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Atmospheric ship emissions in ports: A review. Correlation with data of ship traffic

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ABSTRACT

Ports represent a source of atmospheric pollutants that can contribute significantly to jeopardise air quality of port cities. NOx, SOx, PM and VOCs (Volatile Organic Compounds) are emitted by ships during manoeuvring in ports at arrival or departure and during hotelling when moored at wharves. Several methods exist to estimate emissions in function of ships' activity and engine parameters. However, there is still a significant uncertainty in these calculations. This is a severe limitation to develop effective plans of mitigation of air pollution in port cities. In this paper data of NOx and PM10 emitted in port and traffic of passenger and commercial ships have been reviewed and critically analysed. All vessels are lumped into three categories: cruise, passenger ships other than cruise and commercial ships. Emissions have been correlated with traffic data per year: passengers, hours at hotelling and manoeuvring, calls and tons of goods transported. The result is a summary of regression equations that can be used for the estimation of ship emissions in ports based on traffic data. The analysis does not consider emissions of all the ancillary activities that take place at land inside a port like: upload and download of goods, vehicular traffic, manipulation of containers and others.

1. Introduction

The maritime sector is becoming a more and more important role in the transport of goods and persons all over the world. In fact, over 80 per cent of global trade by volume and more than 70 per cent of its value being carried on board ships and handled by seaports worldwide (UNCTAD, 2017). On 1st January 2018, the world commercial fleet comprised 94,171 ships, with a combined tonnage of 1.92 billion dwt (dead weight tonnage). Dry bulk carriers represent the largest share in tons of dead weight and most of the total load capacity, at 42.5%, followed by tankers, which carry crude oil and its products (29.2%), and container ships (13.1%). Moreover, projections of world seaborne trade for the medium term also point to continued expansion, with volumes growing at an estimated compound annual growth rate of 3.2 per cent up to 2022 (UNCTAD, 2017). Therefore, the size of the ships for new deliveries continued to be greater than the existing fleet.

A similar situation is also observed for passenger traffic recording maximum growth rate at 2.2% in 2017, (UNCTAD, 2018). In particular, cruise sector is characterized by a continuous growth for over three decades (Pallis and Vaggelas, 2018). In 2017, the number of passengers of cruise ships around the world were 24 million. This number will likely increase to 25 million by 2019, and 30 million by 2024 (Peisley, 2014).

Together with the growth of maritime traffic the attention toward the effect of ships on the environment is rising. The impact of ship emissions on air quality has different aspects. It can be studied on a global or local scale. The effect on the global scale depends mainly on emissions during navigation between ports, while the local effects depend mainly on emission in ports or in their proximity. Emissions of CO_2 contribute significantly to the global warming effect while emissions of NOx, SOx, PM and VOCs impact mainly on human health of port cities.

With respect to the global warming problem emissions of carbon dioxide due to maritime transport are estimated around 1 billion tons per year, and the contribution of global greenhouse gas emissions are about 2.5 per cent of the fuel combustion sector (UNCTAD, 2017; Smith et al., 2015). H. Liu et al. (2016a) estimate for East Asia that 16% of global CO2 emissions are due to maritime transport. Very high is also the contribution of ship sector to anthropogenic emissions: NOx (15%) and SOx (5–8%) (Eyring et al., 2005; Corbett et al., 2007) on a global scale. With reference to East Asia the contribution is 9% (NOx) and 5% (SOx) (H. Liu et al., 2016a). About 70% of ship emissions are estimated to occur within 400 km of land (Endresen et al., 2003). Therefore, ships can

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give a significant contribution to jeopardise air quality of coastal areas. On local scale, Zhao et al. (2013) report that ship emissions are responsible for 4.23% of the total PM2.5 concentration in Shangai. For the same port Z. Liu et al. (2016b) indicate that ships can contribute to 20–30% of the total PM2.5 but only during ship-plume-influenced periods, and about 11% at 10 km from the coastline.

By 2050, depending on future economic growth and energy developments, shipping emissions may increase by between 50 and 250 per cent (Smith et al., 2015). This increment is not compatible with the imperative in reducing worldwide emissions to limit the global average temperature increase. For this reason, environmental sustainability in maritime transport is an imperative of the 2030 Agenda for Sustainable Development (UNCTAD, 2017).

To limit ship emissions several national or international directives are emitted. With respect to CO_2 and GHG emissions the 72nd IMO meeting in 2018 put forward more stringent emission reduction requirements to reduce annual emissions by at least 50% by 2050. Meanwhile, IMO's strategy ordered to reduce CO_2 emissions from commercial ships of 40% by 2030 and 70% by 2015 compared with 2008 (IMO, 2018).

Regarding NOx, the Marine Environment Protection Committee adopted amendments designating the North Sea and the Baltic Sea (which are emission control areas for sulphur oxides) as NOx emission control areas under the International Convention for the Prevention of Pollution from Ships, annex VI, regulation 13. Marine diesel engines operating in these areas will be required to comply with the stricter tier III NOx emissions limit when installed on ships constructed after 1 January 2021. Guidelines on selective catalytic reduction systems were also adopted (IMO, 2017, annex 13).

Regarding SOx, according to the current IMO and EU legislation, ships trading in designated zones (Emission Control Areas-ECAs) from 1 January 2015 must use on board fuel oil with sulphur content up to 0.1%, against the limit of 1% in effect until 31 December 2014. Outside the ECA, the current limit for sulphur content of fuel oil is 3.5%, reduced to 0.5% from 1 January 2020, as set out in the International Convention for the Prevention of Pollution from Ships, annex VI, regulation 14.1.3 (IMO, 2016a; annex 6). The EU Directive 2005/33/EC on sulphur emissions from ships incorporates the IMO sulphur regulation but requires in addition that from January 2010 onwards all ships at berth in harbours use fuels with sulphur content of less than 0.1% by weight (Merico et al., 2017).

Methodologies for the assessment of ship emissions goes from: full top-down approach to full bottom-up approach (Miola and Ciuffo, 2011). In the full top-down approach total emissions are calculated at a large scale, generally national, and then geographically reduced at a smaller scale (regional or urban) using proxy variables. In the full bottom-up approach, air pollutants emitted by each ship in its specific position and during a specific activity is estimated. Then data are aggregated over the time and the space.

