: Load factor

$SFOC_{base}$: the base value for SFOC, which is constant for each engine (208.6 g/kWh based on average fuel consumption data)

Engine and voyage specific data obtained during on-board measurement is presented in Table 5-3, followed by the development of a set of emission factors for this particular voyage from the measurements acquired.

Table 5-3 Vessel parameters at different shipping modes

Parameters	At berth		Manoeuvring	Cruising
	ME	AE	ME	ME
Installed power (kW)	6880	460	6880	6880
Load factor	0.06	0.58	0.35	0.80
Average power (kW)	385.0	265.0	2429.3	5494.9
SFOC (g/kWh)	259.0	256.0	226.5	209.3
Exhaust mass flow rate (kg/hr)	4531.6	2929.8	28515.2	63255.1
Measured time (hours)	0.585	2.674	1.833	4.467

5.3.3. Emission factors and total emission calculation

An energy-based emission factor (EF) presented in the units of g/kWh is derived from the on-board measurements by normalizing each emission type to a consistent unit. The emission factor for the gaseous species measured in ppm of gas was obtained as:

$$EF_{i,k} = (E_{i,k} \times 10^{-6}) \times \frac{PV}{RT} \times \frac{MW_k}{P_p} \tag{3}$$

Where,

EF (g/kWh): emission factor

i: engine type

k: emission type

E (ppm): concentration of gaseous species

P (N/m^2): pressure

V (m^3/hr): exhaust flow rate

R (J/molK): ideal gas constant, 8.3145

T (K): exhaust gas temperature

MW (g/mol): molecular weight

P_p (kW): engine power

For the PM measurements, the emission factor for the mass concentration of PM measured in mg/m^3 is obtained as:

$$EF_{i,n} = \frac{V \times PM_{i,n} \times DR}{P_p \times 1000} \tag{4}$$

Where,

n: size of PM (PM10, PM2.5, PM1.0)

PM (mg/m^3): mass concentration of PM

The power of the vessel at each operating mode is calculated as the average instantaneous engine power of the corresponding operating mode. Considering the calculated emission factor and operation time of the vessel at each particular mode, the emissions were calculated as:

$$EM_{i,k,n} = EF_{i,k,n} \times P_p \times t \tag{5}$$

Where,

EM (g): emissions

t (hours): operation time of the vessel

5.3.4. Comparison analysis

The emission factors derived are used as the basis for the calculation of the emissions for each inventory method in the comparison analysis. The emissions measured from the on-board measurement are benchmarked against thirteen existing methodologies. Each method is compared by the deviation from the on-board obtained values by calculating the absolute value of error (%).

As observed in Table 5-4, some inventory methods do not account for all types of pollutants and operating modes. Hence the results are compared first individually for each pollutant at different operating modes, followed by applying the methods that calculate all primary emissions at individual operating mode. Finally, the methodologies that estimate all primary emissions for all three operating modes are compared with each other.

Table 5-4 Summary of emission inventories investigated, where AB: At berth, M: Manoeuvring and C: Cruising

Methodology	Mode			Emission type (ME)						Emission type (AE) - At berth					
	AB	M	C	NOX	SOx	CO2	CO	HC	PM	NOX	SOx	CO2	CO	HC	PM
Experimental	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Tier I, 2013			✓	✓	✓		✓	✓	✓						
Tier II, 2013			✓	✓	✓		✓	✓	✓						
Tier III, 2013	✓	✓	✓	✓	✓[C]		✓[C]	✓	✓	✓					
Corbett, 2003			✓	✓	✓	✓		✓	✓						
ENTEC ,2007	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓
MEET, 1999	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
STEAM, 2009	✓	✓	✓	✓	✓	✓				✓	✓	✓			
MOPSEA, 2007	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓
NERI, 2009	✓	✓	✓	✓	✓	✓[C]	✓	✓	✓	✓	✓		✓	✓	✓
EMS, 2010	✓			✓	✓	✓	✓	✓	✓						
US EPA, 2000	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SMED, 2004	✓[AE]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
IMO, 2014			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

5.4. Results and Discussion

5.4.1. Measurement analysis

In this section, results from the on-board measurement of the bulk carrier are provided for different shipping modes, and the variations of the emission factors is discussed.

Measurements at berth

Heavy fuel oil with 2.77 % Sulphur content is used in both engines. This is the most typical fuel currently used for many ship engines and boilers [83]. The sulphur content of HFO used in ships globally is typically in the range 2.0% to 3.5% with a global average around 2.6% on a mass basis [84]. Many of the ships visiting Australia use HFO that is likely to have higher sulphur content than the global average [85]. When the ship is at berth, rather than the main engine, auxiliary engine is mostly running for all auxiliary power requirement [71]. Some of the activities while at berth include, but are not limited to, supplying the ship's lighting, heating, refrigeration, ventilation and electric loads of the electric equipment [71]. The AE is used to power them hence the average load factor for the AE is more than the ME (shown in Table 5-5). This results in higher exhaust emission factors in for the AE. The measurements for the AE was carried out at different loadings, which means that the diesel engine has a constant speed with variable loads. The on-board measurement while at berth was carried out when the ship was about to depart for the voyage.

Table 5-5 Emission Factors for the ME and AE at berth

Modes	Load Factors (%)	NOx (g/kwh)	CO (g/kwh)	SOx (g/kwh)	CO_2 (g/kwh)	HC (g/kwh)	PM (g/kwh)
At berth (AE)	57.6	9.16	1.78	26.00	1136.04	N/A	N/A
At berth (ME)	5.85	6.00	1.41	7.34	485.48	0.40	1.69

Fig. 5-2 shows the amount of measured O2 [%], CO2 [%], NOx [ppm], CO [ppm], and SOx [ppm] while at berth. Apart from the initial peak, the amount of emissions remains stable (Fig. 5-2). The initial peak is due to the cold start of the engine. Further details regarding the cold start, incomplete combustion, and its effect can be found in the literature [38, 86-91]. After the cold start, the engine operates on stable condition.

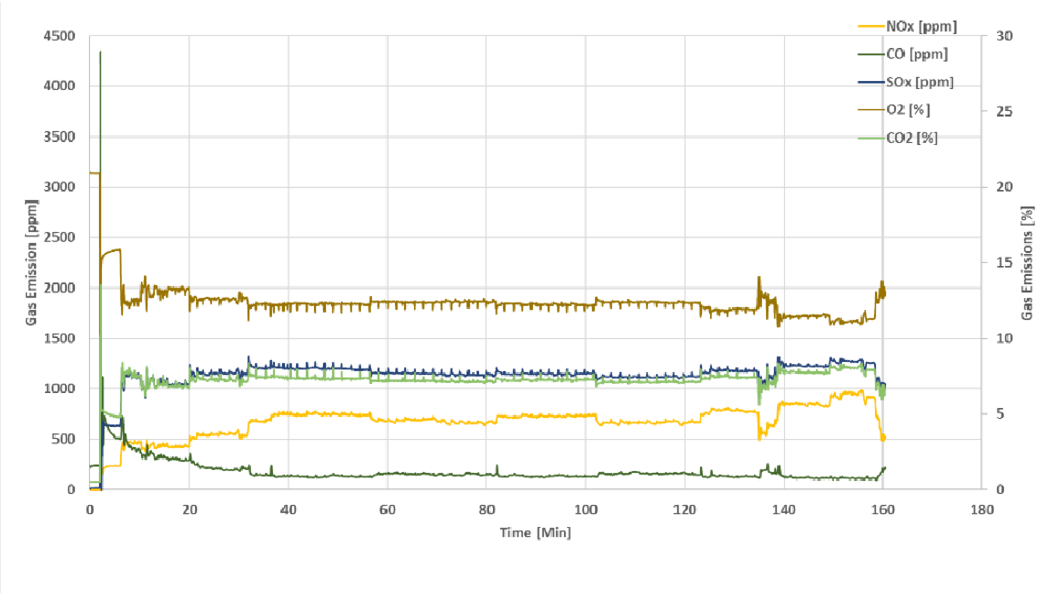


Fig. 5-2 Measured O2 [%], CO2 [%], NOx [ppm], CO [ppm], and SOx [ppm] for the AE at berth.

Measurements on ME were also conducted when the ship arrived at its destination port (Fig. 5-3). As demonstrated in Fig. 5-4, both the shaft power and the shaft speed change continuously at berth. This has an effect on the amount of emissions. In other words, when the engine speed and power experience sudden changes (Fig. 5-4), the amount of emissions change accordingly (Fig. 5-3). Apart from cruising, the ship navigates at a constant speed (rpm). During manoeuvring and at berth, both the the speed vary at different timings. The sudden changes are due to different factors such as wind and wave currents [92]. At other time lapses, rather than the sudden changes, a stable trend can be seen for the shaft speed and the shaft power, which indicates a normal working condition of the ME while at berth (Fig. 5-4).

