

1 **Evaluating air emission inventories and indicators from cruise**
2 **vessels at ports**

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1 **Abstract**

2 This paper provides an estimation of air emissions (CO₂, NO_x, SO_x and PM) released
3 by cruise vessels at the port-level. The methodology is based on the “full bottom-up”
4 approach and starts by evaluating the fuel consumed by each vessel on the basis of its
5 individual port-activities (manoeuvring, berthing and hoteling). The Port of Barcelona
6 was selected as the site at which to perform the analysis, in which 125 calls of 30
7 cruise vessels were monitored. Real-time data from the Automatic Identification
8 System (AIS), factor emissions from engine certificates and vessel characteristics from
9 IHS-Sea web database were also collected for the analysis. The research findings
10 show that the most appropriate indicators are inventory emissions per “port time-Gross
11 Tonnage”, “port time-passenger” and “port-time”. These emission indicators improve
12 our understanding of cruise emissions and will facilitate the work that aims to estimate
13 reliably and quickly the in-port ship emission inventories of cruise ports.

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15 **Keywords:** cruise vessel emissions, port-level, air pollution, emission inventories,
16 emission indicators

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1 **1. Introduction**

2 Although maritime transport is the most sustainable transport mode, emissions from
 3 the maritime transport sector account for a significant portion of total emissions,
 4 affecting air quality and contributing to climate change. Thus, in recent years, public
 5 concerns regarding the environmental impacts of maritime transport have increased.

6 International shipping was estimated to have emitted 870 million tons of CO₂ in 2007
 7 (no more than 2.7% of the global total of that year) and 949 million tons of CO₂ and
 8 972 million tons of CO₂e greenhouse gases (GHG), combining CO₂, CH₄ and N₂O, in
 9 2012.

10 A multi-year average estimate for all shipping, using bottom-up totals for 2007–2012,
 11 was 1,016 million tons of CO₂, which accounted for approximately 3.1% of annual
 12 global CO₂, 20.9 million tons of NO_x (as NO₂) and 11.3 million tons of SO_x (as SO₂)
 13 (IMO, 2014).

14 In the context of port-city areas, emissions released by vessels operating in port
 15 negatively affects local communities, albeit with a small percentage compared to the
 16 total amount released by shipping (Dalsoren et al., 2009). Nevertheless, it inevitably
 17 constitutes a source of pollution concentration in the air and has a significant
 18 environmental impact on the coastal communities, as 70% of the ship emissions occur
 19 within 400 km of land (Eyring et al., 2005).

20 Moreover, the urban character of some ports and their populated surroundings are the
 21 main focus of the negative effects of exhaust pollutants (NO_x, SO_x, VOC, CO and PM)
 22 due to the associated local impacts on human health. Of particular importance to the
 23 human health in urbanised ports is that around 95% of the ship-generated total PM is
 24 of an aerodynamic diameter of less than 2.5 µm (PM_{2.5}) (Whall et al., 2007). Thus, the
 25 need to control air pollution at ports is widely acknowledged as an active policy issue
 26 by various authoritative port associations (IAPH, 2007; ESPO, 2003) as a reaction of
 27 main regulations (IMO, EC, EPA, etc.), which are indicated in Table 1.

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Table 1. Main regulations for the prevention of air pollution from ships

Regulation	Targets and limits
<p>MARPOL 73/78 (IMO)</p> <p>Annex VI “Regulations for the Prevention of Air Pollution from Ships”</p>	<p>Sets limits on NO_x and SO_x emissions for ships exhausts and prohibits deliberate emissions of ozone-depleting substances</p> <p>NO_x emission limits:</p> <ul style="list-style-type: none"> • Tier I (2000) limits are global and depend on the engine max operating speed (9.8–17 g/kWh) • Tier II (2011) limits are global and depend on the engine max operating speed (7.7–14.4 g/kWh) • Tier III (2016) only for NO_x Emission Control Areas (1.96–3.4 g/kWh) <p>Sulphur content of fuel:</p> <ul style="list-style-type: none"> • ECA zones: 1.5% (2000); 1.0% (2010–2012) and 0.1% (2015–2020) • Global: 4.5% (2000–2010); 3.5% (2012–2015) and

Regulation	Targets and limits
<p data-bbox="225 465 549 495">European Commission (EC)</p> <p data-bbox="225 521 584 577">Directive 2012/33/EU amending Directive 1999/32/EC</p>	<p data-bbox="762 253 916 282">0.5% (> 2020)</p> <p data-bbox="667 286 1353 365">Sets the maximum sulphur content of marine fuels used in territorial seas, exclusive economic zones and pollution control zones of Member States, including SOx Emission Control Areas</p> <p data-bbox="667 394 943 423">Sulphur content of fuel:</p> <ul data-bbox="715 450 1353 701" style="list-style-type: none"> <li data-bbox="715 450 1353 589">• ECA zones: 1% until 31st December 2014; as of 1st January 2015, EU Member States have to ensure that ships in the Baltic, the North Sea and the English Channel are using fuels with a sulphur content of no more than 0.10%. <li data-bbox="715 593 1353 645">• Higher sulphur contents are still possible but only if the appropriate exhaust cleaning systems are in place. <li data-bbox="715 649 1353 701">• The IMO standard of 0.5% for sulphur limits outside SECAs will be mandatory in EU waters by 2020 <p data-bbox="667 728 1230 757">The limits for NOx are the same than IMO standards</p>
<p data-bbox="225 761 616 817">Environmental Protection Agency (EPA)</p> <p data-bbox="225 857 440 887">2015 Amendments</p> <p data-bbox="225 902 480 931">2012 Direct Final Rule</p> <p data-bbox="225 947 639 1055">2010 Final Rule: Control of emissions from New Marine Compression-Ignition Engines at or above 30 liters per cylinder</p> <p data-bbox="225 1070 592 1126">2003 Final Emission Standards: Tier 1 Marine Diesel Engines</p>	<p data-bbox="667 790 1353 846">To address emissions from large ships, including ocean vessels and Lakers, flagged in the United States and in other countries.</p> <p data-bbox="667 873 1062 902">EPA's coordinated strategy includes:</p> <ul data-bbox="715 907 1353 1048" style="list-style-type: none"> <li data-bbox="715 907 1353 1048">• EPA domestic actions under the Clean Air Act; and U.S. Government action through the International Maritime Organization, including: Designation of Emission Control Areas for U.S. coastal waters; and Adoption of new international standards for all ships in global waters <p data-bbox="667 1070 1310 1099">The limits for NOx and SOx are the same as IMO standards</p>

