Evaluating air emission inventories and indicators from ferry vessels at ports

G. De Melo Rodríguez & J.C. Murcia-González
Faculty of Nautical Studies – UPC BarcelonaTech, Barcelona, Spain

E. Martín-Alcalde & S. Saurí
Center for Innovation in Transport (CENIT), Barcelona, Spain

ABSTRACT: This paper provides an estimation of exhaust emissions released by passenger ferries at the port-level. The methodology is based on the "full bottom-up" approach and starts by evaluating the fuel consumed by marine diesel engines on the basis of its individual port-activities (manoeuvring, berthing and hoteling). Specific air emissions are estimated as regards to the different propulsion sources: main engine, auxiliary engines, thrusters and boilers. The Port of Barcelona was selected as the site at which to perform the analysis, in which 25 passenger ferries operating in the Mediterranean Sea were monitored. Real-time data from the Automatic Identification System (AIS), factor emissions from engine certificates, engine loads during port time, and vessel characteristics from IHS-Sea web database were also collected for the analysis. The research findings will improve our understanding of local pollution at port-cities and help to derive appropriate measures to improve air quality.

1 INTRODUCTION

In the context of port-city areas, emissions released into the atmosphere by vessels operating in port negatively affect local communities (Dalsoren et al., 2009) since it has a significant environmental impact on the coastal communities, as 70% of the ship emissions occur within 400 km of land (Eyring et al., 2005).

Moreover, the urban character of some ports and their populated surroundings are the main focus of the negative effects of exhaust pollutants due to the associated local impacts on human health. Thus, the need to control air pollution at ports is widely acknowledged as an active policy issue by various authoritative port associations (IAPH, 2007; ESPO, 2003) as a reaction of main regulations (IMO, EC, EPA, etc.).

A fundamental requirement for emission control, assessing the impacts of growing shipping activity and planning mitigation strategies is developing accurate emission inventories for ports (ICF, 2006). These port emission inventories would aid policy makers in developing effective regulatory requirements or port environmental management systems Tzannatos (2010).

In such a context, the goal of this paper is to develop accurate emission inventories (CO_2, SO_X, NO_X and PM) and emission indicators for ports where passenger ferries are dominant by estimating the fuel consumed by each vessel on the basis of its activities in port.

The paper is organised as follows: Section 2 reviews relevant literature on the issue; Section 3 introduces the methodological approach and the formula used to estimate inventory emissions; Section 4 presents the case study results and the most relevant emission inventories; and finally, Section 5 highlights the main conclusions.

2 LITERATURE REVIEW

According to published research, which incorporates extensive reviews of ship emission estimation methodologies (Miola et al., 2010; Tichavska and Tovar, 2015), a wide variety of studies relate to emission inventories at global or regional levels but only a few do so at the port-level.

The representative approach for emission estimation in port studies was the bottom-up approach, based on port calls and estimated vessels operating at a port (Tichavska and Tovar, 2015). Furthermore, normally activity-based and/or fuel-based estimations were made because of they are more accurate than top-down methodologies that require detailed data such as routing, engine workload, ship speed, location, duration, etc. (Song, 2014).

For example, Goldsworthy and Goldsworthy (2015) have produce a model using AIS data to describe ship movements and operating modes capable of providing a comprehensive analysis of ship engine exhaust emissions in a wide region that contains numerous Australian ports. Tichavska and Tovar (2015) used Automatic Identification System (AIS) data and the Ship Traffic Assessment Modee (STEAM) emission model to calculate emissions from cruise ships and ferries in Las Palmas Port. Chang et al. (2013) calculated the emissions from ships in the port of Incheon, Korea, and compared a bottom-up approach with a top down approach and found large discrepancies.

Winnes et al. (2015) built a model that calculates GHG emissions from ships in various scenarios for individual ports and different kinds of measures for emission reductions. Maragkogianni and Papaefthimiou (2015) presented a “bottom-up” estimation based on the detailed individual activities of cruise ships in the Greek ports of Piraeus, Mykonos, Santorini, Katakolo and Corfu and Dragovic et al. (2015) estimated ship exhaust emission inventories and their externalities in the Adriatic ports of Dubrovnik (Croatia) and Kotor (Montenegro) for the period 2012–2014. The methodology for emission estimation relied on the distinction of various activity phases (manoeuvring and berth/anchorage) performed by each cruise ship call (bottom-up) as a function of energy consumption during each activity multiplied by an emission factor.

The present paper proposes a methodology based on the full bottom-up approach and begins by evaluating the fuel consumed by each vessel on the basis of its individual port-activities (manoeuvring, berthing and hoteling) and differentiating between the main vessel propulsion, auxiliary propulsion, boilers and thrusters.

