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Original Research Article

An improved emission inventory method for estimating engine exhaust emissions from ships

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ABSTRACT

The maritime transport industry is recognised as one of the cleanest modes of global transport. It is important to measure engine exhaust emissions to maintain its ecological superiority over road, rail, and other forms of transport.

Emission inventories are needed to estimate emissions. Current inventories need to review the emission factors (EFs) they currently employ, which generally yield over- or under-estimations. There is a need to consider more relevant measurements that will enhance the accuracy of emission prediction models. There is also a need to consider different mathematical approaches, to find better ways to manage the many changeable parameters of fuel consumption and engine specifications used to estimate emissions.

In this study, new sets of EF equations are developed to take into consideration real-time emission measurements during 11-d emission measurements on-board of two ocean-going vessels at berth and during sailing. They were tested on two ocean-going vessels, running on slow speed diesel main engines at berth while manoeuvring and cruising. Both vessels ran on heavy diesel fuel. Regression analysis, along with a consideration of fuel consumption and engine parameters, was used to develop the equations.

The results show a better prediction of emission quantity than current inventories for different engine types, in in-port and at-sea activities, with the sum of primary emissions coming closest to the actual sea emission calculations and also to the smallest standard values. This should be helpful when upgrading environmental policies.

1. Introduction

Maritime transport is recognised as the preferred mode of global transport for goods transfer [1]. It is superior to other modes of transport such as road and rail in the large payload it can carry [2]. The global fleet is expected to triple by 2050 [3], so too will their primary emissions (NO_x, SO_x, CO_2 and CO), and it becomes important to monitor the consequent pollution.

As diesel marine fuels combust, heat energy is given out. Crude oil is the source of many of the hydrocarbon compounds which are produced during this process. Contaminants like sulphur, vanadium, nickel, and ash are present in crude oil, and are retained during the production of marine fuels; heavy fuel oils (HFOs) are used to contain them after intensive refining. Several factors influence the quality of marine fuels: the refinery process, the crude oil quality, what kind of demands are there for the middle distillate and other residual fuels, and so on. Refinery processes often influence properties and characteristics of marine fuels like specific gravity, viscosity, asphaltenes, sediment, water, flash point, and compatibility [4].

In general, low quality fuel oil is used in the shipping industry [2]. HFO is the most common, currently used in many low-to medium-speed engines [5]. The sulphur content of HFO used in ships is typically 2.0–3.5%, with a global average around 2.6% [6].

There is also concern that shipping emissions are associated with adverse effects on human health, including lung cancer and heart attacks: for example, NO_x, CO_2 and CO can result in flu-like symptoms [7], while SO_x can cause breathing issues [7] and particulate matter (PM) may be implicated in premature deaths [8]; some

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epidemiological studies have revealed instances of asthma and heart disease [9,10]. Researchers have reported that Ocean Going Vessels account for 14–31% of global emissions of NO_x, 4–9% of SO_x, and 3% of CO_2, worldwide [11]. Many studies [11–13] have reviewed the impact of shipping emissions on ecology, using a variety of methodologies on different scales. Emissions from vessels may also have a major effect on marine boundary layers and marine productivity, as well as on ozone production and ocean acidification [14].

The importance of on-board measurement, a practical approach to measuring emissions, has been the focus of many reviews [15–21]. Most studies collecting data from slow speed diesel and medium speed diesel engines are based either on plume measurements or on engine test rigs [18–21], but they should also take into account on-board measurement of emission factors (EFs), which are more up-to-date and detailed, in terms of types of fuel, the regions to be studied, the characteristics of individual vessels, specifics of the engine, and activities both in-port and at-sea [22]. Moreover, they need to be more precise, and revised in terms of mathematical approaches.

Two ocean-going vessels (Vessel I and Vessel II) had their engine exhaust emissions measured in order to develop models for the emissions produced during different shipping operations. Although on-board measurement may be precise but it is not always practical, as time and human resources may be limited; and it can be difficult to find vessel owners willing to install the necessary instrumentation. However, on-board measurement data were acquired in this study in order to develop new sets of EF equations through non-linear regression analysis, to help improve emission models and inventory calculations for different main engine types for at-sea and in-port operations.

2. Method

2.1. On-board measurement campaign

Vessel I, travelling from Port of Brisbane to Port Gladstone, underwent the first on-board measurement at a distance of 700 km; vessel II, travelling from Port Gladstone to Newcastle, underwent the second 1300 km. The routes of these vessels are presented in Fig. S1.

