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Emission Evaluation of Marine Traffic

Jingwen Qi[1][0000-0003-1838-9061], Shuaian Wang[2][0000-0001-9247-4403] and Xiaobo Qu[3][0000-0003-0973-3756]

[1] The Hong Kong Polytechnic University, Hung Hom Kowloon Hong Kong, 999077, China,
`jingwen.qi@connect.polyu.hk`
[1] The Hong Kong Polytechnic University, Hung Hom Kowloon Hong Kong, 999077, China,
`hans.wang@connect.polyu.hk`
[2] Department of Architecture and Civil Engineering, Chalmers University of Technology,
Gothenburg, Sweden,
`xiaobo@chalmers.se`

Abstract. Air pollution is an issue that has been widespread concern in all sectors of society. The pollutants, including toxic gases, greenhouse gases and particulate matters, have permeated every aspect of our daily life and have a negative impact on human health, agriculture, industry, and climate change. Found by hard and thorough search, the human activities account for the majority and the transport sector is one of the most challenging areas, when it comes to abatement of local air pollution. Marine traffic, which covers over 80% of international trade, is mainly powered by cheap fuel oil with high impurities, so it will affect the social welfare of the coastal areas. Various measures that can be adopted to alleviate the problem to customize suitable regulations through research of the emission from shipping should be conducted. Also, the emission evaluation is critical to measure the efficiency of the regulation. Therefore, following the main steps of Ship Traffic Emissions Assessment Model, we summarize an activity-based framework of shipping emission evaluation that takes advantage of data from Automatic Identification System.

Keywords: Emission evaluation, Activity-based method, AIS data.

1 Introduction

Atmospheric pollution has always attracted the attention of international community. The main pollutants include sulfur oxides, carbon hydride, carbon oxides, nitrogen oxides and particulate. These pollutants have adverse influence on many aspects such as human health, agriculture, industry, and climate change. The transport sector is one of the most challenging areas, when it comes to abatement of local air pollution. Marine traffic, which covers over 80% of the cargo volume of international trade (Qu and Meng, 2012; UNCTAD, 2017), has become an important contributing factor because the large capacity vessels tend to use cheap fuel oil with high level of impurities. According to the greenhouse gas studies conducted by the international maritime organization in 2009 and 2014, exhaust emissions from shipping industry make up 15% nitrogen oxides, 13% Sulphur dioxide and 2.7% carbon dioxide of global anthropogenic emission. Statistics shows that near 70% of the maritime emissions occur near port areas. And the coastal cities are always densely-populated and highly-developed. So, although the proportions are not astonishing, the threats of maritime emissions are not to be neglected. Different measures have been taken to reduce the marine traffic emission and mitigate the bad influence it may bring. The measures in different areas should be customized according to the situation and the efficiency of the measures need to be calculated, so the work of emission evaluation is of great importance. In this paper, we summarize a framework of marine traffic exhaust emission evaluation.

For exhaust emission evaluation, the common methods can be divided into two types, fuel-based and movement-based approaches. A fuel-based approach evaluates exhaust emission of ships mainly with the fuel oil consumption data and makes little use of ship activities and movement information. When the fuel consumption details are available, namely the volume of fuel oil that has been consumed is already known, the emission volume can be easily calculated by multiplying the fuel usage and emission factor (emission volume exhausted by consuming unit mass fuel). Because of the simplicity of the input data and calculating process, this type of method requires computer hardware of lower function, but the results are rather rough. Therefore, fuel-based methods are used in few researches to estimate emissions for different countries and regions (Kesgin and Vardar, 2001; Endresen et al., 2005; Hulskotte and Denier, 2010).