The full top-down approach is applied in several studies (Corbett and Fischbeck, 1997; Corbett et al., 1999; Skjølsvik et al., 2000 and Endresen et al., 2007) and by national agencies (ISPRA, 2018; MINENV, 2009; Kentair, 2013; MEIC, http://www.meicmodel.otg). Common opinion is that top-down approach can be very useful to obtain a preliminary estimation of local emissions, but results must be confirmed by bottom-up studies (Eyring et al., 2009; Miola and Ciuffo, 2011; Perez et al., 2009; Saxe and Larsen, 2004; Tzannatos, 2010; Jalkanen et al., 2012; Ng et al., 2013). Due to the increase in the ships data availability and particularly following the introduction of the Automatic Identification System (AIS), bottom-up studies are nowadays generally more popular than top-down. AIS was introduced by the IMO International Convention of Safety of Life at Sea (SOLAS) to improve safety and efficiency of navigation (Tichavska and Tovar, 2015a), (Tichavska and Tovar, 2015b). But is now often used to estimate ship emissions because it transmits for each ship useful information: i) IMO identification number; ii) size; iii) weight; iv) name; v) type; vi) position; vii) heading; and viii) speed (Coello et al., 2015); (Tichavska and Tovar, 2015b); (Winther et al., 2014).

Bottom-up methods estimate the emission rates during each specific activity (hotelling, manoeuvring and navigation) as the product of an emission factor (EF) multiplied by the energy output of the engine or the fuel consumption (EEA, 2016). Energy output is generally estimated using the maximum continuous rated engine power multiplied by a load factor.

The Emission Factors are expressed in terms of mass of pollutant per power unit [g/kWh] or mass of pollutant per mass of fuel [g/g fuel]. EFs depend on various parameters: vessel category, type of fuel, type and load factor of engine (main and auxiliary), speed (Corbett and Koehler, 2004) and ambient conditions, in particular wind speed and wave heights and the mean wave direction (Jalkanen et al., 2009).

In the literature there are many bottom-up studies. The majority of them use activity-based methodologies and emission factors derived from literature (Tichavska and Tovar, 2015a; Tichavska et al., 2017; Maragkogianni and Papaefthimiou, 2015; Papaefthimiou et al., 2016; Dragović et al., 2018; Saraçoğlu et al., 2013; Kilic and Tzannatos, 2014; CAIMANs, 2015; APICE, 2013; Nunes et al., 2017a; Alver et al., 2018; Deniz and Kilic, 2009; Kiliç and Deniz, 2010; Berechman and Tseng, 2012; Yau et al., 2012; Ng et al., 2013; Song, 2014; Chen et al., 2016; Chen et al., 2017; Saxe and Larsen, 2004). De Melo Rodriguez et al. (2017) use EFs from literature but a fuel-consumption based methodology. Some studies modify EFs reported in literature on the basis of different considerations (Tzannatos, 2010; Murena et al., 2018). Other studies measure emissions on board (F. Zhang et al., 2016; Zetterdahl et al., 2016) or on land using DOAS or LIDAR technologies (Merico et al., 2016; Boselli et al., 2019).

Even though bottom-up methodology would be more accurate than top-down, uncertainties still exist due to the quality of numerous input parameters like engine load factors, fuel type and consumption rate which are generally known only as average values depending on the vessel classes (Eyring et al., 2009; ICF, 2005; Maragkogianni et al., 2016). Therefore, uncertainties on emission factors are generally between 20% and 50% for the different pollutants (Cooper and Gustafsson, 2004). Other uncertainties are related to ship traffic details. Considering that errors are random, some underestimations could be balanced by other overestimations so that a reasonable value of 30% could be assumed as uncertainty on estimated emissions (Broome et al., 2016; Merico et al., 2016).

Several reviews have been published on the survey of ship emissions. Miola and Ciuffo (2011) provided a meta-analysis for both bottom-up and top-down modelling approaches and available data sources to estimate emissions from shipping. The authors demonstrated the uncertainties associated to different methods and attributed the level of uncertainty to the different sources of the input information used. A comparative analysis of current methods for estimating energy consumptions and shipping emissions during navigation mode is reported by Moreno-Gutiérrez et al. (2015). They use several methodologies (Corbett and Koehler, 2003; Environmental Protection Agency (EPA, 2000); Entec, 2005 (Environmental Engineering Consultancy); Endresen et al., 2007; Eyring et al., 2005; IMO, 2010 (International Maritime Organization); STEAM (Ship Traffic Emission Assessment Model) by Jalkanen et al., 2009; and TNO (Netherlands Organisation for Applied Scientific Research) by van der Gon and Hulskotte (2010) to calculate fuel consumption of ships crossing the Strait of Gibraltar and corresponding emissions in the atmosphere. A difference among the results up to 27% is observed, mainly due to the relationship between engine use (from main to auxiliary) and engine loads. However, they conclude that the most reliable model of emissions assessment is the STEAM model by Jalkanen et al. (2009, 2012).

Nunes et al. (2017b) analysed 26 articles published since 2010 that used activity-based methodologies to estimate ship emissions. The study provides a summary of the main sources and procedures used to obtain the parameters necessary to calculate ship emissions. The main conclusions are: i) most of the emissions are emitted during the mooring phase; ii) container vessels are responsible for 60% of total emissions; iii) cruise ship emissions are higher in the summer.

Y. Zhang et al. (2017) reviewed and summarized the studies reporting all relevant aspects of maritime emissions and their impact on air quality in China.

Many papers give data or information on emission factors. The most adopted reference is Entec (2002). The emission factors of ENTEC are relative to NOx, SOx, CO_2, VOCs and PM for five kind of engine (slow speed diesel - SSD, medium speed diesel - MSD, stream turbine - ST and gas turbine - GT) and three type of fuels (residual oil - RO, marine diesel oil - MDO and marine gas oil - MGO). These EFs are adopted by European Environment Agency (EEA) in chapter 1.A.3.d. namely Navigation (Shipping) of air pollutant emission inventory guidebook. Tzannatos (2010) adopts emission factors of ENTEC opportunely modified using different load factors for both main and auxiliary engines. Yau et al. (2012) and Ng et al. (2013) adopted EFs by Entec (2002) implemented with correction factors by Starcrest Consulting Group (2005a), Starcrest Consulting Group (2005b) reports.