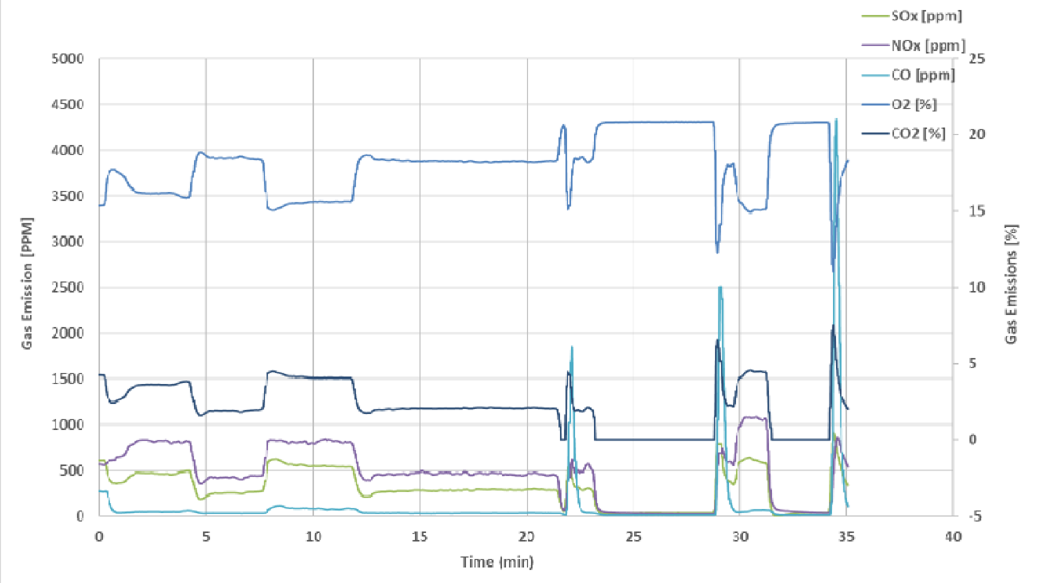


Fig. 5-3 Measured O2 [%], CO2 [%] NOx [ppm], CO [ppm], and SOx [ppm] for the ME at berth.

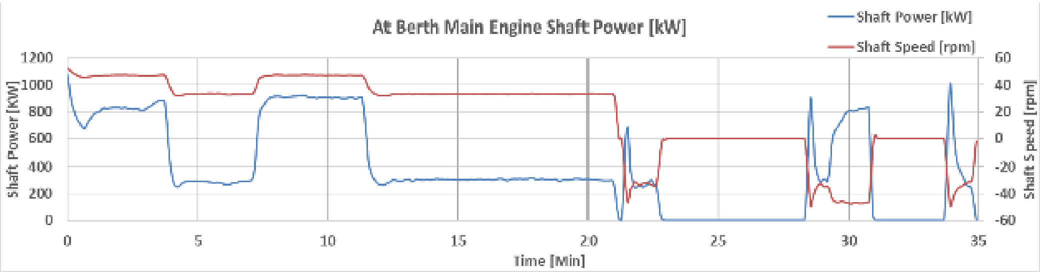


Fig. 5-4 Shaft speed and shaft power for the ME at berth.

Measurement during Manoeuvring

Emissions during manoeuvring differ significantly from the emissions while at berth and cruising. Fig 5-5 shows the amount of measured O2 [%], CO2 [%], NOx [ppm], CO [ppm], and SOx [ppm]. Similar to at berth conditions, the emission amounts change abruptly when the shaft speed and shaft power have a sudden change (Fig 5-6). These changes are due to the underwater hull geometry, the pivot point, the lateral motion, the rudder, propeller and the thrusters function [92]. The land shape and insufficient under keel distance when entering shallow water for manoeuvring, should be also taken into consideration. Navigation is always directly affected by shallow water, and at the same time, elements derived from propeller action and the combined effects of the surrounding environment on the hull, affect the navigation in manoeuvring [93].

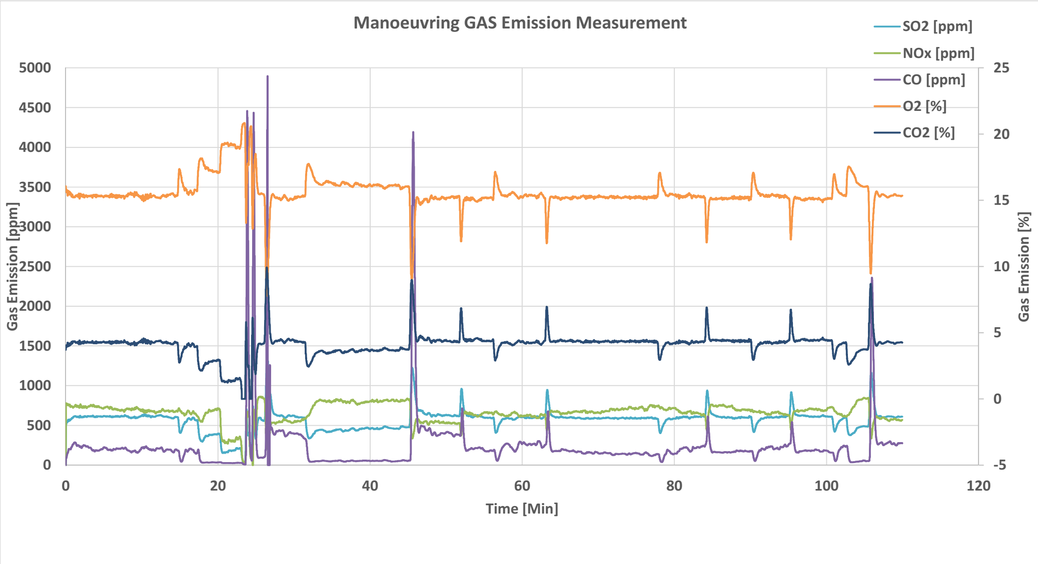


Fig 5-5 Measured O2 [%], CO2 [%], NOx [ppm], CO [ppm], and SOx [ppm] for the ME during manoeuvring.

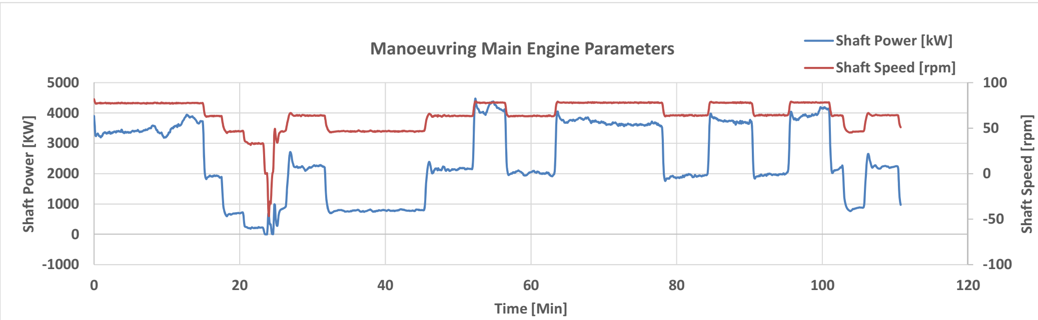


Fig 5-6 Shaft speed and shaft power for the ME during manoeuvring.

Measurement during cruising

When the ship departed and was at normal cruising speed, the measurement for emissions was carried out on three different occasions but only one is presented here (Fig. 5-7). Fig. 5-7 shows the amount of measured O_2 [%], CO_2 [%], NOx [ppm], CO [ppm], and SOx [ppm]. While cruising, the ship moves at a constant speed (rpm) and hence only the shaft power changes in different timings (Fig. 5-8). Except the initial cold-start of the ME at cruising which may need a higher shaft power to run the ship initially, a stable trend can be seen for the emissions as the engine experiences a normal working condition at cruising (Fig. 5-8).

IAMU International Association of Maritime Universities (AMC)

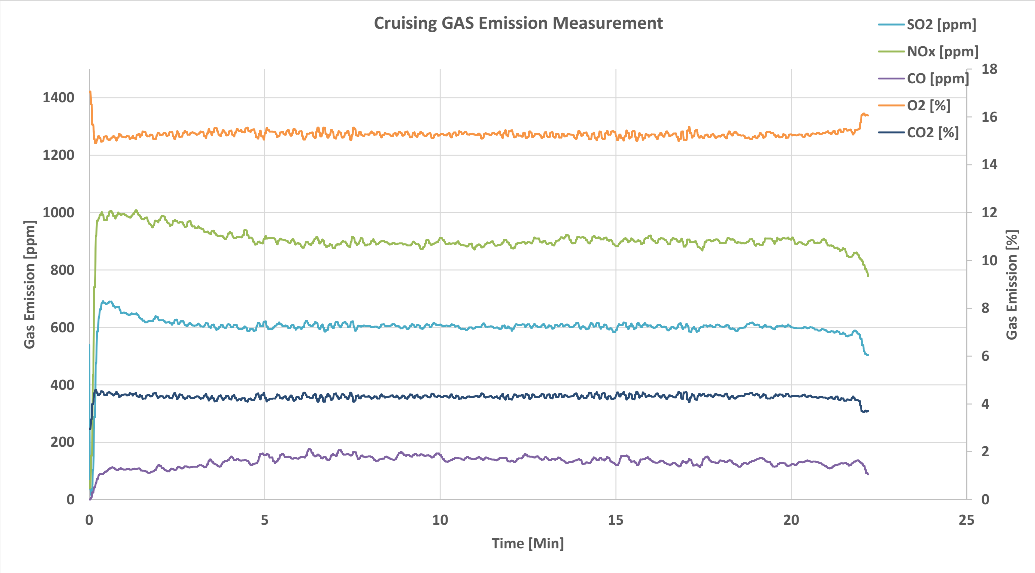


Fig. 5-7 Measured O2 [%], CO2 [%], NOx [ppm], CO [ppm], and SOx [ppm] for the ME during cruising

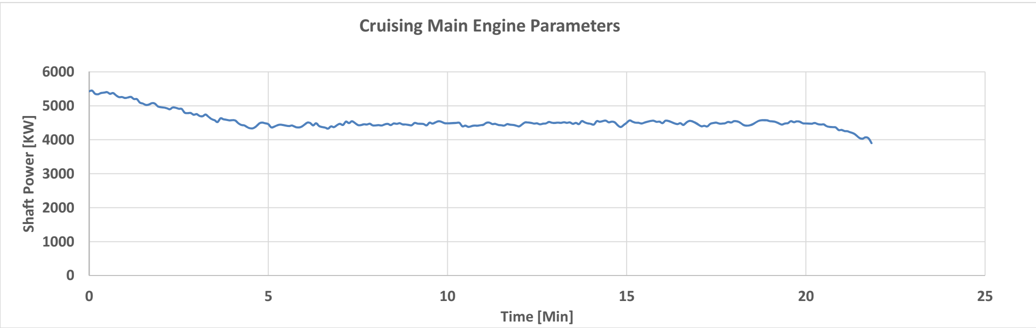


Fig. 5-8 Shaft power for the ME during cruising.