The ports at Brisbane, Gladstone and Newcastle, like many Australian ports, are close to urban centres, and a large percentage of the emissions from the ships, both in transit and at berth, directly affect nearby residents. As many coastal areas around the world are facing rapid and unplanned population growth, demographic change and development [23], there is a strong likelihood that they, and many Australian ports, will grow to keep up with growth in shipping, and the development of a reliable method to quantify and estimate emissions will become increasingly important.

Procedures ISO 8178-1:2006 [24] and ISO 8178-2:2008 [25] were used to measure on-board engine exhaust. These were also used to calculate the gas-phase species emissions [24,25]. Table 1 contains the engine specifications.

Fuel samples were collected from both vessels and analysed in the laboratory to determine their chemical contents. The main chemical composition and physical properties of the HFO tested are presented in Table 2, which also indicates the percentage of sulphur present.

These results help to determine the exhaust gas flow rate, used to calculate the EFs of the vessel at various operating loads. The % mass carbon and sulphur contents are of particular interest, as they are considered the most influential when analysing the combustion process and, more importantly, the emissions generated.

Emission measurements were carried out by collecting samples using different portable instruments. Measured parameters and technical details of the applied devices are presented in Table 3 [26].

Emissions were measured and converted to weight (g). Eq. (1) gives the instantaneous emission for gaseous species, whose measurements are in ppm or percentage of gas [27]. The process used specific fuel consumption (SFOC) and formed CO_2 to provide the exhaust gas flow, calculated from fuel flow and air flow—basically the sum of fuel consumption (kg h^{-1}) + air consumption (kg h^{-1}). The exhaust mass flow was converted into volume flow rate by using air density (at 30 °C air density is ~1.2 kg m^{-3}).

$$\text{Emission}_k = \left(\text{ER}_k \times 10^{-6}\right)\frac{PV}{RT}\,\text{MW}_k t \tag{1}$$

where Emission_k is emissions (g), subscript k refers to emission type (NO_x, SO_x, CO_2 and CO), ER (ppm) measures gaseous species ERs, P is average pressure of 101.3 kPa in standard conditions and a temperature of 273.1 K, V (m^3 h^{-1}) is calculated volumetric flow rate of the exhaust based on the available data, R (J mol^{-1} K^{-1}) is ideal gas constant, T (K) is average temperature of 273.1 K in standard conditions and an average pressure of 101.3 kPa, MW (g mol^{-1}) is molecular weight, and t (h) is recorded operation time of the vessels in different shipping modes.

The dilution ratio (DR) of each load and speed settings was then calculated. To determine the DR, CO_2 was used as a tracer gas. The concentration of CO_2 in the raw exhaust was measured directly by the Portable 5-Gas Analyser (Horiba MEXA 584L) (CO_2 (Raw)) and by the concentration of CO_2 after dilution was measured by Sable CA-10 (CO_2 (Diluted)); then the DR was calculated by applying Eq. (2). These calculations assume that all carbon in the fuel is completely converted to CO_2 [28].

$$\text{DR} = \frac{CO_2(\text{Raw}) - CO_2(\text{Background})}{CO_2(\text{Diluted}) - CO_2(\text{Background})} \tag{2}$$

2.2. Development of emission equations

Equations were developed applying 70% of measured ERs randomly for at berth, manoeuvring and cruising modes for each primary emission.

The regression models were based on the independent variables, which in this study were data on maximum continuous rate (MCR) (as x_1), shaft speed (SS) (as x_2), and emissions (Y). Applying dependant variables affects the accuracy of the results. In the case

Table 1
Ships' engines specifications.

Vessel	Main engine
Vessel I	MITSUI B&W 6L80GFCA 12,080 kW × 102 RPM
Vessel II	MAN B&W 6S50MC 6880 kW × 102 RPM

Table 2
Chemical composition and physical properties of HFO.

Parameter	Units	Method	Vessel I	Vessel II
Density at 15 °C	kg m^{-3}	ISO 3675	986.2	986.2
Kinetic viscosity at 50 °C	mm^2 s^{-1}	ISO 3140	283.0	377.0
Carbon	% mass	AR 2816	88.1	88.1
Micro-carbon residue	% mass	ISO 10370	18.0	14.7
Sulphur	% mass	ISO 2719	2.9	2.8
Ash	% mass	ISO 6245	0.02	0.06
Nitrogen	% mass	AR 2816	0.6	0.7

Table 3
Applied instrumentation specifications.