Different emission factors for NOx, PM, SOx, CO2 and CO are used in STEAM model. (Jalkanen et al., 2009, 2012, 2014). The NOx EF in STEAM is estimated by the rotation data of the motor shaft (rpm, revolutions per minute) (Jalkanen et al., 2009). The emission factors change according to the engine load and can be higher for engines that operate at low loads, which is particularly true during manoeuvres in port (Jalkanen et al., 2012).

Unfortunately, not always papers report both data of emissions and of ships traffic in port. Data on ships traffic are generally published by port authorities in terms of number of passengers, number of calls, tons of good, TEU depending on if they are referred to passenger or commercial ships. Typically, data of passenger ships are divided in cruise and “other than cruise” ships; while data on commercial ships are often only given as global.

To assess PM10 emission factor information about the composition of particulate matter in function of the engine load and the sulphur content in the fuel are used (Jalkanen et al., 2014). SOx and CO_2 EFs are modeled (Jalkanen et al., 2014) in function of the combustion conditions and specific fuel consumption. Finally, the CO EF is estimated (Jalkanen et al., 2014) following the procedure reported by Sarvi et al. (2008a, 2008b).

Obviously, a correlation of ship emissions with traffic level must exists. However, a comparison of results of different studies is difficult because data often are non-homogeneous. But differences in the findings of survey of emission in ports are in some cases relevant and a study of correlation with traffic data is useful.

In this paper the focus is on local scale effects due to the emissions of noxious gases from ships in port. We have analysed papers collected by a research on www.googlescholar.com and www.scopus.com using the following key words: “shipping emission” and “inventory”.

All the papers analysed are listed in the supplementary material section (Table S1) corresponding to 38 ports and 45 annuality. The ports are organised for geographic area. Data reported is: the year of the study (calendar time); the use of AIS data (yes or not); the methodology adopted (“LF” load factor or “FC” fuel consumption); the references of load factors and emission factors adopted.

The aim of this paper is to obtain correlations between yearly emissions (t/y) with traffic data expressed as: number of passengers, hours per activity (hotelling, manoeuvring and total as sum of hotelling and manoeuvring) and calls (passenger ships); and tons of good, hours at hotelling and calls (commercial ships). Two pollutants are considered (NOx and PM10). In this way three goals are reached: i) a comparison of the results of surveys of different ports can be performed; ii) uncertainties and anomalies (data far away from average) can be evidenced and the reasons for discrepancies interpreted; iii) a powerful tool is realised to all stakeholders (public authorities, port authorities and others) that need an estimate of port emissions. The methodology adopted consists of: i) review of data reported on ships atmospheric emissions and ships traffic in many ports in the world; ii) their analysis, and homogenization; iii) build-up of a data-base; iv) correlation with traffic data.

Even though, ships emission in port of SOx and its impact on nearby urban area is very important, it was not possible to correlate it with traffic data because emission rate of SOx depends strongly on the S content in the fuel. Unlikely, this parameter is not homogeneous ranging from 0.1% to 2.7% wt depending on the year, on the geographical area and on the activity phase. Dragovic et al. (2018) to estimate passenger ship emissions for the ports of Kotor and Dubrovnik assume a sulphur content of 1.5% during navigation and manoeuvres, and of 0.1% during hotelling. Tichavska et al. (2017) assume: i) for the port area of Las Palmas a sulphur content of 0.1% for all ships at hotelling, 2.7% for non-passenger ships and 1.5% for passenger ships during the manoeuvre; ii) for the port of St. Petersburg and for all ship categories, a sulphur content of 0.1% at hotelling and 1% during the other phases; iii) for Hong Kong a sulphur content of 2.7% for all ships and for all phases.

The S fuel content also influences PM10 emissions, but on a more limited degree. In fact, the sulphur content in fuel influences both emissions of primary and formation of secondary particles. A reduction in the PM2.5 contribution of tourist vessel traffic emissions was associated by Contini et al. (2015) with the implementation of a directive reducing sulphur content from 2.5% to 1.5% in the port of Venice (Italy). Cesari et al. (2014) observed a contribution of in-port ship emissions at Brindisi (Italy) to the formation of non-sea salt sulphate ($nssSO_4^{2-}$) corresponding to about 40% of total $nssSO_4^{2-}$.

2. Methodology

One of the main difficulties in the elaboration of data on ship emissions in ports is the poor homogeneity. Data on emissions may be reported as global data or divided in the main vessel categories: passenger and commercial. The single global data of emission is of scarce utility for elaboration and comparison with other ports because it depends strongly on the percentage of contribution of passenger and commercial ships. In the same way data on emission of passenger ships can be global or specified for cruise ships or other categories (ferries, hydrofoils or other) also in this case more the data is referred to a specific category higher is its utility. Data on commercial ships are generally rarer than data on passenger ships.

Another inhomogeneity is how emissions data are attributed to the different activities in ports. Also in this case sometimes only a global data is given. More frequently specific activities are indicated as hotelling, manoeuvring or navigation. Hotelling is when the ship is stopped at wharves but emit exhaust gases from engines producing heat and electrical power for all the services necessary for the crew and the passengers or to upload and download of goods, maintenance or others. The terms manoeuvring and navigation in port indicate the activities when the ship is moving inside the port or in its proximity. Some authors make differences between these terms other do not. If both activities are considered, manoeuvring represents the high non-stationary phase during which the ship changes speed or direction to rapidly approach the dock, while navigation is the movement of the ship inside the port area at quite constant and reduced speed. Another inhomogeneity is the length of the route corresponding to the navigation phase. For some authors it is the distance from the port entrance to the final mooring point and is generally a few miles, for others it is much longer because they consider that ship emissions could impact urban air quality from tens of miles from the coast. However, the hotelling phase represents generally the largest fraction of total emissions in port: NOx 90.1%; PM2.5 78.0% and SOx 88.5% (Papaefthimiou et al., 2016). These percentages can vary depending mainly on time at hotelling and length of manoeuvring phase.

