Science of the Total Environment 650 (2019) 575–584

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

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

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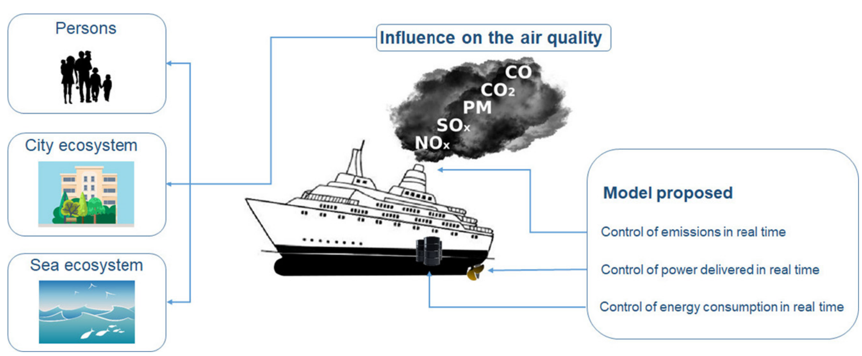
## HIGHLIGHTS

- 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




## ARTICLE INFO

*Article history:*
Received 21 July 2018
Received in revised form 3 September 2018
Accepted 3 September 2018
Available online 05 September 2018

Editor: D. Barcelo

## 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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https://doi.org/10.1016/j.scitotenv.2018.09.045

*Keywords:*
Shipping energy
Shipping emissions
Ro-Pax
Ship energy load factors
Emission factors

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