Applied devices	Measured parameters	Range	Accuracy	Flow rate (L min^{-1})
A Portable 5-Gas Analyser (The Horiba MEXA 584L)	HC, CO, CO_2, O_2 and NO_x (as well as monitoring air–fuel equivalence ratio λ)	0–60,000 ppm 0–25%	25–60 ppm 0.03–0.01%	
Sable CA-10	CO_2	0–5% standard 0–10% optional	1%	5–500 ($\times 10^{-3}$)
DMS 500	Particle size and concentration	5 nm–2.5 μm	–	8.0
Testo 350 XL	SO_2, CO, CO_2, O_2, NO and NO_2	0–10,000 ppm 0–25%	5% of mass-volume 0.8% of fixed-voltage 5 ppm	1.2
Dust Trak	PM_1, $PM_{2.5}$, PM_{10}	0.1–10 μm	5%	3.0

of this study, fuel consumption was dependent on engine load, and the base SFOC value was influenced by engine stroke type and power. Primarily, engine-model specific base values of SFOC provided by the engine manufacturers were used.

Instantaneous total fuel consumption is influenced by many independent factors. The fuel consumption of main engines used in propulsion is commonly estimated as a product of the constant SFOC and instantaneous engine power, which gives a linear relationship between fuel consumption and engine power. Ideally, all power systems that require fuel to operate should be modelled separately: the main engines for propulsion, auxiliary engines for power generation, and boilers for heat generation; however, in practice separate modelling is currently not feasible. In any case the methodologies for evaluating power and fuel consumption are fairly simple, and different assumptions were observed to provide biased estimates, especially for auxiliary engines. The SFOC effect, dependent on MCR quantities, was hidden in the developed equations; but as the objective was to analyse the variation effect of independent variables over time on final emissions, the chemical contents of the fuel (carbon, sulphur and nitrogen) were not considered as these are not time-dependant.

Table 4 shows the range of on-board measurement datasets used to develop the equations. The data on engine power, engine revolution, and other parameters including intercooled air temperature, scavenging air pressure and cooling fresh water were recorded every 5 s for the main engine. The only restrictions on the use of the developed EF equations would have been any datasets outside the ranges noted in Table 4 for Emissions, MCR and SS, but the applied dataset roughly covered a good range for all the variables mentioned in practical shipping operations.

Datafit 9 software, using different model groups including three-parameter power, three-to eleven-parameter polynomial, six and ten Taylor series polynomial, was employed to define the models. The actual emission rates (measured instantaneously in variable timings (h) and variable engine powers (kW)) recorded every 5 s as the base for EFs in units of either ppm or %. They were then normalised to standard conditions: a temperature of 273.1 K and pressure of 101.3 kPa. Final emissions in grams were then calculated.

Having applied Datafit software, the maximum quantity of six parameters was used in this study. The equations, developed from non-linear regression analysis, are at a 95% confidence interval. The regression model's curve's alignment with the data points can be predicted by the R_a^2 value (Eq. (3)), where n is the number of points in the data sample and k is the number of independent regressors (the number of variables in the models excluding dependant variables and constants) [29]. The adjusted R^2 is necessary because the value of the percentage of variation can only be explained by those independent variables that affect the dependent variables. Simply put, the adjusted R^2 will increase if a more useful variable is added and decrease if an un-useful (dependant) variable is added. The methodology framework is shown in Fig. 1.

$$R_a^2 = 1 - \left[\frac{(1-R^2)\,(n-1)}{n-k-1}\right] \tag{3}$$

Table 4
Applied dataset range (the minimum and maximum points).

Mode		Emissions (g)	MCR[a] (%)	SS[b] (RPM)
At berth	SO_2	8.7–18.8	2.5–12.8	31.5–47.4
	NO_x[c]	6.0–20.0	1.0–12.6	−46.1 to 49.4[d]
	CO_2	337.6–951.5	1.8–12.6	31–47.2
	CO	0.3–0.9	3.3–12.0	30.3–47.2
Manoeuvring	SO_2	60.1–108.5	37.4–60.0	73.8–89.0
	NO_x	31.1–68.4	29.4–63.7	69.8–80.9
	CO_2	2949–4303	29.4–63.7	69.8–80.9
	CO	7.7–15.3	31.3–63.5	71.1–80.9
Cruising	SO_2	108.7–145.0	59.6–91.6	85.9–90.8
	NO_x	81.2–108.8	59.6–91.6	85.9–90.8
	CO_2	4949.0–5888.0	59.6–90.8	85.9–90.8
	CO	8.9–15.7	59.6–91.6	85.9–90.8

[a] Maximum continuous rate.
[b] Shaft speed.
[c] NO + NO_2.
[d] Negative amounts occur when the shaft churns backward to completely stop the ship at berth.

