



## Critical Assessment of the Main Methodologies for Estimating Atmospheric Emissions From Vessels

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**Abstract:** Coastal communities neighboring port terminals are impacted by the air pollutants emitted by vessels during their activities. One of the sustainable management tools adopted by these cities is the preparation of emission inventories for local pollutants and greenhouse gases (GHG) to quantify these atmospheric emissions. There are a variety of bottom-up methodologies developed to estimate air emissions from ships. Given this fact, the objective of this study was to evaluate the methodologies proposed by the United States Environmental Protection Agency (US EPA), the California Air Resources Board (CARB), and the European Environmental Agency (EEA), to highlight the assumptions, limitations, and uncertainties associated with the application of each one. Only the US EPA and CARB methodologies proposed estimation for GHG (CO<sub>2</sub>). In addition, the analysis showed that although the methodologies adopt the same approach (bottom-up methodology), the results can be quite different due to the input data required by each one. This fact highlights the need for the development of experimental studies to obtain emission factors appropriate to the circulating vessels fleet, to reduce uncertainties in the estimates, since reliable emission inventories are a subsidy for the elaboration of environmental management policies and the creation of atmospheric emission control programs in port regions.

**Keywords:** Emission inventories, Maritime transport, Mobile sources, CO<sub>2</sub>, Air pollution.

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## Avaliação Crítica das Principais Metodologias de Estimativa de Emissões Atmosféricas de Embarcações

**Resumo:** As comunidades costeiras vizinhas a terminais portuários são impactadas pelos poluentes atmosféricos emitidos por embarcações durante suas atividades. Uma das ferramentas de gestão sustentável adotadas por essas cidades é a elaboração de inventários de poluentes locais e de gases de efeito estufa (GEE) para quantificar essas emissões atmosféricas. Há uma variedade de metodologias *bottom-up* desenvolvidas para estimar as emissões atmosféricas provenientes de navios. Diante disso, o objetivo deste estudo foi avaliar as metodologias propostas pela Agência de Proteção Ambiental dos Estados Unidos (US EPA), pelo Conselho de Recursos do Ar da Califórnia (CARB) e pela Agência Europeia do Meio Ambiente (EEA), destacando os pressupostos, limitações e incertezas associados à aplicação de cada uma. Apenas as metodologias da US EPA e da CARB propuseram estimativas para GEE (CO<sub>2</sub>). Além disso, a análise mostrou que, embora as metodologias adotem a mesma abordagem (*bottom-up*), os resultados podem ser bastante diferentes devido os dados de entrada exigidos por cada uma. Esse fato evidencia a necessidade do desenvolvimento de estudos experimentais para obter fatores de emissão adequados à frota de embarcações em circulação, a fim de reduzir as incertezas nas estimativas, já que inventários de emissões confiáveis são subsídio para a elaboração de políticas de gestão ambiental e a criação de programas de controle de emissões atmosféricas em regiões portuárias.

**Palavras-chave:** Inventários de emissões, Transporte marítimo, Fontes móveis, CO<sub>2</sub>, Poluição do ar.

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## Análisis de Calidad en una Industria de Hilado en Paraná

**Resumen:** Las comunidades costeras vecinas a los terminales portuarios se ven afectadas por los contaminantes atmosféricos emitidos por los buques durante sus actividades. Una de las herramientas de gestión sostenible adoptadas por estas ciudades es la elaboración de inventarios de contaminantes locales y de gases de efecto invernadero (GEI) para cuantificar estas emisiones atmosféricas. Existen diversas metodologías *bottom-up* desarrolladas para estimar las emisiones atmosféricas procedentes de los buques. Ante este hecho, el objetivo de este estudio fue evaluar las metodologías propuestas por la Agencia de Protección Ambiental de los Estados Unidos (US EPA), la Junta de Recursos del Aire de California (CARB) y la Agencia Europea de Medio Ambiente (EEA), destacando los supuestos, limitaciones e incertidumbres asociadas a la aplicación de cada una. Solo las metodologías de la US EPA y de la CARB propusieron estimaciones para GEI (CO<sub>2</sub>). Además, el análisis mostró que, aunque las metodologías adoptan el mismo enfoque (*bottom-up*), los resultados pueden ser bastante diferentes debido a los datos de entrada requeridos por cada una. Este hecho resalta la necesidad de desarrollar estudios experimentales para obtener factores de emisión adecuados a la flota de buques en circulación, con el fin de reducir las incertidumbres en las estimaciones, ya que los inventarios de emisiones confiables son un apoyo para la elaboración de políticas de gestión ambiental y la creación de programas de control de emisiones atmosféricas en regiones portuarias.