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As a consequence, relatively recently ports in North America (Los Angeles-Long Beach, Seattle, Vancouver, New York, etc.) and Europe (Venice, Barcelona, Gothenburg, Antwerp, etc.) have started to introduce specific measures and policies to directly address GHG emissions (through the reduced use of conventional fuel) and, indirectly, to control local air pollutants since a significant share of emissions are derived from the time the vessels remain in port (Gibbs et al., 2014). Most of the measures are related to the introduction of LNG bunkering infrastructure, cold-ironing, the provision of shore-side electricity at berth or by defining incentives for fuel switching or green ships (Merk, 2014).

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). Furthermore, as stated in Tzannatos (2010a), port emission inventories would aid policy makers in developing effective regulatory requirements or port environmental management systems. In such a context, in the port of Naples, two experimental campaigns were carried out in 2012 to investigate the air quality (sulphur dioxide, nitrogen dioxide and benzene, ethylbenzene, toluene and xylene) and to compare the observed concentration values with limits established by European legislation (Prati et al., 2015).

1 With regards to emissions in urban-ports, the growth of cruise activities should be
2 underlined since cruise shipping is a relatively large emitter, due to large hoteling load
3 and extended turnaround times, which sometimes exceed 48 h (home-ports). As an
4 example, the cruise activity in the five busiest Greek ports contributed 6.2% and 3.1%,
5 respectively, to the relevant national NO_x and SO₂ inventory (Maragkogianni and
6 Papaefthimiou, 2015).

7 In 2014, the cruise industry met a demand of more than 21 million global passengers
8 through the supply of 296 cruise vessels and a total of 500,854 berths, mainly
9 concentrated in America (Caribbean and North America) and Europe (Mediterranean
10 and North Europe). Looking at long-term projections, the cruise industry is expected to
11 exceed 25 million cruise passengers in 2018 and 30 million in 2030 (Pallis, 2015);
12 therefore, main cruise ports have recognised the need to reduce emissions from the
13 cruise industry, mainly in cruise terminals (e.g., Venice and Barcelona) that are close to
14 city centres and where the exposure of the population will be high.

15 In such a context, the goal of this paper is to develop accurate emission inventories
16 (CO₂, SO_x, NO_x and PM) and emission indicators for cruise ports by estimating, firstly,
17 the fuel consumed by each vessel on the basis of its activities in port. By integrating the
18 evaluation over time (i.e., one year) and over the fleet that calls at a specific port, a
19 yearly inventory can be achieved. On the other hand, the development of emission
20 indicators will facilitate reliably estimating the emission inventories of cruise ports at the
21 port-level. Indeed, this information is essential to properly assess the impacts of
22 strategies for regulating and controlling air emissions from vessels at ports.

23 The paper is organised as follows: Section 2 reviews relevant literature on the issue;
24 Section 3 introduces the methodological approach and the formula used to estimate
25 inventory emissions; Section 4 introduced the data used for the particular case study
26 and the main results; Section 5 presents the most relevant emission indicators and
27 finally, Section 6 highlights the main conclusions.

28

1 **2. Literature review**

2 According to published research, which incorporates extensive reviews of ship
3 emission estimation methodologies (Miola et al., 2010; Tichavska and Tovar, 2015),
4 two different approaches can be used to estimate atmospheric emissions arising from
5 maritime transport: top-down and bottom-up approaches.

6 The top-down approach calculates emissions without considering the characteristics of
7 the individual vessels, which are instead spatially assigned later. The bottom-up
8 approach evaluates the individual pollution emitted by a single vessel in a specific
9 location and then, by integrating the evaluation over time and over the fleet, obtains the
10 total emissions. In addition, as it is stated in Miola et al. (2010), a combination of
11 bottom-up and top-down approaches in the evaluation of total emissions is possible if
12 geographical factors are considered. Thus, two factors must be considered in order to
13 evaluate atmospheric emissions: the quantity of emissions produced and where they
14 are emitted.

15 **2.1 Emission inventories at global, regional and port-level**

16 With regards to the state-of-art, a wide variety of studies relate to emission inventories
17 at global or regional levels but only a few do so at the port-level (local approach). The
18 most relevant studies at global or regional level are Endresen et al. (2003, 2004, 2007),
19 Corbett and Koehler (2003), Eyring et al. (2005), Corbett et al. (2007), Wang et al.
20 (2007) and IMO (2009), whose estimations where based on fuel sales statistics. These
21 studies reported average CO₂ emissions, as well as upper and lower levels and the
22 important uncertainties between them were quantified (Miola et al., 2010). In addition,
23 the study of Moreno-Gutiérrez et al. (2015) should be highlighted since it compares
24 several different methods of estimating emissions and fuel consumption and makes a
25 comparative analysis between the main papers and reports published in areas of the
26 EU and USA.

27 On the other hand, methodologies to evaluate emissions due to port activity, which
28 sometimes are included in city inventories, have increasingly become an important
29 research topic over the last two decades and the number of scientific studies
30 addressing this concept has broadly increased. The representative approach for
31 emission estimation in port studies was the bottom-up approach, based on port calls
32 and estimated vessels operating at a port (Tichavska and Tovar, 2015). Furthermore,
33 normally activity-based and/or fuel-based estimations were made since they are more
34 accurate than top-down methodologies that require detailed data such as routing,
35 engine workload, ship speed, location, duration, etc. (Song, 2014).