Using Equations 3 and 4, the emission factors for the ME in different ship modes are calculated as shown in Table 5-6. From berth to manoeuvring, and then cruising, emission factors for NOx, SOx, and CO_2 are increasing. CO emission factors show low quantity during all modes. PM and HC have a decreasing trend from at berth to manoeuvring and then cruising.

Table 5-6 Emission Factors for the ME while at berth, manoeuvring and cruising

Modes	Ave. Power (KW)	Load Factors (%)	NOx (g/kwh)	CO (g/kwh)	SOx (g/kwh)	CO2 (g/kwh)	HC (g/kwh)	PM (PM2.5 +PM10 +PM 1.0) (g/kwh)
At berth	384.99	5.85	6.00	1.41	7.34	485.48	0.40	1.69
Manoeuvring	2429.27	35.31	9.54	2.49	13.81	689.19	0.24	1.22
Cruising	5494.89	79.86	14.89	1.41	16.84	743.79	0.16	0.48

The EFs for PM vary significantly between the three stages. This is because the concentration of PM depends on engine load conditions. Usually it is higher at low load and vice versa [90]. The PM emissions include different types of particle sizes [90]. Similar observations are also applicable for the EFs of HC. The emission factors for CO_2 and SO_x in different engine operations vary at a steady rate. These EFs are dependent on fuel's sulphur content as well as fuel consumption. As ships go from berth to manoeuvring and then cruising, it consumes more fuel and hence these emissions increase. NOx emission factors depend on the engine temperature and hence depends on the engine load [90]. The higher the engine load, the more NOx emissions there will be. Thus, as the engine load increases from at berth emissions to manoeuvring and then cruising, the NOx emissions increase. In general, CO emission factors are low due to high excess oxygen concentrations and an efficient combustion process [94]. However, in poorly maintained engines or at low power ranges, the proportion of CO may be expected to increase considerably in relative concentration [94]. CO emission is low when going from at berth to cruising in this study, however in the manoeuvring phase it has increased, due to poor air supply [94].

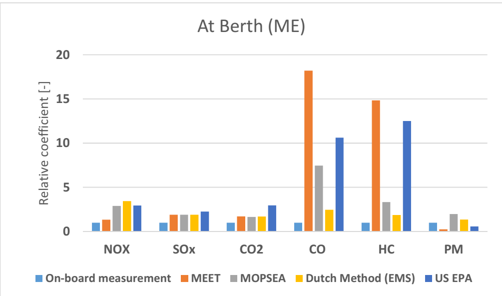
5.4.2. Comparison analysis

As discussed previously, there are many different methodologies for emissions estimation from ocean going ships. These methods all have different procedures for calculating the final emissions, and considering different factors in each method produces a lot of uncertainty in the final results. In this section, the on-board measurement of emissions is compared with thirteen previously selected methods for emission inventory in shipping. Fig. 5-9 shows the results for the primary emissions of the ME and AE calculated by individual estimation method while the vessel is at berth. For the ME, most methods over predicted the primary emissions. Considering estimation of the individual pollutant, MEET gives the best estimate for NOx (34%), STEAM for SOx (5.8%), NERI for CO (14%) and HC (24%) respectively. ENTEC best estimated CO_2 (40%) and PM (3%) emissions. For the AE, only the NOx, SOx, CO_2 and CO measurements were taken from the on-board measurement. The results showed that all the methods over predicted NOx emissions, while CO_2 and SOx emissions are under predicted. For individual pollutants, US EPA best predicted NOx (17%) and SOx (37%) emissions. MEET and NERI provided the best estimate for CO_2 (28%) and CO (10%) emissions respectively.

Fig. 5-9 Primary emissions (AE+ME) considering the individual inventory method while ships at berth.

The inventory methods that considered all the primary emissions while at berth (AE+ME) were compared against the on-board measurements. Fig 5-10 illustrates the relative total emissions per pollutant for both the ME and AE while at berth. Emissions, while at berth, from the ME were least accurately represented across all the other modes. Considering the overall emissions, EMS provided the best representation against the on-board measurement with an average deviation of 111%. For the AE, US EPA was the best predictive method with an average error of 27%.

Considering the scarce assured information on the energy use and fuel consumption of seagoing ships, estimation of emissions while at berth are still considerably inaccurate [76]. Most methods only assumed the fraction of engine load or fuel consumption as a constant value at different operating modes in the development of their methodology. The results showed that the assumptions while at berth were the least accurate. For example, MOPSEA assumed 20% of the engine load while at berth, while 12% of engine load was applied by MEET. However, the on-board measurement only recorded an average load factor of 6% for the ME while at berth. Attempting to fill this information gap, EMS carried out an in depth study on sea going vessels while at berth, which included questionnaires for 89 ships regarding the ship's characteristics, ship's name, type, volume, year of manufacture, and IMO number [45]. Furthermore, the fuel consumption data on different ship activities, with the most emphasis given to ships while at berth and their duration of stay, were also requested. Lastly, they obtained information on the fuel quality and the type of engine and machinery installed on-board. Understandably, this resulted in the closest prediction to the results from the on-board measurement in this study considering the vast amount of information collected specifically on vessels while at berth.



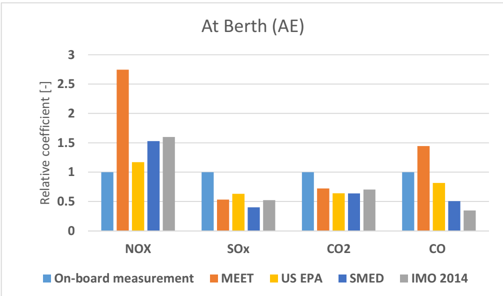


Fig 5-10 Relative total emissions per pollutant while at berth (AE+ME). Baseline coefficient from on-board measurements: 1

Similar analysis was conducted for manoeuvring. Fig 5-11 shows the results for individual pollutants calculated by each method during manoeuvring. As observed, CO_2 was well estimated for each method, with discrepancies topping out at only approximately 5%. For the pollutants calculated during manoeuvring, it was found that NERI produced the best NOx (26%) estimation, while both ENTEC and SMED had the least deviation for CO2 (1%). The SOx (5%), CO (5%) and HC (32%) was best represented by US EPA, while ENTEC has the best estimation for PM (26%).

Fig 5-11 Primary emissions (for the ME) considering the individual inventory method during manoeuvring

The methods that considered all the primary emissions during manoeuvring were compared against the on-board measurements as depicted in Fig. 5-12. The results showed that US EPA provided the best estimate. Considering the overall emissions, US EPA estimate resulted in an average error of 23%.

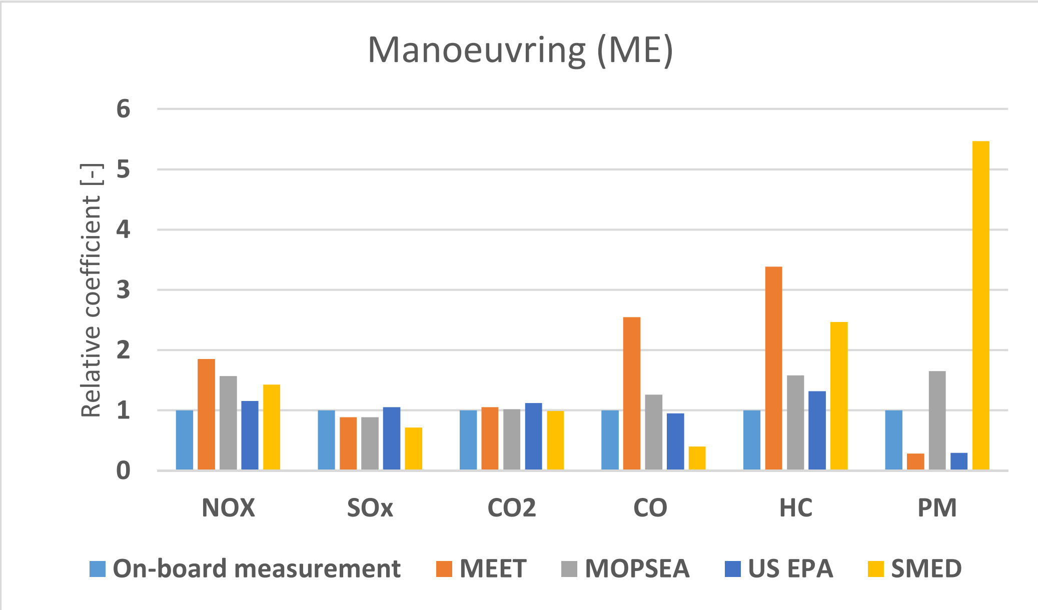


Fig. 5-12 Relative total emissions per pollutant during manoeuvring. Baseline coefficient from on-board measurements :1

Fig. 5-13 demonstrates the results for individual pollutants calculated by each methodology during cruising mode. Compared to the at berth and manoeuvring modes, many more methods included the emission estimation while cruising. NOx, CO_2 and CO emissions are observed to be relatively well predicted, while SOx is under predicted, and HC and PM are generally over-predicted by the methods. Considering the individual pollutants, MOPSEA provided the best estimation for NOx (5%) and CO (8%) emissions, while all the other pollutants were best predicted by US EPA (SOx-20%, CO_2-5%, HC-42%, PM-19%).

