Comparative Analysis of Inventory Compilation Methods for Ship Emissions

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Abstract: In recent years, a variety of inventory compilation methodologies have been developed for ship emissions. With a detailed comparative analysis of the 5 major methods on applicability scope, calculation difficulty, accuracy, time and space distribution etc., this paper aims to be of reference for the selection of the most appropriate approach to emission inventory compilation.

1. Introduction
China, with over 1.5 million times of annual vessel traffic, plays an important role in the global shipping industry, which as a major source of atmospheric pollution, has given rise to researches on methodologies for the compilation of emission inventories (EI) that could be roughly categorized as activity-based and fuel-based approaches. The former approach bases the emission calculation on the vessel engine power and operating hours, namely the AIS-based and vessel-based methods; while the latter on vessels’ actual or estimated energy consumption, which could be further divided into three methods: fuel consumption by single vessels, regions, passenger and freight turnover respectively. The paper provides a systematic analysis of the five methods aforementioned, which are also the mainstream methods widely applied at home and abroad.

2. Approaches to Emission Inventory Compilation

2.1. AIS-based Methods
AIS-based methods calculate atmospheric emissions by means of vessel activity levels indicated by AIS(Automatic Identification System) data. AIS transponders automatically broadcast a data set every few seconds or minutes. By matching the dynamic navigational data with the basic vessel information, the quantity and location of ship emissions could be calculated with emission factors. With the information from a fleet of vessels, an emission inventory could be compiled[2][3].

Data Requirement: AIS data, basic vessel information (power output of main engine, auxiliary engine, boilers etc.), emission factors based on the power output, engine load factor, adjustment coefficient of control measures[4][5]. Refer to formula (1)-(4) for more details.

2.1.1. Total Emission. The emission of a single vessel is the total emission from its main engine, auxiliary engine and boiler. Regional emission is the totality of all ship emissions in a region.

\[
E = \sum_{i=1}^{p} \left( E_M + E_A + E_G \right)
\]  (1)
\( \bar{E} \): total ship emissions in a region (t); \( \bar{E}_M \): total emission from main engines (t); \( \bar{E}_A \): total emission from auxiliary engines (t); \( \bar{E}_G \): total emission from boilers (t); \( p \): number of vessels in a region.

### 2.1.2. Emission from Main Engines

\[
\bar{E}_M = MCR \times LF \times T \times CF \times EF_i \times 10^{-6} \quad (2)
\]

- \( MCR \): main engine rated power (kw);
- \( LF \): load factor (dimensionless);
- \( T \): working hours (h);
- \( CF \): emission control factor (dimensionless);
- \( EF_i \): emission factor (g/kwh) of main engine powered by fuel-\( i \).

### 2.1.3. Emission from Auxiliary Engines

\[
\bar{E}_A = ELD \times T \times CF \times EF_i \times 10^{-6} \quad (3)
\]

- \( ELD \): engine power (kw), auxiliary engine rated power by load factor, or main engine power by power coefficients of main and auxiliary engines;
- \( T \): working hours (h);
- \( EF_i \): emission factor (g/kwh) of auxiliary engine powered by fuel-\( i \).

### 2.1.4. Emission from Boilers

\[
\bar{E}_G = GLD \times T \times CF \times EF_i \times 10^{-6} \quad (4)
\]

- \( GLD \): boiler power (kw);
- \( T \): working hours (h);
- \( EF_i \): emission factor (g/kwh) of boilers powered by fuel-\( i \).

### 2.2. Vessel-based Methods

Vessel-based methods calculate atmospheric emissions by means of vessel activity levels indicated by the number of vessels at port. With a principle similar to AIS-based methods, vessel-based methods group vessels by class and tonnage.

**Data Requirement:** number of inbound and outbound vessels from the maritime information system, average vessel power, emission factors based on power output, engine load factor etc. Refer to formulas (5)-(8) for more details.

#### 2.2.1. Total Emission

\[
\bar{E} = \sum_{n, m} \left( \bar{E}_M + \bar{E}_A + \bar{E}_G \right) \quad (5)
\]

- \( m \): number of vessel class;
- \( n \): number of tonnage type

#### 2.2.2. Emission from Main Engines

\[
\bar{E}_M = N_{m,n} \times MCR \times LF \times \frac{L}{u} \times CF \times EF \times 10^{-6} \quad (6)
\]

- \( N \): number of class-\( m \) and tonnage-\( n \) vessels, used for emission calculation of inbound and outbound vessels, and average number of vessels for emission calculation of mooring vessels;
- \( L \): nautical mileage (nm);
- \( u \): nautical speed (nm/h).

#### 2.2.3. Emission from Auxiliary Engines

\[
\bar{E}_A = N_{m,n} \times ELD \times T \times CF \times EF \times 10^{-6} \quad (7)
\]

- \( T \): working hours (h). \( T \) is calculated by \( L/u \) for vessels cruising, entering or exiting ports. Otherwise \( T \) is the mooring time.