Unlike previous studies, the input data model is based on empirical data and extended work field (only Cooper (2001) make emission measurements of passenger ferries, but it such case it was on-board during normal service routes) and, on the other hand, it also provides accurate emission indicators (rates per hour, per passenger, per Gross Tonnage (GT) or a combination of all three) for passenger ferries, which can be used by other researches to reliably and quickly estimate emission inventories in other ports at the port-level.

3 METHODOLOGY

3.1 *General approach*

The first step in the evaluation of emissions is the estimation of the fuel consumed by each vessel on the basis of its activities. Specific fuel oil consumption (measured in g/kWh) is therefore an important input to the appraisal. Once the fuel consumption is calculated, it is possible to use emission factors to estimate the emission of different pollutants.

This paper considers the full bottom-up approach but takes into account separately the fuel consumption and emissions of the following propulsion systems of ferry vessels during port operations:

– Main diesel engines as a source of power for propulsion (main propulsion);
– Auxiliary engines for providing electrical energy used during hoteling
– Transversal propulsion (thrusters) for berthing and unberthing operations
– Boilers for steam production used to heat up heavy fuel oil (HFO) fuel and modify its viscosity and for heating up water;

Then, for every vessel call the fuel consumption (based on the power consumed) and corresponding emissions will be estimated for: (a) incoming manoeuvring from the Landfall Buoy to the passenger terminal dock; (b) berthing approach; (c) stay at the terminal dock (port time); (d) unberthing operations and (e) outgoing manoeuvring from the terminal dock to the Landfall Buoy.

Figure 1 shows the methodological framework considered in this paper, in which steps 1 and 2 are related to the input data model and steps 3 to 6 are methodological aspects that are described in Section 3.2.

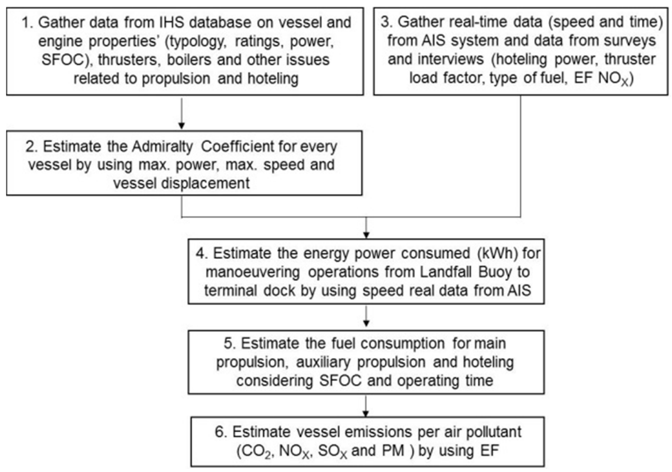

Figure 1. Methodological scheme to estimate air pollutant emissions.

3.2 *Formulation*

In this section, the formulation used to estimate the power and fuel consumption for each type of propulsion is introduced:

3.2.1 *Main propulsion for incoming/outgoing manoeuvring*

The Admiralty Coefficient method is proposed for estimating the propulsion power for manoeuvring, which is based on the basic assumption that the all resistance is frictional and that the power varies as the cube of the speed.

This method, which determines the required propulsion power according to the given ship speed and the displacement, has been used by several authors, such as Tupper (2013), Watson (1998), Taylor (1996) and Schneekluth and Bertram (1998) because of the advantages of the practicality of this methodology.

In this context, the estimation of the fuel consumption for manoeuvring is calculated as follows:

$$C_P = \sum_{ij} \left(P_{B_{ij}} t_{ij} \right) c_e \quad (1)$$

where C_P denotes the amount of fuel consumed by the main propulsion of the vessel moving (tones); i represents those sections in which the travel distance between the dock and the Landfall Buoy is divided and velocity data is registered; j is the vessel's activity stage (incoming/outgoing manoeuvring); t_{ij} is the time (h) the vessel spends moving within the port; c_e is the specific fuel oil consumption (g/kWh) and $P_{B_{ij}}$ is the propulsion power required (kWh) during manoeuvring, which is calculated according to equation (2):

$$P_{B_{ij}} = \frac{{\Delta_{ij}}^{2/3} V_{ij}^3}{c_a} \quad (2)$$

where Δ_{ij} is the real vessel displacement, V_{ij} is the vessel speed (kn) and c_a is the Admiralty Coefficient, which is related to the vessel's resistance, that is:

$$c_a = \frac{{\Delta_{max}}^{2/3} {V_{max}}^3}{P} \quad (3)$$

in which Δ_{max} is the vessel's displacement related to the propulsion power at maximum speed, V_{max} is the maximum vessel speed and P the effective energy power (kW) which is equal to the maximum propulsion power.

