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Comparative analysis between different methods for calculating on-board ship's emissions and energy consumption based on operational data

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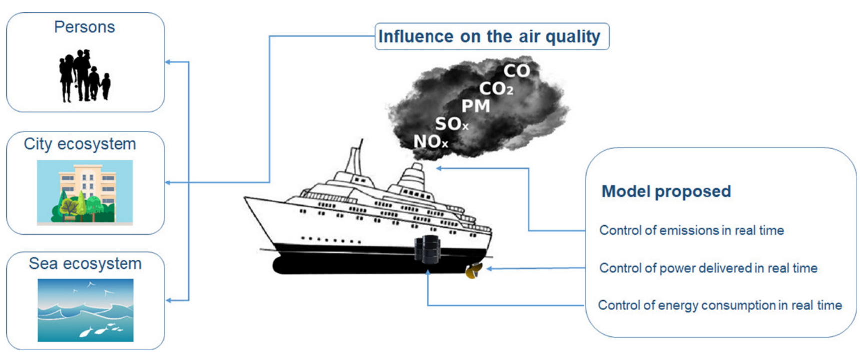
HIGHLIGHTS

- Ships' energy and emission inventories are subject to many significant uncertainties.
- Models for calculating ship's energy and emissions in real-time have been proposed.
- Models for monitoring delivered power in real-time have been proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

With the aim of more reliably measuring ships' fuel consumption and emissions several different estimation methods have been put forward and are in use but there is ongoing debate still on the best way to measure maritime emissions. Fuel and emissions monitoring are already a common practice in the shipping industry. But there are currently neither harmonised guidelines nor legal requirements that clearly define the method and the rules to follow to monitor on-board fuel consumption for each situation during navigation.
In this context, this article describes and compares four existing methods (EPA, IMO, Jalkanen and MAN) for calculating energy consumption and emissions, and presents a more realistic method, based on a case study. The purpose is to examine the differences between all of these methods, in order to propose the most suitable method

Abbreviations: AE, auxiliary engine; AIS, automatic identification system; Bottom-up, inventory methodology type; Cruise mode emissions, in the near-port analysis these are produced while the ship is within 25 nautical miles of the end of the SRZ lanes.; Dwt, deadweight ton; EEA, European Environment Agency; EF, emission factor; ENTEC, Environmental Engineering Consultancy; EPA, Environmental Protection Agency (USA); GHG, greenhouse gas; HFO, heavy fuel oil; HOTELLING, this provisioning operation (also known as dwelling) takes place while the vessel is docked or anchored near a dock; HSD, high speed diesel (engine type); IHS, Register of Ships Directory; IMO, International Maritime Organization; LF, load factor (percentage of the engine's total MCR power); LRIT, long range identification and tracking of vessels; MANOEUVRING, these are operations carried out in close proximity to the dock; IN PORT (SRZ), Manoeuvring that occurs within Port at limited speed; MCR, maximum continuous rating; MDO, marine diesel oil; MEPC, Marine Environment Protection Committee (IMO); ME, main engine; MFO, medium fuel oil M; MRV, monitoring, reporting and verification emissions; MSD, medium speed diesel (engine type); MW, mega watts; nm, nautical mile; Noon Report, daily on-board data sheet; PM, particulate matter; ROB, fuel oil remaining; RoPax, ship type designed principally for freight vehicle transport (roll-on) but with accommodation for passengers; RoRo, roll-on roll-off vessels that are used to carry wheeled cargo; SFOC, specific fuel oil consumption; SRZ, speed-restricted zone; SSD, slow speed diesel (engine type); tonne, a metric unit of mass equal to 1000 kg, also known as a metric ton.

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of obtaining the data needed for better energy management, and a method that can be applied to any type of ship. The case study was carried out on Ro-Pax ships, comparing these four different methods through the application of a bottom-up integrated system approach. The study describes in detail and applies the most complete methodology for calculating energy consumption and emissions during cruising, operating in a Speed Reduction Zone (SRZ), manoeuvring and berthing.
Application of the new improved method proposed in this paper could be the first step in implementing operational measures for detecting both abnormal high emissions and abnormal fuel consumption. The application of this method does not, in itself, reduce fuel use or improve efficiency, but it should be the necessary first step to establish uniform operational measures that will improve the management of energy on board ship and monitor accurately the performance of the fleet.

1. Introduction

Shipping-related emissions are one of the major contributors to global air pollution, especially in coastal areas (Viana et al., 2014). These emissions contribute significantly to air pollution in the vicinity of harbours (Eyring et al., 2010); another significant finding is that over 70% of total ship emissions can spread up to 400 km inland. They can also cause an increase in the levels and composition of both particulate and gaseous pollutants, as well as the formation of new particles, in densely populated regions (González et al., 2011).

It is estimated that particles emitted specifically by ships caused around 87,000 cardiopulmonary and lung-cancer deaths each year worldwide (Winebrake et al., 2009). This atmospheric pollution has particularly strong and consistent associations with both mortality and morbidity, and with respiratory infections and asthma in young children (WHO, 2012). Caiazzo et al. (2013) estimated that shipping contributed 3500 premature deaths from $PM_{2.5}$ and O_3 pollution across the US in 2013, while Huan et al. (2016) estimated 14,500–37,500 premature deaths per year due to shipping across East Asia. The WHO in 2013 considered that the relationship between PM emitted as primary pollutants and deaths produced must be expressed as a supra-linear function, whereas other authors (Penn et al., 2017, Krewski et al., 2009 and Lepeule et al., 2012) assume this relationship to be a linear function.

In this study, the origin of these pollutants emitted is essentially the combustion of fuel by the ship's engines. A detailed analysis is made of four existing methods and a new method is proposed, that will provide the operators of a ship with quantified information on the pollutants emitted by the ship in real time, so that they may also be aware of the number of deaths that may be produced by this pollution.

The International Convention for the Prevention of Pollution from Ships (MARPOL), Annex VI Regulations for the Prevention of Air Pollution from Ships (which includes 18 regulations, from application to fuel oil availability and quality), was established by the International Maritime Organization (IMO) as the global strategy for mitigating shipping emissions (Ling-Chin and Roskilly, 2016); it defines the methodology to be used for recording the energy and emissions inventories of ships. However, the issue of how best to calculate a ship's emission inventory is much debated, and contradictory papers have been published over the last ten years (Durán-Grados et al., 2018).