**Palabras clave:** Inventarios de emisiones, Transporte marítimo, Fuentes móviles, CO<sub>2</sub>, Contaminación del aire.

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### INTRODUCTION

One of the main challenges for the management of coastal cities with the presence of port terminals is to ensure sustainable development, reducing the environmental impacts on local communities caused by port activities (Chang and Wang, 2012; Chen *et al.*, 2017, Cammin *et al.* 2020). According to the International Maritime Organization - IMO (2020), emissions from ships could increase between 50 and 250% by 2050, varying according to future economic growth and energy development. Therefore, the control of exhaust gas emissions from maritime transport has become an urgent task, as the exponential use of the modal has grown. Recent studies emphasize that the shipping sector is responsible for approximately 3% of global greenhouse gas (GHG) emissions, necessitating high-resolution databases to improve inventory accuracy (Sun *et al.*, 2025; Wang *et al.*, 2025).

The IMO (2025) recently published the regulatory package known as the “IMO Net-Zero Framework” to aim decarbonize international maritime transport, approved during the 83rd session of the Marine Environment Protection Committee (MEPC). This package was incorporated into Annex VI of the MARPOL Convention, which currently applies to 97% of the world’s merchant ship fleet by tonnage. Moreover, according to Zhang *et al.* (2018), about 15% of the global nitrogen oxide (NO<sub>x</sub>) and 5 to 8% of sulfur oxide (SO<sub>x</sub>) are emitted by vessels into the atmosphere. The assessment of emissions from individual vessels, such as the Marella Discovery, provides crucial insights into the impact of specific operations (Faber, 2021). The adoption of

these new regulatory frameworks is critical, as regional assessments show that port-related emissions continue to impact coastal air quality significantly (Shen *et al.*, 2025).

Despite the relevance of this issue, few studies have been found on an inventory of air pollutants or GHG emissions emitted by ships. Besides, there are two common approaches to preparing ship emissions inventories: (1) top-down methodology, based on fuel consumption, and (2) bottom-up methodology, based on activity (Zhang *et al.*, 2017; Lee *et al.*, 2020). Comparative analyses of these approaches indicate that activity-based models are increasingly preferred for their ability to integrate real-time data, such as Automatic Identification System (AIS), to reduce estimation uncertainties (Khayenzeli *et al.*, 2025).

The top-down methodology was widely applied until the 2000s, due to the lack of detailed maritime traffic data. It is based on average fuel consumption from ship combined with corresponding emission factors (FE) for each type of air pollutant (Yau *et al.*, 2012; Zhang, 2017; Zhang, 2018). On the other hand, the bottom-up methodology is applied when information is available about the ship and its operation (activity). According to Yau *et al.* (2012), the specifications involved in the application of the bottom-up approach are more accurate than the top-down method, once the necessary parameters are available for the application of this methodology.

Lopes *et al.* (2024) suggest the activity-based method should be used whenever possible, since the detailing of the input parameters increases the accuracy of the estimation. Lee *et al.* (2020) and Nunes *et al.* (2017) report the most common parameters are detailed information on the ship's specifications, such as fuel and ship type, IMO number, ship dimension, and engine characteristics, as well as operational and research data (e.g., travel distances, instantaneous speed, maximum speed, port calls, estimated ship operations, uptime, ship tracking, and real-time operations).

There are a variety of bottom-up methodologies for estimating ship emissions, such as those proposed by the United States Environmental Protection Agency (US EPA, 2006), the California Air Resources Board (CARB, 2011), European Environment Agency (EEA, 2019). Beyond these established frameworks, the field includes additional approaches such as the IMO's MARPOL-based guidelines, high-resolution AIS based methodologies (Chen and Yang, 2024; Yi *et al.*, 2025), and specific regional inventory models utilized in major maritime hubs, including China's Pearl River Delta and the European Union's Monitoring, Reporting, and Verification (MRV) framework (EMSA, 2023; Mao *et al.*, 2023). These specialized methodologies often leverage

localized emission factors and dynamic operational data to provide granular spatial-temporal assessments.

Despite the emergence of these diverse approaches, the four methodologies selected for this study (US EPA, EEA, CARB, and Der Meer) remain the most widely adopted in global literature. Their prevalence is justified by their high degree of standardization, widespread availability of required input data, and frequent use as benchmarks in comparative studies. Furthermore, these frameworks provide a robust basis for assessing emissions across different regulatory jurisdictions, ensuring comparability and reliability for environmental management policies in port regions (Nunes et al., 2017; Borén et al., 2023).

