Assessing Ship Emissions: An Estimation Approach Applied to the Port of Catania (Italy)

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Abstract. In recent years, reducing emissions from maritime transport has become a priority for many port cities. Indeed, ships are a significant source of pollutants such as carbon dioxide (CO_2), nitrogen oxides (NOx), sulphur dioxide (SO_2), particulate matter (PM) and other pollutants that contribute to air pollution and climate change. The problem is particularly relevant in ports, where ships spend long periods at berth with their engines running to keep on-board systems running, an operational phase known as hoteling. To address this problem, there are different methods of monitoring ship emissions. One approach is direct monitoring, which involves the use of sensors that are installed on ships or in the vicinity of port areas to measure the amount of pollutants being emitted. Although it provides very accurate data, this approach involves high costs and requires specialized equipment. Another methodology is the fuel consumption-based emission inventory, which uses data declared by ship operators. However, this approach may be affected by inconsistencies in reporting and does not always provide precise emission estimates for specific ship activities and operating conditions. In this work, emissions are estimated using available data, including technical characteristics (such as gross tonnage, engine power, etc.) and ship operational information (such as arrival and departure times, dwell time, etc.). Special attention is paid to the time at hoteling, i.e. the period during which the auxiliary engines remain active while the ship is at hoteling, as it contributes significantly to the total emissions. The estimation is based on regression curves and considers variables such as load factor and pollutant-specific emission factors. The necessary information was obtained from databases such as the Automatic Identification System (AIS) and international studies. In this context, the port of Catania was chosen as a case study to analyze the contribution of Ro-Ro ships to local emissions. This type of ship, used to transport vehicles and rolling stock, is among the main sources of pollution. Estimates show that fuel consumption and emissions vary significantly depending on the size and frequency of ship trips, highlighting the importance of

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targeted strategies to reduce environmental impact. This analysis thus provides a useful framework for understanding the dynamics of maritime pollution and represents a first step towards a more detailed and in-depth quantification of emissions, taking the selected case study as a reference.

Keywords: Vessel emissions · Maritime transport · Air quality · Estimation models

1 Introduction

Maritime transport plays a key role in global trade and economic development, enabling the movement of goods and passengers over long distances. However, it is also a significant source of air pollution, contributing to emissions of carbon dioxide (CO_2), nitrogen oxides (NOx), sulphur oxides (SOx), particulate matter (PM) and other harmful pollutants [1]. These emissions, mainly generated by marine engines and fossil fuel combustion, have serious environmental implications, especially in coastal and port areas where shipping activities are concentrated [2].

Among the various operational phases of ships, hoteling, i.e. the period during which ships remain docked with their auxiliary engines running to ensure power on board, is one of the main causes of local pollution [3, 4]. This problem is particularly relevant in ports located near urban centers [5, 6], where ship emissions directly affect air quality and public health [7, 8]. Indeed, emissions in ports are a growing challenge for environmental sustainability, which has integrated the environmental impact of ports into European and international policies [9, 10]. In this context, reducing emissions is closely linked to the Sustainable Development Goals of the 2030 Agenda [11], including Goal 11 (Sustainable cities and communities), Goal 13 (Combating climate change) and Goal 9 (Industry, innovation and infrastructure) [12]. Measures such as dock electrification (cold ironing) [13], the use of clean fuels, logistical optimisation and emissions monitoring are now key tools for the greening of ports [14, 15].

In this context, effective methods for assessing and estimating ship-generated emissions are essential for the definition of effective operational strategies and environmental policies [16]. Several approaches have been explored [17], including direct monitoring through sensors installed on board ships or in port areas, and indirect methods based on fuel consumption data [14, 18]. Although direct monitoring offers high accuracy, it requires specialized equipment [15, 19] and many ports cannot afford to install sensors due to the high costs associated with their purchase, maintenance, and operation [20, 21]. On the other hand, emission inventories based on fuel consumption may be subject to inconsistencies in reported data, limiting the accuracy of emission estimates for specific activities and operating conditions [22].

In this regard, we proposed a data-efficient approach based on the work of Albo-López et al., 2023 [23] to estimate the emissions generated by Ro-Ro vessels during the hoteling phase in the port of Catania. The choice of this specific case study is based on several reasons: the port of Catania is a medium sized port with mainly Ro-Ro traffic, a characteristic common to many ports in the Mediterranean basin, making it representative for the validation of the proposed model. These conditions allowed

a solid application experiment, useful to verify the effectiveness of the method in a realistic operational context. The approach adopted is based on a bottom-up methodology with low information requirements, based on the use of ship technical and operational data (AIS), and is designed to be replicable in other port contexts, both nationally and internationally. It allows not only to estimate emissions as a function of docking time, but also to assess the relative influence of variables such as ship size and docking time.