3.2.2 *Auxiliary engines consumption*

Following the methodological approach, the fuel consumption due to the auxiliary engines (C_{AE}) during port time at the terminal and during manoeuvring is estimated as:

$$C_{AE} = c_{ec}^{AE} \left(P_{AE} t_p + P_{AE}^* t_{ij} \right) \quad (5)$$

where t_p is the port-time at the terminal dock, P_{AE} is the auxiliary engine power (kW) and P_{AE}^* is the auxiliary engine power developed when the vessel is moving.

3.2.3 *Thrusters consumption for berthing/unberthing operations*

The fuel consumption required for a vessel to manoeuvre around can be estimated as:

$$C_T = \sum_{jk} (n_k P_k c_e) \left(t_{l_{kj}} r_{l_{kj}} + t_{e_{kj}} r_{e_{kj}} \right) \quad (6)$$

where c_T is the fuel oil consumption of the thrusters (kg/h); k is the type of thruster propeller (stern and bow); n_k is the number of propellers; $t_{l_{kj}}$ is the time that each type of propeller is working on load; $t_{e_{kj}}$ is the time that each type of propeller is working empty; $r_{l_{kj}}$ is the ratio (%) corresponding to the load factor and $r_{e_{kj}}$ is the ratio (%) corresponding to the empty factor.

3.2.4 *Boiler consumption*

Finally, the fuel consumption provided to the boilers will be estimated as:

$$C_B = \left(\sum_{ij} t_{ij} + t_d \right) c_B \quad (7)$$

where c_B is the fuel oil consumption of the boiler (kg/h). In this paper, this parameter is obtained through a survey completed by ship-owners. In particular, it is usually registered in the "Engine Room Log Book".

3.2.5 *Total fuel consumption*

Once the individual fuel consumption is estimated, the next step is to quantify vessel emissions per air pollutant by multiplying fuel consumption and emission factors (g/kWh), that is:

$$E_z = (C_P + C_{AE} + C_T + C_B) EF_z \quad (8)$$

where *z* is the type of air pollutant.

Combustion emission factors (EF) vary by: engine type (main and auxiliary engines, auxiliary boilers); engine rating (Slow Speed Diesel - SSD, Medium Speed Diesel - MSD, High Speed Diesel - HSD); whether engines are pre-IMO Tier 1, or meet IMO Tier I, II or III requirements; the type of service in which they operate (propulsion or auxiliary); type of fuel (Heavy Fuel Oil - HFO, Marine Diesel Oil - MDO, Marine Gas Oil - MGO and Liquefied Natural Gas - LNG), etc.

Table 1 shows the EF used and data sources.

Table 1. Emission Factor (EF) and data sources used for calculations

Air pollutant	Data source and EF (g / g fuel)
CO_2	IMO regulations – HFO: 3,114 g CO_2/g fuel – MDO/MGO: 3,206 g CO_2/g fuel
NO_X	IMO regulations (limits set in Annex VI, MARPOL) and EIAPP (Engine International Air Pollution Prevention) certificate These EF ranges from 0,061 to 0,086 g NO_x/g fuel for main engines and from 0,051 to 0,065 g for auxiliary engines. The difference is based on engine ratings (rpm).
SO_X	IMO regulations – HFO (1,5% S): 0,030 g SO_X/g fuel – MDO/MGO (0,1% S): 0,002 g SO_X /g fuel
PM	IMO regulations – HFO (1,5% S): 0,00426 g PM/g fuel – MDO/MGO (0,1% S): 0,00097 g PM/g fuel

4 EMISSION INVENTORIES AND INDICATORS FOR FERRIES

4.1 *Data samples*

The data sample for this particular study comprises 25 passenger ferries that were monitored during 2015-16. According to the statistics of the Port of Barcelona, those 25 vessels accounted for more than 3.000 calls which represents about 86% of total passenger vessel calls in 2015 (the total number of ferries calls was 3.545).

At the same time, the data sample has been divided in two groups. The first one (G_1) includes data from 12 passenger ferries and 100 vessel calls during 2015. For every vessel call, manoeuvring and berthing time and vessel speed real-time data are obtained from the modern AIS. The second data set (G_2) is just related to the berthing activity of 13 vessels, since AIS data was not available. Therefore, we have a complete data set of 12 passenger ferries (G_1) and berthing activity data set of 13 passenger ferries (G_2).

