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Development of a tool for calculating ship air emissions

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Abstract This paper describes the development of a ship air emissions calculator, which will be part of the ECOMARPOL platform of the Intelligent Research Infrastructure for Shipping, Supply Chain, Transport and Logistics (EN.I.R.I.S.S.T.). The tool developed with the Python programming language and is based on a variant of the Bottom-up method. The input parameters are the main particulars of one or more ships and produces results in the form of tables and diagrams for the analysis of ship air emissions by ship type, emission type, speed and age. The tool may be used for different vessels and calculates air emissions including: carbon dioxide (CO_2), sulphur oxides (SOx), nitrogen oxides (NOx) and particulate matter (PM). Furthermore, this paper presents two illustrative applications that showcases the potential of the developed tool. The first one used departure and arrival data of 100 ships within the European Economic Area (EEA) in 2018, while for the second, Automatic Identification System (AIS) movement data of a Bulk Carrier in the Baltic Sea for 24 hours were collected. The development of such tools is considered important as they can contribute to establish appropriate measures for reducing air emissions and help the shipping industry to comply with existing regulations.
Keywords: Ship air emissions; Bottom-up method; Emissions calculator; Sensitivity analysis; Environmental impact of shipping

1. Introduction

The shipping industry is under considerable pressure to reduce air emissions and contribute to global efforts against climate change. There are two categories of ship air emissions, Greenhouse gases, mainly Carbon Dioxide (CO2), and atmospheric pollutants, mainly Sulphur Oxides (SOx), Nitrogen Oxides (NOx) and Particulate Matter (PM). Measures to limit ship air emissions have been taken by the International Maritime Organization (IMO) with the adoption of MARPOL Annex VI. In addition, the European Union has adopted the MRV Regulation (European Commission, 2020), a legislation to monitor, report and verify CO_2 emissions. Following EU MRV, IMO adopted Data collection system for fuel oil consumption of ships (IMO DCS). Digital computing tools can contribute to that effort of measuring and monitoring ship air emissions, providing material for research activities and supporting decision-making. This paper describes the development of a ship air emissions calculator which will be part of the ECOMARPOL platform of the Intelligent Research Infrastructure for Shipping, Supply Chain, Transport and Logistics (EN.I.R.I.S.S.T.) - an innovative digital infrastructure for research in the maritime, supply chain, and transport domains in Greece. This tool has been developed with the Python programming language and takes as input the main particulars of one or more ships and produces results in the form of tables and diagrams for the analysis of ship air emissions. The tool may be used for Bulk Carriers, Tankers, Containerships, Ro-Ro vessels and calculates the following air emissions: CO_2, SOx, NOx and PM. The rest of the paper is structured as follows. Section 2 describes the methodology for calculating ship air emissions on which the calculator is based. Section 3 presents the results of a sensitivity analysis. Section 4 presents the results of two illustrative applications of the emissions calculator. Section 5 summarizes the conclusions of this paper.

2. Estimating Shipping Emissions Methodology

The first step to develop the ship air emissions calculator was the choice of the appropriate method for calculations. There are two basic methods, the top-down and bottom-up (or activity-based). The most suitable for the purposes of the developed calculator is the bottom-up method, because it takes into account the particulars of a single ship (Ventikos, Stamatopoulou et al., 2019). Applying this method for a number of ships can give the emissions for a fleet or an entire geographic area (Miola, Ciuffo 2011). In this paper a combination of the IMO and MAN variants of the bottom-up method is used, as proposed in a study by Moreno-Gutierez et al. (2018). The mathematical formula used in the bottom-up method, as expressed in various studies (Bilgili & Celebi, 2018; IMO, 2014; Nunes, Alvim-Ferraz, Martins & Sousa, 2017), is shown in Eq.1:

$$E = T \cdot [\, ME \cdot LF \cdot EF \,] \quad \text{Eq. 1}$$

Where,

E: emissions [kg]

T: total time at sea [h]

ME: the maximum continuous power of the main engine [kW]

LF: Load Factor, the ratio of actual power (Ptr) to rated power (P1) of the main engine (LF=Ptr/P1)

EF: Emission Factor [kg/kWh]

The IMO formula for calculating the load factor (LF) is shown in Eq.2:

$$LF = \frac{(\frac{t_{tr}}{t_1})^{\frac{2}{3}} \cdot (\frac{v_{tr}}{v_1})^n}{n_w \cdot n_f} \quad \text{Eq. 2}$$

Where,

t_{tr}: actual draft

t_1: design draft

v_{tr}: actual speed

V_1: service speed

nw: weather factor

nf: fouling factor

n: constant for power-speed relationship

In the IMO approach, n is constant (n=3) for all ship types, while MAN proposes different values for n according to the ship type. Thus, the IMO formula is modified to consider the following values: n=3.2 for Bulk Carriers and Tankers, n=3.5 for Ro-Ro, n=4 for Containerships (Moreno-Gutierez et al., 2018).