In the present study, the authors propose a new method based on the other four which removes all of these uncertainties, since it is based on a bottom-up method, it applies an original approach to estimating a ship's energy consumption and emissions from its operations each day during each voyage, using operational data, and it gives calculated emissions of greenhouse gases (GHG's) and particulate pollutants, instead of analyses carried out using calculations of generalised maritime activity for categories of ships. The proposed method will also be useful for application in the new concept of the **Monitoring, Reporting and Verification (MRV) of emissions** by Maritime Transport (MRV Shipping Regulation, 2015).

This proposed method removes the uncertainty attributable to the use of fuel oil consumption average values and represents a substantial improvement in the reliability and accuracy of aggregate data on shipping activity, energy demand and emissions. Four different methods and equations for calculating energy consumption (possibly using oil flowmeters by consumers) and emissions have been studied and compared, and the results are used to propose an original method that can be applied to all types of ships. The validity of fuel consumption should be compared on a periodic basis through comparison with the fuel figures derived from flowmeters (if available) and tank soundings. The ship operator's maintenance records should provide guidance on comparison frequency.

As an illustrative case study, the existing and proposed methods have been applied to a Ro-Pax ship operating in the waters of the Strait of Gibraltar (Spain), no shallow waters and no ECA (Environmental Control Area) transit.

The proposed models are based on theoretical emission factors like the other inventories published to date, but operators are able to perform on-board tests to calculate the deviation between the theoretical and actual emission factors. Furthermore the method proposed here calculates the fuel consumption for each category of ship's speed.

Given that the models of Krewski et al. (2009) and Lepeule et al. (2012) use a direct relationship between mortality and the precursor pollutants (NOx, SOx and PM), in tons, emitted by ships, each shipping zone and type of shipping activity requires careful analysis, because the emission impacts of specific ships and specific routes differ quite significantly and will depend on a range of factors: route distance, ship capacity, service speed, engine power, average work load, type of fuel used, and fuel consumption.

This clearly suggests that each type of maritime transport service has to be evaluated individually (Jalkanen et al., 2009); and that is the approach taken here.

In order to measure as precisely as possible the amount of pollutants emitted to the atmosphere and, given the proximity to the coastal area in which the pollutants are emitted (in the case study the ships always travel in fixed lanes, no further than 13 nm from each port), the results from applying the proposed methods may help to define the air quality model in the study area. This is because, in the case of Maritime Transport, such assessments are based on air quality dispersion models in which the amounts of primary pollutants (CO_2, NO_x, SO_X, CO and PM) that are emitted directly into the atmosphere are calculated by a bottom-up approach (inventories compiled from ship activity records and activity-based emission factors for different ship types); these data serve as the main input for the models (Matthias et al., 2010). The problem is that both air quality models and ships' emission inventories present many uncertainties. The method proposed in this study reduces scientific uncertainties in respect of emissions inventories and may help to define the air quality model in the study area more precisely.

Regarding our case study, the significance of this type of shipping activity in this area is clearly evident from the total fuel consumption by maritime traffic in the Strait of Gibraltar: in 2007 it amounted to 290,000 t. Domestic traffic of Ro-Ro and Ro-Pax ferries accounted for 46% (134,810 t consumed) of this, and only while operating in cruising mode (Moreno-Gutiérrez et al., 2015).

Four energy and emission calculation methods were studied and compared for a series of complete individual voyages of a Ro-Pax ship in the Strait of Gibraltar, from leaving dock at the Port of Algeciras (Spain) to docking at the Port of Tangier (Morocco). The study took into account the ship's cruising speed, its reduced speed near to port, and the low-speed manoeuvring in port and berthing stages. The influences of currents, waves, wind, hull/propeller fouling, trim, cargo load and propulsion system efficiency (from the on-board database) were used for the application of the IMO method.

This could be the first step for monitoring accurately the performance of the fleet; it could, for instance, detect abnormal high emitters, thus providing information to the relevant authorities on the possible installation of equipment tampering and poor durability of pollution control systems fitted to the ship. This topic has been proposed by the European Commission for research in its H2020 projects.

2. Methodology

2.1. Description of the method

The so-called bottom-up, or activity-based method, was used in this study. The object of this method, applicable to all types of ship, is to estimate the emissions of each main pollutant by a particular ship, on a day-by-day basis, by accurately calculating its energy consumption. The method needs information on the ship's characteristics (vessel type and size, engine type, fuel type, total power installed and 100% MCR for main and auxiliary engines.) and movements, as well as the corresponding fuel consumption figures and emission factors. The approach allows many possible variants, mainly depending on how the set of inputs is obtained and what models or other assumptions are used (David Segersson, 2013). In this case study, only data from the Ro-Pax Noon Report completed on board was used, and no AIS data was used. To date all models of emissions inventories previously published have used the AIS system that has many uncertainties (Smith et al., 2014), Table 1.

The method proposed by the authors uses the Goldsworthy and Galbally (2011) method for calculating Emission Factors, the Jalkanen et al. (2009) calculation for Specific Fuel Oil Consumption, the Basic Principles of Ship Propulsion (2012) model for defining a ship's power and speed relationship, and the IMO method for the calculation of actual main engine power. This method guarantees the highest level of data consistency and tries to serve as a first step towards a regulation on emissions reduction and can only be guaranteed if emissions data is easy to collect, survey and verify.

The data for previous years are unreliable due to uncertainty stemming from the ship activity data, essentially because of the lack of satellite AIS data. Therefore that activity data has not been used in this study, because better information is available from the ship's Noon Reports (Daily on-board data sheet), Table 1.

Three primary sources of emission can be found on a ship: the main engine (ME), the auxiliary engines (AE) and the thermal boilers. The emissions from the boilers are the least significant and depend heavily on their size and the extent of their use. On container vessels, boilers are usually used for auxiliary hotel loads, whereas on crude oil lightering vessels the boilers are used when discharging the crude oil. Given that an oil boiler is not used on board the ship in the case studied, only energy consumption and emissions from the main and auxiliary engines, are quantified in this study.