It is characterized by low data requirements, relying on the technical characteristics of ships and on operational data. The approach uses information provided from the Automatic Identification System (AIS) and emission estimation models to quantify the environmental impact of ship operations. Additionally, it assesses the relative influence of various factors, such as ship size and the time spent in port, on emission levels.

The reminder of the paper is organized as follows: after the introduction in Sect. 1, Sect. 2 analyses the case study of the port of Catania, describing its geographical and operational characteristics and the importance of Ro-Ro traffic in this area. After that, in Sect. 3, the methodological approach is detailed through the data collection process, the emission estimation models and the use of regression analysis to refine the calculations. The results obtained, summarised in Sect. 4, highlight the main trends in emissions and the reliability of the estimation methods applied. Finally, the study concludes with a discussion of possible implications and indications for future research aimed at improving the accuracy of the estimates and supporting more sustainable maritime policies.

2 Case Study

2.1 Territorial Framework

Within this section we introduce the analyzed case study of the port of Catania, a strategic infrastructure for maritime traffic in the Mediterranean basin, located on the east coast of Sicily (Fig. 1).

The strategic geographical position of the port of Catania extends its influence over the entire regional territory. As an important hub, it supports a land area represented by six of the nine Sicilian provinces, with a total population of three million inhabitants [24]. Its management falls under the jurisdiction of the Port System Authority of the Sea of Eastern Sicily, which also oversees the port of Augusta.

The port of Catania is located close to the historical city center, a characteristics that has influenced both urban development and local socio-economic dynamics (Fig. 2). This proximity creates opportunities for port-city integration, while also posing challenges in spatial planning and historical heritage preservation. Moreover, it raises concerns about pollutant emissions and their impact on urban air quality. The main sources of emissions in the port include docked ships, cargo handling activities and associated vehicular traffic. This study focuses on the docking phase, which has the greatest influence on the emission impact.

In this context, the port of Catania represents a particularly important case study: its strategic location, proximity to the city centre and the nature of its predominantly ro-ro traffic make it an emblematic example for assessing the local impact of ship emissions. These characteristics, together with the possibility of accessing operational data,

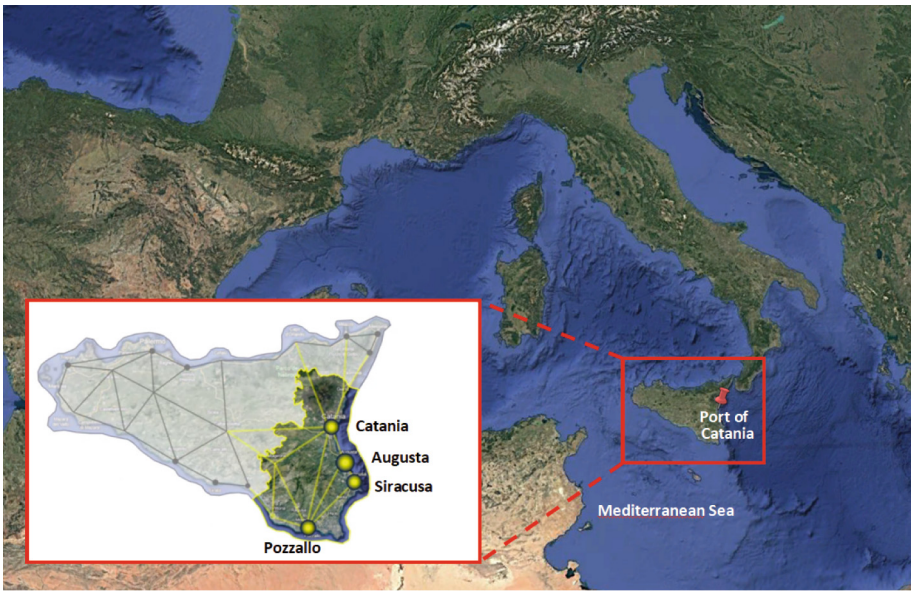

Fig. 1. Territorial framework. Source: Author elaboration from Google Earth



Fig. 2. Port layout and proximity to the city center. Source: Author elaboration from Google Earth

make it an ideal test-bed for testing replicable estimation methods in ports with similar configurations.