For each vessel, engine and vessel characteristics (typology, ratings, electrical power and specific fuel consumption, GT, Length Over All - LOA, draught, beam, passenger capacity) and thruster and boiler properties (power and specific fuel consumption) were obtained from IHS-Sea web database. Lastly, the load factor and working time of the thrusters, type of fuel used (HFO, MGO/MDO) and auxiliary electric power (kW) used during berthing activity are obtained through surveys and interviews of shipping companies (steps 1 and 2 from Figure 1), but only for data related to G_1.

4.2 *Annual inventory at port-level*

The total greenhouse gas - GHG (CO_2) and air pollutant emissions (NO_X, SO_X and PM) for 25 passenger ferries during 2015 at the Port of Barcelona (about 3.000 vessel calls and 20.050 hoteling hours) are estimated in this section.

Figure 2 shows the yearly emission inventory within the Port of Barcelona considering the arriving-berthing-leaving activities for vessels included in the G_1 data set; while Figure 3 shows the yearly emission inventory during berthing for the whole data set (25 passenger ferries). In both figures, the vertical axis shows the identification code for each chosen vessel, the number of calls in 2015 and its GT.

Then, the emission distribution per type of power used during the completely approaching-berthing-leaving cycle is depicted in Figure 4.

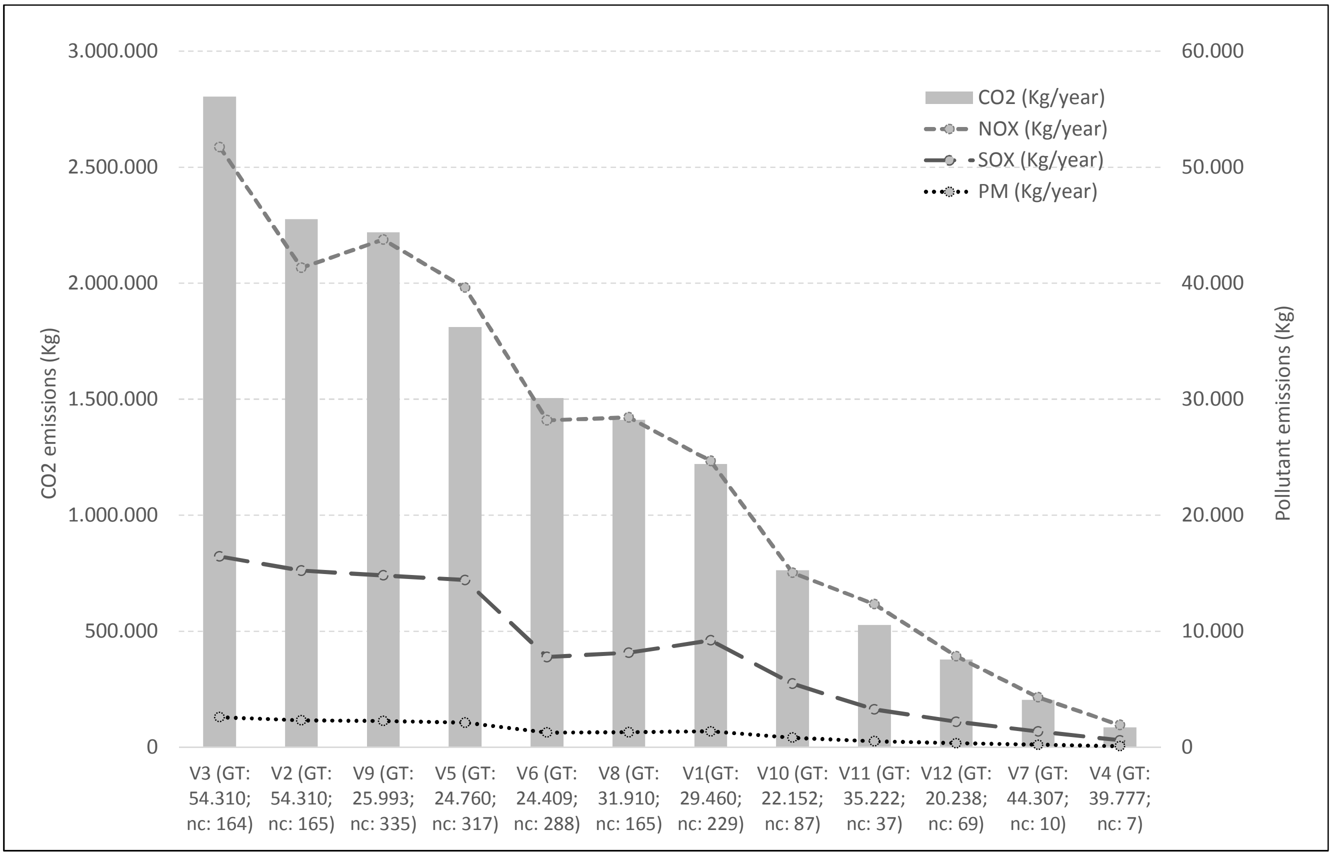

Figure 2. Emission inventory during 2015 for 12 passenger ferries within the Port of Barcelona maritime area