Fig. 5-13 Primary emissions (for the ME) considering individual inventory method during cruising.

Fig. 5-14 shows the comparison of the six methods that estimated all the primary emissions during the cruising phase against the on-board measurements. US EPA underestimated all the primary emissions, however it provided the best estimation overall with an average deviation of 23% from the on-board measurements.

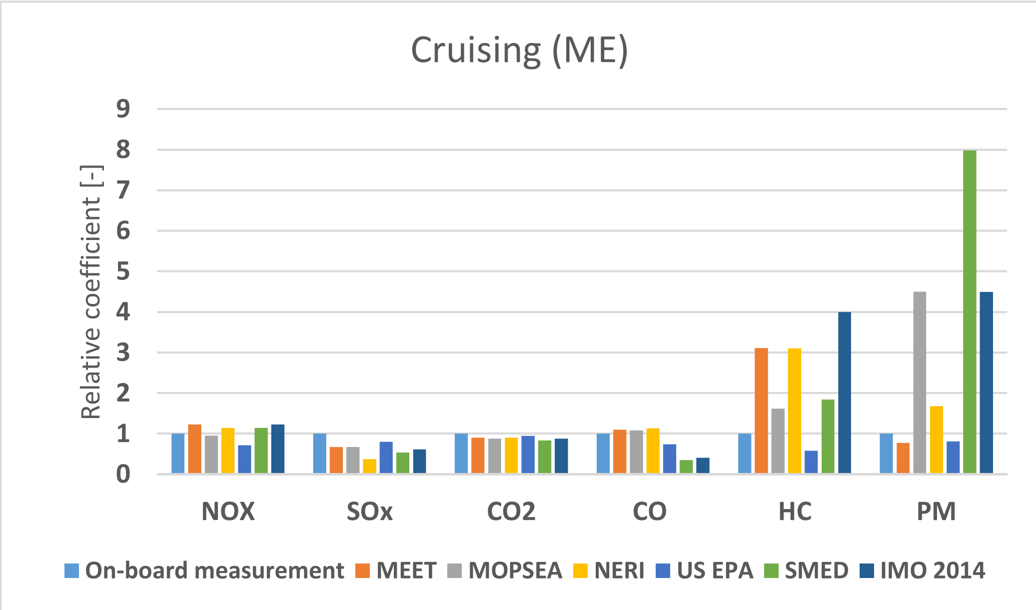


Fig. 5-14 Relative total emissions per pollutant during cruising. Baseline coefficient from on-board measurements :1

Finally, the four methods, MEET, MOPSEA, US EPA and SMED that considered primary emissions from both the ME and AE at all operating modes were compared to the on-board measurements (Fig. 5-15). The results confirmed that the US EPA reigned over all the other methods with the closest overall prediction for each pollutant at each operating mode with a reasonable deviation (27% while at berth (AE), 23% while manoeuvring (ME), 23% while cruising(ME)) from the experimental results. The ME emissions while at berth was an exception, where the results showed a large over prediction. The EMS provided the best estimation of the ME emissions while at berth.

The comparison showed that US EPA is the best method for the overall estimation of primary emissions from all three operating modes, with a deviation of 19% from the on-board measurements for both engines (ME+AE). The US EPA performed an extensive review of nine reports pertaining to diesel powered marine vessels as the basis of its study. It considered all the critical test data parameters such as the raw concentration-based primary emission measurements, test engine specifications, load, speed and volumetric fuel consumption, test fuel density and carbon, hydrogen, nitrogen, and sulphur mass fractions and ambient test conditions when developing their methodology. Furthermore, most of the test data analysed were on vessels with a rated output less than 8000 kW, spanning the full range of engine operating loads (from idle to 100% rated output) which complemented this case study (rated output of 6880 kW).

Unlike the other methods, a regression analysis was applied in US EPA to derive the emission factors as a function of the engine load factor. Underpinning this unique approach is the investigation from their study that suggested statistical regression structures based on emission mass by fractional load as the most promising basis for emission factor algorithms. In addition, this direct method of utilizing the engine load factor to compute the emission factors, expressed in units of mass per unit engine work was to address findings from their study which suggested that additional uncertainty were introduced into the emissions estimation process over the use of fuel mass-based emission factors [77]. With strong focus on data cleaning techniques to identify and eliminate the data errors, the US EPA approach manages to capture a close representation of the pollutants emitted for all modes except for ME emissions while at berth, with reference to the study considered in this paper. EMS was best suited for that application.

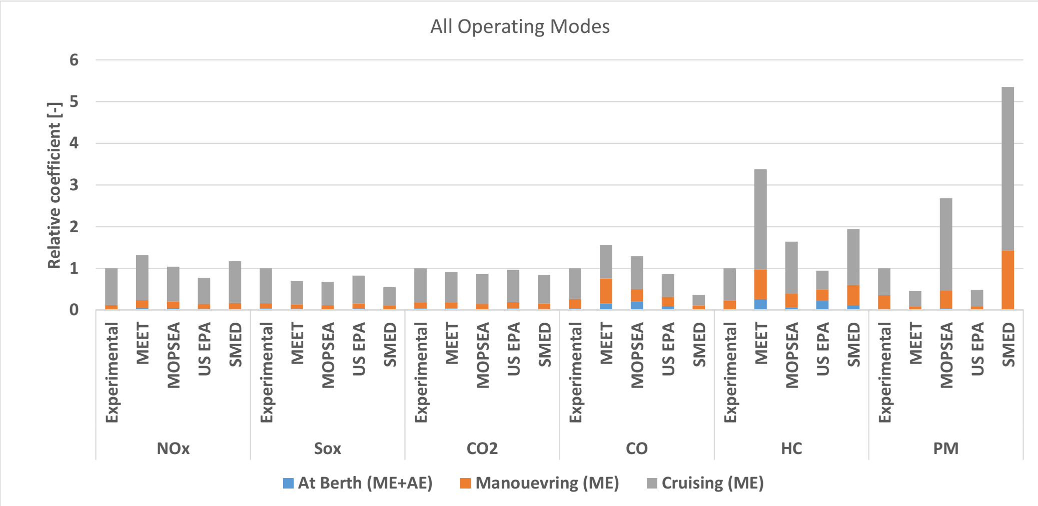


Fig. 5-15 Relative total emissions per pollutant for the ME and AE in all operating modes baseline coefficient from on-board measurements: 1

5.5. Conclusion

On-board emission measurements were conducted on a bulk carrier operating on HFO at three operating modes of at berth, manoeuvring and cruising. The primary emissions from the ME and AE of the vessel were measured on a voyage.

The results show higher values of emission factors in terms of the AE rather than ME while at berth. When at berth, the cold start of the AE affects the emission quantities in terms of initial spikes. When at berth and manoeuvring, sudden changes in the amount of emitted emissions are observed. During cruising, the cold start of the ME causes the emissions to be initially affected. From at berth to manoeuvring and then cruising, the general trend for NOx, SOx, and CO_2 is an increase for the ME emission factors while for PM, and HC emissions, a decreasing trend is observed. The general emissions of CO are in low quantities.

Application of the thirteen methodologies to an on-board measurement shows that many of them overestimate and / or underestimate the true amount of emissions. For the ME, MOPSEA can be recommended while at berth in terms of NOx; USEPA, SMED, and IMO at cruising for CO, and SMED for PM emissions. In the case of the AE, MEET can be suggested in terms of NOx, and MOPSEA for CO.

The comparison analyses confirmed that EMS provided the best estimate for the ME while at berth, due to the comprehensive study performed, which targeted only seagoing vessels while at berth. In all the other modes, US EPA best predicted the emissions using a regression analysis to derive the emission factor as a function of a variable load factor. In summary, US EPA gives the best overall prediction of the primary emissions of all three operating modes for both the ME and AE with a reasonable 19% average deviation from the on-board measurements obtained.

5.6. Acknowledgement

Authors thankfully acknowledge support provided by National Centre for Maritime Engineering and Hydrodynamic (NCMEH) and Australian Maritime College (AMC). Also, the authors gratefully acknowledge the Port of Brisbane Corporation for their ongoing support in the project, Maritime Safety Queensland and stevedore operators (AAT, Patricks and DP World). The authors would like to acknowledge the outstanding support received from all employees and crew of CSL Group Inc. in coordinating this project. In addition, the materials and data in this publication have been obtained through the support of the International Association of Maritime Universities (IAMU) and the Nippon Foundation in Japan.