2.1.1 Traffic

The port of Catania has a total area of approximately one million squares meters (i.e. land and water areas). The land areas cover 470,000 sqm, the cargo storage yards 280,000 sqm and the total length of the berths of the 26 operational quays is 4200 ml.

It is characterized by predominantly handling Ro-Ro (Roll-on/Roll-off) ships, as well as ferries and cargo units. A total volume of around 7.5 million tons was recorded in 2023, handling over 6.6 million tons for Ro-Ro, followed by containers (around 528,000 tons) and dry goods (over 419,000 tons). The number of containers handled, expressed in Twenty-foot Equivalent Units (TEUs), was 53,212, (Table 1).

Table 1. Traffic within the Port of Catania. Source: Port Authority System [24]

	2020	2021	2022	2023
TOTAL TONS	8.324.867	8.064.127	7.862.342	7.585.488
LIQUID GOODS tons	0	0	0	0
DRY GOODS tons	342.724	373.203	355.995	419.842
GENERAL CARGO tons	7.982.143	7.690.924	7.506.347	7.165.646
Of which				
Container	568.429	557.413	499.225	527.954
Ro-Ro	**7.413.714**	**7.133.511**	**7.004.137**	**6.637.329**
Other	0	0	2.985	363
NUMBER OF SHIPS	1.551	1.380	1.392	1.410
PASSENGER SHIPS RO-RO RO-PAX	56.945	8.118	5.553	4.682
CRUISE PASSENGERS	4.673	12.273	154.152	221.558
Disembarked/embarked in port	711	730	34.454	57.696
In transit	3.962	11.543	119.698	163.862
NUMBER OF CONTAINERS (in TEU)	62.177	58.471	51.666	53.212

The Port Authority's strategy for the future is to further diversify traffic. The plan is to increase the share of dry bulk and containers and gradually reduce the dependence on liquid bulk, which is traditionally less sustainable. An important step in this direction is the transfer of container traffic to the Port of Augusta, which has more space and infrastructure better suited to this type of activity.

From an infrastructure point of view, significant measures are being implemented to improve the port's competitiveness. These include the rehabilitation of the commercial dock and a dock electrification project. With an investment exceeding €56 million, the electrification initiative will reduce ship emissions while at dock, contributing to the port's environmental sustainability.

As stated above, the Port of Catania is an important hub for Ro-Ro transport, allowing the rapid movement of trucks and trailers between Sicily and the rest of the Mediterranean, reinforcing the port's role in the Motorways of the Sea (from Italian "Autostrade del Mare"). The timing of operations for these Ro-Ro ships can vary depending on several factors, including the specific type of operation carried out and the frequency of sea connections [25, 26]. This variability adds complexity to the estimation of emissions, as it can influence the ship's hoteling time within the port. In this regard, we propose a data-efficient approach based on real data provided by the Automatic Identification System (AIS).

3 Methodological Approach

We propose an estimation approach, which uses ship-specific data to estimate port emissions from one of the operational phases, i.e. the hoteling one. The method considers the structural characteristics of the ships and the operational parameter linked to the hoteling phase, retrieved from AIS data. Among those, we consider (i) the *time of hoteling* (T_h), and (ii) the *Gross Tonnage (GT).*

The methodological approach is characterized by three phases:

1. Data collection;
2. Model emission estimation;
3. Estimation using regression curves.

3.1 Data Collection

Structural characteristics and operational parameter of ship is retrieved from AIS data, collected through the Vessel Finder platform [27]. AIS provides a wide range of information, which can be divided into three main categories: static data, dynamic data, and operational data. For this work, the *Gross Tonnage (GT)* which represents a measure of a ship's internal volume and can influence energy consumption and emissions during the hoteling phase. It has been directly exported by AIS data. Additionally, we retrieved other information such as the dimensions of the ship in terms of length and width, draw-ing which indicates how deep the ship is in the water and depends on the cargo carried, Deadweight (DWT) which is the total carrying capacity of the ship and IMO number, as the unique identification code of each ship. These data provide an overview of the main characteristics of each ship, useful for identifying cargo capacity, size and international registration.

We also collected the *time of hoteling* (T_h), which refers exclusively to the duration of the berthing phase, during which the ship remains at the berth with the auxiliary engines running to ensure on-board services (hoteling). It does not include the waiting, manoeuvring or handling phases. This choice is motivated by the fact that emissions from auxiliary engines during the hoteling phase are a significant contributor to local pollution in ports..