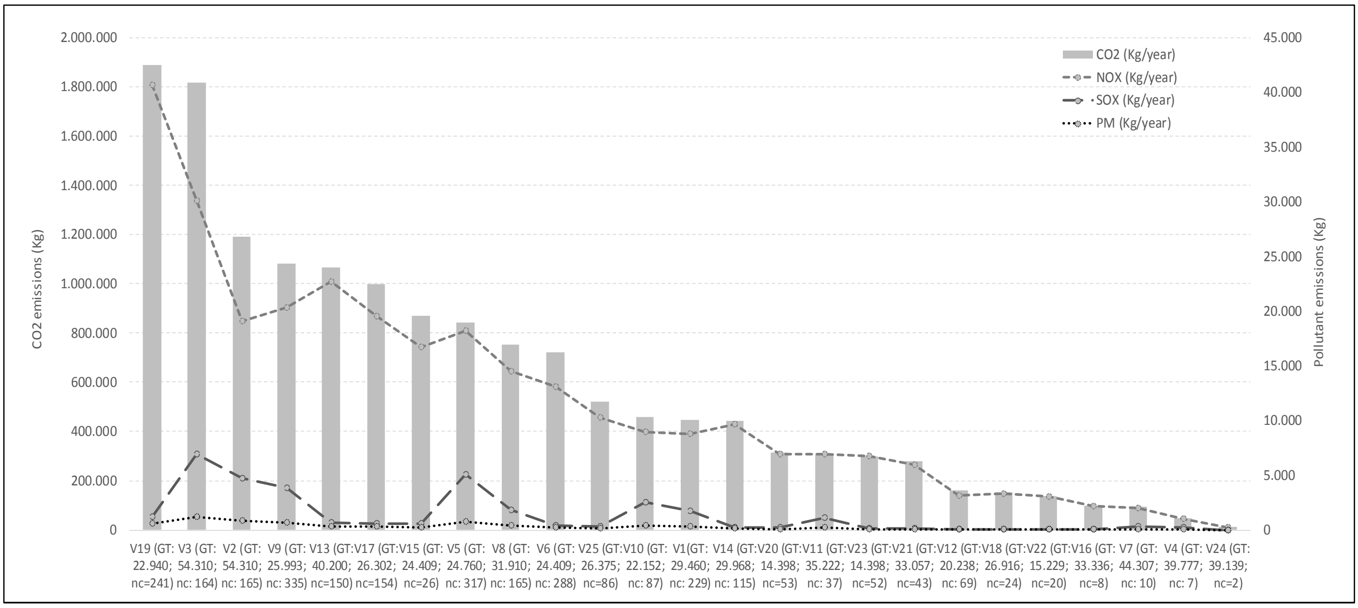

Figure 3. Emission inventory during 2015 for 25 passenger ferries during berthing activity (hoteling) at the Port of Barcelona