However, even though they all adopt the same methodological approach, these methodologies can generate very different results (Nunes et al., 2017). Recent intercomparisons of these specific methodologies have demonstrated discrepancies exceeding 20% in emission estimates, particularly when ships operate under off-design conditions like slow steaming (Borén et al., 2023). Furthermore, the integration of geographical and berth-specific data has been proposed to refine these established methodologies (Daniel et al., 2024). In this context, the objective of this study is to provide a critical assessment of the main methodologies for estimating atmospheric emissions from vessels, evaluating their core assumptions, operational limitations, and highlighting the inherent uncertainties of these predominant bottom-up approaches.

## MATERIALS AND METHODS

A bibliometric analysis was carried out looking for the most applied bottom-up methodologies to estimate ship emissions. A literature search was conducted in Scopus and Web of Science using the keywords vessels, ships, maritime, atmosphere, emission, GHG, inventory and air pollution. Studies were selected based on the following criteria: articles published between 2000 and 2025 and show emission estimate calculation. No AI-based tools were used to select or write the literature.

The main methodologies were those proposed by the United States Environmental Protection Agency (US EPA, 2006), the California Air Resources Board (CARB, 2001), European Environment Agency (EEA, 2019) and others, which are described below.

### US EPA Methodology

The compilation of air emissions factors model developed by the US EPA (2010) is used to estimate emissions from vessels using energy-based emission factors, along with activity profiles for each vessel. The calculation involves the determination of representative engine power for each vessel and the development of activity profiles for each ship stopover. Through this information, emissions by scale and mode of ship can be determined using Equation 1 (USEPA, 2006)

$$E = P \times HR \times A \times FE \quad (1)$$

Where:

E = emissions (t);

P = maximum continuous rated power (kW);

HR = load factor (percentage of the total power of the vessel) (%);

A = activity (h);

FE = emission factor ( $\text{g kW}^{-1}\text{h}^{-1}$ ).

The US EPA (2006) adopts the HR for auxiliary engines (AE) determined by Starcrest Consulting Group LLC (2005), published in the document Baseline AI Emissions Inventory of the Los Angeles Port. These factors were determined through interviews conducted with ship captains, chief engineers, and pilots during their embarkation programs. The HR depending on ship types and uptime, and they should consider the full auxiliary power.

Regarding the emission factors for AE, the US EPA (2006) specifies that the most current set of emission factors for this engine type is provided by Entec (2002). For example, the emission factors for AE, considering a sulfur content in the fuel (S%) of 1.5% for marine diesel oil (MDO) for an average operating speed (MSD). According to USEPA (2006), the SO<sub>x</sub> emission factors (FE<sub>SO<sub>2</sub></sub>) were based on a conversion factor from fuel sulfur (S) to SO<sub>2</sub>, assuming that 97.753% of the fuel sulfur was converted to SO<sub>2</sub> and considering the difference in molecular weight between SO<sub>2</sub> and S (SO<sub>2</sub> molecular weight = 2 times the sulfur), calculated according to Equation 2.

$$FE_{SO_2} = BSFC \times 2 \times 0.97753 \times S\% \quad (2)$$

Where:

FE<sub>SO<sub>2</sub></sub> = mass of SO<sub>2</sub> emitted per tonne of fuel consumed (kg t<sup>-1</sup>);

S% = sulphur content;

BSFC = specific fuel consumption of the brake.

Where BSFC has its value tabulated by the US EPA (2006), according to engine type and fuel used. Therefore, when calculating the emission factors of PM<sub>10</sub> and SO<sub>2</sub>, they must be adjusted according to the sulfur content of the fuel adopted according to the location where the ships were fueled. The PM<sub>10</sub> emission factors (FE<sub>PM<sub>10</sub></sub>) were determined by the US EPA based on existing engine test data and adjusted based on fuel type, according to Equation 3.

$$FE_{PM_{10}} = 1.35 + BSFC \times 7 \times 0.02247 \times (S\% - 0.0246) \quad (3)$$

Where:

FE<sub>PM<sub>10</sub></sub> = mass of PM<sub>10</sub> emitted per tonne of fuel consumed (kg t<sup>-1</sup>);

S% = sulphur content;

BSFC = specific fuel consumption of the brake.

