Methodology for predicting maritime traffic ship emissions using AIS data

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ABSTRACT: The aim of this thesis is to develop a methodology to estimate ship emissions of NO_X, SO_2, CO_2, HC and PM using Automatic Identification System data. The methodology includes methods for AIS messages decoding, for ship type identification based on the visited terminal and for ship emission estimation based on the ship technical and operational characteristics. The methodology is implemented in a computational tool, SEA (Ship Emissions Assessment). First, the accuracy of the method for ship type identification is assessed and then the methodology is validated by comparing their predictions with those of two other methodologies. The tool is applied to three case studies, using AIS data of maritime traffic along the Portuguese coast and in the Port of Lisbon for the period of one month. The first case study compares the estimated emissions of a ferry and a cruise ship, with the ferry emitting much less than the cruise ship. The second case study estimates the geographical distribution of emissions in the port of Lisbon, with terminals corresponding to areas of heavier concentration of exhaust products. The third application focuses on the emissions from a container ship sailing off the Portuguese Continental west coast, differing considerably from port traffic since it operates exclusively in cruising mode.

Keywords: Automatic Identification System, Port and Coastal Marine traffic, Ship Emissions.

1. INTRODUCTION

1.1 *Background and Motivation*

Since the first steamboats were built in the XVIII century, maritime transportation has been an active cause of atmospheric pollution. For the particular case of ship emissions, the optimum case to control the mass of exhausted products would be the installation of sensors and transmitters in every vessel, sending data through satellite to its respective flag state. With this implementation being nearly impossible, the estimation of emissions based on data from the Automatic Identification System (AIS) seems a promising alternative. AIS is a system of communications between ships and base stations. Ship's equipped with this tool will automatically send messages reporting operational data, like instantaneous speed, position and heading.

Some parameters in AIS messages are manually input in the system, like draft, destination and Estimated Time of Arrival (ETA). Another issue is the low detail of the ship type data, defining bulk carriers, general cargo, container and ro-ro ships all as Cargo. These are the two main issues with ship emission estimates using AIS, however, there is great potential in this application.

Part of the motivation for this thesis comes from that potential, because, if these issues were to be solved and more information added to AIS messages, the possibilities for other studies and other areas are nearly limitless.

1.2 *Objectives*

The main objective of this thesis is to develop a methodology to estimate emissions from coastal and port maritime traffic using operational data from the Automatic Information System and technical data from a database. In addition to describing the methodology, this thesis develops a tool "SEA" (Ship Emissions Assessment) that after validation is applied to study three different case cases.

1.3 *Thesis Outline*

Chapter 1 introduces the topic to be discussed, the related background and the goals and structure of the work.

Chapter 2 contains the literature review, contemplating an analysis on the most relevant studies on the ship emissions topic, as well as a brief introduction to AIS applications and its main source of error.

Chapter 3 describes the methodology proposed to produce estimates on ship emissions, scrutinizing the different steps of the procedure, from the reading of the AIS messages to the factors applied to the obtained output. This chapter also presents a method to identify ship types based on the visited terminal. This method was developed as an alternative to the poorly description of AIS data on this regard.

Chapter 4 addresses the application of the alternative method to determine the type of ship based on the type of terminals called, discussing its success rate when applied to the port of Lisbon.

Chapter 5 shows the results of this methodology applied to each of the three studied cases. The first case study consists of a particular application of the proposed methodology, comparing the emissions of a cruise ship and a ferry for the duration of the cruise ship's call to the port of Lisbon, and attesting the methodology's credibility by applying data from this study to another methodology, that of Trozzi (2010), and implementing the methodology proposed by this thesis in the modelled data from a third study, Jiang, et al. (2010).After this application, a more general case study is presented, showing the geographical distribution of ship emissions in the port of Lisbon for the period of study.

Finally, to demonstrate the application of the proposed methodology to coastal areas, the emissions are estimated for a container ship sailing along the Portuguese western coast.

Chapter 6 sums up this thesis, presenting the main conclusions and recommendations for possible research works and developments of this field of study

2. LITERATURE REVIEW

Due to its direct and negative impact on human live, exhaust emissions are a common topic of study, with authors continuously investigating new methods to tackle the adverse impact of air pollution. To ensure an accurate and effective implementation of environment-friendly measures, the assessment of emission inventories is a critical step of the process, guaranteeing a precise intervention to the most precarious and hazardous situations. The active measurement of exhausted pollutants for every ship in the world fleet is unattainable. For this reason, sizeable registers of ship emissions are produced with estimated values, with different methods being applied.

Emissions from maritime traffic have been studied by numerous reports, presenting various methodologies to produce estimates or developing emission inventories, with some of the most referenced works being Entec (2002) and IMO (2014).

Commercial databases are generally the source of ships' technical data, especially Lloyds Register, providing detailed information on the world fleet.