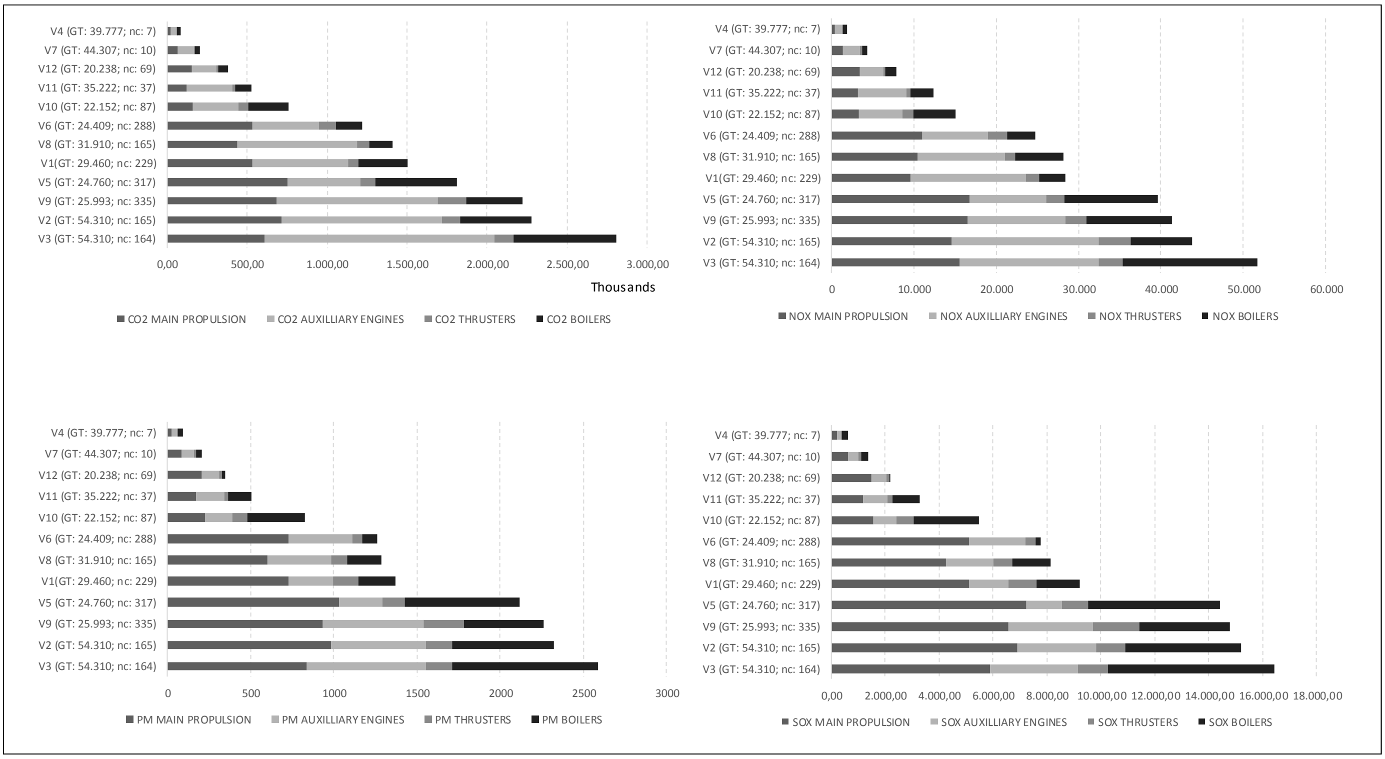

Figure 4. Share of emission inventories during 2015 for emission sources (Data set G_1-12 passenger ferries)

According to the above figures, the following first conclusions can be obtained:

1) Arriving-berthing-leaving operations (total)

- In absolute terms, the total yearly emissions derived from the 12 passenger within the Port of Barcelona amounted to 15.210 tons of CO_2, 300 tons of NO_X, 98 tons of SO_X and 15 tons of PM.

- On average, per vessel call, the estimation of emissions was: 10,25 tons of CO_2, 210 kg of NO_X, 67 kg of SO_X and 10 kg of PM.

- Regarding the emissions derived from the different type of emission sources, the resulting share was:
  - Emissions CO_2: 31% main engine, 43% auxiliary engines, 20% boilers and 6% thrusters.
  - Emissions NO_X: 34% main engine, 38% auxiliary engines, 22% boilers and 6% thrusters.
  - Emissions SO_X: 47% main engine, 22% auxiliary engines, 21% boilers and 9% thrusters.
  - Emissions PM: 43% main engine, 28% auxiliary engines, 21% boilers and 8% thrusters.

The main share's differentiation is based on the type of fuel used (HFO for manoeuvring and MGO for berthing activity) and the type of engine (main or auxiliary).

2) Berthing operations (hoteling)

- In absolute terms, the total yearly emissions derived from the 25 passenger ferries during berthing (hoteling) amounted to 15.000 tons of CO_2, 295 tons of NO_X, 18 tons of SO_X and 7,5 tons of PM.

- On average, per vessel call, the estimation of emissions was: 7,25 tons of CO_2, 145 kg of NO_X, 6,50 kg of SO_X and 3,15 kg of PM.

- Regarding the emissions derived from the different type of emission sources, the resulting averaged share was: 57% for auxiliary engines and 43% for the boilers.

4.3 *Passenger ferries emission indicators*

Based on the estimation of emissions represented above, the next step is to estimate indicators with the aim of extrapolating the estimations for other passenger ferry vessels based on vessel dimensions (GT and capacity) and port time (manoeuvring and berthing time).

In order to choose appropriate indicators, a regression analysis is performed between total pollutant emissions/hoteling emissions and independent variables (port time, passenger capacity and vessel GT). In case the regression model (linear regression) is deemed satisfactory, in the sense that a relationship exists among variables, then an indicator combining those independent variables will be chosen.