Energy consumption and emissions from the main propulsion engine(s) ME(s) vary as a function of the engine's rated power output, load factor and build year. The main engine power output and load factor vary over time as a result of the ship's operational mode (e.g. at berth, anchoring, manoeuvring, reduced speed mode, cruising mode) (Aldous et al., 2013).

The bottom-up model applied in this study calculates these specifics (main engine power output and load factor) for each operational mode of the ship and for each trip. Energy consumption and emissions by the AEs vary as a function of auxiliary power demand (typically changing with each vessel operating mode), auxiliary engine rated power output, load factor and the engine build year.

Because the voyages in both directions (opposing) were taking place over short periods of time, the wind direction, wind speed, wave direction and wave height were not taken into account.

This study first calculates sea transport emission factors for GHG and pollutants (CO_2, CO, NO_x, SO_x), and PM emissions, as well as fuel consumption. In this case, a specific Ro-Pax ferry serving the sea routes connecting mainland Southern Spain and Northern Africa was studied over a period of 2 months in 2017. It provided results from the application of four different methods (EPA, 2000; Smith et al., 2014; Basic Principles of Ship Propulsion, 2012 and Jalkanen et al., 2009). Based on these methods, a new method has been proposed by the authors, which is a combination of all four. The quantity of fuel consumed was compared with data from on-board records. Because the fuel consumption data is obtained from changes in tank levels, the results for the four methods show differences greater than 20% compared with the calculation using the new method proposed. Thereafter, the overall total levels of CO_2, CO, NO_x, SO_x and PM emissions and fuel consumption are calculated per voyage/trip.

The study was carried out on four different operational modes of the ship studied, for each complete voyage from/to each Port:

1. Cruising (for between 0.98 and 1.25 h, on-board database).
2. Slow steaming, in Speed Restriction Zones (1 mi at 12 knots, on-board database).
3. Manoeuvring into port (0.22 h at 9 knots, on-board database).

Table 1
Comparison between uncertainties from using the AIS system and the new method proposed.

Uncertainties, quoted from Third IMO GHG Study, 2014	Proposed model
The uncertainties (particularly AIS data) remain, particularly in the estimation of the total number of active ships and the allocation of ships or ship voyages between domestic and international shipping.	The use of the models proposed in this paper removes any uncertainty attributable to the use of average values from AIS data.
In cases where data from AIS are missing, values are estimated either from interpolation or by referencing another publicly available data source.	No missing data in this study
It has recognized several ships for which there is no corresponding IHSF and activity data. Ships from domestic traffic are included in all emissions, but with high uncertainty because their technical characteristics cannot be given.	This problem is not possible in this proposal because only on-board data are used
The environmental conditions are not reflected to their full extent in the AIS-based modelling. It fails to take into account that the fuel consumption and emissions can easily double or triple in strong wind/bad weather conditions.	All the models proposed here take into account weather conditions and the condition of the ship's hull and propeller (data from on-board).
Uncertainty level (10%) within the Monitoring Plan for fuel oil measurement by manual sounding	Not applicable in this study

4. Arrival at and departure from berth (0.083 h at 3.1% LF/0.083 h at 3.9% LF, respectively, on-board database).

Average time per voyage: 2 h 10 min
Average distance per voyage: 18.5 mi
Number of voyages analysed: 405
Number of voyages per year: 2,400

The on-board database (from the Noon Reports) includes the following parameters:

- ACTUAL SPEED FOR EACH MODE
- MAXIMUM DESIGN SPEED at 100% MCR: 19.2 knots
- MAXIMUM DRAUGHT FOR FULL LOAD [m]: 5.570 m
- DRAUGHT FOR EACH MODE [m]
- DWT: 4030 t
- VOYAGE DISTANCE SAILED
- SPECIFIC FUEL OIL CONSUMPTION (SFOC) BASE: 0.213 g/kWh and 0.210 g/kWh for RO and MDO respectively. Depending on the voyage stage, both values will be used as the base for the application of Eqs. (6) and (7).
- SPEED OVER GROUND FOR EACH MODE
- SPEED THROUGH THE WATER FOR EACH MODE
- TOTAL INSTALLED POWER Main engines (2 × 5850 kW, 100% MCR) and auxiliary engines (2500 kW, 100% MCR)
- TIME IN PORT
- TIME SAILING (Cruising, reduced speed, manoeuvring, arrival and departure)

TYPE OF FUEL FOR EACH SITUATION: as stated in the on-board design guide, the type of fuel used is RO for the main and auxiliary engines and MDO for the auxiliary engines (only in port). As stated in the on-board database, 1978 kg of HFO and 168.5 kg of MGO were consumed in each trip.

Statistical data values have been inserted in Tables 20 and 21. The sample size was 160.

The bottom-up method usually provides an initial per-ship estimation of observed activity, energy consumption and emissions, but only on ships that appear concurrently in both the IHSF and AIS databases. This method combines activity data (derived from AIS and LRIT raw data sources) and technical data (derived from IHS, see Eqs. (1) and (2)). This method has several uncertainties. Our main aim is to reduce these uncertainties by applying explicit quality control to calculate fuel use and emissions using the technical details of each specific vessel.

One significant uncertainty is the calculation of the LF of the ME (see Eq. (3)), a second concerns the equations used for calculating fuel consumption (see Eqs. (6) and (7)) and a third is the value of the EF (see Eq. (8)) used for calculating the total emissions per pollutant. Both parameters are taken as constant values in most previous studies but in actual fact, they both depend on the specific LF, of both the ME and AE.

One important contribution of the proposed method to reducing uncertainty is the direct observation of activity data for each individual vessel, e.g. speed and draught.

On this point, the power output of the main engines is dependent on the propulsion speed of the ship (Eq. (3)), under the assumption that friction parameters are ship-specific constants. It should be noted that this method only requires knowledge of two parameters: power and ship speed at 100% MCR from the on-board test. However, Jalkanen et al. (2009) also introduce a safety margin of 0.5 knots to account for ship speeds, as recorded in the AIS (see Eq. (4)), that sometimes exceed the stated maximum. In the study described here, it was not necessary to use the AIS data because the Noon Report was used, as already stated in this methodology section. The Noon Report data represent a low resolution dataset (the sampling frequency is approximately every 24 h) from which it is possible to extract the principal variables required to define a ship's performance in terms of fuel consumption. Furthermore, a ship's actual performance needs to be measured in order to assess the fuel savings that may be achieved from management and technological interventions (Trozzi and de Lauretis, 2013), Table 2.