#### 2.2.4. Emission from Boilers

\[
\bar{E}_G = N_{m,n} \times GLD \times T \times CF \times EF \times 10^{-6} \quad (8)
\]
2.3. **Fuel-based Method by Single Vessels**

This method calculates emissions by means of vessel activity levels indicated by fuel consumption per vessel per voyage from the maritime information system that is currently under construction. Hence it is difficult to scale up at this stage. However, it has the potential to become mainstream for accuracy concerns in the future.

Data Requirement: fuel consumption per vessel per voyage from the maritime information system that is currently under construction. Hence it is difficult to scale up at this stage. However, it has the potential to become mainstream for accuracy concerns in the future.

**Data Requirement:** fuel consumption per vessel per voyage from the maritime information system, emission factor based on power output, engine load factor etc. Refer to formulas (9) for details.

2.3.1. **Total Emission.**

The same as formula (1).

2.3.2. **Emission from Main Engines/Auxiliary Engines/Boilers**

\[ E = Y \times EF_i \] (9)

Y: main engine, auxiliary engine and boiler fuel consumption (kg); EF: main engine, auxiliary engine and boiler fuel-i emission coefficient (g/kg fuel)

2.4. **Fuel-based Method by Regions**

This method calculates emissions by emission factors per unit fuel as well as vessel activity levels indicated by fuel consumption in a region. Its accuracy depends on the data of fuel consumption.

Data Requirement: regional vessel fuel consumption, emission factors based on fuel consumption. Refer to formulas (10) for details.

\[ E = \sum_i \left( F_i \times EF_i \right) \times 10^{-6} \] (10)

\( F_i \): total fuel-i consumption (t)

2.5. **Fuel-based Method by Passenger and Freight Turnover**

This method calculates emissions by means of fuel consumption based on vessel activity levels derived from passenger and freight turnover in a region.

Data Requirement: regional passenger and freight turnover, energy intensity per turnover unit, emission factors based on fuel consumption etc. Refer to formulas (11)[7] for details.

\[ Y_i = \left( 0.065 \times Z_k + Z_h \right) \times YX_i \] (11)

\( Y_i \): total fuel-a consumption(t); \( Z_k \): passenger turnover \( (10^4 \text{persons-km}) \); \( Z_h \): freight turnover \( (10^4 \text{t-km}) \); \( YX_i \): energy intensity per turnover unit(t/10^4 \text{t-km})

Use 0.05 if no data available.

3. **Comparative Analysis**

Based on the principles of calculation and existing emission inventories, the paper studies the data requirement, applicability, accuracy of the 5 major methods for compiling emission inventories. Refer to table 1 for detailed information. For countries and larger areas, the recommended methods in order are as follows: method 1(method 3), method 4, method 2, method 5; whereas for regions, ports or smaller areas, the order is method 1(method 3), method 2, method 4, method 5. Note that method 3 is still at a conceptual stage, which will be of the same ranking as method 1 once reaching maturity. In practice, the selection of compilation method should depend upon the specific use case and data availability.
Table 1. Comparative Analysis

| Name                          | Method 1                          | Method 2                          | Method 3                          | Method 4                          | Method 5                          |
|-------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Data Requirement              | AIS data, basic vessel information| number of vessels arriving at port, basic vessel information | energy consumption per vessel | regional energy consumption | passenger/freight turnover |
| Applicability                 | country = region = port           | port > region > country           | country = region = port           | country > region > port           | country > region > port           |
| Complexity & Calculation Time | ★ high & long                     | ★★★ medium & medium              | ★ high & long                     | ★★★ low & short                  | ★★★ low & short                  |
| Accuracy                      | ★★★★★ medium-high               | ★★★★ medium-high                 | ★★★★★ high                      | ★★★ medium-low                  | ★ low                             |
| Time Distribution             | ★★★ precise                      | no                                | ★★★ rough                        | no                                | no                                |
| Spatial Distribution          | yes                               | not at port level; low-accuracy at regional and national levels. | yes | no, boundary of calculation unclear | No, boundary of calculation unclear |
| Count in Passing Vessels      | yes                               | no                                | yes                               | no                                | no                                |
| Vessel Class Separation       | yes                               | yes                               | yes                               | no                                | no                                |
| Operation Conditions Separation| yes                              | yes                               | yes                               | no                                | no                                |
| Emission Sources Separation   | yes                               | yes                               | yes                               | no                                | no                                |

Note: For applicability level, > means “superior to” and = means “equal to”.

4. Conclusion

1) Methodologies of emission inventory compilation can be roughly categorized as activity-based and fuel-based approaches.

2) The technical characteristics of the 5 methods differ from one another. In terms of applicability, method 4 and 5 are more optimal for larger areas whereas method 2 for smaller areas such as ports. Method 1 and 3 are universally applicable for countries, port clusters and ports. Method 2 and 3 are most suitable for accuracy. In terms of distribution, method 1 can provide accurate time and special distribution of emissions while the results of methods 2 and 3 are of lower accuracy. Method 4 and 5 are not able to provide any distribution information.
3) The recommended methods for countries and larger areas in order are: method 1(method 3), method 4, method 2 and method 5; whereas the recommended order for regions, ports and smaller areas is method 1 (method 3), method 2, method 4, and method 5.

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