Emission performance of major ship classes: An estimation based on a new set of emission factors and realistic activity profile data

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Abstract. The maritime sector significantly contributes on the major environmental problems that humanity is being confronted with their consequences. The Greenhouse Gases (GHGs) emitted from the sector, which are responsible for the global phenomenon of climate change, are estimated in 2.89% of total anthropogenic GHGs. Ships are also an important source of local air-quality degradation in coastal areas by emitting major quantities of pollutants such as Nitrogen Oxides (NOₓ), Sulphur Oxides (SOₓ) and Particulate Matter (PM). The overall emitted quantities of the sector seem not to be equally allocated to the major ship classes (containers, dry and liquid bulk carriers, cruise ships, ro-ro ships etc.), even though the engine technologies that are being used in these classes are approximately the same (slow speed, medium speed, high speed diesel engines). A factor of differentiation among the ship types is the activity profile. Depending on the ship type, engines (main, auxiliary, boilers) present different power needs and therefore are being operated at different load points which among others are related with the sailing profile (cruising, maneuvering, hoteling), the cargo type and weight conditions (laden, ballast). In this context the target of the present paper is to evaluate the emission performance of the major ship classes. This evaluation is performed by using a new set of engine load-dependent Emission Factors for ships, which have been derived by a statistical analysis of emission rates found in literature, in combination with average activity profiles per ship type as these are found in dedicated shipping inventory databases and in literature. These activity data concern a global scale of consideration. Results aim to highlight the differences and similarities in the emission performance of ship types, enhancing the understanding of policy makers and ship operators, on the principle of tackling pollutants especially at ports, close to cities.

1. Introduction

The maritime sector significantly contributes on the major environmental problems that humanity is being confronted with their consequences [1], [2]. The Greenhouse Gases (GHGs) emitted from the sector, which are responsible for the global phenomenon of climate change, are estimated in 2.89% of total anthropogenic GHGs [3]. Ships are also an important source of local air-quality degradation in coastal areas by emitting major quantities of pollutants such as Nitrogen Oxides (NOₓ), Sulphur Oxides (SOₓ) and Particulate Matter (PM) [4],[5],[6]. The overall emitted quantities of the sector seem not to be equally allocated to the major ship classes (containers, dry and liquid bulk carriers, cruise ships, ro-ro ships etc.), even though the engine technologies that are being used in these classes are
approximately the same (slow speed diesel-SSD, medium speed diesel-MSD, high speed diesel-HSD engines) [7]. A factor of differentiation among the ship types is their activity profile. Depending on the ship type, engines (main, auxiliary, boilers) present different power needs and therefore are being operated at different load points which among others are related with the sailing profile (cruising, maneuvering, hoteling) [8], the cargo type and weight conditions (laden, ballast). In this context the target of the present paper is to evaluate the emission performance of the major ship classes at a global scale of consideration.

2. Materials and Methods
This evaluation is performed by using a new set of Emission Factors (EFs) for ships, which have been derived by a statistical analysis of published emission measurements found in literature, in combination with average activity profiles per ship type as these have been retrieved from dedicated shipping inventory databases and literature.

Emission Factors
The new set of EFs, which has been developed within the SCIPPER project [9] and it is included in the STEAM model [10] concerns various gaseous pollutants such as NO\(_X\), SO\(_X\), CO, HCs, Greenhouse Gases (GHGs), as well as PM and PN. Energy consumption factors are also included in the developed set. All the EFs are expressed in emitted quantity (or consumed energy) per useful energy produced (g/kWh) and are specific to the engine type (SSD, MSD, HSD), as well as the fuel type (residual and distillate). In order to incorporate the variance of emissions under various operating conditions that are met in practice, EFs have been expressed in relation with the ship engine load, leading to the formation of engine load dependent emission functions. An example of the functions that have been used are provided in Figure 1, where the variance with the engine load of CO, HC, NO\(_X\) and SFOC that representing mean engine type and average fuel properties is depicted.

![Figure 1. CO, HC, NO\(_X\) EF and SFOC in relation with ship’s engine load.](image)

Similar functions (adjusted to the specific engine and fuel types) have been used in combination with average ship activity data retrieved from literature to estimate the absolute emission levels of major vessel categories.

Activity data
These activity data used as input concern the average operating load points per ship class for main and auxiliary engines during the operating modes (cruising, maneuvering, hoteling), the average installed power for main and auxiliary engines, the percentage of operating time that each vessel category spends in an operating mode, the penetration of each engine type and emission standard (Tier) within each vessel category, the fuel used per vessel category and the total operating hours per ship class. The sources that have been used so as to estimate the activity profile of each ship type are the following: [11] – [20]. The outputs of the accumulation of activity data are provided in Table 1. Table 1 consists of an average of activity values that have been found in the inventories. These data correspond to the overall global activity of shipping.