The methodology used here calculates the total emissions and energy consumption by summing the emissions on a trip-by-trip basis. A single trip was considered to be from when the ship was at berth in the port of origin (A), up to the time of its departure from the port of destination (B). The energy consumption and the emissions are expressed as follows:

- During docking, manoeuvring, departure from port A
- During docking, manoeuvring, arrival in port B
- During manoeuvring into port A
- During manoeuvring into port B
- During slow steaming, in SRZ zone on leaving port A
- During slow steaming, in SRZ zone on approaching port B
- During cruising

The same sequence from Port B to Port A was also analysed.

2.2. General equations to use

The use of configurable expressions makes the emission calculations very flexible. For most users, the expressions already provided in the system will be the ones they use for the calculations. It should be noted that the methods currently used have been chosen based on the available input data.

Eqs. (1), (2) and (3) have been used in all the ship energy and emissions inventories published to date. This approach is consistent with the methodology proposed by the EEA (Trozzi and de Lauretis, 2013) and the methodology outlined by the U.S. EPA-420-R-10-013 (2010). Both methodologies usually require use of both the AIS system to calculate the activity time and the Lloyd's Register (IHS Fairplay) data for the ships' characteristics (Andersen et al., 2005).

In Eq. (1), ME signifies the Maximum Continuous Rating (MCR) for a main engine when an energy and emission inventory is applied, for a specific zone. This data is extracted from the IHS Fairplay for each ship. The problem lies in knowing or calculating the LF value. Although a ratio of 80% at sea to 20% while manoeuvring is common in the

Table 2
Comparison between all the methods.

Method	Power delivered	SFOC	Emission factor	Relation-ship between speed and power, n
EPA	$P_{transient} = P_1 \left(\frac{V_{transient}}{V_1}\right)^n$	Constant value depending on the type of engine	ARB, ENTEC (2002)	Constant value, n = 3
IMO	$P_{transient} = \frac{P_1 \left(\frac{t_{transient}}{t_1}\right)^{\left(\frac{2}{3}\right)} \left(\frac{V_{transient}}{V_1}\right)^n}{\eta_w \ \eta_f}$	Variable (Eqs. (6) and (7))	IMO	Constant value, $n = 3$
Jalkanen	$P_{transient} = \varepsilon_p * P_{installed} \left(\frac{V_{transient}}{V_{design} + V_{safety}}\right)^n$	Variable (Eqs. (6) and (7))	ENTEC (2002)	Constant value, n = 3
MAN	$P_{transient} = P_1 \left(\frac{V_{transient}}{V_1}\right)^n$	Constant value depending on type of engine	NA	Variable depending on the type of ship
Proposed	$P_{transient} = \frac{P_1 \left(\frac{t_{transient}}{t_1}\right)^{\left(\frac{2}{3}\right)} \left(\frac{V_{transient}}{V_1}\right)^n}{\eta_w \ \eta_f}$	Variable(Eqs. (6) and (7))	Compilation of ARB, ENTEC (2002), EMEP/EEA and IPCC	Variable depending on the type of ship

literature [EMEP/EEA, 2016], in Eq. (3) most authors suggest that $n = 3$ be used for all types of ship and for all types of operating mode.

In a previous study (Basic Principles of Ship Propulsion, 2012), it suggested that the exponent "n" should be expressed as a variable value that depends on the type of ship when a propeller is used as the propulsion system. The use of Eq. (4) makes sense if the AIS system is used but it is not recommended when Noon Reports are used, given that ship speed is data collected on-board and in real time.

Eq. (5) from the Smith et al. (2014) introduces additional parameters (draught, propulsion efficiency due to weather, and the modification of propulsion efficiency due to fouling) for the calculation of the transient power when the ship is propelled by propellers, but it also uses the constant value of $n = 3$.

If more detailed information about a ship's characteristics is available, it is evident that more specific expressions that make use of this should be implemented in order to improve the calculations. An example of this would be to include dependency on engine load in emission factors for pollutants (Eq. (8)) and specific fuel consumption (Eqs. (6) and (7)), both of which are taken as constant values in the existing methods.

The method proposed in this paper uses Eq. (5), taking into account that "n" is a variable value which depends on the type of ship. All the variables shown in this equation can be taken from on-board data.

2.2.1. Calculation of energy consumption

$$Energy = \frac{D}{v}[(ME.LF_{ME}.SFOC) + (AE.LF_{AE}.SFOC)] \tag{1}$$

where:

D (miles): Distance that the ship travels within the study area
v (knots): Average speed of the ship
Activity time: $(\frac{D}{v})$(hours)
ME (kW): Maximum continuous rating (MCR) for a main engine.
LF_{ME}(fraction): Load factor for a main engine as a fraction of the MCR
AE(kW): Maximum continuous rating (MCR) for an auxiliary engine
LF_{AE}(%): Load factor for an auxiliary engine as a fraction of the MCR

2.2.2. Calculation of total emissions

$$Emissions = [(ME\ Energy).EF_{ME} + (AE.Energy).EF_{AE}] \tag{2}$$

where:

$ME\ Energy\ and\ AE\ Energy(kWh) : ME.\ LF_{ME} and\ AE.\ LF_{ME}$ from Eq. (1)
EF_{ME} (g[kWh]$^{-1}$): Emission factor for a main engine, for the pollutant in question (varies by engine type and fuel consumed rather than by activity mode)
EF_{AE}(g[kWh]$^{-1}$): Emission factor for an auxiliary engine, for the pollutant in question.

2.2.3. Calculation of load factors

The general equation for calculating the Main Engine Load factor is described in Eq. (3)

$$LF = \frac{P_{transient}}{P_1} P_{transient} = P_1 \left(\frac{V_{transient}}{V_1}\right)^n \tag{3}$$

where:

P_1 and V_1 are power and ship speed respectively at 100% MCR from the on-board test (Winebrake et al., 2009); $V_{transient}$ is actual ship speed; $P_{transient}$ is the instantaneous power for calculation.

n = the constant ship speed coefficient and represents the relationship between speed and power. EPA-420-R-10-013 (2010) uses a constant value of $n = 3$ for all types of ships.