3. Results and discussion

3.1. On-board measurement campaign

Measurements of main engine at berth were conducted when Vessel I arrived at its destination port but before the main engine were turned off. Both shaft power and SS keep changing while berthing to stop the ship making headway (Fig. 2); and both strongly affect the quantity of emissions, as depicted in Fig. 2: that is, when engine speed and power suddenly undergo either positive or negative change, emissions fluctuate accordingly. Sudden change may be caused by external factors such as wind, waves or currents, or by tugs or anchors. Fig. 2 shows the primary emissions, measured while the vessel was manoeuvring at the destination port. As with at-berth conditions, the levels of emissions change abruptly when SS and shaft power undergo a sudden change, often required to ensure smooth and safe berthing [30], but changes may also be caused by the geometry of the hull, the pivot point, lateral motion, the rudder, the propeller or the thrusters. The geological features of the port and under-keel clearance also affect emissions levels. Normal cruising speed was also visible for emissions (Fig. 2).

3.2. Validation of emission equations

Applying the percent-predicted method, the remaining random 30% of the emission datasets of Vessels I and II were predicted using

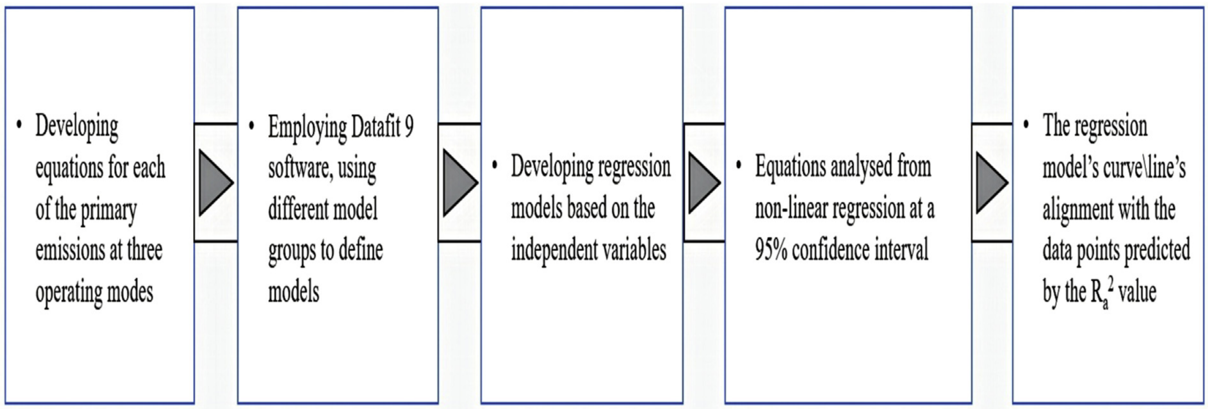


Fig. 1. The methodology framework for developing the equations.

the equations presented in Table S1. By comparing existing inventories with the actual emissions calculated using Eq. (1), it is possible to estimate primary emissions for various engine types. Our predicted inventories are closest to actual on-board estimations, at berth or while manoeuvring or cruising (Table S2).

The standard error of the regression or estimate value (S) (Eq. (4)) demonstrates the mathematical superiority of our predicted emission inventory over other inventories in use. The value is calculated with y' as the instantaneous calculated emission in our and other inventories and N as the total number of datasets for each primary emission of different engine types in different shipping operations. Having the smallest values, our inventories show superiority over other inventories (Table S3).

$$S = \sqrt{\frac{\sum (y - y')^2}{N}} \tag{4}$$

Fig. 3 presents some samples of the trends of instantaneous emissions at different MCRs, and again our predicted inventories show the greatest affinity with on-board measurements (Figs. S2–4). Full samples of the primary emissions in different shipping operations are presented in Figs. S2–4.

Current inventories lack detailed EF datasets for different engine types, shipping modes and emissions. As they also widely ignore national air quality programs, there is a growing need to evaluate their impact on air quality and health.