However detailed fuel consumption data are difficult to obtain since the information is private to shipping companies, in other words, it is not known how much fuel oil has been used in a certain period. In fact, shipping companies are more interested in the average daily fuel usage or the mass of fuel oil consumed in a whole sailing route. This is not accurate enough to depict the distribution of marine traffic emissions. Instead, the more accessible location data with shorter time intervals can be used to calculate the consumed fuel amount, which is necessary for the exhaust emissions determination. So the other type of method, movement-based method, which takes advantage of ship movement data and information about the ship and its engine, is adopted in this paper. A movement-based approach firstly estimates the real-time fuel oil consumption rate according to the sailing speed inferred from the location data and technical details about the ship. Then the emission volume is calculated on the basis of fuel oil amount that has been used. In practical terms, ships keep moving and the sailing speed is varying, as a result, the fuel oil consumption rate changes with time. So, compared with the fuel-based method, movement-based method can yield more accurate results in a short period. On the whole, a movement-based method requires a wide collection of data but is able to yield more precise results and at the same time match the emission at a certain timing node with the location where it was exhausted. With the development of computing power, movement-based methods are extensively adopted by research papers as well as technical reports (Johansson et al., 2013; Marelle et al., 2016; Sofiev et al., 2018; Schrooten et al., 2008; Cooper and Gustafsson, 2004; Ng et al., 2012; Ng et al., 2016).

Existing researches about shipping emission evaluation can be divided into two types, academic papers and technical reports. Academic papers tend to put strength on the evaluation methods (Kesgin and Vardar, 2001; Endresen et al., 2005; Hulskotte and Denier, 2010; Johansson et al., 2013; Marelle et al., 2016; Schrooten et al., 2008); they focus on the approach but usually make rough assumptions about the parameters. As a result, evaluation results of high precision requirements cannot be obtained by simply applying methods from papers. Meanwhile, technical reports (Starcrest Consulting Group, 2018; Ng et al., 2012; Ng et al., 2016; IMO, 1997, 2009, 2014), which are always conducted as a commission from government organizations or supported by them, have access to abundant and detailed data for the evaluation work. However, the approaches they use are more straightforward. At the same time, due to the various main purposes and databases, data of reports differs in level of detail and structure. Therefore, the data cannot be borrowed directly to use in a research. In order to find a scheme that is both operative and comparatively precise, this paper combines the method with data; reconciles them and summarizes an activity-based framework of shipping emission evaluation that takes advantage of data from Automatic Identification System and Ship Traffic Emissions Assessment Model.

2 Framework Description and Data Sources

The emission evaluation follows the main steps of Ship Traffic Emissions Assessment Model (STEAM), meanwhile some parameters and technical details are obtained from a number of authoritative reports, such as those conducted by the IMO (1997, 2009, 2014) and two reports led by Ng et al. (2012, 2016) with the help of the Marine Department and the Environmental Protection Department of the Hong Kong Special Administrative Region Government. STEAM is originally proposed by Jalkanen et al. (2009) which has been used in a lot of emission evaluation works (Jonson et al., 2015; Smith et al., 2014; Johansson et al., 2013; Marelle et al.,2016; Sofievet al.,2018) after that. However, different from the original model, this paper does not take the performance penalty due to waves into consideration because of the absence of detailed historical data about sea waves. Also, from another aspect, the influence of waves for ships sailing in different areas along different directions can offset each other.

The input data of the calculation includes two types of information, properties of ships, as shown in Table 1, and vessel movement data.

Table 1. Input data regarding ships' property.

Property types	Description
Physical Properties	Ship type Design speed v_{design} (knot)
Engine Properties	Engine speed of main and auxiliary engines Total installed power of main engine $p^{\text{M}}_{\text{installed}}$ (kw)
Fuel Properties	Fuel type used by the main and auxiliary engines $FuelT_{\text{M}}$, $FuelT_{\text{A}}$ Sulphur content of different fuels SC_{λ} (mass%), $\lambda \in \{\text{HFO,MGO/MDO}\}$

HFO = heavy fuel oil; MDO = marine diesel oil; MGO = marine gas oil.