However, the relationship between a ship's power and speed often results in a higher power (n) than three. Usually, the relationship used for estimating the LF for MAN Diesel and Turbo MEs (2012) is as follows:

- For large, high-speed ships such as container vessels: $n = 4.0$.
- For medium-sized, medium-speed ships such as feeder container ships, reefers, Ro-Ro ships, etc.: $n = 3.5$.
- For low-speed ships such as tankers and bulk carriers: $n = 3.2$.

Since this study was designed for a Ro-Pax ship, a value of n = 3.5 is used.

2.2.4. Calculation of power transient

Jalkanen et al. (2009) proposes Eq. (4) to calculate the power transient of the main engines (STEAM method)

$$P_{transient} = \varepsilon_p * P_{installed}\left(\frac{V_{transient}}{V_{design} + V_{safety}}\right)^3 \tag{4}$$

where:

$P_{installed}$ is the total installed power (kW) of the main engine(s), and V_{design} and V_{safety} are the design speed and the safety margin (in m/s), respectively. The ε_p is assumed to be equal to 0.8, as the maximum continuous rating of the engine is thought to be 80% of the total installed main engine power (kW). In this equation, propeller efficiency is considered to be a constant, as well.

However, as can be deduced from Eqs. (3) and (4), the power that the propulsion engines have to develop does not depend solely on the speed, In addition to the transit speed there are other factors that influence the power that these engines must develop in order to achieve that speed. Logically these other factors also influence both the fuel consumption and the emissions released. These factors are those that increase the resistance of the vessel to movement through the water (Smith et al., 2014), i.e. the following three factors:

- Increased draft and displacement.
- Worsening of weather conditions.
- Worsening of hull and propeller roughness (i.e. fouling condition).

On this point, the Smith et al. (2014) proposes an Eq. (5) for the calculation of the power transient of main engines, as follows:

$$P_{transient} = \frac{P_1\left(\frac{t_{transient}}{t_1}\right)^{\left(\frac{2}{3}\right)}\left(\frac{V_{transient}}{V_1}\right)^n}{\eta_w\,\eta_f} \tag{5}$$

where:

P_t, V_t and t_t are respectively the instantaneous (transient) power, speed and draught at time t; P_1, V_1 t_1 are ship power, ship speed and draught respectively at 100% MCR, from the on-board tests; η_w is the modification of propulsion efficiency due to weather; η_f is the modification of propulsion efficiency due to fouling; and n is an index that represents the relationship between speed and power, $n = 3$. This uses the Admiralty formula, which assumes that power is related to displacement to the power of 2/3.

Given that the difference between speed through the water and speed over ground were constant values, η_w was considered constant, as was the η_f value.

For the input values, this modelling approach uses the position reports generated on-board a ship each trip. The data from the 2011 reports was extracted. This area of the sea is well represented in this data.

The energy consumption and emissions figures presented in this paper are evaluated based on the four different models above.

2.2.5. Calculation of energy consumption

Eqs. (6) and (7) were applied in the calculation of Energy Consumption.

$$SFOC : SFOC_{Relative} \times SFOC_{base} \tag{6}$$

$$SFOC_{Relative} : 0.455\ LF^2 – 0.71\ LF + 1.28 \tag{7}$$

where:

LF: Load Factor, a value from 0 to 1
SFOC: Specific Fuel Oil Consumption
$SFOC_{base}$: From design guide

2.2.6. Calculation of emission factors

Emission factors are used in conjunction with energy or fuel consumption to estimate emissions, and will vary by pollutant, engine type, duty cycle and fuel. Emission quantities are used to produce emission factors in g/kWh and/or grams of pollutant per gram of fuel consumed. The baseline fuel for producing the bottom-up emission factors is defined as HFO fuel and this has a sulphur content of 2.5%.

Internationally, there is no agreement about the values to apply to the emission factors. For example, IPCC (2006) recommends emission factors in its guidelines, the EU has the EMEP EEA (2016) data base emission factors. On the other hand, the Starcrest Consulting Group (2004), the European Parliament and Council (2010), Cooper and Gustafsson (2004) and the EPA (2000) have published other values to apply to the emission factors. A compilation of all of these (Goldsworthy and Galbally, 2011) is shown in Table 3 for its application in this study.

It is very important to note that the emission factor for each pollutant and engine type, expressed in g/kWh (see Table 3), takes a constant value when the ME loading is between 100% and 20%. For ME loadings of less than 20%, Eq. (8) was applied, as follows:

$$y = a(LF)^{-x} + b \tag{8}$$

where:

y = emissions in g/kWh
a = coefficient
b = intercept
x = exponent (negative)

3. Results and discussion

The fundamental objective of this study is to reduce as much as possible the uncertainties that will exist in the emissions inventories of ships when they are calculated making use of the AIS for positioning (i.e. changes in ships' positions over a known time period) and a database of the characteristics of a ship's engines, including data of a ship's characteristics when those of the engines are not known. Both of these uncertainties are eliminated. However, there are other parameters employed in this study that, in addition, use values closer to reality, as can be observed in the results reflected in the tables.

In Eq. (1), which defines the energy consumption, there are two decisive factors: the Load Factor and the specific fuel consumption. Since the Load Factor of the Main Engines is related to the real instantaneous power developed by these engines, the most precise possible definition of this power will ensure that these calculations are as close as possible to the true values, because normally the emissions inventories attributed to maritime transport are based on mean values of these load factors.

For example, the Smith et al. (2014) utilizes a criterion to define the Load Factor for the main engines, in the following way:

Speed Mode	
Less than 1 knot	At berth
1 knot to 3 knots	Anchored
Greater than 3 knots and less than 20% MCR	Manoeuvring
Between 20% MCR. and 65 % MCR	Slow-steaming
Above 65 % MCR	Normal cruising

With such wide margins as these, uncertainties in the values increase very significantly. For example, Table 10 (Supplementary material) gives values for the Main Engine's Load Factors ranging from 50 to 59.3% in the normal cruising operating mode: the Load Factor does not reach 65%. In the case of manoeuvring, values are between 8.9 and 9.3%, not coming close to 20% which is taken as the average value when the vessel is in the manoeuvring situation. These examples give a measure of the importance of try to get as close as possible to reality, and not resort to using average values. In the case of SFOC, the values defined in the Smith et al. (2014) (0.215 g/kWh) were practically the same as those employed in the present study. In this case, the SFOC (Table 10) was calculated by applying Eqs. (6) and (7), based on 0.213 g/kWh and 0.210 g/kWh for HFO and MDO values respectively. It can be seen that these values are variable depending on the load. The Load Factor values were calculated based on the actual ship speed.