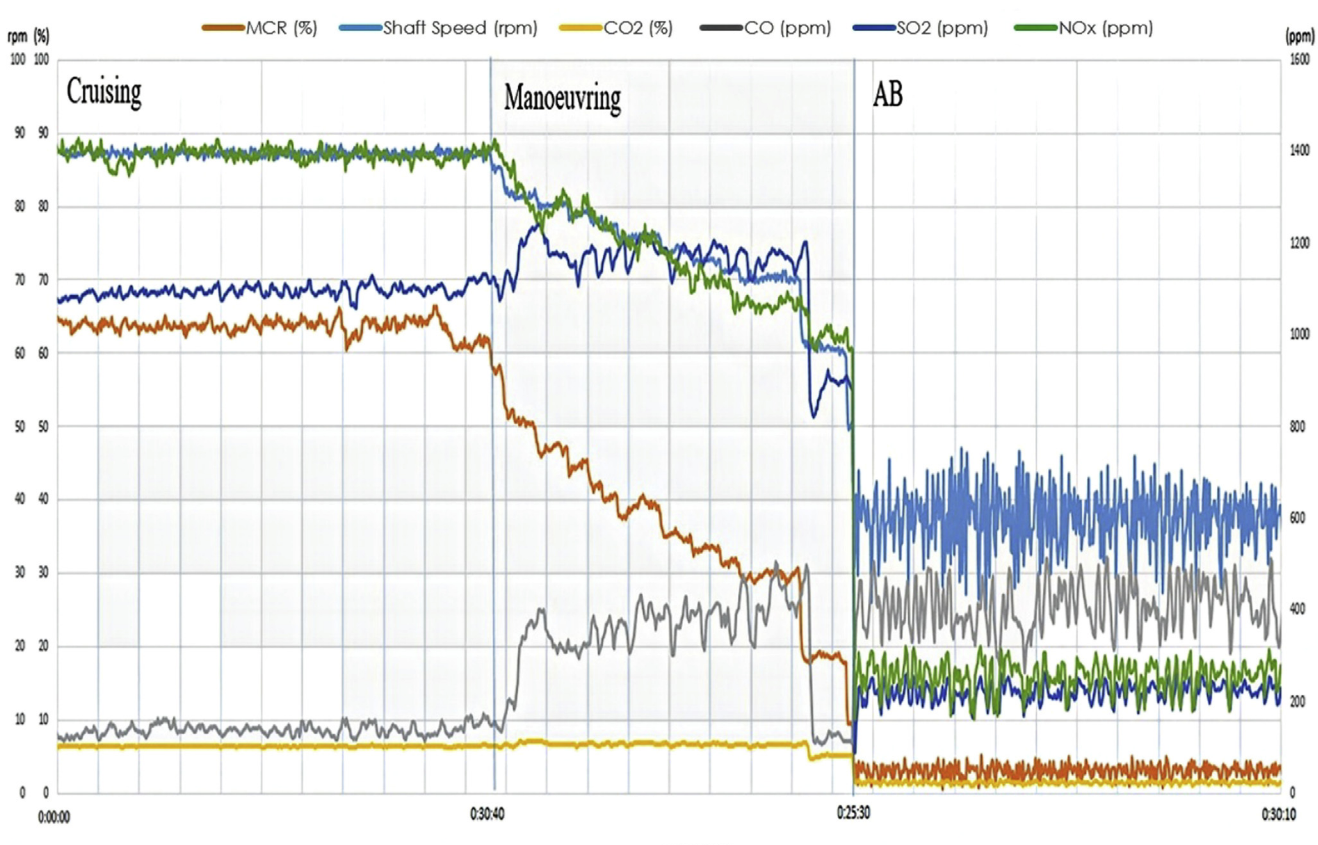


Fig. 2. Main engine emission changes at berth, manoeuvring, and cruising.

The engine ER changes (Fig. 2) are non-linear, indicating a need to simulate emissions more practically in the mathematical model. In our study the effects of changes in engine parameters on emissions are considered for the first time.

Reasons for some non-precise estimations by each of the inventories are provided below:

TIER III [31] datasets do not include CO_2 emissions for main engines; the effects of engine type and shipping activity not taken into account; and only limited averages of the fuel sulphur content and SFOC are considered. The data on fuel consumption are based on national data on sold fuels, not on engine fuel consumption.

Entec [27] assumes the engine EF values in different shipping activities and engine loads; and there is considerable uncertainty in some of the assumptions about engine load use in port. The quantities of fuel sulphur and carbon contents and SFOC are averaged, and when applying the inventory to smaller fleets, the error between the assigned EFs and the fleet value increases. Other factors that may be relevant, such as how cold-started engines or various engine loads affect performance in the course of manoeuvring, are ignored.

Methodology for Emissions and Energy consumption for Transport (MEET) [32] calculates averaged fuel consumption and engine loads for engines rather than addressing specific situations that may affect performance: for instance, the same EF is used for CO engines at berth and manoeuvring; and for the CO engines of slow- and medium-speed diesel engines. It does not consider the effect of using different marine fuels in engine NO_x EFs in different shipping operations.