Data on traffic reported are also often quite different. For passenger ships data can be: number of passengers, calls, hour at hotelling. For

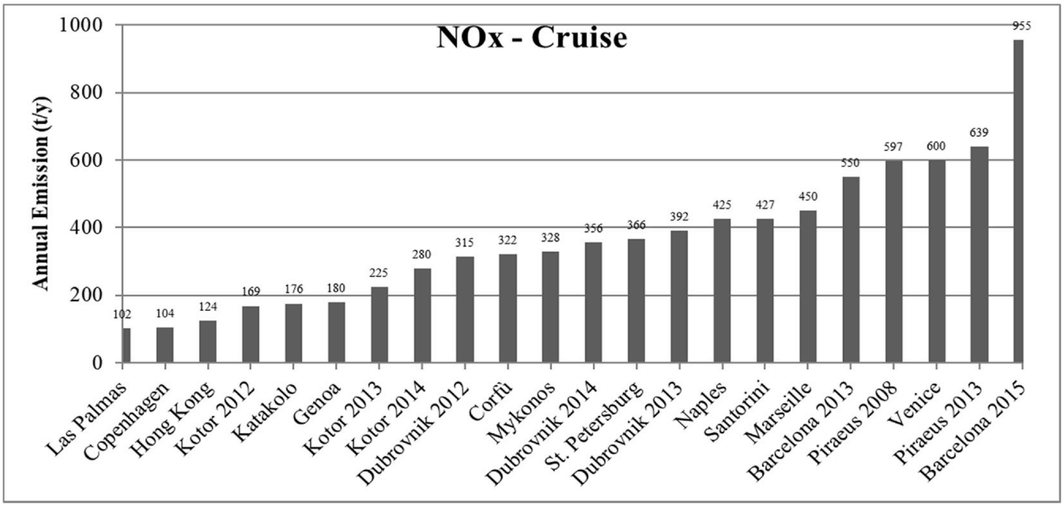

Fig. 1. NOx emissions of cruise ships for all ports in the reviewed studies.

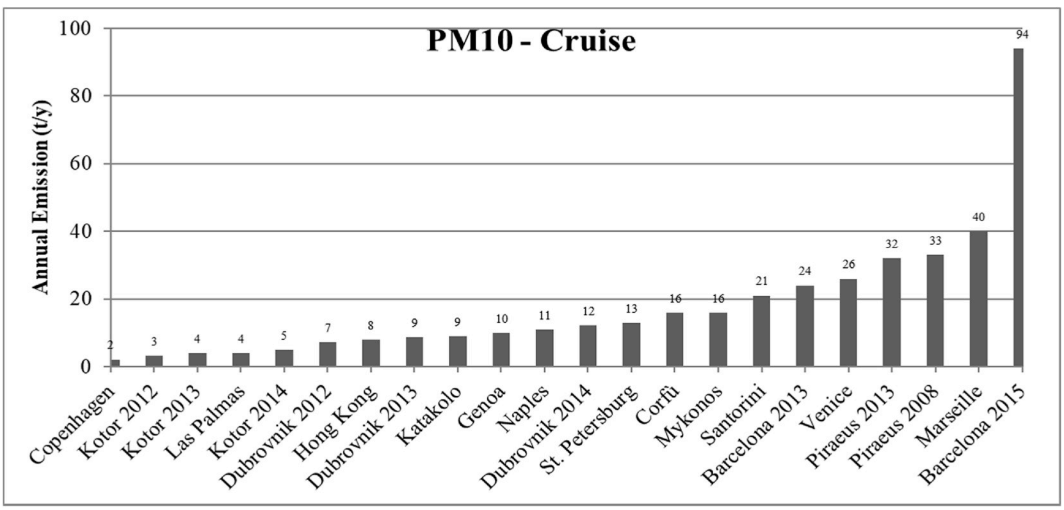

Fig. 2. PM10 emissions of cruise ships for all ports in the reviewed studies.

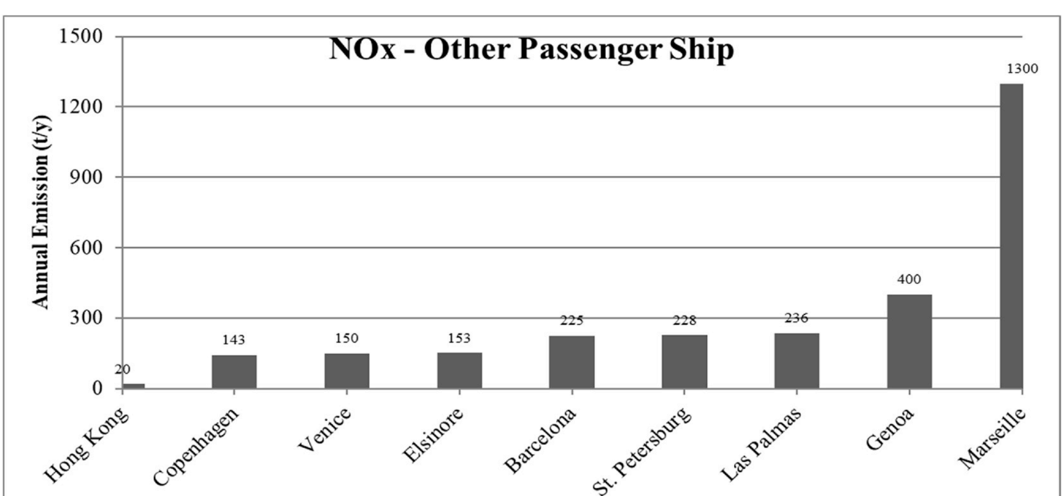

Fig. 3. NOx emissions of other passenger ships for all ports in the reviewed studies.