It can be seen from the above that the results for each pollutant and each method shown in the tables and figures could vary significantly if the mean values defined in the Smith et al. (2014) were employed.

Tables 3 and 4 show the results for Main and Auxiliary Engines total emissions (kg) for each of the pollutants studied and for each of the methods, including the proposed method.

Table 3
Method proposed: Emissions (total and by operating mode) by Main Engines (kg) for each pollutant studied.

Mode	CO_2	CO	SO_X	NO_X	PM_{10}	$PM_{2.5}$
Cruising	3771	8.62	65.60	113.1	9.372	9.12
Speed reduction	238	0.56	4.10	7.06	0.57	0.57
Manoeuvring	621.14	1.4	10.8	18.6	1.44	1.5
Arrival	18.6	0.26	0.32	1.57	0.197	0.19
Departure	22.86	0.266	0.397	1.54	0.18	0.17
At Berth	–	–	–	–	–	–
Total	4671.6	11.106	81.217	141.87	11.759	11.55

*Sample size: 160.

Table 4
Method proposed: emissions (total and by operating mode) by auxiliary engines (kg) for each pollutant studied (same as IMO method).

Mode		CO_2	CO	SO_X	NO_X	PM_{10}	$PM_{2,5}$
Cruising (HFO)		285.7	0.45	5	5.97	0.61	0.6
Speed reduction (HFO)		35.13	0.055	0.615	0.735	0.075	35.13
Manoeuvring	MDO	163.68	0.272	0.54	3.44	0.094	0.086
	HFO	173.88	0.26	3.04	3.64	0.37	0.36
Arrival	MDO	31.7	0.052	0.1	0.66	0.018	0.016
	HFO	33.67	0.052	0.59	0.7	0.072	0.069
Departure	MDO	30.88	0.051	0.1	0.65	0.017	0.016
	HFO	32.81	0.05	0.57	0.68	0.07	0.068
At berth (MDO)		413.37	0.68	1.37	8.68	0.23	0.21
Total		1200.82	1.922	11.925	25.155	1.556	1.498

*Sample size: 160.

Table 5
Specific fuel oil consumption by auxiliary engines (g/kWh), by operating mode, from each of the four previous methods analysed.

Mode	Auxiliary engines specific fuel oil consumption (g/kWh)							
	IMO		EPA		MAN		Jalkanen	
	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO
Cruising		248		210		210		248
SRZ		248		210		210		248
Manoeuvring	224	221	213	210	213	210	224	221
Arrival at berth	224	221	213	210	213	210	224	221
Depart. from berth	224	221	213	210	213	210	224	221
At berth		213.7		210		210		213.7

Tables 5 and 6 show the specific fuel oil consumption and the energy consumption respectively for the AE, based on the LF (average values) for each mode.:

- Cruising and RSZ modes (HFO): 15% of maximum continuous rating (MCR).
- Manoeuvring, arrival and departure modes (MDO and HFO): 45% of MCR.
- At berth (MDO): 60% of MCR.

The difference between the results of the different methods is because the Smith et al. (2014) and Jalkanen et al. (2009) methods use Eqs. (6) and (7), while the EPA (2000) and MAN Diesel and Turbo (2012) methods use constant values for the SFOC.

Because the EFs have the same values for all methods, the results maintain the same relationship between Delivered Power and Energy Consumption. Table 7 shows the total Energy Consumption by Main and Auxiliary Engines. The results shown in this table could be substantially different if mean values had been used.

Tables 8 and 9 (Supplementary material) show the results of the studies, carried out by Goldsworthy and Galbally (2011), that define the EF values based on studies referenced in other articles (David Segersson, 2013). Since most previous authors have taken the SFOC as a constant value, and since the ship speed is taken from AIS data (with its inevitable uncertainties), it can be deduced that the calculation procedure proposed is more exact than other calculation methods using constant SFOC and Load factors.

Table 10 (supplementary material) show the Specific Fuel Oil Consumption obtained by applying the equations from each of the five methods analysed for Main Engines.

Table 11(supplementary material) shows results from Eqs. (1)–(5), depending on the method applied. The biggest differences are seen in Cruising and RSZ modes. The lowest values correspond to the MAN and proposed methods, to which the same reasoning as for Table 6 can be applied.

Table 6
Energy consumption (kg of fuel) by auxiliary engines, by operating mode, from each of the four previous methods analysed.

Energy consumption by auxiliary engines (kg of fuel)					
MODE		IMO	EPA	MAN	Jalkanen
Cruising		96.85	81.82	81.82	96.85
SRZ		12,6	10,64	10,64	12,6
Manoeuvring	MDO	54,7	51,96	51,96	54,7
	HFO	55.48	52,7	52,7	55.48
Arrival berth	MDO	10.59	10.06	10.06	10.59
	HFO	10.74	10.20	10.20	10.74
Departure berth	MDO	10.32	9.80	9.80	10.32
	HFO	10.47	9.94	9.94	10.47
At berth, MDO (0.6 LF)		131.25	131.25	131.25	131.25
Total		337.52	368.37	368.37	337.52

*Sample size: 160.

Table 7
Total energy consumption (by main and auxiliary engines), by operating mode, from each of the five methods analysed.

Total energy consumption (kg of fuel)						
Mode		IMO	EPA	MAN	Jalkanen	Proposed method
Cruising		1394.35	1452.87	1348.73	1403.1	1366.75
SRZ		95.068	92.834	73.38	116.44	105.68
Manoeuvring	MDO	54.7	51.96	51.96	54.7	54.7
	HFO	169.6	156.06	123.26	172.02	169.6
Arrival berth	MDO	10,59	10,06	10,06	10,59	10.59
	HFO	18.32	16.23	16.23	18.32	18.32
Departure berth	MDO	10.32	9.8	9.8	10.32	10.32
	HFO	19.72	17.32	17.32	19.72	19.72
At berth, MDO (0.6 LF)		131.25	131.25	131.25	131.25	131.25
Total		1903.918	1938.384	1781.99	1936.46	1886.93

*Sample size: 160.