### Carb Methodology

The CARB Model was used by the California Air Resources Board (CARB, 2001) to estimate the emissions of air pollutants that would be adopted in California's ocean-going vessel inventory, as presented in the document "Appendix D: Emissions Estimation Methodology for Ocean-Going Vessels". The model is mainly based on actual estimates of ship engine power, number of ships, and actual lodging times. The moment of hoteling operation is also considered, where the ships are in the anchorage area of the Port, operating only with AE. Therefore, emissions are calculated according to Equation 4:

$$E_{y,t,m,e} = \sum Pop_t * FE_{e,m,f} * A_{e,m,t} * P_{e,m,t} * HR_{e,m,t} \quad (4)$$

Where:

E = emissions (t);

POP = population of ocean-going vessels by vessel type;

FE = emission factor by engine type, operation mode, and fuel type (g kW<sup>-1</sup>h<sup>-1</sup>);

A = average annual use by operation mode and vessel type (h);

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P = average power by operation mode and vessel type (kW);

HR = Average engine load factor by operation mode and vessel type (%);

y = year inventoried;

e = engine type (main and auxiliary);

m = operation mode (hoteling, maneuver and cruise);

t = vessel type (bulk carrier, container, general cargo, etc.);

f = fuel type.

For the estimation of the average power outputs of the vessels, CARB adopted the auxiliary power generation capacities available in the Lloyds-Fairplay PC Register database (2007). For the load factor of the AE, a percentage (Table 1), representative of the actual power of the engine used divided by the total installed power of the AE, having as the main source of data the surveys of CARB (2005, 2007) and Starcrest Consulting Group LLC (2005), published in the document Emissions Inventory of the Baseline AI of the Port of Los Angeles (2005).

**Table 1.** Load characteristics of the auxiliary engines (percentage load).

Ship type	Load Factor (%)		
	Hoteling	Manoeuvre	Cruise
Bulk Carrier or General Cargo	10	45	17
Container Ship	18	50	13

**Source:** Adapted from CARB (2001).

### EEA methodology

The European Environment Agency's Air Pollution Emissions Inventory Guide (EEA, 2019) presents a procedure for selecting the most appropriate approach among three tiers called "Tiers". Tiers 1 and 2 use fuel sales reports as the main parameter for evaluating ship activity. For the emission factors assume characteristics of an average vessel to estimate the emissions of air pollutants. The Tier 3 methodology is the most accurate approach, for this reason, it is recommended when technical parameters (e.g. engine power and technology, total installed power, fuel type) and detailed data on individual vessel movements are available, applying Equation 5.

$$E_{m,f} = \sum_m (FC_{e,m,f} \times FE_{e,m,f}) \quad (5)$$

Where:

E = emissions (t);

FC = fuel consumption (t);

FE = emission factor ( $\text{kg t}^{-1}$ );

e = engine type (main and auxiliary);

m = operation mode (hoteling, maneuver and cruise);

f = fuel type (e.g. bunker fuel oil, marine diesel oil/marine gas oil (MDO/MGO), liquefied natural gas (LNG), and petrol).

It should be noted that for the  $\text{SO}_2$ , the author indicates the use of the emission factor available in the Lloyds-Fairplay PC Register database (2007), considering only the fuel type. Trozzi and Lauretis (2019) adopt for HR for AEs during hoteling operations the data proposed by Entec (2002), which is 60%, regardless of the ship type.

Trozzi and Lauretis (2019) also proposed a specific methodology for calculating emissions, based on the installed power and the time spent in the different operation mode (A), when the fuel consumption in each mode is not known. Then, after obtaining the installed power of the main engine (ME), Trozzi and Lauretis (2019) suggest an average ratio to determine the installed power of the AE, described in Table 2. To do this, emissions are calculated considering both engine types using the following Equation 6.

$$E_{j,m} = \sum_f (A_f \sum_e (P_e \times FC_e \times FE_{e,j,m,f})) \quad (6)$$

Where:

E = emissions (t);

FE = emission factor ( $\text{kg t}^{-1}$ );

HR = motor load factor (%);

P = rated motor power (kW);

A = uptime (h);

e = engine type (main and auxiliary);

j = engine category (low, medium, and high-speed diesel, gas turbine, and steam turbine);

f = fuel type (bunker fuel oil, marine diesel oil/marine diesel, LNG, and gasoline);  
m = operation mode (hoteling, maneuver and cruise).

**Table 2.** Main power as a function of Gross Tonnage and average ratio of Auxiliary Engines (AE) by Main Engines (ME) per ship type.