That is, the estimated regression equation or indicator can be used to predict the emission values based on the vessel dimensions (GT) and/or port time.

From the regression analysis it can be stated that the independent variables capacity (passengers) and vessel GT cannot be individually used to predict the total emissions and hoteling emissions, as the correlation coefficient is weak, indicating that there is no relationship between the two variables. However, by combining them with the port-time variable, the regression model results indicate a better relationship.

Therefore, it can be concluded that the best independent variable to predict hoteling emissions emitted by passenger ferries at ports is the port-time – GT or port-time but only port time-GT could be used for extrapolating total port emissions since important differences arise in emission inventories. The regression indicator (Figure 5) for hoteling emissions regarding port time-GT are close to 0,85 but for total emissions at port-level are close to 0,65, which is weak.

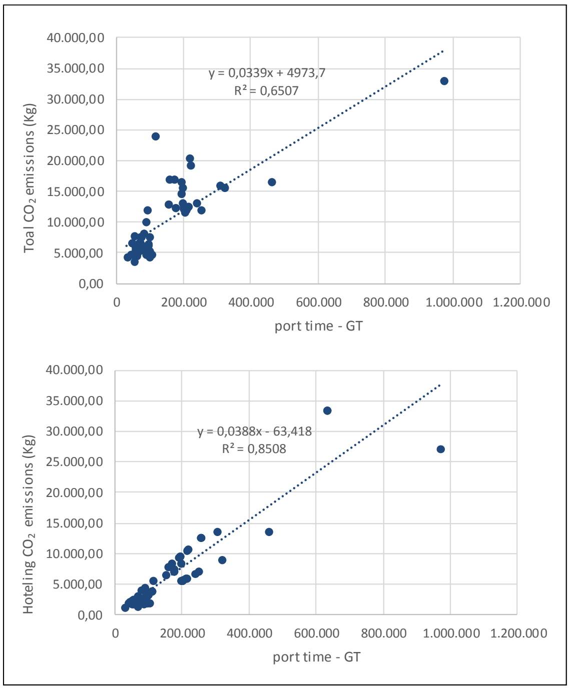

Figure 5. Example of regression analysis. CO_2 emissions as regards to port time-GT.

Finally, Table 2 lists average emission values for every selected indicator.

Table 2. Emission indicators for passenger ferries at port-level

Indicator	**SO_X**	**NO_X**	**PM**	**CO_2**
Arriving-berthing-leaving emissions within the port area				
Emissions / port-time	17,00 kg/h	53,60 kg/h	2,60 kg/h	2.600,00 kg/h
Emissions / port-time-GT	0,50 g/hGT	1,60 g/hGT	0,080 g/hGT	78,85 g/hGT
Emissions / port-time-pax	12,50 g/hpax	38,80 g/hpax	1,90 g/hpax	1.890,0 g/hpax
Berthing at terminal dock (hotelling)				
Hotelling emissions / port-time	2,90 kg/h	24,10 kg/h	0,60 kg/h	1.215,00 kg/h
Hotelling emissions / port-time-GT	0,10 g/hGT	0,75 g/hGT	0,020 g/hGT	38,00 g/hGT
Hotelling emissions / port-time-pax	2,20 g/hpax	20,65 g/hpax	0,50 g/hpax	1.020,0 g/hpax

5 CONCLUSIONS

This paper addresses the estimation of air emissions released by passenger ferries in urban ports. This is of great importance due to a significant share of emissions produced during the time vessels stay in ports and the huge amount of calls involved in regular services. In addition, this paper provides useful passenger ferries emission indicators, which could facilitate reliably estimating the in-port ship emission inventories of other ports without requiring large amounts of data.

The proposed methodology is based on the "full bottom-up" approach and begins by evaluating the fuel consumed by each vessel on the basis of its individual port-activities (manoeuvring, berthing and hoteling at the terminal dock). The methodological scheme also separately considers different types of emission sources: main propulsion (diesel engines), auxiliary propulsion for providing electrical energy for hoteling, thrusters and boilers. Once the fuel consumed is determined, the next step is estimating air emissions from vessels by employing the corresponding emission factors per air pollutant.

The methodology was implemented to a particular case in which 25 passenger ferries and 85 calls were monitored in the Port of Barcelona during 2015. The emission estimations led to the following considerations:

- Main and auxiliary engine emissions were found to be dominant (about 72%), whereas boilers and thrusters represent, on average, 28%, in which boilers were predominant (22%).
- Hoteling emissions (auxiliary engine and boilers during berthing time) represent about 70% of the total emissions for CO_2 and NO_X, whereas for SO_X and PM, it represents about 28%, since EF for MGO are smaller than LSHFO (Low-Sulphur HFO).
- According to the sample data, the average estimation of total emissions per vessel call was: 10,25 tons of CO_2, 210 kg of NO_X, 67

kg of SO_X and 10 kg of PM. And, for hoteling activity, the average amount was: 7,25 tons of CO_2, 145 kg of NO_X, 6,50 kg of SO_X and 3,15 kg of PM.