36 For instance, the study conducted by Saxe and Larsen (2004) analysed the urban
37 dispersion of air pollutants (nitrogen oxides) originating form ships in three Danish
38 Ports using an operational air quality model. De Meyer et al. (2008) gave a better
39 insight to emission inventories on a national scale (Belgian seaports) by using a
40 bottom-up activity-based model. Tzannatos (2010a; 2010b) addressed the issue of air

1 pollution generated by passenger shipping alone at the port of Piraeus. He developed
2 an in-port ship activity-based methodology that was applied for manoeuvring and
3 berthing operations in order to estimate the main vessel exhaust pollutants (NO_x , SO_2
4 and $\text{PM}_{2.5}$) over a twelve-month period in 2008–2009.

5 Then, Berechman and Tseng (2012) estimated the emission costs of ships and trucks
6 in the Port of Kaohsiung (Taiwan) by calculating the time spent at berth, the mean load
7 on the auxiliary engines, the load factor and the emission factors of auxiliary engines
8 for each pollutant. Villalba and Gemechu (2011) used the same methodology to
9 calculate GHG emissions (CO_2 equivalents) in the Port of Barcelona. In particular, they
10 accounted for the emissions due to electricity and fuel consumption in the port area.
11 McArthur and Osland (2013) also estimated the emissions from ships hoteling in the
12 Port of Bergen and placed monetary value on these emissions; whereas Song (2014),
13 estimated both the in-port ship emissions inventory and the emission-associated social
14 costs in Yangshan port of Shanghai for the entire fleet. In that case, a methodology,
15 supported by ship-by-ship and real-time data from the modern automatic identification
16 system (AIS) was developed to obtain accurate results.

17 Similarly, Ng et al. (2012) used AIS data to determine typical main engine load factors
18 through vessel speed and operation mode characterisation for emission inventories of
19 ocean-going vessels in the port of Hong Kong. Finally, a study by Tichavska and Tovar
20 (2015) presented vessel emissions in the port of Las Palmas by developing a full
21 bottom-up model and data transmitted by the AIS in 2011.

22 **2.2 Cruise ship emission inventories at port-level**

23 With regards to cruise ship emissions at ports, Maragkogianni and Papaefthimiou
24 (2015) presented a “bottom-up” estimation based on the detailed individual activities of
25 cruise ships in the Greek ports of Piraeus, Mykonos, Santorini, Katakolo and Corfu. For
26 each studied port and for all approaching cruise vessels they registered ship
27 movements during manoeuvring and berth operations, engine types and sizes, load
28 factors, the type of fuel consumed and the time spent in each mode. For each ship call,
29 the air pollutants (NO_x , SO_2 and $\text{PM}_{2.5}$) produced during the ship's activity in the port
30 was estimated. They stated that emissions during hoteling accounted for 88.5% of the
31 total emissions and highlighted the seasonality effect as summer emissions and
32 associated impacts were significantly amplified.

33 In addition, Dragovic et al. (2015) estimated ship exhaust emission inventories and
34 their externalities in the Adriatic ports of Dubrovnik (Croatia) and Kotor (Montenegro)
35 for the period 2012–2014. The methodology for emission estimation relied on the
36 distinction of various activity phases (manoeuvring and berth/anchorage) performed by
37 each cruise ship call (bottom-up) as a function of energy consumption during each
38 activity multiplied by an emission factor. The results showed that the application of ship
39 activity-based methodology improves the understanding of ship emissions in ports and
40 contributes toward the implementation of effective port policies to control air quality.

1 The present paper proposes a methodology based on the full bottom-up approach and
2 begins by evaluating the fuel consumed by each vessel on the basis of its individual
3 port-activities (manoeuvring, berthing and hoteling) and differentiating between the
4 main vessel propulsion, auxiliary propulsion (thrusters), boilers and electrical
5 generators. Unlike previous studies, this paper also provides accurate cruise ship
6 emission indicators (rates per hour, per passenger, per GT or a combination of all
7 three), which can be used by other researches and stakeholders to reliably and quickly
8 estimate emission inventories in other cruise ports at the port-level.

9

10 **3. Evaluating emissions from cruise ships**

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

16 This paper considers, in general terms, the full bottom-up approach but takes into
17 account separately the fuel consumption and emissions of the following propulsion
18 systems of cruise vessels during port operations:

- 19 • Cruise vessel engines. Modern ships use diesel, diesel-electric engines or gas
20 turbines as a source of power for propulsion (main propulsion);
- 21 • Transversal propulsion (thrusters) for berthing and unberthing operations
22 (auxiliary propulsion)'
- 23 • Boilers for steam production used to heat up heavy fuel oil (HFO) fuel and
24 modify its viscosity and for heating up water;
- 25 • Auxiliary engine generators for providing electrical energy used during hoteling.

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

31

32 **3.1 Methodological approach**

33 *3.1.1 Propulsion power consumption for incoming/outgoing manoeuvring*

34 The Admiralty Coefficient method is proposed for estimating the propulsion power for
35 manoeuvring, which is based on the basic assumption that the all resistance is
36 frictional and that the power varies as the cube of the speed. This method, which
37 determines the required propulsion power according to the given ship speed and the
38 displacement, has been used by several authors, such as Tupper (2013), Watson

1 (1998), Taylor (1996) and Schneekluth and Bertram (1998) because of the advantages
2 of the practicality of this methodology.