Ship Traffic Emission Assessment Model [33] datasets do not include CO emissions. As a requirement of the SO_x Emission Control Area regulations of the International Maritime Organisation (IMO), only a sulphur mass-percentage of 1.5 is assumed and modelled for main engines. Different engine specifications or shipping operations are not considered when assigning engine NO_x EFs. Engine loads can often influence EFs: for instance, engines operating under a low load may have higher emissions, particularly during harbour manoeuvring; such variations in EFs as a function of engine load are not taken into account.

Monitoring programme on air pollution from sea-going vessels (MOPSEA)'s [34] activity data are gathered from information systems not designed for inventory emissions, so it takes time and experience to repurpose the data to suit them to the emission model, and the work needs to be simplified and tailored to be fit for inventory purposes. This model too makes various assumptions about fuel use and the percentage of MCR which do not reflect these parameters in practice: for example, averaged engine EFs per

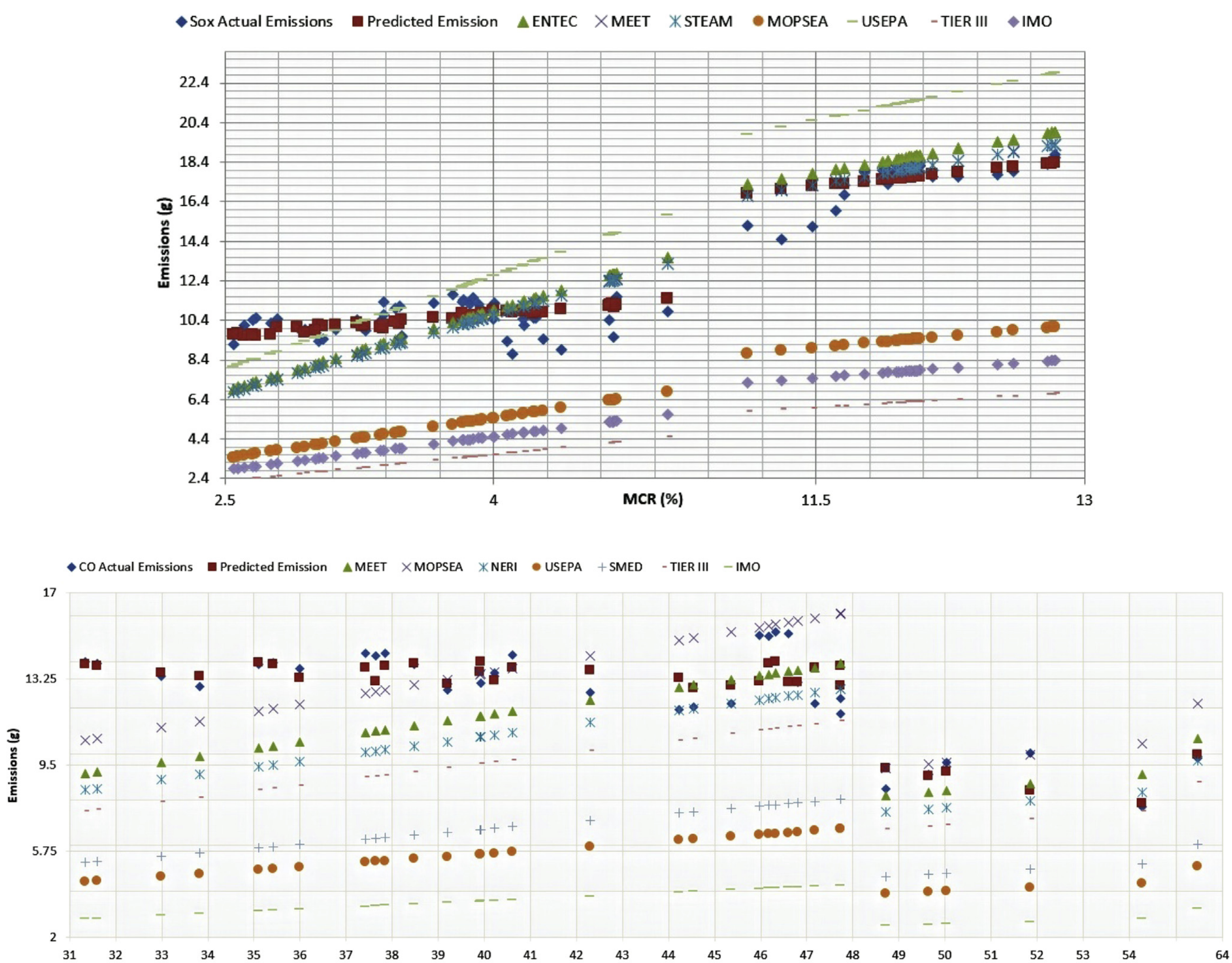
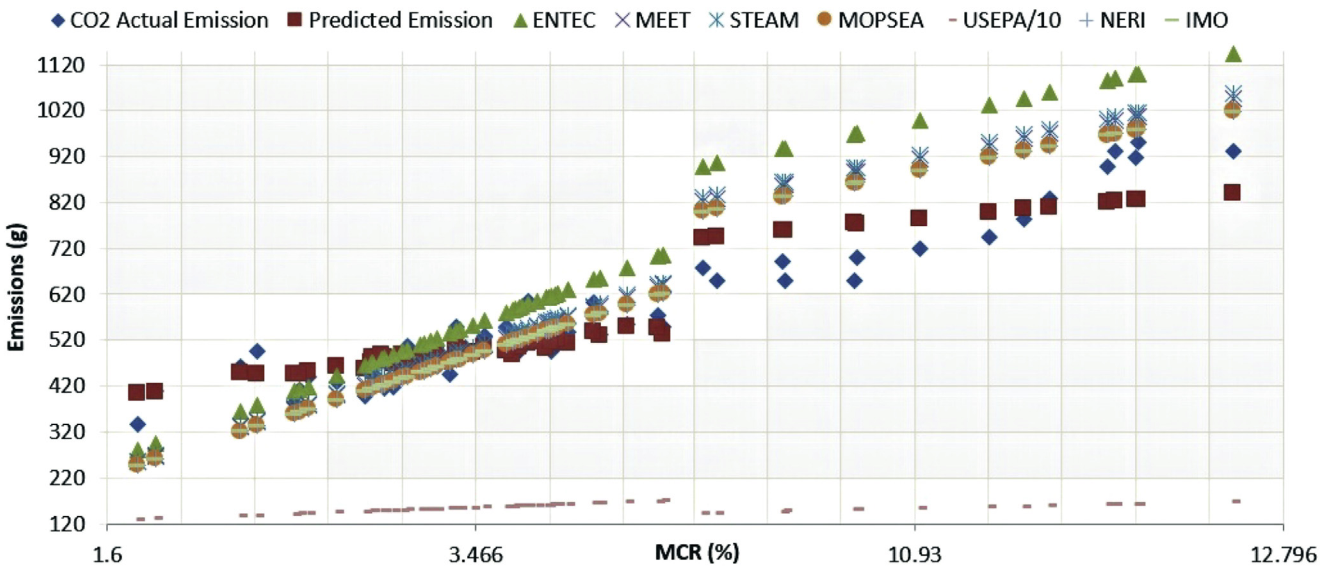