3.2 Model Emission Estimation

Typically, commercial ship estimations are estimated based on each trip, considering the different phases of the journey: cruising, maneuvering and hoteling. In this work, the hoteling phase is considered in relation to the cruising and maneuvering phases because, while the latter involve movement and operations at sea that generate emissions, the hoteling phase occurs when the ship is stationary in port, using auxiliary engines (AEs) to generate electricity powering onboard services. During this phase, the ship continues to consume fuel and emit pollutants without moving, making it a significant source of local pollution, which is especially relevant for ports located near city centers, as in the case study analyzed.

The estimation of the emissions for AEs during hoteling phase $E_{Hoteling,\,i}$ is calculated with Eq. (1), according to [23]:

$$E_{Hoteling,i} = \frac{T_h P_{AE} LF_{AE} EF_i}{10^3} \tag{1}$$

where:

i: pollutant (NOx, SO2, CO2, VOC, PM, CO, N2O);

T_h: time for hoteling (h);

P_{AE}: auxiliary engine nominal power (kW);

LF_{AE}: auxiliary engine load factor;

EF_i: emission factor of "i" pollutant (kg/kW).

From the World Fleet 2010, which relates to Ro-Ro Cargo ships we calculate power of the installed main engine P_{ME} as a function of *GT* [22] (Eq. 2):

$$P_{ME}(kW) = 164{,}578 \cdot GT^{0{,}4350} \tag{2}$$

Then, to obtain the auxiliary engine power for hoteling P_{AE}, P_{ME} must be multiplied by the estimated average auxiliary/main engine ratio (AE/ME) of 0.24, again according to Trozzi per ship type [28].

The accuracy of port emission estimates is highly dependent on the reliability of the emission factors available in the literature, which have significant uncertainties related to vessel type, engine and operating conditions. For the purposes of this paper, emission factors have been taken from [29], which presents a recent and comprehensive study related to emission factors considering the above mentioned features. For ships docking in European ports, ships with engines that can only use marine fuel with a sulphur content limit of 0.1% by mass, such as marine gas oil (MGO) of 0.1%, are considered, (Table 2). Furthermore, for the sole purpose of comparing results due to uncertainty in emission factors, other emission factors from different literature sources are used, in particular the emission factors for hoteling for auxiliary engines from 'USA EPA 2009', (Table 3) [30] and 'ENTEC 2010', (Table 4) [31].

3.3 Estimation Using Regression Curves

Finally, emission estimation based on regression curves is used to establish empirical relationships between the technical parameters of ships and generated emissions.

Table 2. AE emission factors (g/kWh) for hoteling. Source [29].

Engine/Fuel Type	NOx	PM10	PM2.5	SOx	CO_2	VOC	CO	N2O	CH4
Medium-speed/0.1% MGO	12.2	0.19	0.17	0.42	696	0.4	1.1	0.029	0.008

Table 3. AE emission factors (g/kWh) for hoteling USA EPA 2009. Source [30]

Fuel Type	NOx	PM10	PM2.5	SOx	CO_2	VOC	CO
0.1% MGO	13.9	0.18	0.17	0.42	690.71	0.4	1.1

Table 4. AE emission factors (g/kWh) for hoteling ENTEC 2010. Source: [31]

Engine/Fuel Type	NOx Pre-2000 Engine	NOx Fleet Average	SO_2	CO_2	VOC	PM10-PM2.5
Medium-speed/0.1% MGO	13.9	13	0.9	690	0.4	0.3

The main objective of using regression is to create a model that allows emissions to be estimated from readily available variables. This approach is useful when direct data on ship-specific emissions are not available.

The reliability of the model is assessed through statistical indicators, Correlation coefficient R^2 and standard error of the regression.

4 Implementation and Results

The emission estimation was conducted on Ro-Ro vessels operating in the port of Catania, focusing on the hoteling phase, during which the auxiliary engines remain switched on to produce electricity.

First, AIS data were collected from the ships that called at the port of Catania and among those, only Ro-Ro Cargo ships were selected. These data refer to a 10-day period between October and November 2023 (Table 5):

As shown in the table, ships are generally similar in size, except for EcoItalia, which belongs to a new generation. According to Eq. (2) we calculated P_{ME}, and by multiplying it for the estimated average auxiliary/main engine ratio (AE/ME) we obtained P_{AE} (see Table 6). From Fig. 3 it can be observed that also for EcoItalia, the P_{AE} is higher than other ships.