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

$$C_p = \sum_{ij} (P_{B_{ij}} t_{ij}) c_e \quad (1)$$

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

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

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

$$c_a = \frac{\Delta^{2/3} V^3}{P} \quad (3)$$

14 in which Δ is the vessel's displacement related to the propulsion power at maximum
15 speed, V is the maximum vessel speed and P the effective energy power (kW). For
16 diesel-electric engines P_e is equivalent to the electric power engine and for diesel
17 engines, the effective energy power is equal to the maximum propulsion power.

18

19 3.1.2 Hoteling consumption

20 Following the methodological approach, the fuel consumption for hoteling (C_H) during
21 port time at the cruise terminal and during manoeuvring is estimated as:

$$C_H = c_e (P_H t_d + P_{H^*} t_{ij}) \quad (5)$$

22 where t_d is the dwell time at the terminal dock, P_H is the hoteling power (kW) and P_{H^*} is
23 the hoteling power developed when the vessel is moving.

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1 *3.1.3 Thrusters consumption for berthing/unberthing operations*

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

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

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

9

10 *3.1.4 Boiler consumption*

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

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

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

15

16 *3.1.4 Total fuel consumption*

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

$$E_z = (C_P + C_H + C_T + C_B) EF_z \quad (8)$$

20 where z is the type of air pollutant.

21 Combustion emission factors (EF) vary by: engine type (main and auxiliary engines,
22 auxiliary boilers); engine rating (SSD, MSD, HSD); whether engines are pre-IMO Tier
23 1, or meet IMO Tier I or II requirements; the type of service in which they operate
24 (propulsion or auxiliary); type of fuel (HFO, MDO, MGO and LNG), etc.

25 Therefore, a differentiation is made between those emissions that only depend on the
26 fuel consumption and those that depend on the previous engine properties. Table 2
27 shows the main details and data sources.

28

1 Table 2. Emission factors (EF) in terms of grams of fuel consumed per air pollutant. Sources: IMO (2009),
 2 IMO (2014), ENTEC (2002) and EIAPP certificates from ship-owners.

Air pollutant	Characterisation	Data source and EF (g / g fuel)
CO₂	<p>The carbon content of each fuel type is constant and is not affected by engine type, duty cycle or other parameters when considered on a kg CO₂ per tonne fuel basis</p> <p>CO₂ emissions are unaffected by the sulphur content of the fuel burned</p>	<p>IMO GHG Study 2009, Third IMO GHG Study 2014.</p> <ul style="list-style-type: none"> • HFO: 3.114 g CO₂/g fuel • MDO/MGO: 3.206 g CO₂/g fuel
NO_x	<p>EF factors depend on engines rated (SSD, MSD, HSD), specific fuel consumption, type of fuel and MARPOL Annex VI regulations for engines.</p> <p>NO_x emissions are unaffected by the fuel sulphur content</p>	<p>ENTEC 2002, IMO Tier 0, IMO Tier I, IMO Tier II provide EF according to main engine properties. Reference values as an average of global fleet at 2012 (IMO, 2014):</p> <ul style="list-style-type: none"> • HFO: 0.0903 g NO_x/g fuel • MDO/MGO: 0.0961 g NO_x/g fuel <p>However, EF derived from EIAPP certificates of each vessel engine are used to estimate NO_x emissions in this paper.</p> <p>These EF ranges from 0.059 to 0.072 g NO_x/g fuel for 50% load factor.</p>
SO_x	<p>SO_x emissions are directly linked to the sulphur content of the fuel consumed and based on the percentage sulphur content of the fuel</p>	<p>IMO GHG Study 2009, Third IMO GHG Study 2014.</p> <ul style="list-style-type: none"> • HFO (3.5% S): 0,070 g SO_x/g fuel • MDO/MGO (0.1% S): 0.002 g SO_x /g fuel
PM	<p>The PM emission factors are associated with the sulphur in the fuel consumed</p>	<p>IMO GHG Study 2009, Third IMO GHG Study 2014.</p> <ul style="list-style-type: none"> • HFO (3.5% S): 0,00728 g PM/g fuel • MDO/MGO (0.1% S): 0,00097 g PM/g fuel

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4 In summary, Figure 1 shows the methodological framework considered in this paper, in
 5 which steps 1 and 2 are related to the input data model and steps 3 to 6 are
 6 methodological aspects that are described in Section 3.1.