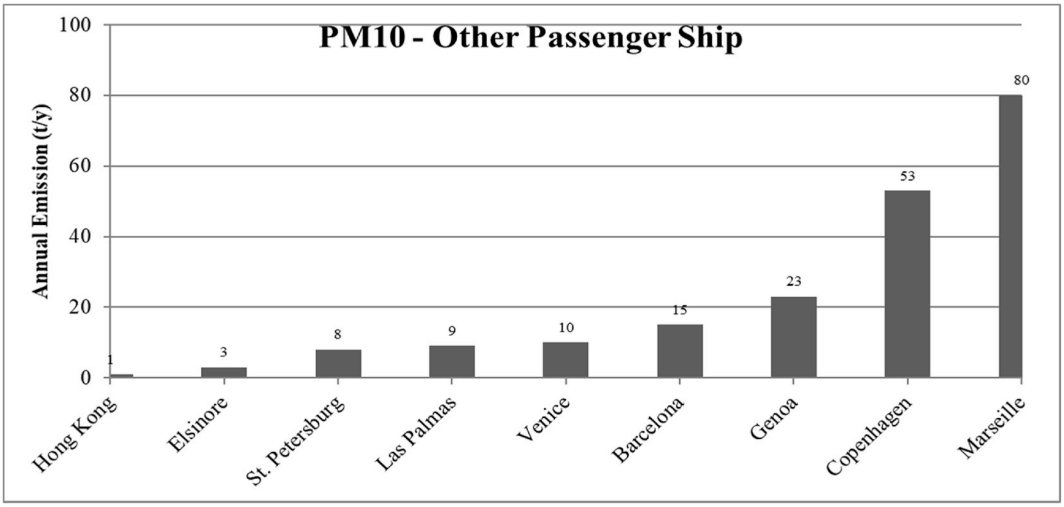

Fig. 4. PM10 emissions of other passenger ships for all ports in the reviewed studies.

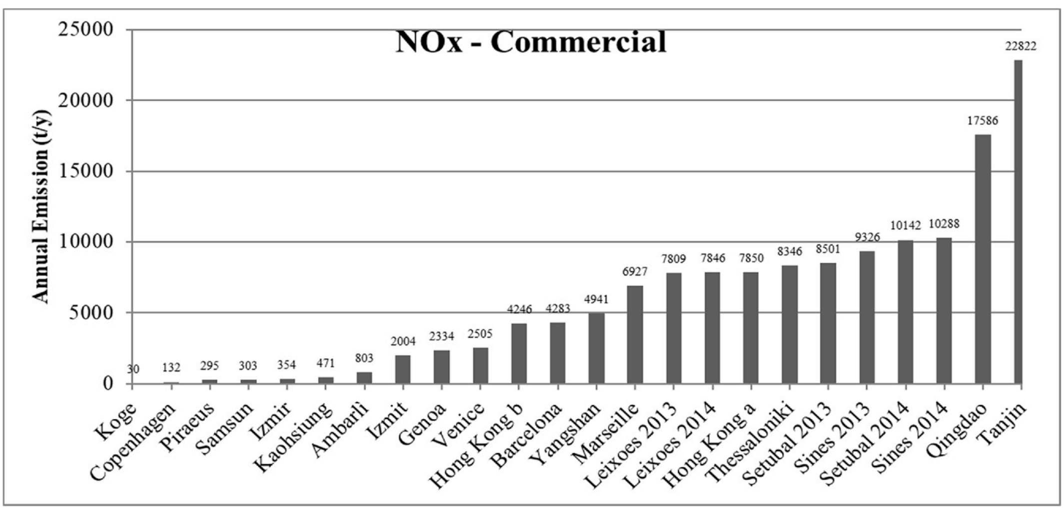

Fig. 5. NOx emissions of commercial ships for all ports in the reviewed studies.

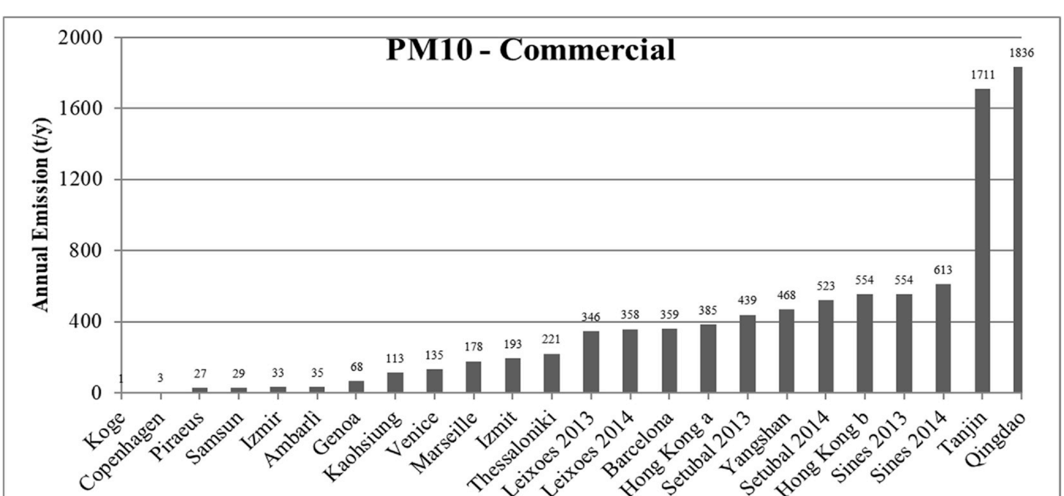

Fig. 6. PM10 emissions of commercial ships for all ports in the reviewed studies.