6. Real Time Emissions Monitoring of Diesel Engines Aboard Marine Vessels

6.1. Abstract

The health and environmental effects of emissions from combustion sources is an important focus for the scientific community. As the risks from gaseous and particulate emissions are determined, the need for public policy is apparent. The International Maritime Organization (IMO) through the International Convention for the Prevention of Pollution from Ships (MARPOL) implemented international regulations capping NOx emissions from vessels by category and build date along with particulate matter (PM) in Emission Control Areas (ECAs). Additional efforts by the United States include the Act to Prevent Pollution from Ships (AAPS) and U.S. EPA regulations further capping emissions of NOx, total hydrocarbons (THC), CO, and total PM from U.S. flagged vessels by engine category and build date. All above policies stipulate a 3-tiered structure of increasingly stringent emissions limits with the third tier generally taking effect between 2016 and 2018 in U.S. waters and other designated Emissions Control Areas (ECAs). These impending emissions limits identify clear openings in the market for drop in fuels, pre-treatment, and after treatment technologies to reduce emissions from new engines or subsequent to major vessel conversions and overhauls. A need for readily available emissions measurement systems for technology benchmarking and in some instances, engine certification, is also clearly identified. This paper describes the development of a mobile gaseous and particulate continuous emissions monitoring system for use on board marine vessels focusing on support of alternative technology emission benchmarking. High acquisition speed equipment was also a primary focus for the measurement of transients. Preliminary emissions data aboard a workboat are presented to demonstrate the performance of the continuous emissions monitoring system.

6.2. Experimental Description

The gaseous emissions measurement system consists of a MKS 2030 Fourier Transform Infrared spectrometer (FTIR), 5Hz acquisition frequency, designed to conform to regulatory requirements for marine engine gaseous emissions testing while retaining the capability to adapt to potential future regulations. Accuracy verification was conducted with a cylinder of 1021 ± 2% ppm CO in a balance of nitrogen. The FTIR registered a steady average value of 1038 ppm ± 2% calibration uncertainty specified by MKS confirming that the measurement is well within uncertainty bounds. Comparison studies with in house gas analysers for NOx and CO were also in good agreement (5% for NOx, 8% for CO).

The emissions system also measures real time total soot particle number concentration with a BMI 1710 high speed mixing based Condensation Particle Counter (CPC). The device features a 180 ms time response to step changes in particle concentration in contrast to typical CPC devices exhibiting a time response of several seconds. The CPC is adapted for marine use to eliminate the risk inherent to most CPCs of instrument tilting and flooding of the device optics. The entire emissions measurement suite is controlled and interfaced in LabVIEW with synchronized real time data logging of all emissions measurements.

The emissions measurement system was installed and tested with diesel fuel aboard the 41 ft Maine Maritime Academy utility vessel *Quickwater*. The *Quickwater* is equipped with two 360 hp Cummins diesel engines. Emissions measurements were conducted on the port engine. Emissions ports for raw exhaust and soot sampling were placed 2 ft after the turbocharger and before the water-jacketed portion of the exhaust.

Fig. 6-1 41ft Maine Maritime Academy utility vessel Quickwater equipped with two 360hp Cummins marine diesel engines.

Fig. 6-2 Continuous emissions and performance monitoring system installed on board the test vessel Quickwater.

Due to unique space constraints, the raw exhaust sample from the exhaust port in the engine room was routed through a 10ft heated stainless steel line, heated filter, Air Dimensions H-Series dual heated head pump, and through another 10ft heated line routed through the engine room bulkhead to the FTIR housed in the cabin of *Quickwater*. Similarly, PM samples are collected through a dual stage heated dilution system consisting of two calibrated flow orifices, two ejectors, and two heated filtered nitrogen flows of known flow rate. The two stages of heated dilution at 150 C result in a total dilution ratio of approximately 1000 and act to remove the effects of VOCs and nucleation mode particles on the measurement of PM number concentration. The diluted sample is routed back to the CPC in the cabin of *Quickwater* through 20 feet of stainless steel line. The acquisition rate of the FTIR was set at 1 Hz and the CPC at 2 Hz. Sample response time due to piping was estimated at approximately 5 seconds for each instrument.

Fig. 6-3 Quickwater during fuel testing with continuous emissions monitoring and performance system.

The duty cycle tested on *Quickwater* conformed to ISO 8178 standards and consisted of starting idle in gear, 100% rated engine load, 75%, 50%, 25%, and back to an idle in gear. All load settings were maintained for a sufficient duration to achieve steady state.

6.3. Data

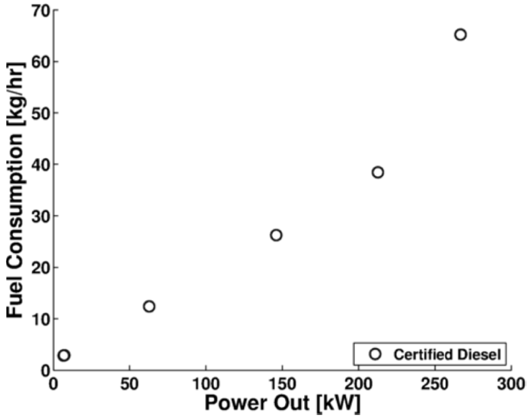


Fig. 6-4 Fuel consumption versus power output

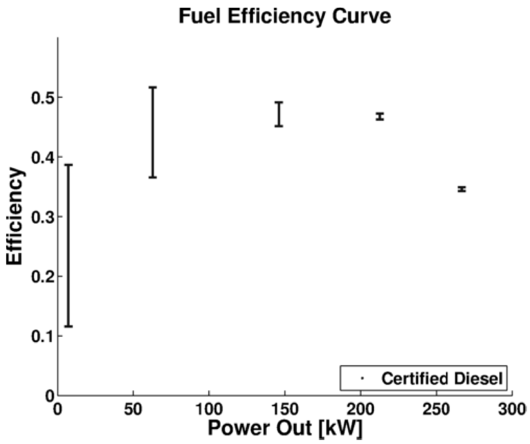


Fig. 6-5 Fuel efficiency curve

Fuel efficiency is calculated based on power output versus input energy from fuel consumption. The large error bars at low power are due to noise in the fuel consumption measurement specifically due to entrained air in the fuel return line.

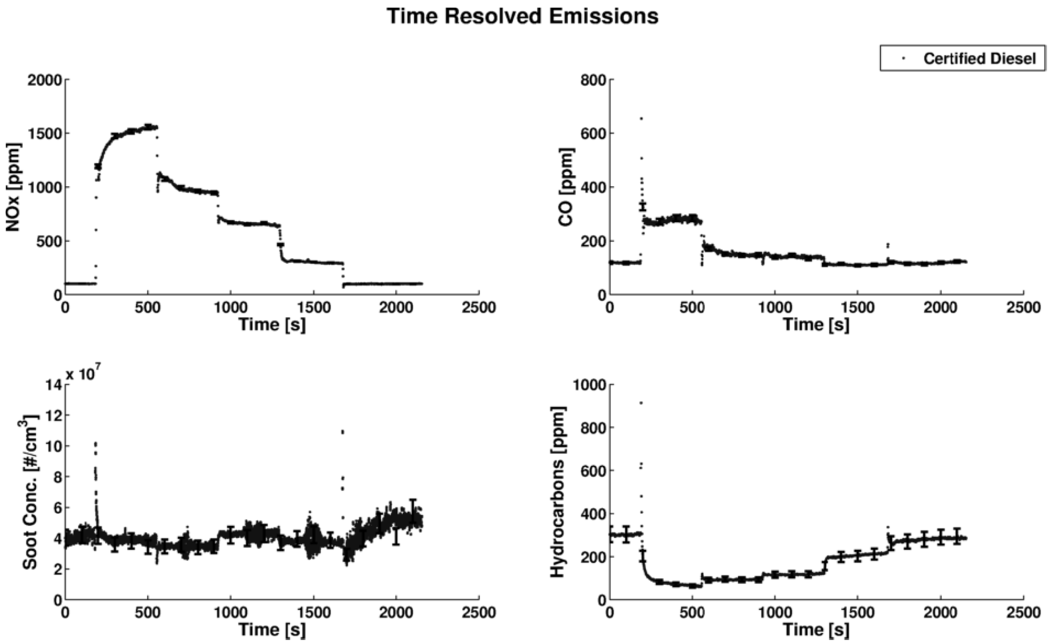


Fig. 6-6 Time resolved raw emissions of the stated pollutants over the entire engine duty cycle from a single test.