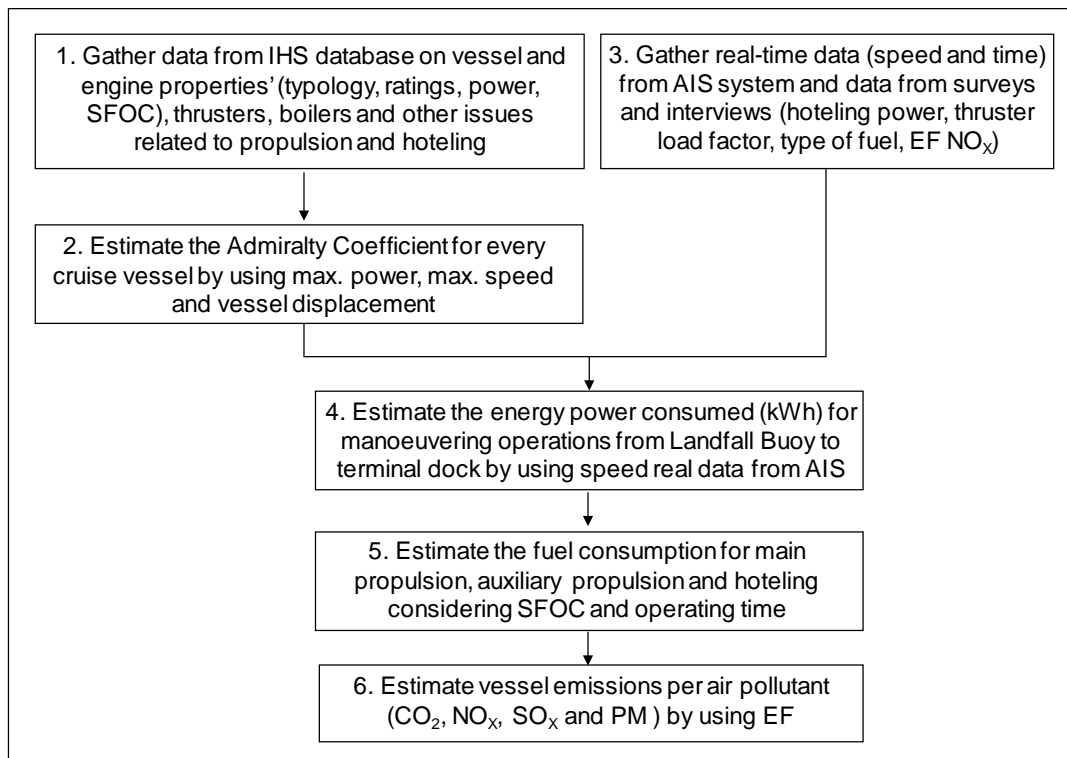


Figure 1. Methodological scheme to estimate air pollutant emissions

4. Inventory of cruise vessels

In this section, emission inventory values (i.e., CO₂, SO_x, NO_x and PM) for cruise vessels in the Port of Barcelona are presented.

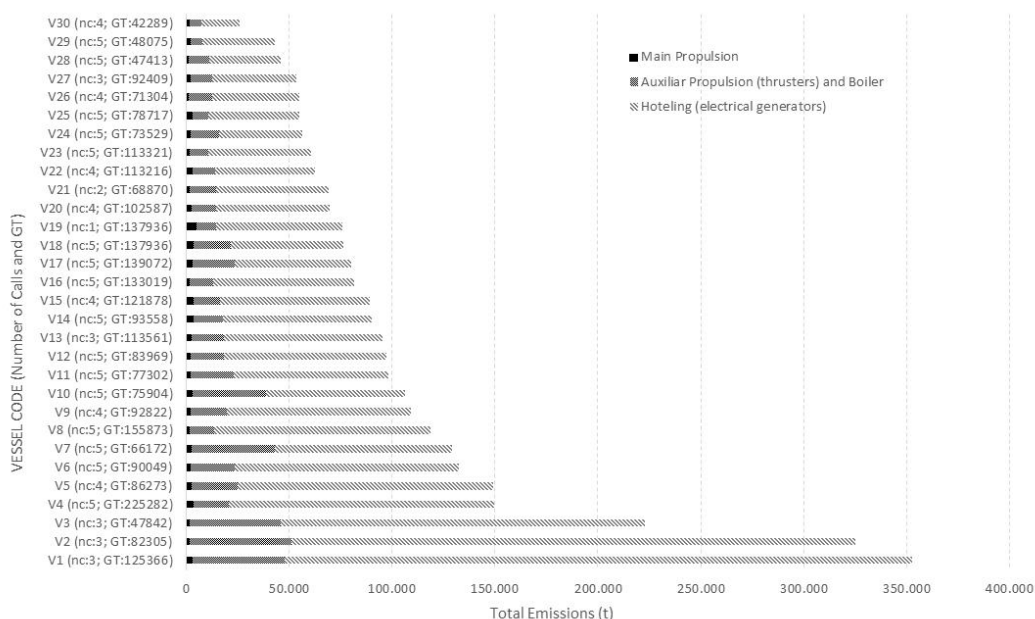
4.1 Data samples

The data sample for this particular study comprises 30 cruise vessels that were monitored during 2015. According to the statistics of the Port of Barcelona, those 30 vessels accounted for more than 520 calls which represents about 70% of total cruise vessel calls in 2015 (the total number of cruise calls was 749). This statement denotes the selection of the data set is suitable because of their relevant significance on the cruise traffic. It also should be mentioned that these vessels are also representative of other European and Caribbean ports that specialise in the cruise shipping industry.

In addition, the sample includes data from 125 vessel calls (the number of calls per vessel is indicated in Figures 2–4) during 2015. For every vessel call, manoeuvring and berthing time and cruise speed real-time data are obtained from the modern AIS. Secondly, for each vessel, engine details (typology, ratings, electrical power, specific fuel consumption), vessel characteristics (GT, LOA, draught, beam, passenger capacity) and thruster and boiler properties (power and specific fuel consumption) come from IHS-Sea web database. Thirdly, the load factor and working time of the thrusters, type of fuel used (HFO, MGO/MDO) and hoteling electric power (kW) used during berthing activity are obtained through surveys and interviews of cruise shipping companies (steps 1 and 2 from Figure 1).

1 **4.2 Results**

2 The total GHG (CO₂) and air pollutant emissions (NO_x, SO_x and PM) for 30 cruise
 3 vessels during 2015 at the Port of Barcelona (about 520 vessel calls and 6,277 hoteling
 4 hours) are estimated in this section. The emissions distribution per type of power used
 5 is depicted in Figure 2, whereas emissions per air pollutant are represented in Figure 3
 6 and Figure 4. In both figures, the vertical axis shows the identification code for each
 7 chosen vessel, the number of calls per vessel and its GT.



8

9 *Figure 2. Emissions annual inventory per type of propulsion for cruise vessels*

10 Hoteling emissions (electrical generators) were found to be dominant (79%), followed
 11 by those emitted by boilers (12%) and thrusters (6%) during manoeuvres. The
 12 remaining percentage (3%) corresponds to the main propulsion used to move the
 13 vessel from/to the Landfall Buoy/Cruise terminal dock.

14 It should be stated that the above rates are in accordance with the study of
 15 Maragkogianni and Papaefthimiou (2015) for Greek ports, which concluded that
 16 emissions during hoteling corresponded to 88.5% of total and those produced during
 17 ship manoeuvring activities about 11.5% of total. However, it was said that emissions
 18 during ship operations were overestimated.