Studies are divided on how they obtain values of ship speed. Some used raw values coming from AIS, mostly because this method has reduced necessity for additional calculations. Ship speed based on ship's location also had a significant implementation, with authors defining values based on the distance to port or coast. The same happens for the definition of navigation modes with some literature pieces pointing ship speed as the determinant factor to define its navigation mode, assuming different speed ranges for cruising, maneuvering and in port. These defining thresholds vary between 5 and 8 knots. On the other hand, some studies used the ship's location to determine the navigation mode, considering the distance to the port (when arriving and departing). It's noteworthy the definition by USEPA (2009) of a reduced speed zone, between the terminal and 25 nm of the port, where ships should sail at 5.8 knots.

Emission factors are essential for the estimation of ship emissions. However, due to the resources required to produce reliable emission factors, the majority of studies and reports work obtain their values from the literature, with the most frequent option being Entec (2002). Other important reference for emission factors calculation is Jalkanen et al. (2009) that obtain its values based on the engine's revolution speed. However, the utilization of this method requires very specific technical information of the ship's engines, which is very hard to acquire.

The type of exhausted gases also lacked consensus, with some works, like Smith (2013), focusing only in a certain emission (CO_2 in this particular case) while the majority of consulted literature pieces addressed the five exhausted gases identified in this thesis (nitrogen oxides (NOx), carbon and sulfur dioxides (SO_2, CO_2), particle matters (PM) and hydrocarbons (HC)).

The Automatic Identification System has proven to be a useful tool, applied by authors, especially on studies addressing ship trajectories and collisions, as is the case of Silveira *et al.* (2013). The application of AIS in defining maritime traffic may represent another opportunity for shipping companies to assess their efficiency and design new strategies to augment their gains. However, as Silveira *et al.* (2013) states, AIS' main objective, as a marine routing system, is to contribute to safety of life at sea, protection of the marine environment and safety of navigation in critically conditioned areas.

Despite its usefulness and the amount of information that it provides, AIS' reliability is still highly compromised by human error, not only because the information of certain fields being regularly changed (like draft or destination), but also due to errors while defining settings during the transponder's installation (registering a wrong ship type or name).

Harati-Mokhtari *et al.* (2007) analyzed 400 009 AIS messages from ships leaving or entering Liverpool Bay, between September and October 2005, comparing the data with Liverpool's Vessel Traffic Service Station (VTS) database, detecting and registering inconsistent information and concluding that AIS is not reliable in many cases, greatly due to the ambiguity of parameter filling options, especially regarding navigation status and vessel type.

3. METHODOLOGY FOR EMISSION ESTIMATES

A methodology is proposed for estimating gaseous emissions of nitrogen oxides (NOx), carbon and sulfur dioxides (SO_2, CO_2), particle matters (PM) and hydrocarbons (HC) produced by ships operating in ports and coastal areas.

Figure 1 – Processes for ship emission estimation.

The methodology includes methods for AIS messages decoding, for ship type identification based on the visited terminal and for ship emission estimation based on the ship technical and operational characteristics. This process is illustrated in Figure 1, while Figure 2 provides a more detailed scheme. As Figure 2 illustrates, AIS data is the main input of this methodology, with the dynamic information of types 1, 2 and 3 messages (ship's speed, position and time) being matched with static information messages of type 5 (containing the IMO number, the ship's name, its type, length over all and beam) with correspondent MMSI numbers. This process will generate a profile for the ship, describing both its operation and main characteristics. For the cases when AIS does not identify properly the type of ship, an alternative method must be used, determining the type of ship based on the visited terminal or the vessel's dimensions.

This methodology requires technical information of the ships' machinery, which is not provided by the AIS. For this reason, a database containing main and auxiliary installed powers, engine types (according to its revolution rate, as slow, medium or high-speed diesel engines) and maximum speeds of ships is necessary. If a vessel is identified by AIS but is not in the database, these technical characteristics are approximated according to their ship's type, length and beam.

The emission factors used are obtained from the literature, Entec (2002), and depend on the type of engine as well as the fuel it consumes. As for the load factors, for the main engine are obtained by applying the Propeller's Law, using the AIS-provided speed and the maximum ship speed indicated in the database, for the auxiliary engines, it will depend on the navigation mode, which itself depends on ship speed. With the emission factors, load factors and installed power the estimated instantaneous emission is obtained.

The proposed methodology is implemented in the tool SEA, which divides the process in 5 steps:

i) AIS decoding;

ii) Area restriction;

iii) Ship profile definition;

iv) Emission estimation;

v) Results preparation.

The first step comprises the decoding of AIS data, from the reading of the files containing AIS messages to the sorting of necessary information. As for the second step, it defines the area of study, identifying ships that navigate through it. Those ships are then associated with their correspondent technical data, producing ship profiles, in the third steep. With the ship profiles defined, instantaneous emissions estimates are ready to be calculated, at the fourth step of the implementation. As the fifth and final step, the results of instantaneous emissions are organized to produce the desired output (total amount of emissions, geographical distribution per voyage, geographical grid distribution). The following sections will address with more detail each of these different steps.