Ship types	Main power as a function of Gross Tonnage	Average ratio of AE/ME
Carriers	$35.912 * GT^{0.5276}$	0.30
Containers	$2.9165 * GT^{0.8719}$	0.25
General cargo	$5.56482 * GT^{0.7425}$	0.23

**Source:** Adapted from EEA (2019).

### Der Meer Methodology

The Der Meer model was developed in 2012 based on the "Methodologies for estimating shipping (EMS) emissions in the Netherlands published by Netherlands Environmental Assessment Agency (2012), which proposes methodologies and emission factors for the calculation of ships emission during operation, which consider Gross Tonnage (GT) the main information for this calculation, in addition to fuel consumption, which is differentiated by the ship types, as described in Equation 7.

$$E_m = GT \cdot FC \cdot A \cdot FE \quad (7)$$

Where:

E = emissions (t);

GT = Gross Tonnage (t);

FC = fuel consumption ( $\text{kg GT}^{-1}\text{h}^{-1}$ );

A = uptime (h);

FE = emission factor ( $\text{kg t}^{-1}$ );

m = operation mode (hoteling, maneuver and cruise).

Emissions were estimated using specific NO<sub>x</sub> emission factors, as published in the study by Cooper (2002), where it is assumed that each 1 ton of fuel consumption has 52 kg of NO<sub>x</sub>, where FE is  $52 \text{kg t}^{-1}$  for NO<sub>x</sub>. To estimate the pollutant SO<sub>2</sub>, the FE proposed by Der Meer (2012) is based on an empirical relationship of the percentage of sulfur under emissions (Equation 8) for AE.

$$FE_{SO_2} = 20 \times (S\%) \quad (8)$$

Where:

$FE_{SO_2}$  = mass of  $SO_2$  emitted per tonne of fuel consumed ( $kg\ t^{-1}$ )

S% = sulphur content.

It should be noted that the Der Meer Model, unlike the other models presented, provides a proposal for a calculation methodology to estimate the fuel consumption using a correlation described from the GT with the average fuel consumption by ship types.

## RESULTS AND DISCUSSION

Since the main bottom-up methodologies applied worldwide for estimating emissions from vessels have already been presented in the methodology, it can be seen that these differ, mainly, by the input data types that each one adopts. The methodologies for the estimation of atmospheric emissions from vessels can be grouped into two key factors:

Factor 1 – involves the energy output from the engine over the activity time, where the main factors are the engine power and the associated load factors.

Factor 2 – involves the fuel consumption by the engine over the activity time, according to the operation mode and ship type.

### Factor 1: Engine Power and Load Factors

For the calculation of the energy output from the engine, during the specific period of operation of the ships, and according to the ship type, the powers of the ME and AE and load factors of the respective engines are used, as applied by the US EPA and CARB methodologies. For these two methodologies, the Lloyd's database (LRS, 2007) is used as the main source of information, to obtain average values of engine power (main and/or auxiliary) associated with the vessel type addressed in the study.

The database contains a high level of ME power information for the worldwide fleet, however, for AE, it does not provide complete coverage. EEA (2019) describes the need to use data proposed by Entec (2002), which proposes 60% as the AE Load Factor in hoteling mode.

However, the use of the model requires knowledge of information about propeller characteristics and ship design speeds for more accurate data generation. Without this data, emission forecasts will also be less accurate, as it will require the application of average values to be able to advance in the calculations. Another disadvantage that can be observed by the use of average power values refers to the lack of consideration of the application of energy efficiency from ships.

Another key factor that significantly influences the emissions results derived from both methodologies is the AE power. The US EPA (2006) approach utilizes an average value from its tabulated data, whereas the EEA (2019) methodology estimates power based on the GT of each vessel. Table 3 presents an example of the discrepancies between the average powers of the AE adopted for some of the methodologies for different ship types. It is noteworthy that only general cargo ships showed similar values estimated from EEA (2019), USEPA (2006) and CARB (2011), the other ship types presented considerably discrepant values.

**Table 3.** Average auxiliary engine powers indicated by EEA (2019), US EPA (2006), and CARB (2011) for general cargo ships, container ships, and bulk carriers.

Ship type	Average power of auxiliary engines (kW)		
	USEPA (2006)	CARB (2011)	EEA (2019)
General cargo	1,776	1,799	1,552
Container Ship	6,800	8,156	9,871
Bulk Carrier	1,776	2,459	601

**Source:** Adapted Lopes *et al.* (2024)

Although the LRS database is recommended by major methodologies in the literature, its power information for the global fleet may be extensive, yet it lacks broad coverage for AE. Consequently, combining this database with others may introduce greater uncertainties in the estimates, as the data on specific ship characteristics may not accurately represent the actual conditions of the studied fleets. According to Der Meer (2012), ships have an average useful life of 25 years (longer than the road modal). Therefore, new ships have the implementation of emission reduction techniques and more efficient engines, which also generates uncertainties in the estimate.