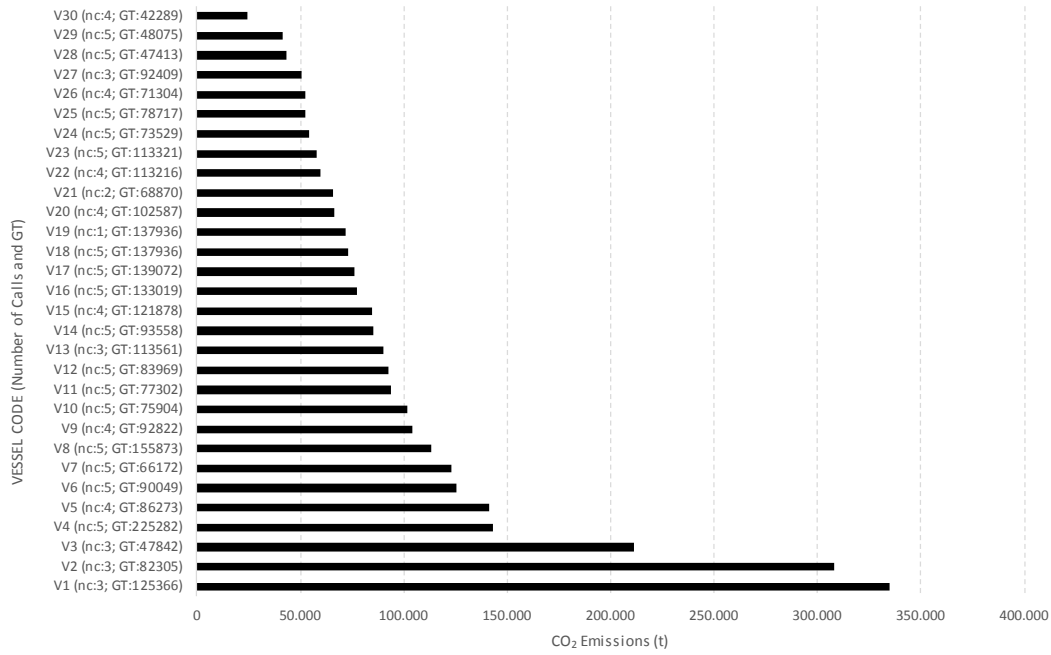


Figure 3. CO₂ annual inventory for cruise vessels

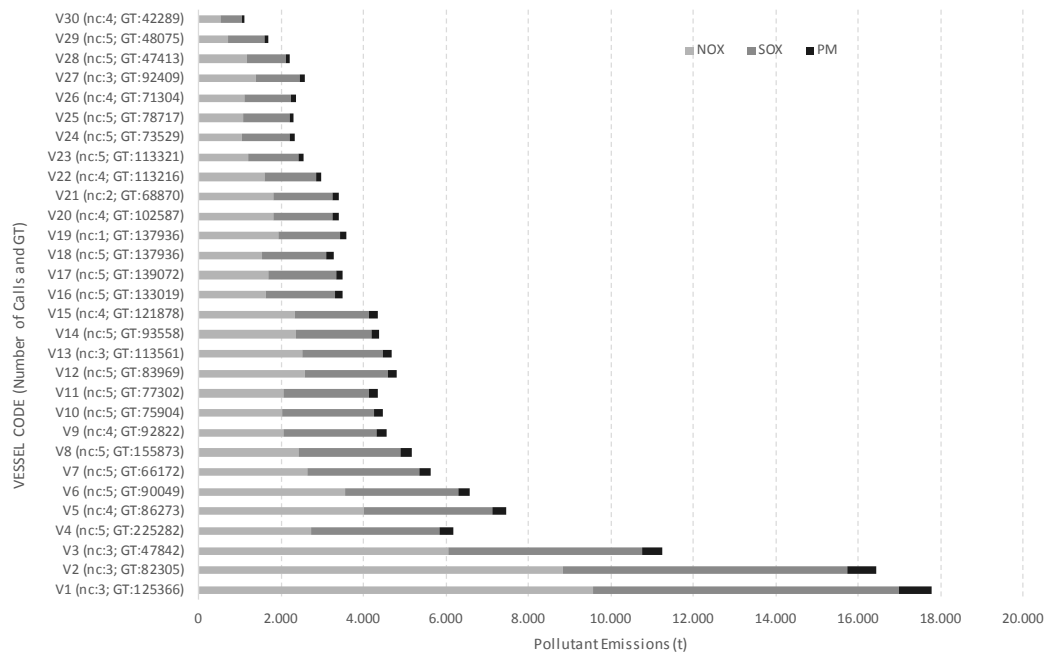


Figure 4. Pollutant emissions (NO_x, SO_x, PM) annual inventory for cruise vessels