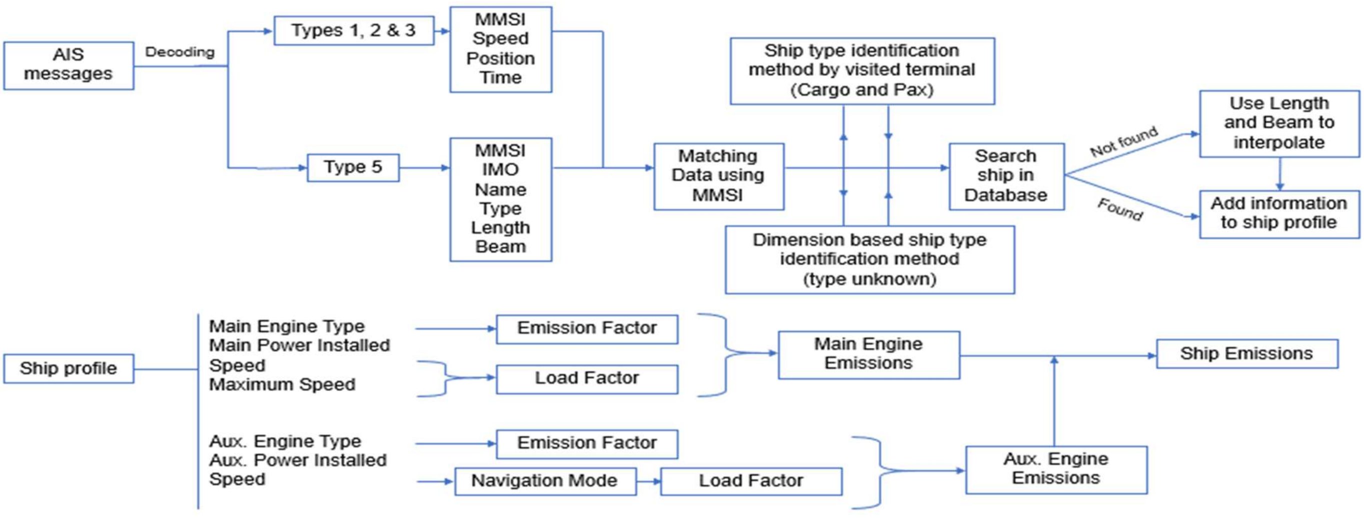

Figure 2 - Methodology for ship emissions estimate.

3.1 *AIS decoding*

A file containing rows of AIS messages is the input for the implementation of this methodology with the tool SEA. When reading each row of this file, the various segments of the correspondent message are isolated and identified. After checking if the message is complete, by comparing the AIS sentence segments respecting message part and message size, the payload is decoded. This is done by cycling through the payload's string, translating every character to their correspondent ASCII value and again to a 6-bit binary vector. By concatenating every 6-bit vector, a payload vector is obtained.

With a complete binary payload, SEA reads the first 6 bits, which define the message type, and finding it to be of types 1, 2 or 3, the implementation tool proceeds to identify the ship's MMSI, speed, latitude, longitude and the message's timestamp.

Using the same file containing AIS messages, SEA reads again each row, each AIS sentence, isolating and identifying each segment. However, this time, after obtaining binary payload, the implementation tool searches for messages identified in the first 6 bits as type 5. Upon finding a message of this type, with a new MMSI number, SEA decodes from the binary vector the IMO number, the length overall and the beam, as well as ship's name and type. The ship type is obtained from the binary payload as an integer, with a table provided by ITU (2005) being used to translate this number to an actual type of ship.

With the data properly defined, SEA saves the numerical variables as a new entry on a matrix, while the ship's name and type are added to cell arrays. It is important to note that the row correspondent to the ship's entry in the matrix will be the same as the one for the cell arrays.

Finally, SEA proceeds to match the information acquired from message types 1, 2 and 3 with that from type 5. Being the only common link between them, the MMSI number is used, adding the new information from type 5 messages to a structure assigned for the ship, containing the information on its activity, previously obtained.

3.2. *Area restriction*

Firstly, the coordinates defining the area of study are manually inputted (being particular to every and each study). Then, the implementation tool starts cycling through ships' matrixes of positions, eliminating entries whose coordinates are not comprised between the limits established for latitude and longitude in the definition of the study area. For each entry eliminated from the positions' matrix, its correspondent entry is also eliminated from the vectors of speed and time. Finished with restricting ship positions, SEA eliminates the remaining data for ships with empty position matrixes.

3.3. *Ship profile definition*

Before assigning technical data to each ship, their ship type is properly defined. This is firstly attempted by applying a method developed by this thesis, defining the type of ship based on the visited terminal. This method's focus are ships defined by AIS as "Cargo", "Passengers" and "HSC", defining them as "General Cargo", "Bulk Carrier", "Container Ship", "Ferry" and "Cruise", accordingly to the type of terminal where the ship more often reveals speeds below 1 knot. For ships identified as "Cargo" without speed values below 1 knot, the specific ship type is assigned according to its length overall and beam.