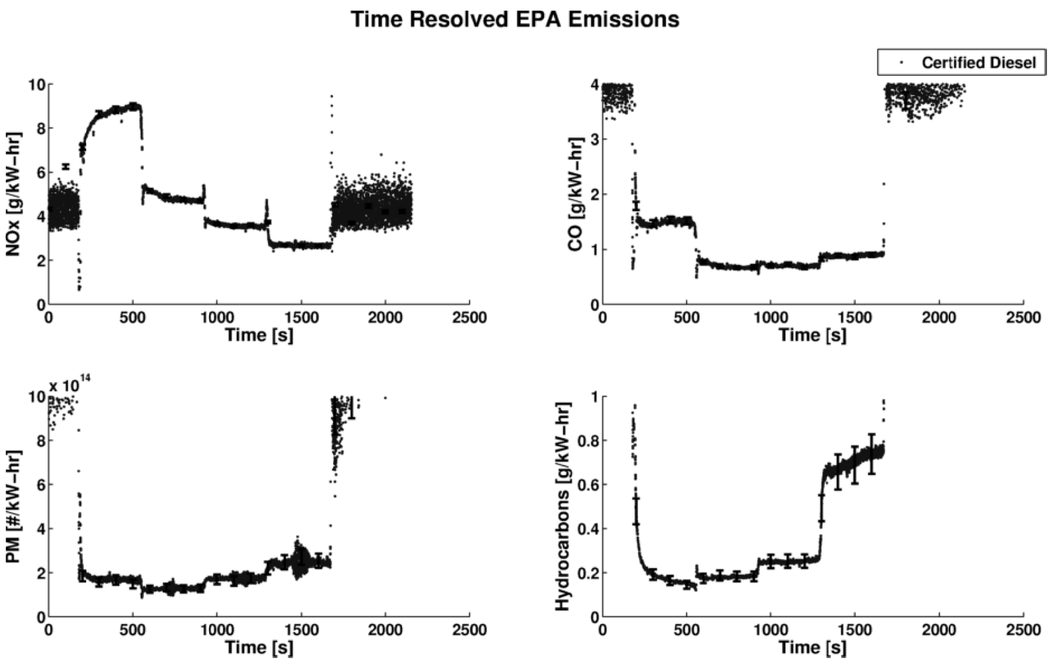


Fig. 6-7 Time resolved unit output energy normalized emissions of the same pollutants as shown above.

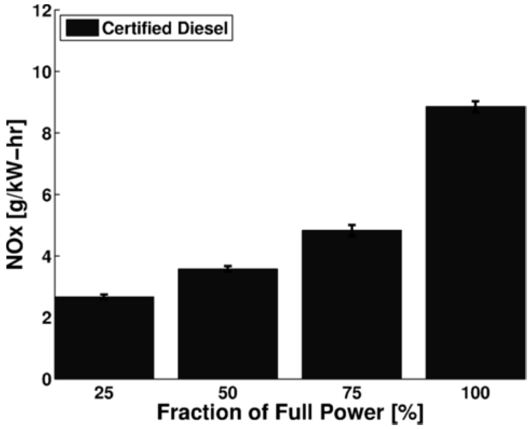


Fig. 6-8 Energy weighted mass emissions of NOx averaged over each load setting of the ISO 8178 duty cycle.

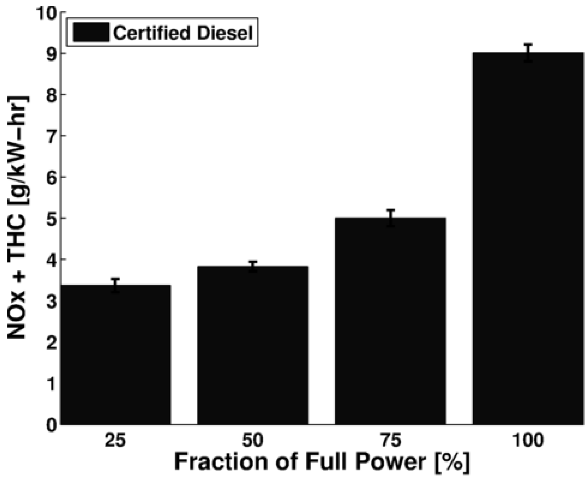


Fig. 6-9 Energy weighted mass emissions of NOx +THC averaged over each load setting of the ISO 8178 duty cycle.

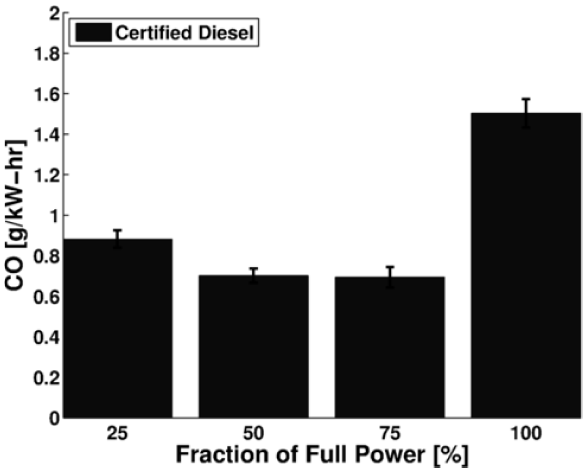


Fig. 6-10 Energy weighted mass emissions of CO averaged over each load setting of the ISO 8178 duty cycle.

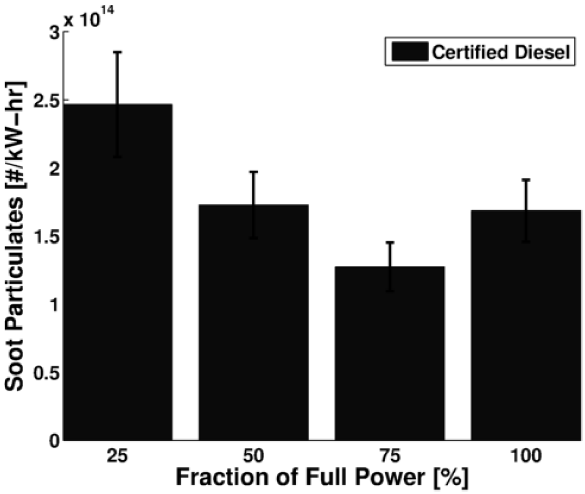


Fig. 6-11 Energy weighted number emissions of soot particulates averaged over each load setting of the ISO 8178 duty cycle.

7. Conclusion and Future work

This research project led by the AMC, in collaboration with QUT and MMA demonstrate a continuous emission measurement system (CEMS) and analysis of emissions. The Port of Brisbane measurement campaign allowed for the fuel oil characteristics to be determined and assessed, and on-board measurements of the primary emissions were used in the development of emission factors. The results from the measurement showed that fuel Sulfur content and the engine load are key factors in significant emission variations. For example, the auxiliary engine emissions at berth were far more significant than main engine emissions due to a higher engine load, whereas primary emissions from the main engine became dominant when the vessel was manoeuvering and cruising. Furthermore, a study on the particle number size distribution obtained from the on-board measurement campaign showed that the numbers peaked at 35-45nm in diameter, with significant decline in numbers as the engine load is increased. Finally, on-board measurements were used to develop emission factors at three operating stages of the vessel (at berth, manoeuvring and cruising) for this study, and a comparison analysis was performed against 13 emission inventory methodologies studied. It was found that for vessels at berth, EMS and US EPA method has the best overall predictions of emission for the main and auxiliary engines respectively. For main engine operations during maneuvering and cruising, the US EPA method gave the closest estimate. Finally, for the total voyage, which includes all three operation modes, the analysis showed that the US EPA method provided the closest overall estimation for primary emissions from vessels operating in all the three operating stages.

It is recommended that further investigative studies and on-board measurements be carried out on different vessel types installed with different engine configurations to better understand ship emissions. PM and their size distribution is also a great concern for scientific environmental community. Further research is planned to study the effect of the concentration of metals (in particular vanadium) on particulate emissions. This research project initiates a further collaboration between the research team and the CSL Group on this subject.

References

1. Reda, A.A., J. Schnelle-Kreis, J. Orasche, G. Abbaszade, J. Lintelmann, J.M. Arteaga-Salas, B. Stengel, R. Rabe, H. Harndorf, O. Sippula, T. Streibel, and R. Zimmermann, *Gas phase carbonyl compounds in ship emissions: Differences between diesel fuel and heavy fuel oil operation.* Atmospheric Environment, 2015. 112(0): p. 370-380.
2. Mueller, L., G. Jakobi, H. Czech, B. Stengel, J. Orasche, J.M. Arteaga-Salas, E. Karg, M. Elsasser, O. Sippula, T. Streibel, J.G. Slowik, A.S.H. Prevot, J. Jokiniemi, R. Rabe, H. Harndorf, B. Michalke, J. Schnelle-Kreis, and R. Zimmermann, *Characteristics and temporal evolution of particulate emissions from a ship diesel engine.* Applied Energy, 2015. 155: p. 204-217.
3. Blasco, J., V. Duran-Grados, M. Hampel, and J. Moreno-Gutierrez, *Towards an integrated environmental risk assessment of emissions from ships' propulsion systems.* Environ Int, 2014. 66: p. 44-7.
4. Corbett, J.J., J.J. Winebrake, E.H. Green, P. Kasibhatla, V. Eyring, and A. Lauer, *Mortality from Ship Emissions: A Global Assessment.* Environmental Science & Technology, 2007. 41(24): p. 8512–8518.
5. Viana, M., P. Hammingh, A. Colette, X. Querol, B. Degraeuwe, I.d. Vlieger, and J. van Aardenne, *Impact of maritime transport emissions on coastal air quality in Europe.* Atmospheric Environment, 2014. **90**(0): p. 96-105.
6. González, Y., S. Rodríguez, J.C. Guerra García, J.L. Trujillo, and R. García, *Ultrafine particles pollution in urban coastal air due to ship emissions.* Atmospheric Environment, 2011. 45(28): p. 4907-4914.
7. Eyring, V., I.S.A. Isaksen, T. Berntsen, W.J. Collins, J.J. Corbett, O. Endresen, R.G. Grainger, J. Moldanova, H. Schlager, and D.S. Stevenson, *Transport impacts on atmosphere and climate: Shipping.* Atmospheric Environment, 2010. 44(37): p. 4735-4771.
8. Corbett, J.W., E. H. Green, P. Kasibhatla, V. Eyring and A. Lauer, *Mortality from ship emissions: A global assessment.* Environmental Science & Technology 2007. 41(24): p. 8512-8518.
9. Hassellöv, I.-M., D.R. Turner, A. Lauer, and J.J. Corbett, *Shipping contributes to ocean acidification.* Geophysical Research Letters, 2013. 40(11): p. 2731-2736.
10. Corbett, J.J., *Updated emissions from ocean shipping.* Journal of Geophysical Research, 2003. 108(D20).
11. Organization, I.M., *International Convention for the Prevention of Pollution from Ships MARPOL 73/78: The Regulations for the Prevention of Air Pollution from Ships (Annex VI) London* 1997: IMO.
12. Organization, I.M., *Resolution MEPC 176(58): Amendments to the annex of the protocol of 1997 to amend the international convention for the prevention of pollution from ships, 1973, as modified by the protocol of 1978 relating thereto.* 2008a: IMO.
13. Organization, I.M., *Resolution MEPC 177(58): Amendments to the technical code on control of emission of nitrogen oxides from marine diesel engines.* 2008b: IMO.
14. Organization, I.M., *Resolution MEPC.203(62): Regulations on EEDI (Energy Efficiency Design Index) for new ships, and the SEEMP (Ship Energy Efficiency Management Plan) for all ships.* 2011: IMO.
15. European Parliament, C.o.t.E.U., *Directive 2005/33/EC of the European Parliament and of the Council of 6 July 2005 amending Directive 1999/32/EC* 2005: European Commission.