The sailing trajectory and speed of a ship can be deduced from its coordinate at different times. For simplicity, transient speed is substituted with the average speed of a short period and the ship is assumed to sail in straight-line during the period. The shorter the data time interval, the more precise the trajectory and speed. Coordinates are sorted into hours to balance between the accuracy and the data processing time.

3 Evaluation Steps

Based on location and time information extracted from the Automatic Identification System (AIS) and technical information about ships, the mass of SO_x, NO_x, CO_2 and PM emitted by ships can be positioned with a high spatial resolution. Before calculating emissions, the marine area is split by a grid, each square denotes a small area.

We calculate the exhaust emission on a horizon which is equally divided into multiple time periods. Each period is defined by two timing nodes, e.g. the i^{th} period is defined by the i^{th} and $i+1^{\text{th}}$ timing node. For each timing node, ship location information is given in the form of coordinate (x^i,y^i), more concretely x^i and $y^i$are the longitude and latitude of the ship's location at the i^{th} timing node respectively. In the evaluation process of this paper, east longitude and north latitude are set to be positive, naturally, the west longitude and south latitude are set to be negative. Given the coordinate data and technical parameters of the ship, the main steps to figure a ship's emission of NO_x, SO_x, CO_2, PM in the ith period are as follows.

Step1: Obtain the ship's coordinate data at the $i^{\text{th}}$and $i+1^{\text{th}}$timing node(x^i,y^i), (x^{i+1},y^{i+1}).

Step2: Obtain the sailing distance d^i (knot) and calculate the sailing speed v^i (knot)over the i^{th} period, using the equations:

$$d^i = R \times \cos^{-1}[\cos y^i \times \cos y^{i+1} \cos(x^i - x^{i+1}) + \sin y^i \times \sin y^{i+1}] \div 1.852 \tag{1}$$

$$v^i = d^i \div T_{\text{interval}} \tag{2}$$

where R (km)is the radius of the earth and $T_{\text{interval}}$is the span of the period in hours. Equation (1) is the spherical distance formula between two nodes, the constant 1.852 in equation (2) is used to convert the distance into nautical miles. Decide the ship operating mode according to v^i (knot).

$$\text{Operating mode} = \begin{cases} \text{cruise,} & v^i > 12 \\ \text{slow cruise,} & 12 \geq v^i > 8 \\ \text{maneuvering,} & 8 \geq v^i > 1 \\ \text{hotelling,} & 1 \geq v^i \end{cases} \tag{3}$$

Step 3: Calculate the transient power of the main engine p_{M}^i (kw), which can be evaluated as a function of v^i:

$$p_{\text{M}}^i = (\frac{v^i}{v_{\text{design}}})^3 \times \varepsilon_{\text{p}} \times p_{\text{installed}}^{\text{M}} \tag{4}$$

wherev_{design} is the design speed, and the coefficient ε_{p} is assumed to be equal to 0.8 since the maximum power of the main engine is normally 80% of the installed power.

Step 4: Determine the transient power of the auxiliary engine. Information of auxiliary engine's power is not provided, so the data for different vessel types under each operating mode provided by the report conducted by Starcrest Consulting Group (2018) for the Port of Los Angeles are put to use. For cruise, tanker and container ships, the value is related to vessel capacity as shown in Table 2 to 4. Considering the technical advancement and improvement of mechanical efficiency on board, the auxiliary engine load is not strictly proportional to the vessel capacity, especially for vary large container ships that are built recently. Power of auxiliary boiler has been included.

Table 2. Auxiliary engine load (p_{A}^{i}) for container ships(kw)

Capacity (TEU)	Operating mode		
	Cruise/Slow cruise	Maneuvering	Hotelling
0–1,999	1,122	2,462	1,396
2,000–2,999	766	2,391	936
3,000–3,999	1,629	2,897	1,638
4,000–4,999	2,058	3,766	1,524
5,000–5,999	1,635	2,764	1,605
6,000–6,999	1,366	3,556	3,079
7,000–7,999	1,722	3,259	1,570
8,000–8,999	1,882	3,555	1,714
9,000–9,999	2,684	2,808	2,031
10,000–10,999	2,830	4,075	2,290
11,000–11,999	2,790	3,875	2,570
12,000–12,999	2,034	3,002	1,808
13,000–	1,632	2,719	1,520

TEU=Twenty-foot equivalent unit.