Fig. 3. Sample of some trends of predicted and available inventory ME emissions (g) in different shipping operation.



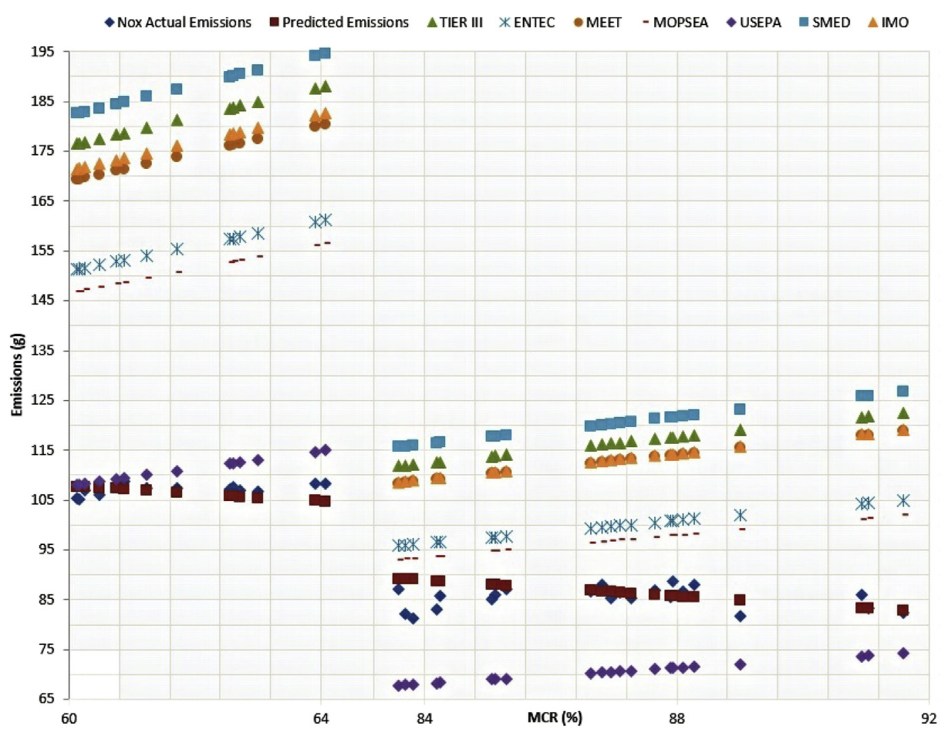


Fig. 3. (*continued*).

ship type are used instead of specific figures. There is inadequate focus on engine loads during different shipping activities, and no coverage of engine load variations over 85% or under 10% in NO_x and CO EFs. Nor is there adequate direction for dealing with missing data, or for implementing and using Automatic Identification System (AIS) data.

National Environmental Research Institute (NERI) [35] uses the same CO EFs without consideration of engine type or shipping activity; nor are consistent emission data available as a function of the engine age. In addition, country-specific EFs for CO_2 do not consider engine types or shipping activities.

United States Environmental Protection Agency (USEPA)'s [36] basis for its operating data seems to have various assumptions that are not validated by the Energy and Environmental Analysis as their contractor. It categorises engines by individual cylinder displacement, which may not indicate a true relationship with high, medium, and slow speeds. Large inconsistencies appear between the output given at full load and the actual ratings of the engine, pointed out in Lloyd's analysis.

The data analysis is mostly carried out on engines with a rating of less than 8000 kW, and the applicability of the EFs obtained to engines of all sizes is debatable. There is no consistency between engines' rated power and testing conditions, so EPA categories cannot be determined. There is no agreement on the actual numbers or types of engine, and no reporting of engine markers or displacements. In some instances, the reported maximum power and engine ratings show discrepancies.

The Environment Canada report defines the three modes and engine load factor variations under which its engines were tested, and does not consider the extent of variation that may exist between engines in the same category; ‘normal cruise’ and ‘docking operation’ conditions are undefined in the procedures of the BC Ferry Test Program. Engine NO_x and CO have the same EFs, regardless of fuel or engine used or consideration of shipping activity.

Swedish Methodology for Environmental Data [37] inventory likewise Entec [27], mentioned in above paragraphs, suffers from non-precise EFs. Also, there is a great deal of uncertainty about ‘manoeuvring’ (the assumption is that engines operate at 20% MCR), as well as the need for manoeuvring emissions to take into consideration that emissions from cold state engines, especially CO emissions, which would be significantly different than those from warmer engines. Variability of emissions can also be caused by rapid changes to load during manoeuvring: this study takes none of these into account.

Engine EFs (derived from steady state loads of 70–100%) are multiplied ‘at sea’ by 0.8 for NO_x and by 2.0 for CO for all engines running on diesel. This means that there is significant uncertainty regarding the results. Emission estimations for engines at berth are not considered. The estimates of the fuel sulphur in various fuels over the years are unspecified, and it is assumed that between 1990 and 2003, fuel-dependent EFs of CO_2 were constant. Considering that EFs are different and there is anticipated uncertainty, specifying exactly how biased emission estimations can be, especially when only at-sea EFs are at play, is difficult.

IMO [38] bases its SO_x base line EFs on a 2.7% sulphur content HMO, although the world average of fuel sulphur is in constant change. The effect of using different fuel types is not considered in applying base SFOC values to engines; the parabolic SFOC dependency on engine load is not considered in HFO; and transient engine load changes are not considered in CO EFs.

There are uncertainties about how many active ships exist, and which are allocated to domestic or international voyages. Currently discrepancies occur between the number of active ships described by the IHSF and those observed on AIS, although this will reduce slightly as the availability of AIS data improves. The bottom-up method is used when location information is available, but AIS coverage is not so consistently high for the voyage-by-voyage details to be identified either. Some uncertainties may also arise if the ship is not visible on AIS and its speed is estimated.

4. Conclusions

The non-linear regression analysis used here to develop new sets of EF equations on each primary emission for engines at berth, manoeuvring, and at sea predicts emissions more accurately than current inventories. The sampling will help in developing emission models and inventory calculations that can be used to outline MCR, SS, and emission datasets more effectively than is currently achieved.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.serj.2018.08.005.

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