It should also be noted that the EEA (2019) approach opted for a different methodology for emission estimate, based on the installed power, that when unknown the power of the ME installed, it can be obtained through the relationship described by Trozzi and Lauretis (2019) and, then, the power of the AE installed.

The comparative analysis of the four predominant bottom-up methodologies (US EPA, CARB, EEA, and Der Meer) reveals that the significant discrepancies in final emission estimates stem from variations in both foundational emission factors and operational assumptions. To substantiate the claim of significant differences in total emissions, it is crucial to first analyze the baseline emission factors adopted by each framework. Table 4 presents a consolidated comparison of these FE for air pollutants (NO<sub>x</sub>, SO<sub>x</sub>, PM<sub>10</sub>) and GHG by four methodologies studied, standardized for a container ship's auxiliary engines operating on Marine Diesel Oil (MDO) with a 0.5% sulfur content during hoteling mode.

**Table 4.** FE for air pollutants and GHG from container ships consuming MDO fuel

Methodologies	NO <sub>x</sub>	SO <sub>x</sub> / SO <sub>2</sub>	PM <sub>10</sub>	CO <sub>2</sub>
	(g/kWh)	(g/kWh)	(g/kWh)	(g/kWh)
US EPA (2009)	13.9	2.27*	0.49	691
CARB (2011)	13.9	2.10	0.31	722
EEA (2019)	14.2	2.27	0.80	-
Der Meer (2012)	12.0	2.27	0.40**	-

**Caption:** \*SO<sub>x</sub> Adjustment in the US EPA: The original EPA table (2009) provided a fixed factor of 4.24 g/kWh based on a higher historical sulfur content (approximately 1.0% to 1.5%). Mathematically adjusting for the 0.5% S limit and considering the US EPA (2009) SFC of 227 g/kWh, the correct value for comparison is 2.27 g/kWh (the same adopted by the European and Dutch methodologies) \*\* Adopting PM fator = 1.76 g/kg fuel (CE Delft., 2021).

**Source:** The authors.

As demonstrated in Table 4, even when normalizing the fuel type and operational mode, inherent differences between the methodologies can be observed. For instance, PM<sub>10</sub> estimated vary by over 150% between CARB (0.31 g/kWh) and EEA (0.80 g/kWh). These foundational discrepancies are then amplified when applied to operational variables, such as engine power and load factors.

The practical application of these methodologies across various global ports reveals significant discrepancies that reinforce the need for local validation. At the Port of Piraeus (Greece), the application of the US EPA methodology demonstrated that inventory accuracy is highly sensitive to maneuvering profiles, showing that generic load factors may underestimate emissions in high-density ports (Fuentes García et al., 2021). Similarly, at the Port of Busan (South Korea), the use of the EEA Tier 3 model integrated with AIS data allowed for a precise

quantification of PM<sub>2.5</sub> reductions, highlighting the effectiveness of this approach for monitoring regional decarbonization goals (Kwon et al., 2023).

Recent studies at the Itaguaí Port Complex (Brazil) using the Der Meer methodology indicated that container ships have significantly higher energy demand and fuel consumption than bulk carriers, directly impacting atmospheric pollutant dispersion in coastal regions (Lopes et al., 2024). Furthermore, comparing CARB and US EPA models in the context of tankers on the US West Coast revealed that while both are activity-based, CARB's frequent emission factor updates tend to better reflect technological innovations in the modern fleet (CARB, 2025).

### **Factor 2: Fuel Consumption**

Only Der Meer (2012) adopts the "fuel consumption" as a key factor in its emissions estimation methodology. He presents a mechanism for fuel consumption estimating by means of the GT per time unit, according to the operation mode and ship type. The analysis of the average fuel consumption by ship types that traveled in the Port Complex of Itaguaí - Brazil published by Lopes *et al.* (2024) showed that container ships had higher energy demand and consequently higher fuel consumption than bulk carriers and cargo ships in general.

However, additional factors must be considered when estimating pollutant emissions based on fuel consumption. According to Doundoulakis and Papaefthimiou (2020), the specific fuel oil consumption can vary depending on the physicochemical properties of the fuel, which are directly linked to its quality, such as water content, lower calorific value, sulfur content, and ash content. Additionally, fuel consumption is influenced by the physical characteristics of the engine and the ship's mechanical components, which evolve over its operational lifespan and maintenance routines.