Table3. Auxiliary engine load (p_{A}^{i}) for cruise ships (kw)

Passenger range	Operating mode		
	Cruise/Slow cruise	Maneuvering	Hotelling
0–1,499	4,404	5,678	3,479
1,500–1,999	7,869	9,869	6,500
2,000–2,499	11,869	12,219	7,769
2,500–2,999	10,650	9,259	6,958
3,000–3,499	9,292	11,369	9,292
3,500–	10,945	12,411	11,445

Table 4. Auxiliary engine load (p_{A}^{i}) for tankers (kw)

DWT (ton)	Operating mode		
	Cruise/Slow cruise	Maneuvering	Hotelling
0–49,999	681	745	3,406
50,000–120,000	728	1,114	4,044
120,000–	1,004	1,479	8,992

DTW: dead weight tonnage.

Table 5. Auxiliary engine load (p_{A}^{i}) of 4 types of vessel (kw)

Vessel type	Operating mode		
	Cruise/Slow cruise	Maneuvering	Hotelling
Bulk	290	769	275
Reefer	617	1,777	1,194
RoRo	501	1,449	1,010
Miscellaneous	676	662	324

Step5: Estimate the $\mathrm{NO_x}$emission $E_{\mathrm{NO_x}}^{i}$ (g) of the main and auxiliary engine:

$$E_{\mathrm{NO_x}}^{i} = T_{\mathrm{interval}} \times \left[EF_{\mathrm{NO_x}}^{\mathrm{M}} \times p_{\mathrm{M}}^{i} + EF_{\mathrm{NO_x}}^{\mathrm{A}} \times p_{\mathrm{A}}^{i}\right]. \tag{5}$$

$\mathrm{NO_x}$ emission factor for main engine$EF_{\mathrm{NO_x}}^{\mathrm{M}}$is related to ship operating mode and engine speed while $EF_{\mathrm{NO_x}}^{\mathrm{A}}$, emission factor for auxiliary engine, only depends on engine speed as shown in Table 6 referring to European Commission (2002) and Ng et al. (2016).In the table SSD, MSD and HSD represent the slow speed diesel, medium speed diesel and high speed diesel respectively.

Table 6. Emission factors for main/auxiliary engine ($\mathrm{gNO_x}$/kwh)

Engine speed	Main engine		Auxiliary engine
	Hotelling/Manoeuvring	Cruise/Slow cruise	
SSD	13.6	17.0	NA
MSD	10.6	13.2	13.9
HSD	9.6	12.0	13.9

Step6: Determine the fuel oil consumption rate of the main engine $FOCR_{\mathrm{M}}$. Main engines are used for propulsion and$FOCR_{\mathrm{M}}$ is related to the transient sailing speed and output power, therefore the fuel oil consumption rate baseline of the main engine$FOCR_{\mathrm{M}}^{\mathrm{B}}$ (g fuel/kwh) is introduced. Firstly determine $FOCR_{\mathrm{M}}^{\mathrm{B}}$ (g fuel/kwh)according to Table 7referring to IMO (2009).As is shown in Table4,$FOCR_{\mathrm{M}}^{\mathrm{B}}$ is closely related to the engine speed and the year of construction, old engines with high speed tend to consume more fuel oil to output a power unit.