16. Winnes, H. and E. Fridell, *Particle Emissions from Ships: Dependence on Fuel Type.* Journal of the Air & Waste Management Association, 2012. 59(12): p. 1391-1398.
17. Rakopoulos, C.D. and E.G. Giakoumis, *Diesel engine transient operation: Principles of operation and simulation analysis*. Diesel Engine Transient Operation: Principles of Operation and Simulation Analysis. 2009: Springer London. 1-390.
18. Blasco, J., V. Duran-Grados, M. Hampel, and J. Moreno-Gutierrez, *Towards an integrated environmental risk assessment of emissions from ships' propulsion systems.* Environment International, 2014. 66: p. 44-7.
19. Ristovski, Z.D., B. Miljevic, N.C. Surawski, L. Morawska, K.M. Fong, F. Goh, and I.A. Yang, *Respiratory health effects of diesel particulate matter.* Respirology, 2012. 17(2): p. 201-212.
20. Corbett, J.J., J.J. Winebrake, E.H. Green, P. Kasibhatla, V. Eyring, and A. Lauer, *Mortality from Ship Emissions: A Global Assessment.* Environmental Scinece & Technology, 2007. 41(24): p. 8512–8518.
21. Nabi, M.N., R.J. Brown, Z. Ristovski, and J.E. Hustad, *A comparative study of the number and mass of fine particles emitted with diesel fuel and marine gas oil (MGO).* Atmospheric Environment, 2012. 57: p. 22-28.
22. Agrawal, H., Q.G.J. Malloy, W.A. Welch, J. Wayne Miller, and D.R. Cocker Iii, *In-use gaseous and particulate matter emissions from a modern ocean going container vessel.* Atmospheric Environment, 2008. 42(21): p. 5504-5510.
23. Mueller, D., S. Uibel, M. Takemura, D. Klingelhoefer, and D.A. Groneberg, *Ships, ports and particulate air pollution - an analysis of recent studies.* Journal of Occupational Medicine and Toxicology, 2011. 6: p. 31.
24. ISO-8178. *Reciprocating internal combustion engines - Exhaust emission measurement - Part 2: Measurement of gaseous and particulate exhaust emissions under field conditions.* 2008; Available from: http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=41171.
25. ISO-8178. *Reciprocating internal combustion engines - Exhaust emission measurement - Part 1: Test-bed measurement of gaseous and particulate exhaust emissions.* 2006; Available from: http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=42714.
26. Cooper, D.A., *Exhaust emissions from ships at berth.* Atmospheric Environment, 2003. 37(27): p. 3817-3830.
27. Anderson, M., K. Salo, Å.M. Hallquist, and E. Fridell, *Characterization of particles from a marine engine operating at low loads.* Atmospheric Environment, 2015. 101: p. 65-71.
28. Anderson, M., K. Salo, Å.M. Hallquist, and E. Fridell, *Characterization of particles from a marine engine operating at low loads.* Atmospheric Environment, 2015. 101(0): p. 65-71.
29. Moldanová, J., E. Fridell, O. Popovicheva, B. Demirdjian, V. Tishkova, A. Faccinetto, and C. Focsa, *Characterisation of particulate matter and gaseous emissions from a large ship diesel engine.* Atmospheric Environment, 2009. 43(16): p. 2632-2641.
30. Moldanová, J., E. Fridell, H. Winnes, S. Holmin-Fridell, J. Boman, A. Jedynska, V. Tishkova, B. Demirdjian, S. Joulie, H. Bladt, N.P. Ivleva, and R. Niessner, *Physical and chemical characterisation of PM emissions from two ships operating in European emission control areas.* Atmospheric Measurement Techniques, 2013. 6(12): p. 3577-3596.
31. Khan, M.Y., S. Ranganathan, H. Agrawal, W.A. Welch, C. Laroo, J.W. Miller, and D.R. Cocker Iii, *Measuring in-use ship emissions with international and U.S. federal methods.* Journal of the Air and Waste Management Association, 2013. 63(3): p. 284-291.

32. Agrawal, H., W.A. Welch, J.W. Miller, and D.R. Cocker, *Emission measurements from a crude oil tanker at sea.* Environmental Science and Technology, 2008. 42(19): p. 7098-7103.
33. Hallquist, Å.M., E. Fridell, J. Westerlund, and M. Hallquist, *Onboard Measurements of Nanoparticles from a SCR-Equipped Marine Diesel Engine.* Enironmental Science & Technology, 2013. 47(2): p. 773-780.
34. Kasper, A., S. Aufdenblatten, A. Forss, M. Mohr, and H. Burtscher, *Particulate emissions from a low-speed marine diesel engine.* Aerosol Science and Technology, 2007. 41(1): p. 24-32.
35. Michaelowa, A., *The Kyoto Protocol.* Ecological Economics, 2000. 34(1): p. 155-156.
36. Wang, C., J. J. Corbett and J. Firestone, *Improving spatial representation of global ship emissions inventories.* Environmental Science & Technology, 2008. 42(1): p. 193-199.
37. Deniz, C. and A. Kilic, *Estimation and Assessment of Shipping Emissions in the Region of Ambarli Port, Turkey.* Environmental Progress & Sustainable Energy, 2010. 29(1): p. 107-115.
38. Martínez de Osés, X., La Castells, , *Emission models: A comparison to determine the impact of maritime transport on emissions in sw european short sea shipping.* 2010.
39. OECD, *The OECD Report on Regulatory Reform Synthesis* 1997.
40. UNCTAD, *Review of Maritime Transport.* 2014.
41. Corbett, J.J.a.P.F., *Emissions from ships.* Science 1997. 278(5339): p. 823-824.
42. CEP, *California Air Resources Board.* 2005.
43. Eyring, V., H.W. Kohler, J. van Aardenne, and A. Lauer, *Emissions from international shipping: 1. The last 50 years.* Journal of Geophysical Research-Atmospheres, 2005. 110(D17).
44. Kim, S., J.W. Hwang, and C.S. Lee, *Experiments and Modeling on Droplet Motion and Atomization of Diesel and Bio-Diesel Fuels in a Cross-Flowed Air Stream.* International Journal of Heat and Fluid Flow, 2010: p. 13.
45. Lu, G., J. R. Brook, M. R. Alfarra, K. Anlauf, W. R. Leaitch, S. Sharma, D. Wang, D. R. Worsnop and L. Phinney, *Identification and characterization of inland ship plumes over Vancouver, BC.* Atmospheric Environment, 2006. 40(15): p. 2767-2782.
46. Kilic, A.a.C.D., *Inventory of Shipping Emissions in Izmit Gulf, Turkey.* Environmental Progress & Sustainable Energy, 2010. 29(2): p. 221-232.
47. Moreno-Gutierrez, J., F. Calderay, N. Saborido, M. Boile, R.R. Valero, and V. Duran-Grados, *Methodologies for estimating shipping emissions and energy consumption: A comparative analysis of current methods.* Energy, 2015. 86: p. 603-616.
48. Merk, O., *Shipping Emissions in Ports.* 2014.
49. Radischat, C., O. Sippula, B. Stengel, S. Klingbeil, M. Sklorz, R. Rabe, T. Streibel, H. Harndorf and R. Zimmermann, *Real-time analysis of organic compounds in ship engine aerosol emissions using resonance-enhanced multiphoton ionisation and proton transfer mass spectrometry.* Analytical and Bioanalytical Chemistry, 2015. 407(20): p. 5939-5951.
50. Chen, G., L.G. Huey, M. Trainer, D. Nicks, J. Corbett, T. Ryerson, D. Parrish, J.A. Neuman, J. Nowak, D. Tanner, J. Holloway, C. Brock, J. Crawford, J.R. Olson, A. Sullivan, R. Weber, S. Schauffler, S. Donnelly, E. Atlas, J. Roberts, F. Flocke, G. Hubler, and F. Fehsenfeld, *An investigation of the chemistry of ship emission plumes during ITCT 2002.* Journal of Geophysical Research-Atmospheres, 2005. 110(D10).
51. Cappa, C.D., E. J. Williams, D. A. Lack, G. M. Buffaloe, D. Coffman, K. L. Hayden, S. C. Herndon, B. M. Lerner, S. M. Li, P. Massoli, R. McLaren, I. Nuaaman, T. B. Onasch and P. K. Quinn, *A case study into the measurement of ship emissions from plume intercepts of the NOAA ship Miller Freeman.* Atmospheric Chemistry and Physics, 2014. 14(3): p. 1337-1352.