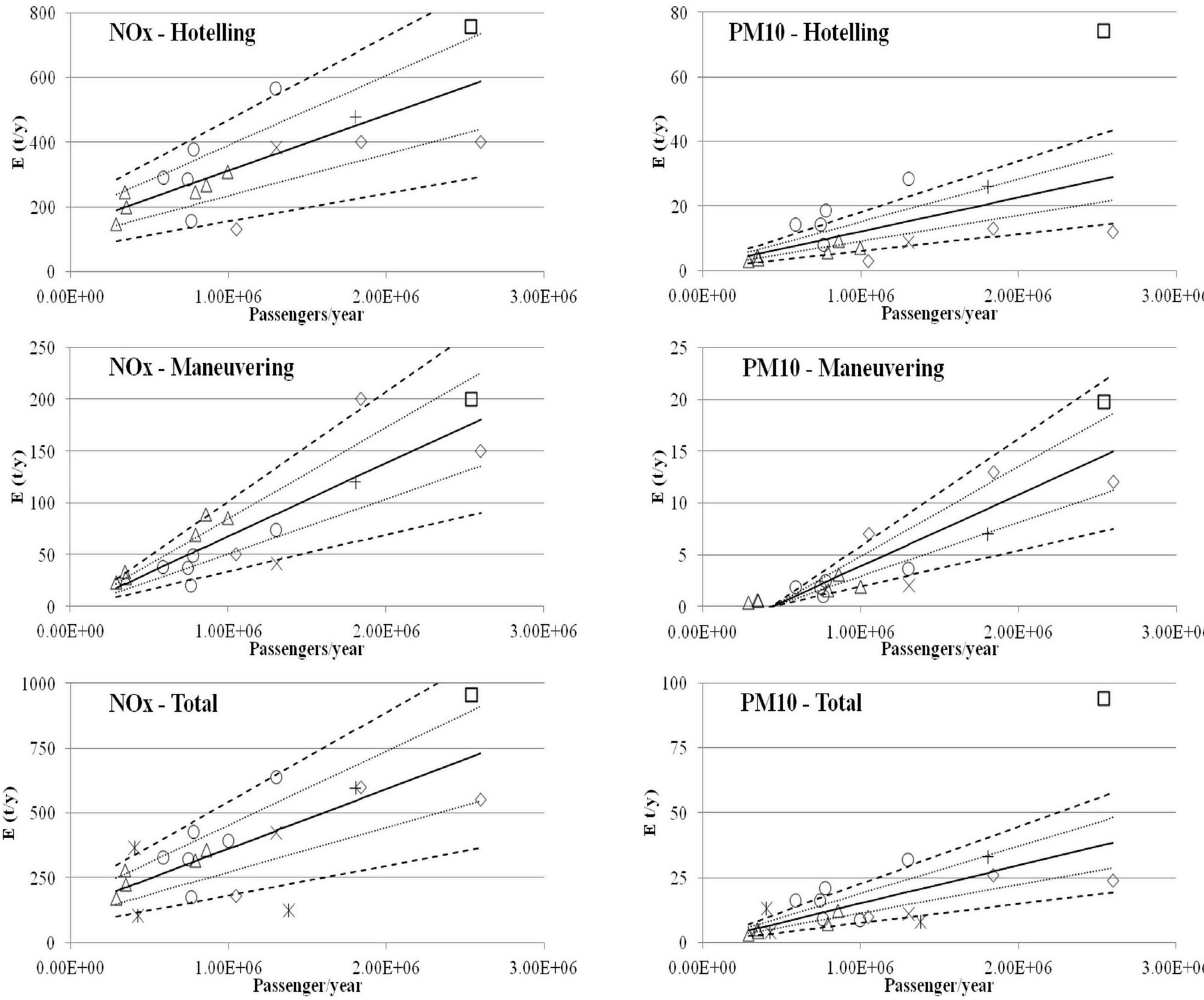

Fig. 7. Cruise ship emissions against number of passengers: hotelling (up); manoeuvring (middle); total (bottom).

commercial ships: calls, tons of goods or TEU are normally used. Data on special purpose vessels like tugs, military, coast guard ships are rarely given.

To analyse this large but inhomogeneous mass of data we have divided passenger ships in cruise and others while commercial ships are considered as a single category. Special purpose ships are not considered since their emissions are generally not relevant. Data on traffic analysed are: calls, passengers, hours at hotelling, tons per year. Emissions during navigation are evaluated for a length corresponding to navigation in port. If a higher length was considered by the authors it was reduced as necessary.

All data are used to build up a data base in ACCESS. Once the database was built, data were extracted by queries and elaborated to obtain the equation of regressions of emissions with traffic through the statistical software JMP. Fit-robust model (Huber, 1973) was used to reduce the effect of outliers. Due to the scarcity of data and their already mentioned lack of homogeneity we prefer using a single parameter correlation model, besides of a multiparametric model. In fact, in many cases two or more traffic parameters are not available for a multi-parameter correlation (e.g.: the number of calls is available but not the number of passengers). Moreover, a multiparametric correlation would limit the practical application of our results depending on the availability of all the parameters.

3. Results and Discussion

The traffic data for each port studied are listed in Table S2. In Fig.s 1-6 annual emissions (t/year) of NOx and PM10 are reported for the ports studied divided per vessel categories: cruise, "passenger ships other than cruise" and commercial. Absolute values vary in a broad range depending on the specific traffic of each port. As an example for cruise ships NOx emissions range from 102 t/y to 955 t/y corresponding to Las Palmas port (Tichavska et al., 2015a) (Tichavska et al., 2017), and Barcelona port (De Melo Rodriguez et al., 2017); while PM10 emissions range from 2 t/y to 94 t/y corresponding to Copenhagen port (Saxe and Larsen, 2004) and Barcelona port (De Melo Rodriguez et al., 2017). For "passenger ships other than cruise" the minimum and the maximum emissions of NOx are 20 t/y and 1300 t/y calculated at Hong Kong (Tichavska et al., 2017) and Marseille (CAIMANs, 2015) while for PM10 the range is between 1 t/y and 80 t/y in the same ports. For commercial ships NOx emissions range from 30 t/y to 22822 t/y in the ports of Koge (Saxe and Larsen, 2004) and Tanjin (Chen et al., 2016), while for PM10 the range is 1 t/y to 1836 t/y in Koge (Saxe and Larsen, 2004) and Qingdao (Chen et al., 2017).

Table 1
Summary of regression equations for cruise ships.

Phase	Traffic data	Pollutant	Correlation equations	R^2	Number of points	Reliability
Hotelling	Passengers	NOx	$140 + 1.72{\cdot}10^{-4}\ P$	0.57	17	Medium
		PM10	$1.46 + 1.06{\cdot}10^{-5}\ P$	0.40	17	Medium
	Hours	NOx	$91.9 + 3.07{\cdot}10^{-2}\ H$	0.70	13	High
		PM10	$-\ 2.18 + 1.22{\cdot}10^{-3}\ H$	0.86	13	High
	Calls	NOx	$6.20 + 5.90{\cdot}10^{-1}\ C$	0.81	19	High
		PM10	$-\ 4.81 + 3.21{\cdot}10^{-2}\ C$	0.65	19	High
Manoeuvring	Passengers	NOx	$-\ 2.84 + 7.06{\cdot}10^{-5}\ P$	0.77	17	High
		PM10	$-\ 3.03 + 6.91{\cdot}10^{-6}\ P$	0.80	17	High
	Hours	NOx	$15.7 + 1.12{\cdot}10^{-1}\ H$	0.98	12	High
		PM10	$-\ 0.87 + 1.07{\cdot}10^{-2}\ H$	0.66	12	High
Total	Passengers	NOx	$132 + 2.33{\cdot}10^{-4}\ P$	0.57	20	Medium
		PM10	$0.51 + 1.46{\cdot}10^{-5}\ P$	0.52	20	Medium
	Hours	NOx	$138 + 2.42{\cdot}10^{-2}\ H$	0.42	15	Medium
		PM10	$2.13 + 1.24{\cdot}10^{-3}\ H$	0.58	15	Medium
	Calls	NOx	$-\ 22.1 + 7.95{\cdot}10^{-1}\ C$	0.89	19	High
		PM10	$-\ 7.14 + 4.66{\cdot}10^{-2}\ C$	0.62	19	High