Concerning emission indicators, it was found through a regression model that the best independent variable to predict hoteling emissions was the combined variable port time – GT. Nonetheless, the variables port time – passenger is also quite robust and any variable can provide excellent results to estimate total port emissions. In relation to the indicator emission per port-time and GT, the following values could be used to estimate hoteling emissions at ports: 38.00 g CO_2/h-GT, 0.75 g NO_X/ h-GT, 0.10 g SO_X/h-GT and 0.020 g PM/h-GT.

As regards to total emissions at port, the regression model analysis showed that any indicator could be used to estimate emissions with high accuracy.

With respect to the reliability of the emission indicators, it should be mentioned that information regarding vessel activities, hoteling power, engine ratings, fuel use, emission factors related to NO_X and load factors are based on empirical and real information (work field) received from shipping crew companies, which means that estimations are quite consistent.

In summary, this paper contributes to the development of emission indicators for passenger ferries, which can be extended to other ports to reliably and quickly estimate emission inventories and to calculate emission inventories, which could help to understand passenger ferry emissions when proposing environmental and policy measures.

REFERENCES

Chang, Y.T., Song, Y., Roh, Y. 2013. Assessing greenhouse gas emissions from port vessel operations at the Port of Incheon. Transportation Research Part D, 25, pp. 1–4.

Cooper, D.A. 2001. Exhaust emissions from high speed passenger ferries. Atmospheric Environment, 35, pp. 4189-4200.

Dalsoren, S.B., Eide, M.S., Endresen, O., Mjelde, A., Gravir, G., Isaksen, I.S.A. (2009). Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports. Atmospheric Chemistry and Physics, 9, pp. 2171–2194.

Dragovic, B., Tzannatos, E., Tselentis, V., Mestrovic, R., Skuric, M. (2015). Ship emissions and their externalities in cruise ports. Transportation Research Part D (in press).

ESPO (2003). Environmental code of practice. ESPO, Brussels, Belgium.

Eyring, V., Koehler, H.W., van Aardenne, J., Lauer, A. (2005). Emission from International Shipping: 1. The last 50 years. Journal of Geophysical Research, 110(D17305), pp. 1-12.

Goldsworthy, L., Goldsworthy, B. 2015. Modelling of ship engine exhaust emissions in ports and extensive coastal waters based on terrestrial AIS data – An Australian case study. Environmental Modelling & Software, 63, pp. 45–60.

IAPH (2007). Resolution on clean air programs for ports. Second plenary session. 25th World Ports Conference of IAPH. Houston, Texas, USA.

ICF (2006). Current methodologies and best practices in preparing port emission inventories. EPA, Fairfax, Virginia, USA. Final report for U.S.

Maragkogianni, A., Papaefthimiou, S. (2015). Evaluating the social cost of cruise ships air emissions in major ports of Greece. Transportation Research Part D, 36, pp. 10–17.

Miola, A., Ciuffo, B., Giovine, E., Marra, M. (2010). Regulating air emissions from ships: the state of the art on methodologies, technologies and policy options. European Commission, JRC reference reports.

Schneekluth, H., Bertram, V. (1998). Ship design for efficiency and economy. Elsevier Ltd., 2nd edition, UK.

Song, S. (2014). Ship emissions inventory, social cost and eco-efficiency in Shanghai Yangshan port. Atmospheric Environment, 82, pp. 288–297.

Taylor, D.A. (1996). Introduction to marine engineering. Elsevier Ltd. UK.

Tichavska, M., Tovar, B. (2015). Environmental cost and eco-efficiency from vessel emissions in Las Palmas Port. Transportation Research Part E, 83, pp. 126–140.

Tupper, E.C. (2013). Introduction to naval architecture. Elsevier Ltd, Fifth Edition, USA.

Tzannatos, E. (2010). Ship emissions and their externalities for the port of Piraeus – Greece. Atmospheric Environment, 44, pp. 400–407.

Watson, D. (1998). Practical ship design. Elsevier Ocean Engineering Book Series, Vol 1, Oxford, UK.

Winnes, H., Styhre, L., Fridell, E. 2015. Reducing GHG emissions from ships in port areas. Research in Transportation Business and Management, 17, pp. 73-82.