With ship types properly assigned, SEA proceeds to complete ship profiles by adding the correspondent technical data to their already known information. For ships with defined ship types, the respective database is loaded from a text file and the search method is defined. This is necessary because, while for ferries, tugs, towing vessels and other small vessels the search for the ship's technical data through the database is performed using the ship's name, for the remaining ship types this is done with the IMO number.

When the ship is found in the database, values are assigned for its maximum speed, main engine's as well as auxiliary engine's power, type and fuel. The definition of engine type is based on it's rated revolution rate, with medium speed diesel engines being assigned to values between 300 and 900 rotations per minute. By surpassing this range, the engine is classified as high-speed diesel engine, and when the revolution rate is inferior to 300 rotations per minute, SEA considers the motor to be a slow speed diesel engine.It is noteworthy that cruise ships are well identified in the database and the value assumed there as main engine's installed power (which is going to be used to estimate emissions based on ship's propulsion) is, as Tzannatos (2010), 78.2% of the installed power from generators. For the cases with undefined ship types, the search through databases is still performed, loading the text files one by one. If the ship is not found in the databases, but the its type is well identified, technical characteristics are obtained using the length overall and interpolating data from ships of the same type whose technical information is known. If the ship, besides not being found in aby database, has its ship type undefined, default values are designated for its technical characteristics. These values depend on the length overall, defining three different profiles. Ships with a length overall smaller than 20 meters, are assigned to the small ship's profile (main engine power of 200 kW). From 20 to 60 meters, ships are identified with a profile defined based on technical characteristics of tugs and ferries (main engine power of 1750 kW). Finally, for ships with a length overall surpassing 60 meters, the profile assigns values of engine power using an exponential regression of general cargo ships in the database, relating the installed power with the length overall. As for the auxiliary engines' power, it is a linear regression based on the value of main installed power obtained. With the technical characteristics defined, these values are added to the ship activity existent profile, producing a complete ship profile, ready to be assessed on its emissions.

3.4. *Emission estimation*

At the beginning of this step, filters are applied to the ship's activity data, in order to remove wrongful data and avoid erroneous results. The first filter is applied to all ships, removing entries from their vector of speed values when these surpass the assigned maximum speed. As for the second filter, it is only applied to ferries and seeks to eliminate entries for when the ship is inactive during night hours. With the timestamp vector containing values in seconds, entries are eliminated if they correspond to the first 19 800 seconds of each day (assuming the service is stopped from midnight to 5:30 am).

After verifying that the application of these filters did not emptied completely the operational information vectors and matrix, SEA proceeds to organize in their respective matrixes the values for emission factors, obtained from Entec (2002) and for low-load factors, obtained according to USEPA (2000).

The main engine's load factors are then defined, based on the Propeller's Law, from the cube of the quotient between instantaneous speed and maximum speed. As for the auxiliary engine's load factors, the values are obtained from Entec (2002), depending on the navigation mode.

The base of calculations for instantaneous emissions in grams per second (e) is edited from Yau, *et al.* (2012):

$$e = \frac{P * LF * EF}{3600} \tag{1}$$

According to Equation 1 the instantaneous emissions are defined by the product of the installed power (P), load factor (LF) and emission factor (EF). The denominator converts the output units from grams per hour to grams per second, since, for convenience, the power is inserted in kilowatts, the load factor is unitless and the emission factor (EF) shall be in grams per kilowatt-hour.

Having all the data required, SEA cycles through the vector of ship speed values, calculating the emission estimates which will vary with the navigation modes and main engines load factor, with both these parameters depending on the ship's speed. This concludes the calculation of instantaneous emissions.

3.5. *Results preparation*

The treatment provided to the values of instantaneous emissions depend on the intent and scope of the study in question. The implementation tool is prepared to present total values of emissions and geographical distributions for one or more ships, as well as a grid distribution of emissions from port traffic.

To obtain the cumulative values of emissions, SEA cycles through the previously obtained ship instantaneous emissions, using the trapezoidal numeric integration for the duration of the study. The implementation tool skips over time gaps of 2 hours or more between consecutive data points.

As for the geographical distribution, SEA plots a scatter graphic over an image of the study area, with the xx and yy axis presenting longitude and latitude values, respectively, and a color gradient defining the mass of ship emissions for each represented instant. The geographical distribution of ship emissions using a grid is slightly more complex. For this presentation of results, values of instantaneous emissions are saved in a matrix with the respective position of the ship. Following the storage of data, the implementation tool defines the dimensions of the grid cells. Then, it starts a cycle to run through the range of latitude of the study area, with a spacing equal to the length of the grid cells. Inside that cycle, SEA runs another one for the longitude range, using the width of the grid cells as spacing. This allows the implementation tool to focus each cell individually, searching through the matrix of instantaneous emissions for those with associated positions within the focused grid cell, storing the sum of every value found in a vector. This process is repeated for every type of emission.