Once P_{AE} for each ship was obtained, the estimation of $E_{Hoteling,\,i}$ of Ro-Ro ships was carried out using Eq. (1) (Table 7), considering a (LF_{AE}) of 0.4 corresponding to the stay in port (i.e. hoteling) [23], in applying emission factors from the Port of Los

Table 5. Structural characteristics and operational parameter of selected Ro-Ro ships. Source: Authors' Data Retrieval from VesselFinder.com

Ship list	length/width	Drawing	GT [t]	DWT [t]	N. IMO	T_h [h]
ECO ITALIA	238 / 34 m	6.9 m	67,311	18,080	IMO 9859612	46
EUROCARGO ALEXANDRIA	201 / 26 m	7.6 m	32,843	10,773	IMO 9465540	20
EUROCARGO CATANIA	193 / 26 m	6.3 m	29,429	11,320	IMO 9503627	55
EUROCARGO MALTA	200 / 26 m	7.3 m	32,841	10,787	IMO 9465514	66
EUROCARGO ROMA	200 / 26 m	7.5 m	32,839	10,786	IMO 9465526	24
EUROCARGO SAVONA	193 / 25 m	6.4 m	29,429	11,415	IMO 9457191	57
EUROCARGO VENEZIA	200 / 26 m	7.8 m	32,841	10,765	IMO 9465552	37

Table 6. Estimated power consumption of main and auxiliary engines (kW).

Ship list	P_{ME} [kW]	P_{AE} [kW]
ECO ITALIA	20729.52	4975.08
EUROCARGO ALEXANDRIA	15171.36	3641.13
EUROCARGO CATANIA	14464.02	3471.37
EUROCARGO MALTA	15170.95	3641.03
EUROCARGO ROMA	15170.55	3640.93
EUROCARGO SAVONA	14464.02	3471.37
EUROCARGO VENEZIA	15170.95	3641.03

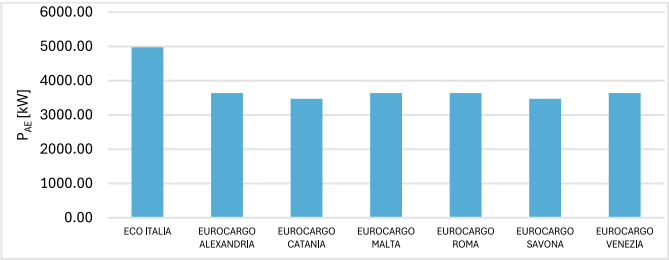

Fig. 3. Auxiliary engines' consumed power (kW)

Angeles 2020 [29]. Results are summarized in Table 7, which provides an overview of the contribution of this category of ships to port air pollution.

Table 7. Emissions (t) estimated from engine power by the emission factors of 'Port of Los Angeles 2020'.

Ship list	Nox [t]	PM10 [t]	PM2.5 [t]	SOx [t]	CO_2 [t]	VOC [t]	CO [t]	N_2O [t]	CH_4 [t]	Total per Ship [t]
ECO ITALIA	1.12	0.02	0.02	0.04	63.71	0.04	0.10	0.00	0.00	65.04
EUROCARGO ALEXANDRIA	0.36	0.01	0.00	0.01	20.27	0.01	0.03	0.00	0.00	20.70
EUROCARGO CATANIA	0.93	0.01	0.01	0.03	53.15	0.03	0.08	0.00	0.00	54.26
EUROCARGO MALTA	1.17	0.02	0.02	0.04	66.90	0.04	0.11	0.00	0.00	68.30
EUROCARGO ROMA	0.43	0.01	0.01	0.01	24.33	0.01	0.04	0.00	0.00	24.83
EUROCARGO SAVONA	0.97	0.02	0.01	0.03	55.09	0.03	0.09	0.00	0.00	56.24
EUROCARGO VENEZIA	0.66	0.01	0.01	0.02	37.51	0.02	0.06	0.00	0.00	38.29

Figure 4 shows how these emissions vary with *Th* and *GT*, for each pollutant:

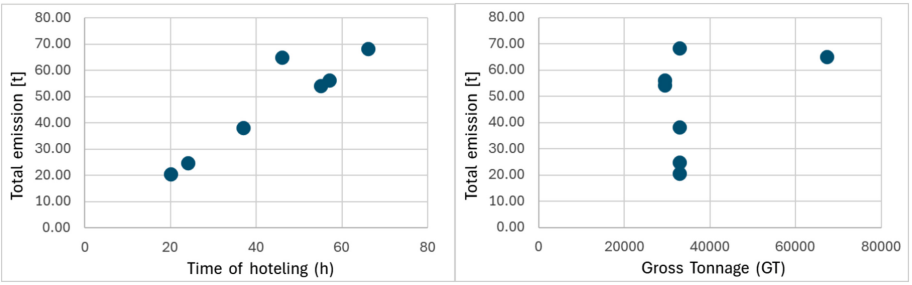

Fig. 4. Analysis of the influence of hoteling time (Th) and GT in emission estimation. Source: Author elaboration.