Table 7. Fuel oil consumption rate baseline of main engine (g fuel/kwh)

Engine year of build	SSD	MSD	HSD
before 1993	205	215	225
1994–2010	185	195	205
post 2011	175	185	195

Then calculate the transient value of fuel oil consumption rate. Following IMO (2014), the equation:

$$FOCR_{\mathrm{M}} = FOCR_{\mathrm{M}}^{\mathrm{B}} \times (0.455 \times \left(\frac{p^i}{p_{\text{installed}}^{\mathrm{M}}}\right)^2 - 0.71 \times \frac{p^i}{p_{\text{installed}}^{\mathrm{M}}} + 1.28) \quad (6)$$

is adopted to explain the relationship between $FOCR_{\mathrm{M}}$ and $FOCR_{\mathrm{M}}^{\mathrm{B}}$ under different output power. As revealed by equation 6, main engine is most efficient at around 80% load, with either higher or lower load it will take more oil for the engine to do the same work.

Step 7: Determine the fuel oil consumption rate of auxiliary engine $FOCR_{\mathrm{A}}$. As stated by Cooper (2004), $FOCR_{\mathrm{A}}$ depends on the fuel type that the auxiliary engine consumes. 227 grams of oil is needed to output 1kilowatt-hour for auxiliary engines with HFO (heavy fuel oil), for those consume MDO (marine diesel oil)/MGO (marine gas oil) $FOCR_{\mathrm{A}}$ equal to 217(g fuel/kwh).

Step 8: Estimate the emission of $\mathrm{SO_x}$ according to the following equation:

$$E_{\mathrm{SO_x}}^{i} = T_{\text{interval}} \times \left[FOCR_{\mathrm{M}} \times p_{\mathrm{M}}^{i} \times SC_{\mathrm{FuelT_M}} + FOCR_{\mathrm{A}} \times p_{\mathrm{A}}^{i} \times SC_{\mathrm{FuelT_A}}\right] \times \frac{M_{\mathrm{SO_2}}}{M_{\mathrm{S}}} \quad (7)$$

where$M_{\mathrm{SO_2}} = 64$,$M_{\mathrm{S}} = 32$, are the molar mass (g/mol) of sulphur dioxide and sulphur respectively, $SC_{\mathrm{FuelT_M}}$ and $SC_{\mathrm{FuelT_A}}$ are sulphur content of fuel for main and auxiliary engine. It is assumed that all the sulphur element is transferred into $\mathrm{SO_2}$through the process of combustion.

Step 9: Estimate the emission of $\mathrm{CO_2}$.It is assumed that the emission factories only affected by fuel type. In this study the emission factor data of different fuel types come from MEPC 63/23, annex 8:

Table 8. $\mathrm{CO_2}$ emission factor of different fuel types ($\mathrm{gCO_2}$/g fuel)

Type of fuel λ	Emission factor $\mathrm{EF}_{\mathrm{CO_2},\lambda}$
MDO/ MGO	3.206
HFO	3.114

The $\mathrm{CO_2}$ emission can be evaluated as:

$$E_{\mathrm{CO_2}}^{i} = T_{\text{interval}} \times \left[FOCR_{\mathrm{M}} \times p_{\mathrm{M}}^{i} \times EF_{\mathrm{CO_2,FuelT_M}} + FOCR_{\mathrm{A}} \times p_{\mathrm{A}}^{i} \times EF_{\mathrm{CO_2,FuelT_A}}\right]. \quad (8)$$

Step 10: Calculate the emission of particulate matter (PM)E_{PM}^{i}.

$$E_{\mathrm{PM}}^{i} = E_{\mathrm{PM,M}}^{i} + E_{\mathrm{PM,A}}^{i} \quad (9)$$

In equation (9) $E_{\mathrm{PM,M}}^{i}$ and $E_{\mathrm{PM,A}}^{i}$ are the PM emission from the main and auxiliary engine respectively. According to IMO (2014), the emission volume of PM is related to fuel type, so different equations are applied to evaluate the PM exhausted emission for engines that consume different fuel oil:

$$E_{\mathrm{PM,\mu}}^{i} = \begin{cases} T_{\text{interval}} \times p_{\mu}^{i}[1.35 + FOCR_{\mu} \times 0.157 \times (SC_{\mathrm{FuelT_\mu}} - 0.0246)], \mathrm{FuelT_\mu} = \mathrm{HFO} \\ T_{\text{interval}} \times p_{\mu}^{i}[0.23 + FOCR_{\mu} \times 0.157 \times (SC_{\mathrm{FuelT\mu}} - 0.0024)], \mathrm{FuelT_\mu} = \mathrm{MDO/MGO}. \end{cases} \quad (10)$$

In the above equation $\mu \in \{\mathrm{M,A}\}$ represents the engine type.