The Emission Factor (EF) is expressed in g pollutant/g fuel and depends on engine and fuel type. EF, which is different for each emission type, is taken from tables (IMO, 2014) and then multiplied by SFOC (Specific Fuel Oil Consumption). In addition, according to the IMO approach, SFOC is also taken from tables (IMO, 2014) and then the correction shown in Eq. 3 is applied:

$$SFOCreal = (0.455 \cdot LF2 - 0.71 \cdot LF + 1.28) \cdot SFOCbase \quad \text{Eq. 3}$$

The Weather factor (nw) quantifies the added resistance in waves and the wind resistance and is defined as nw= 1/1.15 (IMO, 2014).

The Fouling factor (nf) aims to quantify the increase in hull's frictional resistance due to fouling and is defined in Eq. 4 (ICCT, 2017):

$$n_f = 1.02 + [0.044\{(\frac{k2}{L_{BP}})^{1/3} - (\frac{k1}{L_{BP}})^{1/3}\}] / (0.018 \cdot L_{BP}^{-1/3}) \quad \text{Eq. 4}$$

Where,

L_{BP}: length between perpendiculars

k1: initial roughness of a new ship (120 μm)

k2: final hull roughness, depending on ship age (ICCT, 2017

3. Sensitivity Analysis

The following is a brief description of how the emissions calculator works. At first, the emissions calculator reads a file with the following main particulars of one or more ships: ship name, ship type, DWT (or TEU), design draft, service speed, power, fuel type, rpm, total time at sea, total distance, actual speed, actual draft, length between perpendiculars (LBP), and ship age. If one or more particulars are not available, then the calculator will try to fill in the missing values by using available regression formulas and produce a result. For example, length may be inferred from available DWT by ship type and ship type may be inferred from available statistics for a specific geographic region. In this case, the uncertainty that is introduced by the predicted values is considered appropriately for the final output. Finally, using the calculation method described in Section 2, the calculator gives as output tables and diagrams for the analysis of ship air emissions by ship type, emission type, speed and age.

Sensitivity analysis is a procedure to show how variations in input parameters affect emissions calculator results and helps to identify the most critical one. In addition, this analysis can confirm that the emissions calculator works properly, verifying its results are in agreement with the physical interpretation of ship air emissions problem. According to the method described in Section 2, the parameters that can vary during ship operation and are examined here are actual speed, actual draft, weather factor and fouling factor. For this analysis, the particulars of a Bulk Carrier that moved within EEA in 2018 were collected and the annual CO2 emissions were calculated. Speed moved in ± 1 kn from nominal value range, draft in ± 2 m from nominal value range and weather and fouling factors moved according to IMO limits (IMO, 2014). The results are presented in the following tornado chart (Figure 1).

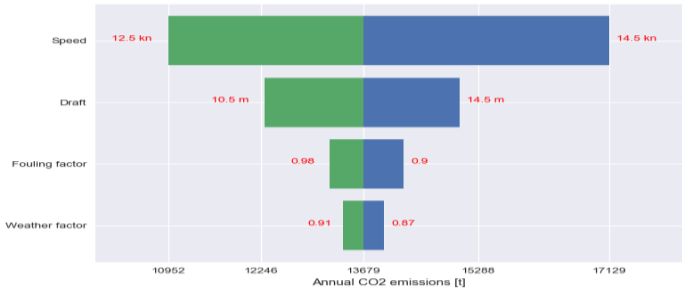

Figure 1. Sensitivity analysis - Tornado chart

As Figure 1 shows, ship speed has the greatest impact on calculator results. This was expected as higher speeds demand higher fuel consumption which leads to air emissions increase. The second parameter that affects most the results is draft. This was again expected as greater draft increases the wetted surface area of the hull which increases the resistance and leads to increased power demand. Finally, fouling factor and weather factor have less impact on ship air emissions.