With the vector of emissions per grid cell, a figure is produced, with an image of the area of study in the background. The same two cycles are applied through longitude and latitude (it is very important that these cycles are exactly executed in the same order and with the same values as the previous ones), plotting squares in the image and coloring them with a grey-scaled gradient with the maximum value of the emissions-per-cell vector defined as black while the color white defines 0+ emissions (cells registering zero emissions are not plotted, otherwise the whole image would be plotted over and it would be impossible to locate the grid cells in the study area).

4. TESTING THE SHIP TYPE IDENTIFICATION METHOD

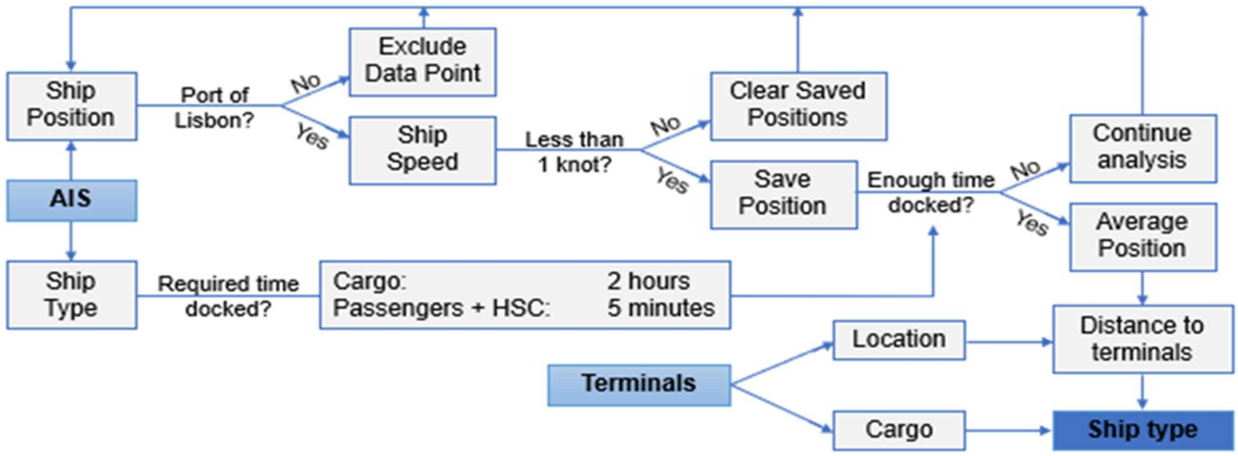

Figure 3 – Method of ship type determination based on visited terminal.

A method is proposed for determining the type of ship according to the visited terminal, being implemented with the tool SEA. Disregarding the utilization of a commercial database, alternative methods, such as this one, should be applied to properly identify the type of ship. As Figure 3 indicates, the inputs of this method are the AIS data, providing information on ship type, position and speed, and the terminal's data, as their location and type of cargo.

With the input being a file containing up to 25 million sentences of AIS communications, SEA, the implementation tool, starts by reading this file, identifying and decoding messages of types 1, 2 and 3, saving operational characteristics to the designated ship profile, generated when a new MMSI number is detected. This process is repeated for type 5 messages, with variables being saved to ship profiles of matching MMSI number.

After decoding and matching AIS messages, SEA searches for ships that visited the studied region for a defined duration. This selection is performed by comparing ship positions against the coordinates defining the area of study. A second selection is made, to obtain exclusively ships whose AIS-defined types matched those targeted by this method ("Passenger", "Cargo" and "HSC").

To determine which terminal is visited by a certain ship, SEA registers ship positions with speeds slower than 1 knot, defining its navigation mode as moored. One very important procedure is the elimination of the saved mooring positions when the speed rises above 1 knot. This reduces the chances of maneuvering ships registering mooring positions away from the visited terminal.

For ships cataloged by AIS as "Cargo", the implementation tool assumes the ship to be visiting a terminal when it is moored for more than 2 hours. The mooring position detected is averaged with the previous four positions received from AIS. As for "Passenger" and "HSC", the time interval is reduced to 5 minutes, due to the short mooring time of ferries, and the registered position is averaged with only the latest 2 points.

After establishing the average position while berthed, SEA calculates the distance to each terminal, using the orthodromic distance. By comparing the distance to each terminal, the shorter value produces an assumption of ship type. This process is repeated for every call detected for the duration of the AIS data provided in the files, defining the ship type as the one most frequently assumed for the ship.

The efficiency of this process was thus evaluated in two distinct phases: Daily assessment, analyzing ships that called in the port of Lisbon on a given day, and, secondly, an individual approach, based on the absolute frequency of correct ship type determinations during daily assessments. Real ship types were defined according to Marine Traffic's website.

Figure 3 illustrates the locations of the studied terminals along the port of Lisbon, while Figure 4 shows the distribution of wrong estimations per terminal and ship type.