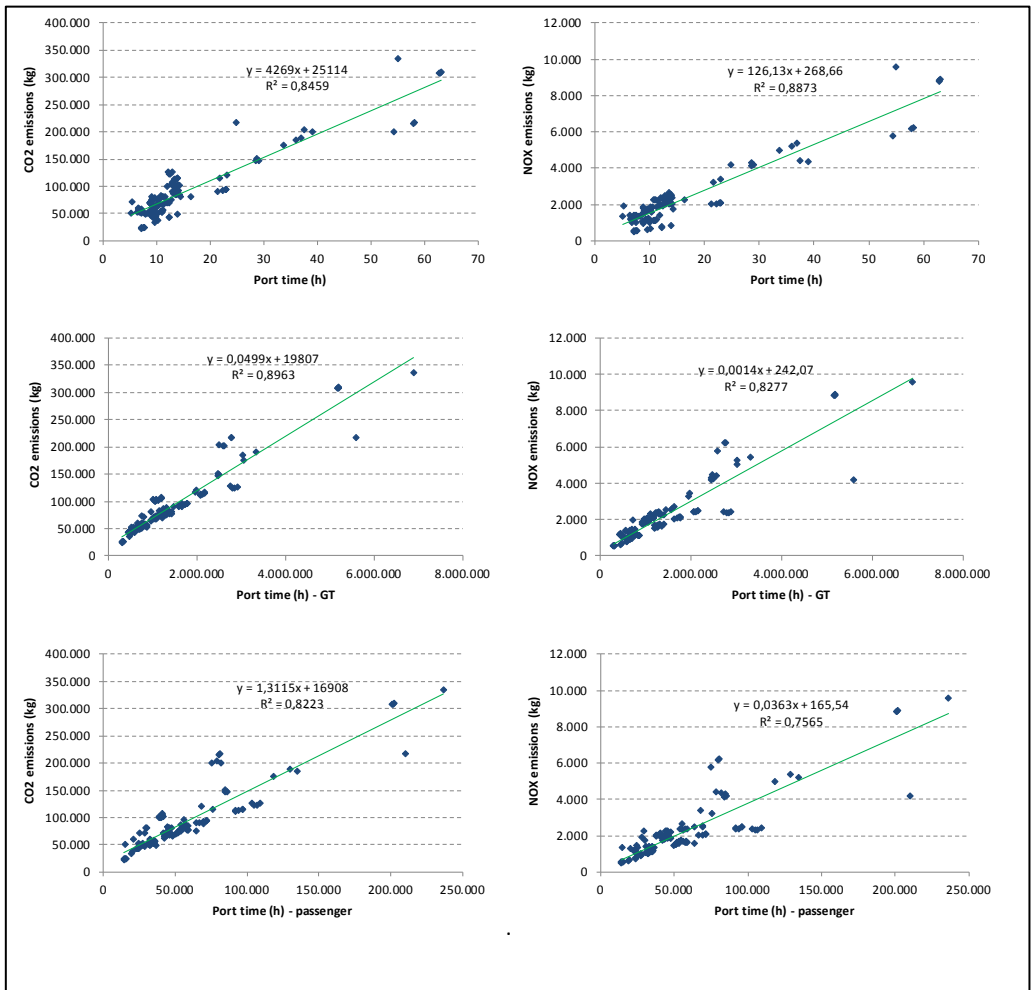
In absolute terms, the total emissions derived from the 30 cruise vessels amounted to 41.750 tons of CO₂, 955 tons of NO_x, 900 tons of SO_x and 94 tons of PM. On average, per vessel call, the estimation of emissions was: 80 tons of CO₂, 1.85 tons of NO_x, 1.75 tons of SO_x and 0.20 tons of PM.

1 **5. Cruise vessel emission indicators**

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

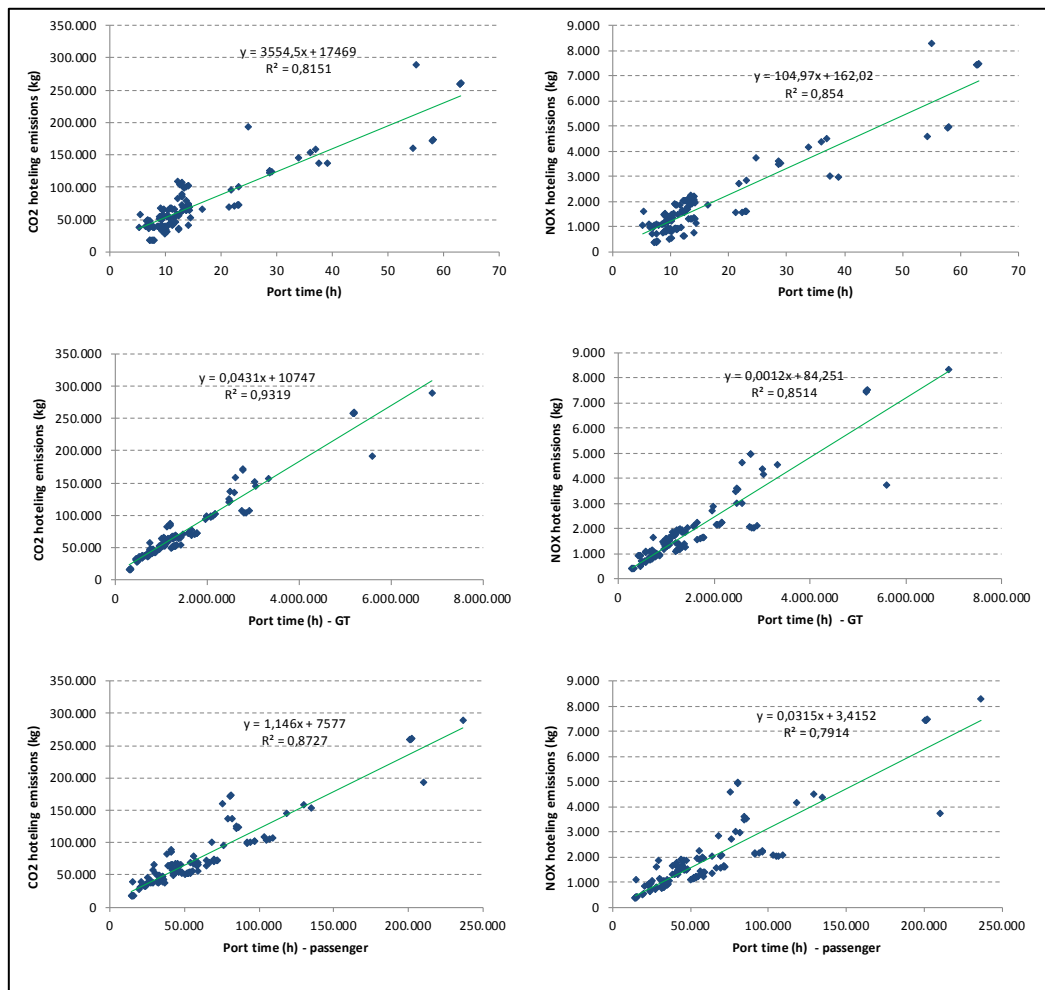
6 In order to choose appropriate indicators, a regression analysis is performed between
7 total pollutant emissions/hoteling emissions and independent variables (port time,
8 passenger capacity and vessel GT). In case the regression model (linear regression) is
9 deemed satisfactory, in the sense that a relationship exists among variables, then an
10 indicator combining those independent variables will be chosen. That is, the estimated
11 regression equation or indicator can be used to predict the emission values based on
12 the vessel dimensions (GT) and/or port time.