4. Application & Results

This section presents the results of two applications that illustrate the functionality of the developed ship air emissions calculator. The first one used departure and arrival data of 100 ships within the European Economic Area (EEA) in 2018. Specifically, 25 Bulk Carriers, 25 Tankers, 25 Containerships and 25 Ro-Ro vessels participated in this application. Actual speed and draft were not available, so values were inferred with a process similar to the one described in Section 3. For the second, Automatic Identification System (AIS) movement data of a Bulk Carrier in the Baltic Sea for 24 hours were collected. For this application every input parameter was available. Its purpose is to highlight the capability of this tool to use real time data from AIS to calculate ship air emissions. A sample of the analysis that emission calculator can provide follows. Figure 2 shows the analysis of ship air emissions by ship type in the first application.

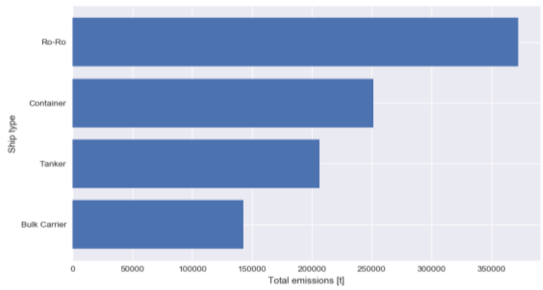

Figure 2. Total CO_2 Emissions per ship type

The majority of annual total air emissions came from Ro-Ro vessels, while Containerships and Tankers follow in air emissions production. Bulk Carrier seems to be the most environmentally friendly ship type. The conclusions about Containerships, Tankers and Bulk Carriers are in agreement with the corresponding results of EU MRV (European Commission, 2020). On the other hand, in EU MRV results Ro-Ro vessels appear to be less polluting than the other three ship types. This is because there is a small number of them travelling within EEA, representing almost 2% of the fleet, while in this application Ro-Ro vessels represent 25% of the sample. Both applications led to same conclusions about analysis by emissions type. Table 1 shows the results of the second application.

Table 1. Emissions per category

Emissions type	Emissions [t]
CO_2	83.94
SOx	1.43
NOx	2.09
PM	0.20

Almost 96 % of ship air emissions were CO2 and the other 4 % was represented by pollutants, namely SOx, NOx and PM. In addition, NOx is the pollutant that was produced the most, followed by SOx. PM is the pollutant that was produced less. Other studies lead to similar conclusions regarding the emission types (IMO, 2014; ICCT, 2017). Figure 3 depicts the percentage share of pollutants for the Bulk Carrier in second application.
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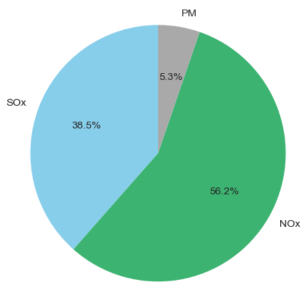

Figure 3. Share of different air pollutants

5. Conclusions

This paper describes the development of a tool for calculating ship air emissions, which is based on a variant of the bottom-up method (Moreno-Gutierrez et al., 2018). Specifically, the variant uses the IMO formula for calculating the Load Factor (LF), modified to consider different n values for each ship type as MAN proposes. The emissions calculator, which was developed with the Python programming language, takes as input the main particulars of one or more ships and produces results in the form of tables and diagrams for the analysis of ship air emissions by ship type, emission type, speed and age. Sensitivity analysis showed that the most critical parameter for calculating ship air emissions is speed. The second more effective one is draft and then fouling factor and weather factor follow with less effect on results.
An application of the calculator, using departure and arrival data of 100 ships within EEA in 2018, showed that most annual air emissions came from Ro-Ro vessels, followed by Containerships and Tankers. Bulk Carrier

appears to be the most environmentally friendly ship type. The same application and another one using AIS movement data of a Bulk Carrier in the Baltic Sea for 24 hours, showed that the vast majority of ship air emissions were CO2, while almost about 4 % was represented by pollutants, namely SOx, NOx and PM. In addition, both applications showed that NOx and then SOx are the pollutants that were produced more, while there was a small production of PM.
The focus of this work is limited in the estimation of ship air emissions and the analysis of results with tables and diagrams. The next step for this calculator would be the study of the dispersion of ship air emissions and the corresponding geographical visualization. In addition, the emissions calculator would be modified to have direct connection with real time data and could also be expanded to be used for more ship types. Finally, the capability of filling in missing data would be significantly expanded and the corresponding uncertainty would be included in the results and visualizations.

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