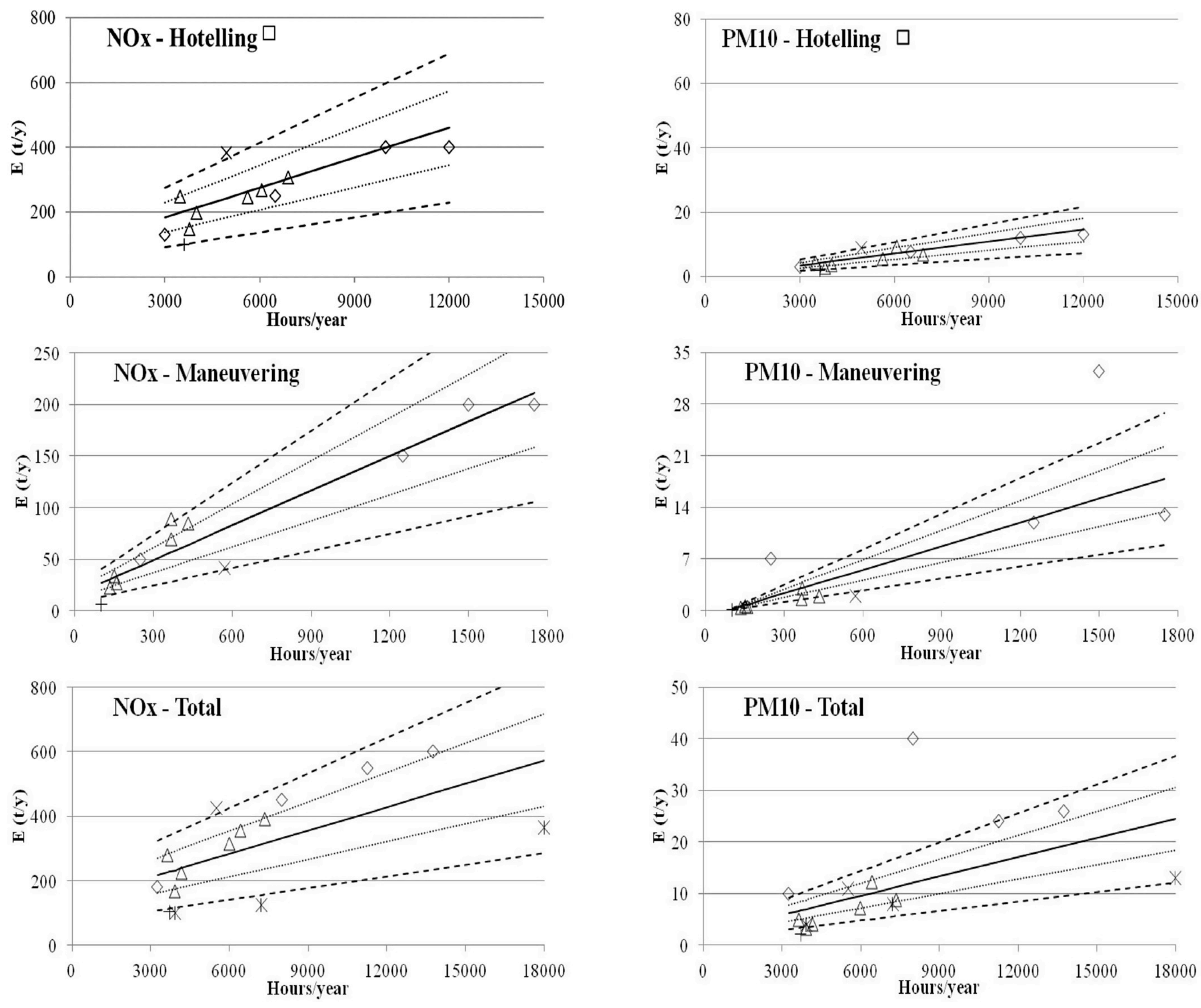

Fig. 8. Cruise ship emissions against hours of activity: hotelling (up); manoeuvring (middle); total (bottom).