### Table 1. Average speed, annual operating hours, share of each operating phase in the trip, ME and AE power per ship category.

| Vessel Type | Average speed (knots) | Operating time (hours/year) | Trip share of cruising/maneuvering/hotelin (\%) | ME Power (kW) | AE Power (kW) |
|-------------|----------------------|-----------------------------|-----------------------------------------------|--------------|--------------|
| Bulk carrier | 14,4                 | 87,713,000                  | 45% / 1% / 54%                               | 7.258        | 1.880        |
| Container   | 20,4                 | 42,658,000                  | 58% / 2% / 40%                               | 26.603       | 5.860        |
| Cruise      | 20,9                 | 3.318,000                   | 51% / 3% / 46%                               | 39.600       | 11.009       |
| General Cargo | 13,3               | 74,085,000                  | 37% / 3% / 60%                               | 5.633        | 1.297        |
| Oil Tanker  | 14,3                 | 47,001,000                  | 37% / 2% / 61%                               | 9.092        | 2.024        |

From Table 1, it can be observed that bulk carriers and general cargo sail in total the most hours in a year compared to the other ship categories. This is attributed mainly to their share in total fleet synthesis (28% combined). In contrast cruise ships operate less, which is mainly related to their share in total fleet as well as the seasonality in the provision of their services (mainly operate in summer). As regards the average observed speed, containers and cruise ships seem to sail faster mainly because of their fixed time-scheduling in their operation while the other ship categories present a similar average sailing speed at around 14 knots.

Cruise ships are characterized by the higher installed capacity both for main and auxiliary engines because they need to cover their increased energy needs for serving passengers accommodation (A/C), while the lowest engine capacity is found in general cargo and bulk carrier ships. Container ships and oil tanker also present high installed power because they have to carry increased cargo loads.

Concerning their engine activity profile, which for the purposes of the present paper is expressed in the average operating load point per operating phase (cruising, maneuvering, hoteling) for main and auxiliary engines, these are presented in Table 2. Table 2 shows that for the main engine the operating loads for all the three phases are almost the same, while the main differentiation is observed in auxiliary engines.

### Table 2. ME and AE engine load per each operating phase for the main ship categories.

| Vessel Type | ME Cruising (%) | ME Maneuvering (%) | ME Hoteling (%) | AE Cruising (%) | AE Maneuvering (%) | AE Hoteling (%) |
|-------------|-----------------|-------------------|-----------------|-----------------|-------------------|-----------------|

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In particular, for cruising the operating load of all ship types is around 80% where the most efficient operating is achieved. In maneuvering the observed operating point is on average 20%, while all ship types except oil tankers in hoteling reduce even further their operating point as the auxiliary engines cover most of the energy needs during this phase. In the operation of auxiliary engines, as it was expected, these mostly operate during maneuvering and hoteling with observed differences per ship type in the operating points.

Feeding the EF load dependent functions with the activity data and fleet synthesis information, the absolute emission level per vessel type is revealed and analyzed. The overall process is schematically presented in Figure 2. Using the activity data of Tables 1 and 2 as an input to the emission functions presented in Figure 1, the absolute emission level per ship class is estimated.

![Figure 2. Schematical representation of the process of emissions estimation.](image)

### 3. Results

Results aim to highlight the differences and similarities in the emission performance of ship types, enhancing the understanding of policy makers and ship operators, on the principle of tackling pollutants especially at ports, close to cities. For the main pollutants (NO\textsubscript{X}, CO, HC, SO\textsubscript{2}) and CO\textsubscript{2} the results are depicted in Table 3. Results are expressed in release rates (kg/h) of the examined pollutants.
Table 3. Total emitted quantities per hour for the main ship categories.

| Vessel Type     | CO₂ (kg/h) | CO (kg/h) | NOX (kg/h) | HC (kg/h) | SO₂ (kg/h) |
|-----------------|------------|-----------|------------|-----------|------------|
| Bulk carrier    | 2459       | 3,60      | 71,9       | 1,48      | 12,4       |
| Container       | 10129      | 12,6      | 241        | 5,58      | 127        |
| Cruise          | 14538      | 23,2      | 295        | 9,23      | 62,1       |
| General Cargo   | 1731       | 3,07      | 41,5       | 1,15      | 7,75       |
| Oil Tanker      | 3031       | 4,55      | 80,0       | 1,91      | 14,7       |

Taking into account the annual operating hours of ships categories, the absolute emitted quantities occur and presented in Table 4.