It can be seen that the ME power values on arrival in port and departure are consistent for all the methods. This is because constant LF values were used. However, these ME power values vary depending on which method is applied. In this case, the MAN method gives the lowest value. This is because the exponent $n = 3.5$ was used while the other methods used $n = 3$.

The proposed method shows the lowest value for cruising mode and this value is very similar to that used in the MAN model for total ME power. The small difference between the MAN Diesel and Turbo (2012) and the proposed methods may arise because the MAN Diesel and Turbo (2012) method does not take into account draught or propulsion efficiency (which depends on weather and fouling). The same reasoning can be used regarding the calculation of Energy Consumption. Figs. 1 and 2 show the results from Table 11.

Tables 12 to 19 (Supplementary material) show the results for Main and Auxiliary Engines total emissions (kg) for each of the pollutants studied and for each of the methods, including the proposed method Tables 20 and 21 show the Statistical analysis of ME and AE energy consumption and emissions, respectively.

Only the AEs use MDO fuel, and MDO is consumed during approximately 44% of the trip time. The rest of the time (56%), HFO fuel is used. Graph 5 shows the comparison between emissions from the two fuels. Even though there is only a minimal difference in the periods of time when each fuel is used, the emissions of SOx, PM_{10} and $PM_{2.5}$ are up to 400% higher when HFO is used (Figs. 3–5).

Currently, there are uncertainties in bottom-up calculations of energy use and emissions by the world fleet of ships. These uncertainties can affect the totals, the distributions among vessel categories and also the allocation of emissions between international and domestic shipping. One of this study's most important contributions to reducing uncertainty is the explicit quality control applied by calculating fuel use and emissions based on the vessel-specific on-board data (daily Noon Reports). This is superior to the calculation methods described in previous studies, which use average technical parameters. Another important contribution to the reduction of uncertainty is the direct observation of activity data for each individual vessel (i.e. speed, draught, etc.), aggregated per trip.

Other studies (Jalkanen et al., 2009; Smith et al., 2014 and Durán-Grados et al., 2018) have estimated greater uncertainty from the bottom-up method for previous years (2007, 2008 and 2009), with the difference between these uncertainty estimates being attributable predominantly to the change in AIS coverage over the period studied. In the proposed method the speed of the ship, distance travelled and time spent in each operating mode are measured and recorded onboard in real time; therefore the uncertainties arising from the use of the AIS system are also eliminated.

Another important contribution of this paper is that the analysis of the ME load factor, specific fuel oil consumption and emission factors

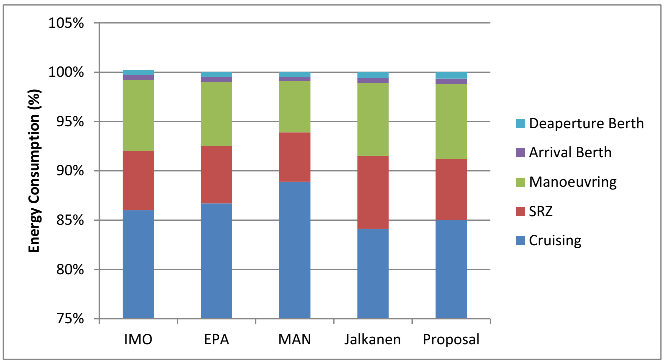

Fig. 1. Energy consumption by Main Engines, from each of the five methods: proportion of total accounted for by each operating mode (percent). Correction: Departure from berth, Arrival at berth.

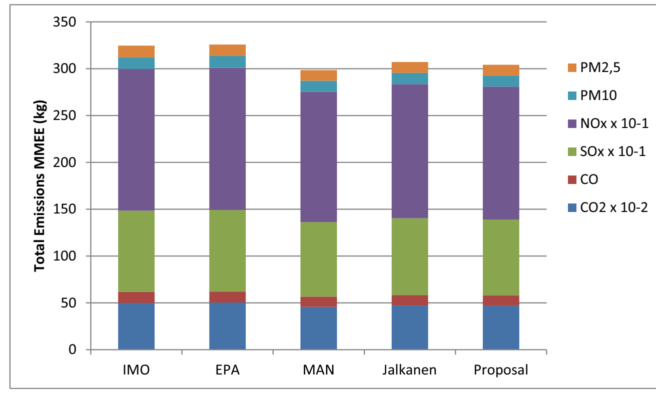

Fig. 3. Total emissions (kg) by Main Engines, from each of the methods analysed: proportion of total accounted for by each pollutant studied (percent).

is applicable to any type of ship. In this case study, they were applied to an actual Ro-Pax ship, whereas in previous studies these were taken as constant values. In this study it has been demonstrated that all these factors need to be taken into consideration as variables. We have also used the new IMO equation (Eq. (5)) for the calculation of the actual ME power, including three new parameters: displacement and propulsion efficiency (according to both weather and fouling conditions).

It can be seen that the results from the EPA and Jalkanen et al. (2009) methods are very similar but the results obtained by applying the proposed method should be considered as the closest to the true values.

In the first inventories produced, by the EPA (2000) and Smith et al. (2014) methods, the ME LF was like a third power relation between speed at 100% MCR and transient speed. The SFOC and EF were considered to be constant values, dependent only on the fuel type. Later, Jalkanen et al. (2009) added 0.5 knots to take into account the new safe transient speed value; and he applied a new model for calculating the SFOC as a variable value depending on the Engine Load. Then MAN Diesel and Turbo (2012) proposed different speed-power relation values for Load Factor calculations, depending on the type of ship. Lastly, the Smith et al. (2014) introduced three new factors that take into account the definition of the M.E power transient: displacement and propulsion efficiency allowing for both actual weather and the vessel's fouling condition. However, neither Jalkanen's safe speed value nor the different speed-power relation values proposed by MAN Diesel and Turbo (2012) were taken into account.

A new method that takes all the aforementioned parameters into account has been proposed here, thus producing a single equation that defines the transient Power.