### **Comparison of Methodologies**

The Table 5 is presented in order to summarize the main characteristics observed in the methodologies used in the estimates of atmospheric emissions from ships. Although, the methodologies differ significantly based on the input data used, according to Lopes *et al.* (2024), the emission estimate proposed by Der Meer (2012) is also higher than the others, as it adopts engine power as a key factor instead of fuel consumption.

**Table 5.** Comparison of methodologies adopted for estimating atmospheric emission from vessels.

	USEPA (2006)	CARB (2001)	EEA (2019)	DER MEER (2012)
Key factor	Medium power	Medium power	Medium power	Fuel
Emission factor	It sets the FE according to the engine type and fuel type.	It sets the FE according to engine type, engine speed, and fuel type.	It sets the FE according to the operation mode and fuel type.	Does not provide the FEs used
Average power of the auxiliary engine	It is based on the values determined by Starcrest Consulting Group LLC, published in the document Emissions Inventory of the Port of Los Angeles (2001)	It is based on the Lloyds-Fairplay PC Register database (2007)	The method proposes the estimation of the average installed power when the factor is unknown	Not applicable
Load Factor	It fixes different load factors according to the ship type involved in the calculation.	It sets the load factors according to the ship type involved in the calculation, with equal values only for bulk carriers and general cargo.	It sets the load factor at 40% for all ships, not considering the different of ship types involved in the estimate.	Not applicable
Variation in S content	It considers the variation of S content in the fuel on equation to adjust FE <sub>SO<sub>2</sub></sub> and FE <sub>PM<sub>10</sub></sub> .	Does not consider the variation of S content in the fuel	Not applicable	It considers the variation of the S content in the fuel on equation to adjust only FE <sub>SO<sub>2</sub></sub>

Source: CARB (2001); EEA (2019); DER MEER (2012); USEPA (2006).

The SO<sub>2</sub> emissions calculated for the methodologies proposed by US EPA (2006) and Der Meer (2012) allow the insertion of information on the sulfur content to estimate the emission factor. In Brazil, the implementation of ANP Resolution No. 789/2019, published by the National Agency of Petroleum, Natural Gas and Biofuels, reduced the S content from 1% to 0.5% of marine fuel oils as of 2021. This type of environmental policy is reflected in the reduction of SO<sub>2</sub> and PM<sub>10</sub> emissions, which are atmospheric pollutants that are directly influenced by the sulfur fraction of the fuel when the US EPA (2006) and Der Meer (2012) methodologies are applied, as these consider the variation in the S content in the calculation of emission estimates. According

to Toscano and Murena (2019), the influence of S fuel content on PM<sub>10</sub> emissions is also more limited, as it is a secondary aerosol and not a primary pollutant, such as SO<sub>2</sub>.

CO<sub>2</sub> emissions can be only possible estimated using the US EPA (2006) and CARB (2001) methodologies, as the other methodologies did not have information to make this estimating. Thus, there is limited methodologies available for estimating GHG.

The selection of the most appropriate inventory methodology is intrinsically dependent on the availability and quality of input data, as well as the specific objectives of port management. The EEA (Tier 3) methodology is particularly suitable for scenarios where direct engine power data is not available for the entire fleet, allowing robust estimates based on Gross Tonnage (GT) and average power-to-ship type ratios (Kwon et al., 2023; Lee et al., 2025). In contrast, the US EPA methodology stands out in port inventories that require a detailed analysis of local pollutants (SO<sub>x</sub> and PM) with dynamic adjustment by fuel sulfur content, being the gold standard for North American ports and regions following national environmental agency guidelines (Fuentes García et al., 2021; Manquele et al., 2025).

For regions with strict berthing regulations and mobile source control, such as California, the CARB methodology is most indicated, as it offers specific load factors and activity profiles for at-berth operations and maneuvers (Daniel et al., 2024; CARB, 2023). Finally, the Der Meer methodology presents a strategic advantage in studies where fuel consumption is the central available metric, allowing a direct correlation between ship tonnage and energy demand (Borén et al., 2023; Lopes et al., 2024).