From these graphs, it can be seen that emissions increase as the hours spent in berth increase, but this is not the case for GT. In fact, in the estimation of total emissions, the weight of hours spent at berth is greater than that of GT. Therefore, the option of performing a simple regression based only on T_h is also considered. These regression

curves are implemented by using the Data Analysis tool and coefficients are reported in Table 8.

Table 8. Regression curves. Source: Author elaboration.

Regression Type	Equation	R^2
Simple linear	$E_{total} = 1.021th + 2.3213$	0.8632
2nd-degree polynomial	$E_{total} = -0.0141th^2 + 2.2026th - 18.837$	0.8885

Results are influenced by the limited number of measurements included in the methodological application. Nevertheless, we can observe that the second-degree polynomial curve has a slightly higher reliability.

If one compares the total emissions obtained with those resulting from the regression curves using Eq. (1), one can see that, for the "Eurocargo" ships, the values obtained with the regression curves are very similar to those calculated, for the "EcoItalia" ship, on the other hand, lower values are found (Table 9).

Table 9. Results comparison of the total emissions (t) estimation with model and applying regression.

Ship list	GT [t]	T_h [h]	Total emissions [t]	Linear Regression [t]	2nd-degree Regression [t]
ECO ITALIA	67,311	46	65.04	49.29	52.65
EUROCARGO ALEXANDRIA	32,843	20	20.70	22.74	19.58
EUROCARGO CATANIA	29,429	55	54.26	58.48	59.65
EUROCARGO MALTA	32,841	66	68.30	69.71	65.12
EUROCARGO ROMA	32,839	24	24.83	26.83	25.90
EUROCARGO SAVONA	29,429	57	56.24	60.52	60.90
EUROCARGO VENEZIA	32,841	37	38.29	40.10	43.36

This demonstrates that a different type of ship influences the correlation with emission estimates, thus, we need to analyze similar ships to enhance a better understanding of this phenomenon. This simplified method would be much quicker and more useful when making an initial estimate of the total emissions from Ro-Ro ships in the port of Catania.

The analysis also showed that hoteling time (Th) has a greater impact on emissions than other parameters, such as gross tonnage (GT). This result can be attributed to the relatively homogeneous composition of the Ro-Ro fleet operating in the port of Catania, where ships present similar dimensions and little variation in GT values. This homogeneity limits the predictive effectiveness of GT in the regression models applied, while Th shows greater variability and is confirmed as the most significant explanatory variable for estimation purposes.

5 Conclusions and Future Research

This study proposed the implementation of a data-efficient methodology prosed in literature for estimating emissions from Ro-Ro vessels in the port of Catania, focusing on the phase in which ships remain docked in port with their auxiliary engines running to ensure the operation of on-board systems, i.e. hoteling. Based on the analysis of AIS data and emission estimation models, it was possible to quantify the environmental impact of these ships. This methodology is applied when no emission data from sensors are available or when no other type of data is available, as it uses readily available data such as AIS data.

A key finding of the study is that time of hoteling (T_h) has a more significant impact on total emissions than Gross Tonnage (GT), suggesting that emission reduction strategies should focus on limiting docking time or the possible adoption of more sustainable technologies, such as cold ironing (shore power). A regression model was then used to establish correlations between ship operating parameters and emissions. The results showed that second-degree polynomial regression provided better reliability than linear regression, although the difference between the two models was not significant.

This method makes it possible to obtain an initial assessment of the environmental impact of maritime traffic without having to carry out complex calculations. However, emission factors must be taken into account, as these present significant uncertainties.

This type of analysis can provide concrete support to port authorities and local authorities in defining strategies to reduce environmental impacts in line with European sustainability and decarbonisation objectives. The flexibility and scalability of the model also allows it to be applied to other ports with similar characteristics, making the method replicable in different geographical contexts and easily integrated into environmental planning tools.

Future research could be expanded to include several type of ships and longer observation periods, as well as the integration of more detailed data on engine operating characteristics. In addition, the implementation of more advanced predictive models could further improve the accuracy of estimates, contributing to a more sustainable management of maritime transport and emissions in ports.

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