The results from the method proposed in this paper are nearer to those of the IMO method than those of the MAN Diesel and Turbo (2012) method. This is because the effects of displacement and propulsion efficiency seem to be more important than the effects of the exponent of the relationship between speed and power.

Moreover, the substitution of this exponent ($n = 3$) from the Smith et al. (2014) equation for any of those proposed by MAN Diesel and Turbo (2012) ($n = 3.5$ for a Ro-Pax ship, in this case) is another very important contribution from this study. From the results of its application, it can be seen that, for the same ship speed as delivered by the engines, there are different values for load factors and power because these depend on draught, weather and fouling.

The results from the MAN Diesel and Turbo (2012) method are the lowest, mainly in the Manoeuvring and Cruising modes, and this is caused by the exponent (n) value being different from the value used in the other methods. The Jalkanen et al. (2009) method presents the highest values and this is caused by applying the safety speed coefficient.

Nevertheless, using the calculation procedures of any of the five methods analysed here, the energy consumption and emissions produced could be calculated for each of the ship operation phases. Based on this data, a simple and feasible algorithm could be introduced by operators in each ship and it could be used for estimating the two top priority control parameters on specific voyages: fuel consumption and emissions.

When using the EPA (2000) model, it can be seen that the load factors are from 50.6% (15.3 knots, 1154.5 kg of fuel/h) to 93.88% (18.8 knots, 2257.43 kg of fuel/h), for the ship operating in cruise

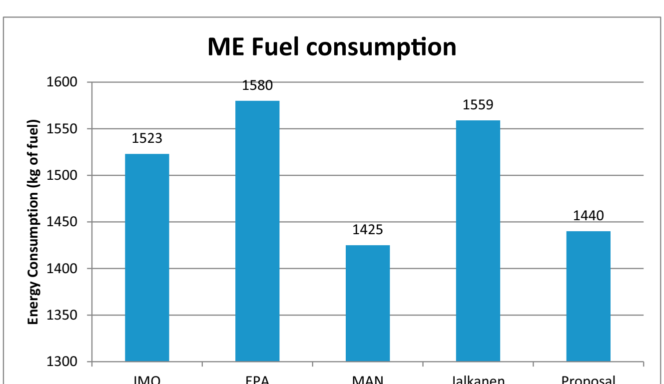

Fig. 2. Energy consumption by Main Engine (kg of fuel), from each of the five methods, for all operating modes.

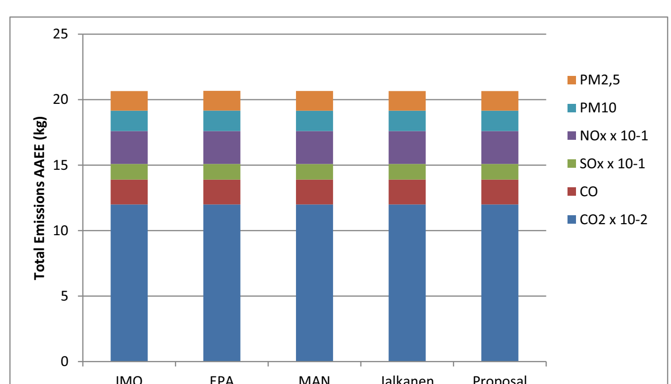

Fig. 4. Total emissions (kg) by Auxiliary Engines, from each of the methods analysed: proportion of total accounted for by each pollutant studied (percent).

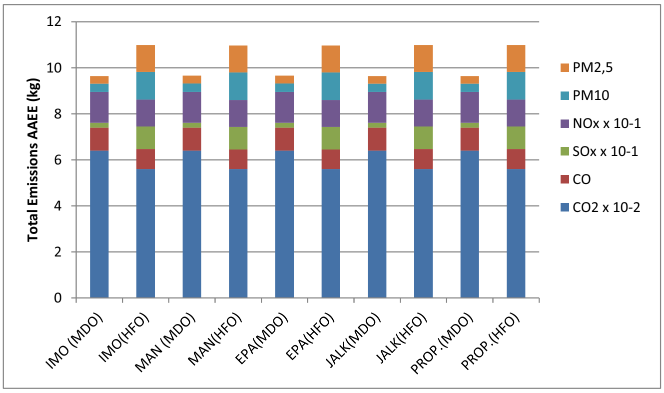

Fig. 5. Total emissions (kg) AE per pollutant and method studied and fuel used.

mode. When the speed is reduced by 3.5 knots, the ME fuel consumption is reduced by up to 50%. For the same case, when using the MAN Diesel and Turbo (2012), IMO and Jalkanen et al. (2009) models, the ME fuel consumption reductions are 46, 43 and 44% respectively. Hence, the data can be utilized and updated daily, instead of estimating a trip's fuel consumption using data from sea trials when the MEs are checked.

Finally, the presentation in this paper of the improved method proposed represents an opportunity for each ship operator to test it on their own fleet.

4. Conclusions

Where fuel economy, cost efficiency and environmental responsibility are top priorities, making the correct decision on the method for measuring ship performance is extremely important. Given that ship operators have considerable information about ship performance from the daily reports, the application of any of the alternative methods should be easy for their respective companies. Based on this comparison of the four existing methods, the authors have proposed a new method combining the best of each. The new method is illustrated for a particular case but is suitable for any ship operator to test on their own fleet.

The range of variation between each method found in the estimation of total energy consumption and emissions of all types of pollutants is from 9% to 10%. In the Smith et al. (2014), the most important sources of uncertainty are attributable to incomplete AIS coverage of a ship's activity and the discrepancies between the number of ships observed in the AIS data and the number of ships described as “in service” in the IHSF database. These sources are not used when this method is applied; hence the uncertainties are practically non-existent compared to those inherent in previous studies, in which AIS data were generally used.

Given that distance, time and speed in service have been taken into account in this study, the application in itself of any of the analysed methods does not reduce fuel use or improve efficiency. However, obtaining reliable and timely data should be the first step to implementing operational and/or technical measures with a view to controlling emissions of pollutants, in order to contribute reliable data to a database for monitoring the emission of greenhouse gases by all ships on international routes.

By applying any of these methods, but particularly the method proposed by the authors, the energy consumption and emissions produced for each operational phase of the ship can be calculated in real time by its operator. This data would give operators better control, and improve management of the energy used on board their ships.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.09.045.

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