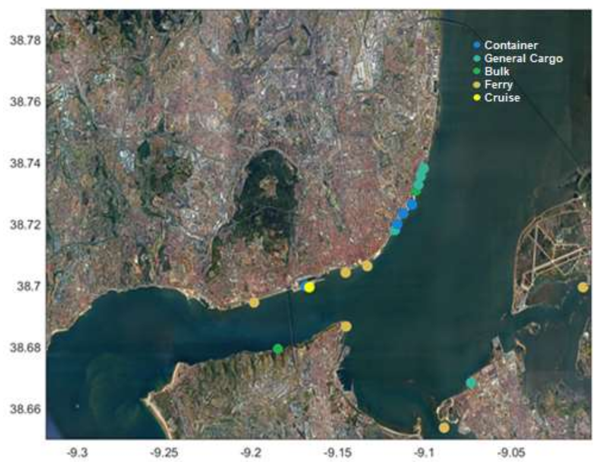

Figure 4 - Studied terminals at the port of Lisbon.

When applying this method to port of Lisbon's marine traffic, between July 9th and August 9th of 2008, it identified correctly 90.7% of calling ships' types, originally identified by AIS as “Passenger”, “High Speed Craft” or “Cargo”.

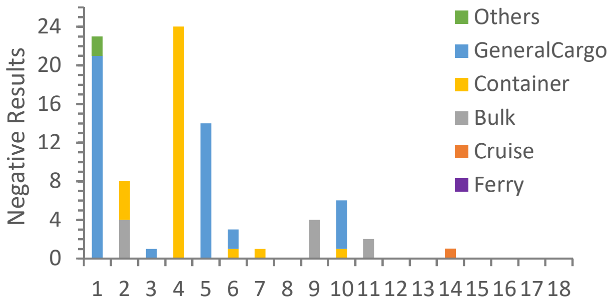

Figure 5 - Distribution of negative results per terminal and ship type.

When evaluating the results per ship, it was observed that 97.7% of passenger vessels were correctly identified, while the correspondent percentage for cargo ships was 77%, resulting in an 81.4% success rate on the identification of ship types based on the visited terminal, using AIS data, which is an acceptable value, to consent, at least for port traffic, its incorporation on the methodology proposed by this thesis.

5. CASE STUDIES

To demonstrate the applications of this methodology, it was implemented solving three different case studies. The first one refers to the determination of ship type based on the visited terminal at the port of Lisbon, presenting the statistical efficiency of this assumption. The first one refers to the maritime traffic of passenger ships, also at the port of Lisbon, comparing emissions of a ferry connecting the North and South banks of the Tagus river (Cais do Sodré to Barreiro) with a cruise ship calling at port of Lisbon’s Alcântara terminal and assessing the credibility of this methodology by applying data from this study to another methodology, Trozzi (2010) and implementing the methodology proposed by this thesis in the modelled data from a third study, Jiang, *et al.* (2010). The second one addresses ship emissions for vessels navigating in the port of Lisbon, presenting its results through a geographical distribution of emissions. The third and final case study demonstrates the application of this methodology to the coastal maritime traffic, showing the emissions of a single ship throughout its voyage along the Portuguese western coast.

5.1. *Cruise vs Ferry emissions at the port of Lisbon*

This case study addresses the contrast in the emissions of a cruise ship, from the moment it enters the port to the moment it leaves (8.7 hours), against the ones from a smaller but more active ferry, for the same period, comparing the results obtained with the presented methodology when applied to two known vessels. Table 1 describes their technical characteristics, while Table 2 shows the time spent in each navigation mode.

Despite both ship types being dedicated to the transport of passengers, there is a significant difference in the operations of a cruise ship and a ferry, inside a port, with the ferry being more active and spending most of the time navigating his everyday-route while the cruise ship is moored for the majority of the call’s duration. Regardless of its more active operation than the cruise ship, as Table 2 illustrates (with a difference of 220 minutes in time spent navigating), with emissions nearly 3 times higher than the moored Cruise ship, the Ferry spent 42% of the duration of the study moored, emitting almost 350 times less than the Cruise ship in the same navigation mode. This was identified as a major cause for the discrepancy observed in the results of total emissions estimations.

Table 1 - Ship's technical characteristics (MSD- Medium Speed Diesel; HSD- High Speed Diesel; MDO- Marine Diesel Oil; MGO- Marine Gas Oil)

	Cruise Ship	Ferry
Propulsion	Electric	Mechanic
Propulsion Power (kW)	28000	4640
Main Engine’s Type	-	HSD
Main Engine’s Fuel	-	MGO
Total Generator Power (kW)	46080	168
Generator’s Type	MSD	HSD
Generator’s Fuel	MDO	MGO
Maximum Speed (knots)	22.4	30

Table 2 - Ship's time distribution per navigation mode (in minutes).

	Cruise Ship	Ferry
Moored	437	218
Maneuvering	17	25
Cruising	69	281
Total	**523**	**523**

For the Cruise ship, emissions are estimated as 0.936 tons, 0.297 tons, 47.978 tons, 0.033 tons and 0.021 tons of NO_X, SO_2, CO_2, HC and PM, respectively.

For the Ferry, emissions are estimated as 54 kg, 20 kg, 3042 kg, 1.9 kg and 1.4 kg of NO_X, SO_2, CO_2, HC and PM, respectively, representing a mass of emissions 14.85 to 17.37 times lower than those of the cruise ship.