52. Endresen, O., E. Sorgard, J.K. Sundet, S.B. Dalsoren, I.S.A. Isaksen, T.F. Berglen, and G. Gravir, *Emission from international sea transportation and environmental impact.* Journal of Geophysical Research-Atmospheres, 2003. 108(D17).
53. Skjølsvik, K.O., A. B. Andersen, J. J. Corbett, and J. M. Skjelvik, *Study of greenhouse gas emissions from ships (report to International Maritime Organization on the outcome of the IMO Study on Greenhouse Gas Emissions from Ships),* M.S.G.C.M.U. MEPC 45/8, Center for Economic Analysis/Det Norske Veritas, Trondheim, Norway, Editor. 2000.
54. LIyods, *Marine Exhaust Emissions Research Programme.* 1995.
55. Kasper, A., Aufdenblatten, S., Forss, A., Mohr, M., Burtscher, H., *Particulate emissions from a low-speed marine diesel engine.* Aerosol Science and Technology, 2007. 41(1): p. 24-32.
56. Cooper, D.A., Peterson, K., Simpson, D., *Hydrocarbon, PAH and PCB emissions from ferries: A case study in the Skagerak-Kattegatt-Oresund region.* Atmospheric Environment, 1996. 30(14): p. 2463-2473.
57. Cooper, D.A., Andreasson, K., *Predictive NOx emission monitoring on board a passenger ferry.* Atmospheric Environment, 1999. 33(28): p. 4637-4650.
58. Cooper, D.A., *Exhaust emissions from high speed passenger ferries.* Atmospheric Environment, 2001. 35(24): p. 4189-4200.
59. Lyyranen, J., Jokiniemi, J., Kauppinen, E. I., Joutsensaari, J., *Aerosol characterisation in medium-speed diesel engines operating with heavy fuel oils.* Journal of Aerosol Science, 1999. 30(6): p. 771-784.
60. Petzold, A., Feldpausch, Ph., Fritzsche, L., Minikin, A., Lauer, P., Bauer, H., *Particle emissions from ship engines.* 2004.
61. Petzold, A., Hasselbach, J., Lauer, P., Baumann, R., Franke, K., Gurk, C., Schlager, H., Weingartner, E., *Experimental studies on particle emissions from cruising ship, their characteristic properties, transformation and atmospheric lifetime in the marine boundary layer.* Atmospheric Chemistry and Physics, 2008. 8(9): p. 2387-2403.
62. Sinha, P., Hobbs, P. V., Yokelson, R. J., Bertschi, I. T., Blake, D. R., Simpson, I. J., Gao, S., Kirchstetter, T. W., Novakov, T., *Emissions of trace gases and particles from savanna fires in southern Africa.* Journal of Geophysical Research-Atmospheres, 2003. 108(D13).
63. LIyods, *Marine Exhaust Emissions Research Programme: Steady State Operation (including Slow Speed Addendum).* 1990.
64. Wright, A., *Marine Diesel Engine Particulate Emissions.* Trans IMarE, 1997. 109: p. 345–364.
65. Corbett, J.J. and H.W. Koehler, *Updated emissions from ocean shipping.* Journal of Geophysical Research-Atmospheres, 2003. 108(D20).
66. LIyods, *Transient Emissions and Air Quality Impact Evaluation, Industry Research Report.* 1993.
67. Dalsoren, S.B., M.S. Eide, O. Endresen, A. Mjelde, G. Gravir, and I.S.A. Isaksen, *Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports.* Atmospheric Chemistry and Physics, 2009. 9(6): p. 2171-2194.
68. Endresen, O., E. Sorgard, H.L. Behrens, P.O. Brett, and I.S.A. Isaksen, *A historical reconstruction of ships' fuel consumption and emissions.* Journal of Geophysical Research-Atmospheres, 2007. 112(D12).
69. Trozzi, C.D.L., R., *International navigation, national navigation, national fishing* 2013.
70. Entec, *Ship Emissions Inventory – Mediterranean Sea, Final Report for Concawe.* 2007.

71. AUTh, T., TUV, DTU, ADEME, BMW, TUG, INFRAS, KALIVODA, MIRA, PSA, TECHNE, TNO, ULIMERICK, VTI, *Methodology for calculating transport emissions and energy consumption (MEET), Transport Research fourth Framework Programme Strategic Research* 1999.
72. Jalkanen, J.P., Brink, A., Kalli, J., Pettersson, H., Kukkonen, J., Stipa, T., *A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area.* Atmospheric Chemistry and Physics, 2009. 9(23): p. 9209-9223.
73. Gommers, A., Verbeeck, L., Cleemput, E. V., *MOnitoring Programme on air pollution from SEA-going vessels EV/43 (MOPSEA)* 2007.
74. IMO, *Reduction of GHG emissions from ships, Third IMO GHG study, Final Report.* 2014.
75. Cooper, D., Gustafsson, T., SCB, *Methodology for calculating emissions from ships: 1. Update of emission factors (SMED)* 2004.
76. Van der Gon, H.D., TNO, Hulskotte, J., *Methodologies for estimating shipping emissions in Netherlands (EMS).* 2010.
77. USEPA, *Inventory of US Greenhouse Gas Emissions and Sinks: 1990 - 2006.* 2008.
78. Olesen, H.R., Winther, M., Ellermann, T., Christensen, J., Plejdrup, M. , *Ship Emissions and air pollution in Denmark (NERI)*. 2009.
79. *Miola, A., Ciuffo, B., Estimating air emissions from ships: Meta-analysis of modelling approaches and available data sources. Atmospheric Environment, 2011.* ***45****(13): p. 2242-2251.*
80. Miola, A. and B. Ciuffo, *Estimating air emissions from ships: Meta-analysis of modelling approaches and available data sources.* Atmospheric Environment, 2011. 45(13): p. 2242-2251.
81. Jalkanen, J.P., Johansson, L., Kukkonen, J., Brink, A., Kalli, J., Stipa, T., *Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide.* Atmospheric Chemistry and Physics, 2012. 12(5): p. 2641-2659.
82. MathWorks. *Morphological Reconstruction From Digital Image Processing Using MATLAB, by Rafael C. Gonzalez, Richard E. Woods, and Steven L. Eddins.* 2010 [cited 2014; Available from: http://www.mathworks.com/tagteam/64199_91822v00_eddins_final.pdf.
83. Goldsworthy, L., Galbally, IE., *Ship engine exhaust emissions in waters around Australia-an overview.* Air Quality and Climate Change, 2011. 45(4): p. 24.
84. IMO, *Report of the marine environment protection committee on its sixty-first session.* 2010.
85. Goldsworthy, L., Goldsworthy, B., *Modelling of ship engine exhaust emissions in ports and extensive coastal waters based on terrestrial AIS data - An Australian case study.* Environmental Modelling & Software, 2015. 63: p. 45-60.
86. Roberts, A., R. Brooks, and P. Shipway, *Internal combustion engine cold-start efficiency: A review of the problem, causes and potential solutions.* Energy Conversion and Management, 2014. 82: p. 327-350.
87. Lee, H. and Y. Jeong, *The effect of dynamic operating conditions on nano-particle emissions from a light-duty diesel engine applicable to prime and auxiliary machines on marine vessels.* International Journal of Naval Architecture and Ocean Engineering, 2012. 4(4): p. 403-411.
88. *Emissions from Ship Machinery* 2012.
89. Jun, P., Gillenwater, M., Barbour, W., *CO2 , CH4 , and N2O emissions from transportation-water-borne navigation*
90. Winnes, H., Fridell, E., *Particle Emissions from Ships: Dependence on Fuel Type.* Journal of the Air & Waste Management Association, 2009. 59(12): p. 1391-1398.

91. Khair, M.K., Jääskeläinen, H., *Emission Formation in Diesel Engines.*
92. Murdoch, E., Dand, I. W., Spencer, C., Clarke, C., Standard House, *The Standard*. 2012.
93. House, D.J., *Ship Handling*. 2007.
94. Kristensen, H.O., Technical University of Denmark, *Energy Demand and Exhaust Gas Emissions of Marine Engines*. 2010.

International Association of Maritime Universities

Meiwa Building 8F, 1-15-10 Toranomon, Minato-ku, Tokyo 105-0001, Japan

Tel : 81-3-6257-1812 E-mail : info@iamu-edu.org URL : http://www.iamu-edu.org

ISBN No. 978-4-907408-14-5