Table 4. Total annual emissions per ship category.

| Vessel Type     | CO₂ (tns) | CO (tns) | NOX (tns) | HC (tns) | SO₂ (tns) |
|-----------------|-----------|----------|-----------|----------|-----------|
| Bulk carrier    | 2,16E+08  | 3,16E+05 | 6,30E+06 | 1,30E+05 | 1,09E+06 |
| Container       | 4,32E+08  | 5,40E+05 | 1,03E+07 | 2,38E+05 | 2,24E+06 |
| Cruise          | 4,82E+07  | 7,70E+04 | 9,80E+05 | 3,06E+04 | 2,06E+05 |
| General Cargo   | 1,28E+08  | 2,27E+05 | 3,07E+06 | 8,53E+04 | 5,74E+05 |
| Oil Tanker      | 1,42E+08  | 2,14E+05 | 3,76E+06 | 8,98E+04 | 6,92E+05 |

Results show that for the calculated hourly release rate, container ships and cruise ships appear to be the higher emitters, while general cargo emit less. These results occur, mainly, because of the engine installed power in these types of ships and the respective allocation of covering the energy needs between main and auxiliary engines. Taking into account the total operating hours at a global level of every ship category, then containers are the leader in total produced emissions, while cruise ships contribute less because of their seasonal operation.

Focusing on the in-port activities (Table 5 and 6), cruise ships and containers are observed as the higher emitters, in respect of the calculated hourly release rate. By incorporating the annual operating time, containerships seem to be the higher emitters, while also cruise ships appear to produce less emissions, also here attributed to their seasonal operation.

Table 5. In-port Total emitted quantities per hour for the main ship categories.

| Vessel Type  | CO₂ (kg/h) | CO (kg/h) | NOX (kg/h) | HC (kg/h) | SO₂ (kg/h) |
|--------------|------------|-----------|------------|-----------|------------|
| Bulk carrier | 713        | 1,96      | 14,4       | 0,641     | 3,11       |
| Container    | 1968       | 5,23      | 41,9       | 1,73      | 8,78       |
| Vessel Type     | CO\textsubscript{2} (kg/h) | CO (kg/h) | NO\textsubscript{X} (kg/h) | HC (kg/h) | SO\textsubscript{2} (kg/h) |
|-----------------|---------------------------|-----------|---------------------------|-----------|---------------------------|
| Cruise          | 3854                      | 11,2      | 58,7                      | 3,49      | 13,4                      |
| General Cargo   | 633                       | 1,91      | 11,1                      | 0,591     | 2,50                      |
| Oil Tanker      | 1253                      | 2,84      | 24,6                      | 1,05      | 5,50                      |

Table 6. In-port emissions per ship category.

| Vessel Type     | CO\textsubscript{2} (tns) | CO (tns) | NO\textsubscript{X} (tns) | HC (tns) | SO\textsubscript{2} (tns) |
|-----------------|---------------------------|-----------|---------------------------|-----------|---------------------------|
| Bulk carrier    | 6,25E+07                  | 1,72E+05  | 1,26E+06                  | 5,63E+04  | 2,73E+05                  |
| Container       | 8,39E+07                  | 2,23E+05  | 1,79E+06                  | 7,37E+04  | 3,75E+05                  |
| Cruise          | 1,28E+07                  | 3,72E+04  | 1,95E+05                  | 1,16E+04  | 4,45E+04                  |
| General Cargo   | 4,69E+07                  | 1,42E+05  | 8,25E+05                  | 4,38E+04  | 1,85E+05                  |
| Oil Tanker      | 5,89E+07                  | 1,34E+05  | 1,16E+06                  | 4,92E+04  | 2,59E+05                  |

4. Comparison with STEAM

In order to examine the accuracy of the results of the adopted approach, results are compared with a published data for an emission inventory development for in-Europe maritime transportation with the use of the STEAM model. The STEAM model exploits AIS data to estimate the actual activity of ships. The comparison performed concerns CO\textsubscript{2} emissions per ship category and per km within each ship category so as exclude the different scale of application between our study and the study that used the STEAM model (Figure 3). In our dataset the quantity of emissions per hour was divided by the average speed of each vessel type in order tn/km to occur. The output of the comparison is provided in Figure 3.

Figure 3. Comparison of CO\textsubscript{2} emissions per km between present analysis and STEAM for major ship categories.

Results show a good agreement between the two methods, indicating that the present method in comparison with the new set of emission factors is capable of producing similar results with the one
provided by the STEAM model. The enhancement of STEAM with the new set of EFs is able to further improve the accuracy of the model in maritime emissions estimation.

5. Conclusion
The use of an updated set of emission factors with average operation profiles found in various inventories and studies reveals the absolute emission levels per ship type. Emissions among ship type are different mainly because of the different installed power as well as the operation of main and auxiliary engines. Comparing the emission release rates per vessel type this shows that cruise ships and containers are the high emitters. When the analysis is extrapolated to the total operating hours per ship category then cruise ships present to have the minimum impact while containers continue to contribute more than the other ship categories.

Focusing on in-port activities, cruise ships emit more in total with containers to follow. A comparison of the present approach with the STEAM model showed comparable results for all available vessel categories once the distance-based emissions per ship type are utilized.

Finally, the overall conducted analysis, apart from revealing the emission performance of major ship classes, can be a useful example for policy makers and local authorities while conducting studies to quantify the impact of shipping at any geospatial level of consideration.

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