13 Figure 5 and Figure 6 represent the satisfactory regression models for total emissions
14 and hoteling emissions per cruise vessel call, respectively. As emissions differ with the
15 type of pollutant (depending on fuel consumption and/or engine ratings), CO2 and NOX
16 emissions are analysed separately. It should be mentioned that SOX and PM
17 emissions analyses are equivalent to CO2, as both of them also depend on fuel
18 consumption (see Table 2).



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Figure 5. Regression model figures with regards to total emissions



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Figure 6. Regression model figures with regards to hoteling emissions

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

11 Therefore, it can be concluded that the best independent variable to predict total
12 inventory emissions or hoteling emissions emitted by cruise vessel at ports is the port-
13 time – GT. Alternative variables to estimate cruise vessel emissions are dwell time –
14 passengers and port-time.

15 Finally, Table 3 lists average emission values for every selected indicator and the 25th
16 and 75th percentile values in order to show the range variability.

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Indicator	CO ₂	NO _x	SO _x	PM
Emissions (g)/port time (h) - GT	69.80 g/h-GT [58/0; 82.70]	1.68 g/h-GT [1.30; 2.00]	1.50 g/h-GT [1.25; 1.80]	0.16g/h-GT [0.13; 0.20]
Hoteling emissions (g) / port time (h) - GT	54.60 g/h-GT [47.30; 63.65]	1.35 g/h-GT [1.10; 1.60]	1.20 g/h-GT [1.05; 1.40]	0.12 g/h-GT [0.10; 0.15]
Emissions (g) / port time (h) - passenger	1,743.40 g/h-pax [1,403,20; 1,815,45]	41.35 g/h-pax [32.00; 50.15]	37.70 g/h-pax [30.15; 39.00]	3.95 g/h-pax [3.15; 4.05]
Hoteling emissions (g) / port time (h) - passenger	1,363,85 g/h-pax [1,122,75; 1,511,70]	33.65 g/h-pax [25.35; 37.75]	29.80 g/h-pax [24.50; 33.40]	3.10 g/h-pax [2.55; 3.45]
Emissions (kg) / port time (h)	6,548.0 kg/h [5,018.5; 8,229.0]	158.0 kg/h [115.9; 190.8]	141.4 kg/h [110.2; 177.0]	14.7 kg/h [11.4; 18.5]
Hoteling emissions (kg) / port time (h)	5,145.0 kg/h [4,055.0; 5,922.0]	125.75 kg/h [91.6; 146.3]	112.55 kg/h [87.9; 140.9]	11.70 kg/h [9.0; 14.5]

1 *Table 3. Emission indicators (average values and 25/75% percentile values [in square brackets]) regarding*
2 *port time, gross tonnage (GT) and number of passengers per vessel*

3

4 It should be said that hoteling emission values from Table 3 included both time at dock
5 (85% of total hoteling) and manoeuvring time (15% of total hoteling) within the port
6 area.

7

1 **6. Conclusions**

2 The need to control air pollution at ports is widely acknowledged as an active policy
3 issue by numerous ports and international port associations. In such a context, a
4 fundamental requirement for emission control and planning mitigation strategies to
5 reduce the environmental shipping impacts is the development of accurate emission
6 inventories for ports.

7 Under this framework, this paper addresses the estimation of air emissions released by
8 cruise vessels in urban ports. This is of great importance due to a significant share of
9 emissions produced during the time cruise vessels stay in ports. In addition, this paper
10 provides useful cruise ship emission indicators, which could facilitate reliably estimating
11 the in-port ship emission inventories of cruise ports without requiring large amounts of
12 data and high levels of detail.

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

21 The methodology was implemented to a particular case in which 30 cruise vessels and
22 125 calls were monitored in the Port of Barcelona during 2015. The emission
23 estimations led to the following considerations:

- 24 • Hoteling emissions (electrical generators) were found to be dominant (79%),
25 followed by those emitted by boilers (12%) and thrusters (6%) during
26 manoeuvring. The main vessel propulsion accounts for the remaining
27 percentage (3%).
- 28 • Hoteling emissions produced during berthing time represent about 85% of the
29 total hoteling emissions, whereas the remaining 15% are produced during
30 manoeuvring activities.
- 31 • According to the sample data, the average estimation of emissions per vessel
32 call was: 80 tons of CO₂, 1.85 tons of NO_x, 1.75 tons of SO_x and 0.20 tons of
33 PM.

34 With regards to emission indicators, it was found through a regression model that the
35 best independent variable to predict total inventory and hoteling emissions was the
36 combined variable port time – GT. Nonetheless, the variables port time – passenger
37 and port-time are also quite robust. In relation to the indicator emission per port-time
38 and GT, the following values could be used to estimate total emissions at ports: 69.80
39 g CO₂/h-GT, 1.68 g NO_x/ h-GT, 1.50 g SO_x/h-GT and 0.16 g PM/h-GT.

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

6 In summary, this paper contributes to the development of ship cruise emission
7 indicators, which can be extended to other cruise ports to reliably and quickly estimate
8 emission inventories and to calculate emission inventories, which could help to
9 understand cruise emissions when proposing environmental and policy measures.

10

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