### Estimation Uncertainties

After surveying the literature of different methodologies, it is possible to verify a large difference between the reported emission factors, since they differ in specific factors such as the correlation with the fuel type used, related operation mode, and engine type. The SO<sub>2</sub> emissions for the methodologies proposed by US EPA (2006) and Der Meer (2012) allow the insertion of information on the sulfur content to estimate the emission factor, which reduces the uncertainty of this variable in the estimation of the rate of emissions of these pollutants, as it inserts more detailed information on the fuel quality. Cooper (2002) presents an estimate of the uncertainty levels for the FE where, considering the 95% confidence interval, the FE<sub>NO<sub>x</sub></sub> at the time of anchoring would present a relative uncertainty of 30% to the assigned value and the FE<sub>SO<sub>2</sub></sub> presents an uncertainty of 20% to the assigned value.

Yuan *et al.* (2016) already highlighted in their work the uncertainty quantification of CO<sub>2</sub> emission reduction for maritime shipping, given the lack of standardization in information when preparing emissions inventories, since for CARB (2011) and US EPA (2006) methodologies adopt different input datas for estimating. In the study conducted by Lopes *et al.* (2024), the estimated emissions using the USEPA (2006) and EEA (2019) methodologies showed differences of 25% and 48%, respectively, for NO<sub>x</sub> and PM<sub>10</sub> at the Port Complex of Itaguaí, Brazil, in 2021.

Another factor of uncertainty is attributed to the methodologies used, since it was found that most of the methodologies use LRS database, due to the lack of technical specifications of the ships, such as the ship type in question and other more detailed information such as the engine types installed, as well as their speed and power. It is also noteworthy, with regard to the Gross Tonnage factor, used in the EEA (2019) and Der Meer (2012) methodologies, they consider the conversion of gross registration tonnage to gross tonnage referring to the oldest fleet (from 1997) used for calculation, considering the International Convention on the Measurement of Ship Tonnage of 1969, adopted by the IMO in 1969.

Regarding the emission factor parameter, Nunes *et al.* (2017) emphasize the need for new campaigns and/or onboard measurement studies to obtain experimentally validated emission factors. However, this process is challenging due to operational and budgetary constraints, as it involves relatively high costs. Consequently, emission factors from the literature are commonly used, introducing a significant uncertainty source, as they do not precisely reflect actual conditions. Due to this issue, Ekmekçioğlu *et al.* (2020) assessed of shipping emission factors through monitoring and modelling studies and Huang *et al.* (2020) proposed a dynamic calculation of ship exhaust emissions based on real-time AIS data. Both researchers showed solutions to discover a more sustainable method for updating emission factors applied in developing emission inventories.

## CONCLUSION

The methodologies adopted worldwide for estimating atmospheric emissions by vessels are activity-based, which involve either the release of energy or the fuel consumption by the engines, according to the operation mode and ship types. This critical assessment highlights that the divergence in vessel atmospheric emission estimates is not merely a reflection of model choice, but a direct consequence of distinct assumptions regarding baseline emission factors and operational variables.

The standardized comparative analysis in g/kWh revealed that, even for the same fuel type and vessel class, emission factors exhibit substantial variations, with discrepancies that can exceed 150% for specific pollutants such as particulate matter. Furthermore, the discussions integrated into the results demonstrate that this uncertainty is significantly amplified by assumptions concerning the installed power and load factors of auxiliary engines during hotelling.

As practical guidance for port environmental management, the study concludes that the EEA methodology is preferable in data-scarce scenarios, whereas the US EPA and CARB approaches offer greater precision for high-resolution local inventories, provided that granular operational data is available. This fact suggests the need for the development of experimental studies to obtain emission factors appropriate to the circulating fleet, as well as new methods of measurement on board ships, to reduce the uncertainties of emission factors. Similarly, obtaining data on a vessel's operations at port terminals from the local port authority or other reliable local organizations can provide valuable and accurate operational information. In addition to the adoption of data from the technical specifications of the ships, such as main and AE power, and load factor, made available by engine manufacturers.

Among the methodologies addressed, the method proposed by the US EPA (2006) proved to be the most comprehensive in terms of considerations addressed in the estimating, such as the fact that it considers the variation of the sulfur content to adjust the emission factors of SO<sub>2</sub> and PM<sub>10</sub>, reflecting more accurately the fuel used, thus providing a refinement in the results. In addition, it also proposes emission factors for CO<sub>2</sub>, thereby incorporating the GHG emission inventories. Moreover, this methodology enables the estimation of CO<sub>2</sub>, which is regulated under the IMO's strategy to decarbonize international maritime transport.

Finally, it is concluded that it is necessary to improve the process of data collection and availability, to improve, update, and standardize the information adopted by the bottom-up methodologies. A reliable emissions inventories can be an important tool for the development of mitigation strategies and environmental policies aimed at reducing the negative health impacts caused by the air pollution from port activities.

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