Step 11: Add$E_{\mathrm{NO_x}}^{i}$,$E_{\mathrm{SO_x}}^{i}$, $E_{\mathrm{CO_2}}^{i}$, $E_{\mathrm{PM}}^{i}$to the total emissions of the square in which the midpoint of the trajectory($\frac{x^{i}+x^{i+1}}{2}$, $\frac{y^{i}+y^{i+1}}{2}$)locates.

Repeat the above 11 steps until all the data for the evaluation horizon are processed, then the distribution of emissions of a ship is completed. The whole picture of marine traffic exhaust emissions is drawn by combining the results of all the ships.

4 Assumptions about Fuel Oil Type and Sulphur Content

Fuel type and fuel sulphur content are two important variables in the exhaust emission evaluation. In practice, to lower the bunker cost, HFO is always used for propulsion in large ships, at the same time a number of ships with lower main engine power may use MDO/MGO. For auxiliary engines, it is common to use MDO/MGO. However, data about the fuel type chosen by each ship is not provided, so corresponding assumptions are made in academic papers and technical reports.

In papers adopting fuel-based method fuel type is known. In researches using activity-based method certain assumptions are made. A number of papers focus on proposing a new method so, for simplicity, they tend to assume certain sulphur content for all the fuel oil (Jalkanen et al., 2009). Others (Sofievet al., 2018; Marelle et al., 2016 and Jonson et al., 2015) always assume that fuel oil with the highest sulphur content allowed in the area according to relative regulations is used. However, technical reports conducted by organizations that have access to more complete information make more precise assumptions on fuel type and fuel quality. In Ng et al. (2012) it is assumed that vessels with main engine power larger than 1100 kw burn HFO, and those with lower main engine power burn MDO/MGO. Meanwhile, sulphur contents of HFO used by main engine auxiliary engine and auxiliary boiler are assumed to be 2.83%, 2.64% and 2.77% respectively, and MDO/MGO are assumed to contain 0.5% sulphur in mass. More concretely, IMO (2009) lists the common fuel type used by ships with various types and sizes. IMO (2014) summarizes the average sulphur content for both HFO and MDO/MGO fuels from 2007 to 2012.

In IMO (2009), the fuel types for various ships are not listed explicitly, for some ships of a certain size both HFO and MDO/MGO can be used according to the report. For emission evaluation adopting bottom-up approach, better defined assumptions are required, so in this paper assumptions are made following Ng et al. (2012) while statistical data from IMO (2014) are considered. For fuel types, auxiliary engines consume MDO/MGO regardless of ship type and size. At the same time, main engines with installed power higher than 3000 kw consume HFO, and those with lower installed power consume MDO/MGO. According to IMO, the latest figures showed that the average sulphur content of HFO tested in 2017 is 2.54%. The worldwide average sulphur content for MDO/MGO in 2017 is 0.08%. Additionally, when sailing in the emission control area (ECA), ships will adopt measures to obey the restriction on fuel oil sulphur content, e.g. switching fuel oil or installing sulphur scrubbers. We expect that machine learning based approaches (Wang et al., 2019; Qu et al., 2020) will be of value to predict the emissions from ships more effectively.

5 Conclusion

We have summarized a marine traffic emission evaluation framework based on the literature. The framework can be used by practitioners and researchers to calculate the emission in a particular area, which is indispensable of studies in the area of emission control and green shipping. We hope that in the future there will be more research on these topics and make the shipping industry more sustainable and environmentally friendly.

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