The credibility of these first results of emission estimates was tested against the methodologies of Trozzi (2010) and Jiang, *et al.* (2010), revealing relative differences in the results lower than 15%.

5.2. *Distribution of emissions at the port of Lisbon*

Being spread along Tagus' river mouth, as well as both of its shores, it is of the outmost interest to assess the distribution of ship emissions throughout port of Lisbon's geographical domain, providing information on the most affected regions. This was implemented by the tool SEA, presenting a grid distribution with each cell representing an area of 222 by 174 meters, estimating emissions of port traffic from July 9th to August 9th of 2008.

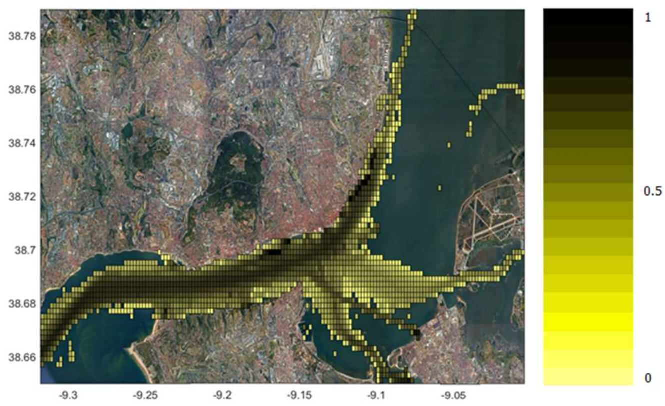

Figure 6 - Distribution of CO2 emissions in the port of Lisbon.

Before proceeding with the estimation of emissions, the fleet under study was divided per ship type, averaging each type's technical characteristics, as in Table 3.

An example of resulting distribution is shown in Figure 5, regarding the emissions of CO_2. Due to the big difference in the order of magnitude from emissions with heavy and scarce emissions, the results were plotted as the logarithmic scale of the ratio to the maximum registered value (highest concentration of instantaneous emissions per cell registering 115 g, 55 g, 5645 g, 4.8 g, 4.1 g of NO_X, SO_2, CO_2, HC and PM, respectively).

Table 3 - Fraction of the observed fleet and averaged technical characteristics per ship type.

	Fleet (%)	ME Power (kW)	AE Power (kW)	Length (m)	Beam (m)
Ferry	30.79	2423	60.7	41.77	10.37
Cruise	1.14	22831	23492	226	28.83
Tanker	7.70	4567	1404	125.15	19.3
Bulk	7.39	6863	1214	160.94	22.7
General Cargo	16.58	3504	619	105	17.89
Container	17.46	10843	2389	152.97	26.9
Port Ops	11.36	526	0	14.54	4.79

As Figure 5 shows, the higher values of emissions appear in coastal areas where terminals are located. To better evaluate the distribution of emissions, these were divided per ship type, and the results are shown in Table 4.

Regarding total emissions, the exhaust product with higher values was the carbon dioxide, with 7999 tons, 53.5 times higher than the emitted mass of nitrogen oxides, the second higher, with 149.4 tons. The emissions of sulphur dioxide reached 36.9 tons. While container ships were the main contributors to SO_2 emissions, ferries emitted more of the remaining exhaust products.

Table 4 - Total emissions per ship type.

	NO_X (t)	SO_2 (t)	CO_2 (t)	HC (t)	PM (t)
Ferry	58.70	6.80	3180.1	1.40	1.50
Cruise	22.40	7.10	1123.9	0.70	0.50
Tanker	4.10	1.40	231.9	0.15	0.13
Bulk	16.67	4.86	964.3	0.61	0.53
General Cargo	5.65	1.87	283.2	0.18	0.14
Container	37.90	13.50	2006.1	1.40	1.10
Port Ops	1.29	0.11	67.7	0.06	0.03
Others	1.41	0.12	74.4	0.06	0.04

5.3. *Ship cruising along the Portuguese coast*

This case study addresses the emissions of a container ship, whose technical characteristics are known (shown in Table 5), navigating along the Portuguese coast, first heading North and 8 days later heading South, not calling at any Portuguese port for the duration of the study.

Table 5 - Container ship technical characteristics (SSD- Slow Speed Diesel; RO- Residual Oil; MSD- Medium Speed Diesel; MDO- Marine Diesel Oil).

	Container Ship
LOA (m)	261
Beam (m)	32.3
Maine Engine's Power (kW)	24300
Main Engine's Type	SSD
Main Engine's Fuel	RO
Total Generator Power (kW)	3990
Generator's Type	MSD
Generator's Fuel	MDO
Maximum Speed (knots)	22

The vessel is firstly detected by AIS during its route heading North. In this leg of the voyage, its journey along the Portuguese coast lasted 17.6 hours, registering an average speed of 18.3 knots, which would represent a distance travelled of 322 nm. Eight days after the first time it was detected, the container ship initiated a second crossing of the Portuguese coast, this time heading South, for 19.1 hours, averaging 18.5 knots through a 354 nm course.

For a single ship operating in cruising mode, the auxiliary engine's operation remains constant and both the main engine's installed power and emission factors also remain unaltered, with the only variating parameter being the main engine's load factor, depending on the cube of the ship's speed, therefore, there is a direct proportionality between the value of instantaneous emissions and the cube of the ship's speed. Figure 6 presents a graphical display of this relation.

For the first voyage, SEA estimated 4.767 tons, 2.686 tons, 167.8 tons, 0.157 tons and 0.204 tons, of NO_X, SO_2, CO_2, HC and PM, respectively. The second voyage registered more emissions, as it was expected due to the its higher average speed, duration and bigger length. The values obtained were 5.325 tons, 3.003 tons, 187.3 tons, 0.175 tons and 0.228 tons of NO_X, SO_2, CO_2, HC and PM, respectively.

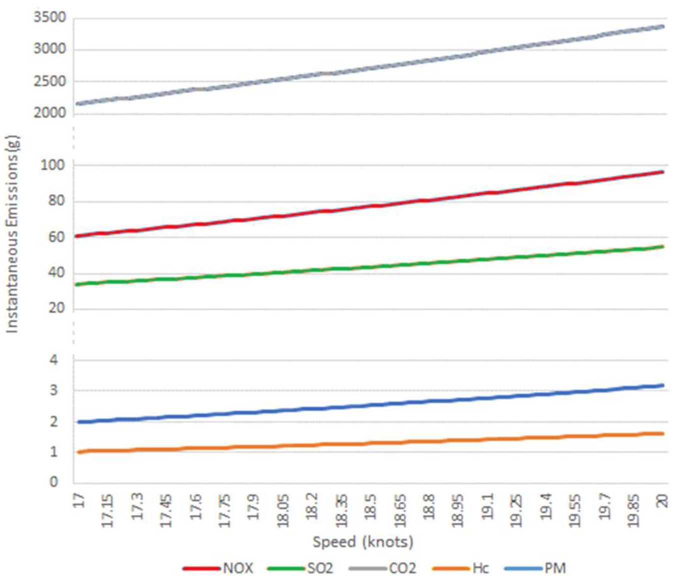

Figure 7 - Relation between instantaneous emissions and ship speed

6. CONCLUSIONS

This thesis proposed and developed a methodology to estimate ship emissions based on data available in messages from the Automatic Identification System, with a computational tool being created to implement said methodology, and an alternative method being designed to estimate ship types based on the visited terminal.

When applied to port of Lisbon's marine traffic, between July 9th and August 9th of 2008, it identified correctly 90.7% of calling ships' types, originally identified by AIS as "Passenger", "High Speed Craft" or "Cargo". The majority of wrong estimations were motivated by the existence of multipurpose terminals.

Despite demonstrating a more active operation than a cruise ship, a ferry spends 42% of the duration of the study moored, emitting almost 350 times less than the cruise, in the same navigation mode. This was identified as a major cause for the discrepancy observed in the results of total emissions estimations.

Ferries represent about 31% of ship calls at the port of Lisbon, followed by container ships and general cargo ships, with respective representations of 17.5% and 16.6%.

It was concluded that the low value of SO_2 emissions was a consequence of the predominance of ferries over the global emissions, since the majority of these vessels are equipped with high speed diesel engines fueled with marine gas oil that has sulphur content of 0.5%. Additionally, it is also associated with the enforcement from the port of Lisbon of the Community Directive 2005/33/EC that regulates the sulphur content of the fueled used by ships as well as the fuel supplied by oil companies, prohibiting fuels with sulphur concentrations above 1.5%.

By only operating in cruising mode, without reducing the main engine's load below 20%, emission estimates depend only on the ship speed, with a linear relation between the instantaneous emissions and the cube of the instantaneous ship speed.

As a final conclusion, the assessment of the accuracy of the alternative method of ship type identification based on the visited terminal and three case studies addressing the estimation of ship emissions put to the test this methodology, allowing satisfactory results to be obtained. It was demonstrated by means of the case studies conducted that the methodology developed is not only accurate but also independent of commercial databases, which was the objective of this thesis.

As recommendations for further work, the methodology proposed in this thesis can be improved by establishing up-to-date empirical and probabilistic models to determine the technical characteristics of ships, allowing its immediate application to the world maritime traffic.

As suggestion for future studies, AIS could be used to evaluate port queues and environmental impacts, due to the unnecessary time in voyage spent by ships, observable in their trajectories described by AIS positions.

Another interesting topic to be developed would be the assessment of water contamination from port traffic, associated with the utilization of humid exhaustion of main engines, as used nowadays in some ferries and towing vessels.

Regarding ship emissions, AIS has the potential to be used in the future to assess and control emissions of the world fleet, in real time. As there are messages in AIS dedicated to dynamic and static data, a new type of message could be included, reporting environmental data and values of instantaneous emissions, power consumptions and type of fuel being used.

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