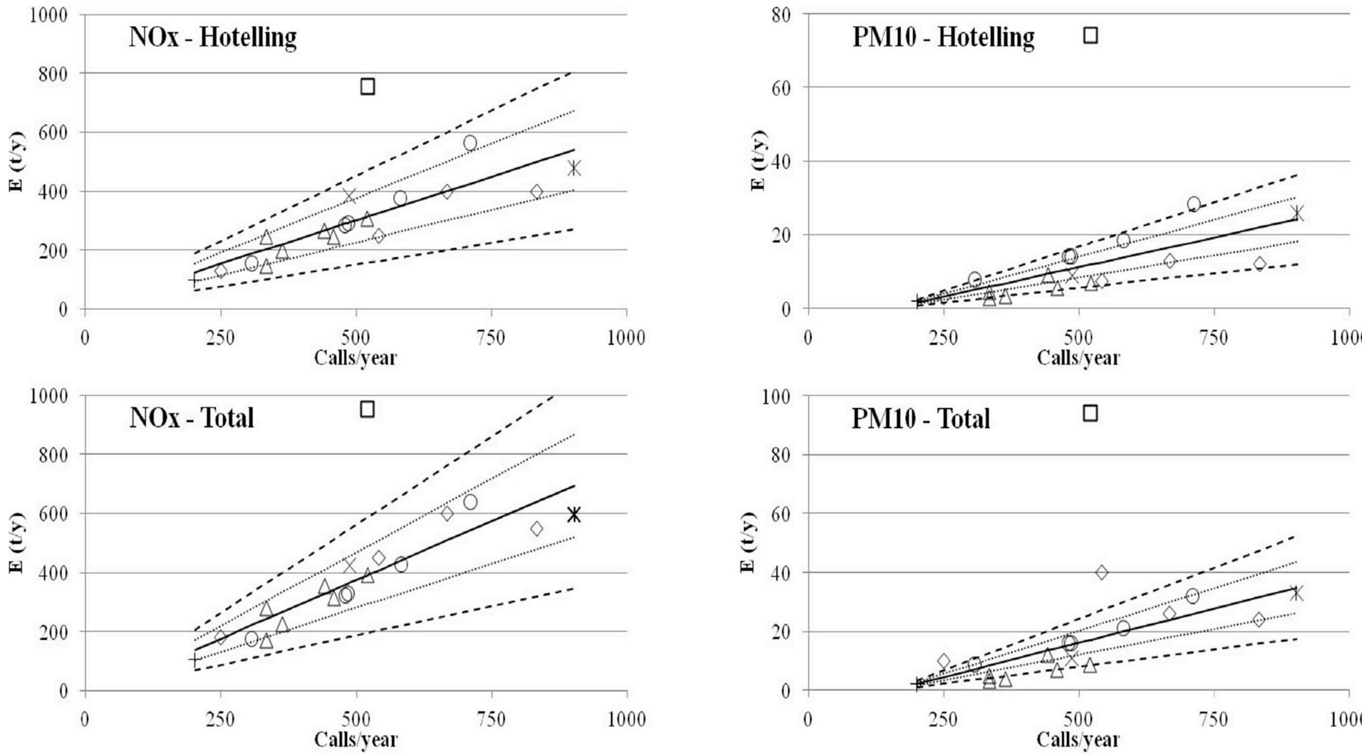

Fig. 9. Cruise ship emissions against calls: hotelling (up); total (bottom).

In the following data of ship emissions for each of the three categories (cruise, passenger ships other than cruise and commercial) and for different phases of activity (hotelling, manoeuvring and total) are correlated with data of traffic.

Fig. 7 shows the correlations between cruise ship emissions against the number of passengers. Data of NOx and PM10 are reported respectively on the left and on the right diagrams. The graphs also show the interval of confidence lines ± 25% and ± 50%. Data comes from 8 different studies concerning 20 ports, all in the Mediterranean area. Five studies (Tzannatos, 2010), (CAIMANs, 2015), (Papaefthimiou et al., 2016), (Dragović et al., 2018), (Murena et al., 2018) calculate the engine energy output, corresponding to each activity phase, from data of MCR (maximum continuous rated) engine power applying a LF (load factor). Sources of data of LFs are in Table S1.

De Melo Rodriguez et al. (2017) use real data to estimate fuel consumption in function of the actual power applied in the different phases (reported as square in Fig. 7).

Generally, data show a limited spread with some points outside ± 25% and only few outside ± 50%. The spread is higher in the manoeuvring phase and lower if total emissions are considered.

Focusing on the hotelling phase, the results are that 65% of points for NOx and 18% for PM10 lie within the ±25% CI, while 88% for NOx and 59% for PM10 of values are outside the ±50% CI.

Emissions of PM10 at greek ports of Piraeus, Mykonos, Corfù and Santorini (circle in Fig. 7 up) are above the confidence line +50%. Higher emission rates evaluated depend on higher load factors used (Table 1 in Papaefthimiou et al., 2016) because authors take in account the effect of yearly season on LFs. In the project CAIMANs for the ports of Barcelona, Genoa, Marseille and Venice (rhombus in Fig. 7 up) the authors followed the EMEP guidelines using the gross tonnage to evaluate emissions. Using a fuel-based methodology for the Barcelona port De Melo Rodriguez et al. (2017) obtain data (square in Fig. 7 up) about on +25% CI line for NOx but out of +50% CI line for PM10.

Manoeuvring phase (Fig. 7 middle) shows a higher spread of data. This mainly depends on the differences among the ports in regard to the length of the manoeuvring routes and, therefore, of the corresponding time. However, emissions in this phase are lower than during hotelling, and therefore less relevant.

In the diagrams of total emissions (Fig. 7 bottom), data from ports of Las Palmas, St Petersburg and Hong Kong are added (Tichavska et al., 2017). In this case the correlations get better. In fact, 55% of data for NOx and 25% for PM10 are within the ±25% CI, and 80% of data (NOx) and 70% (PM10) within the ±50% CI. Concerning total NOx emissions, data of the Genoa port (rhombus) are on the border of −50% CI. This is probably due to the limited number of hours spent in the two phases (hotelling + manoeuvring) by cruise ships in Genoa in one year (CAIMANs, 2015). In fact, if compared with data of Dubrovnik (Dragović et al., 2018) in correspondence to a similar traffic of passengers, cruise ships spent about 3000 h in Genoa compared to 7300 h in Dubrovnik (Dragović et al., 2018). Concerning PM10, the emissions of the Barcelona port, if a fuel based methodology is adopted (De Melo Rodriguez et al., 2017) fall outside the +50% IC (square in Fig. 7 bottom), else using a MCR+LF methodology (CAIMANs, 2015) data is inside the −50% of CI interval (rhombus in Fig. 7 bottom). Data of greek ports of Mykonos, Santorini and Piraeus are slightly above the +50% CI for the reasons already cited.

Fig. 8 shows the correlations of cruise ship emissions (t/year) for NOx (left) and PM10 (right) with the time spent in each phase (hours/year). Data come from 6 different studies concerning 15 ports. Analyzing the correlations with hours spent in hotelling, it results that 62% of points for NOx and 54% for PM10 lie within the ±25% CI, while 77% both for NOx and PM10 of values are in the ±50% CI. Data relating to the port of Barcelona (square in Fig. 8 up) are considerably higher than in the other ports. In this case the authors (De Melo Rodriguez et al., 2017) used a fuel-based method, while others studies (Saxe and Larsen, 2004), (Tzannatos, 2010), (CAIMANs, 2015) (Dragović et al., 2018) and (Murena et al., 2018) used a MCR-LF method. Data for the port of Copenhagen for NOx emission (symbol + in Fig. 8 up) is below the −25% IC. This is partially due to the lower emission factors used (Saxe and Larsen, 2004) 12 [g/kWh] for NOx, compared to those adopted in other ports: 12.4 [g/kWh] (Dragović et al., 2018) – 13.9 [g/kWh] (Tzannatos, 2010).

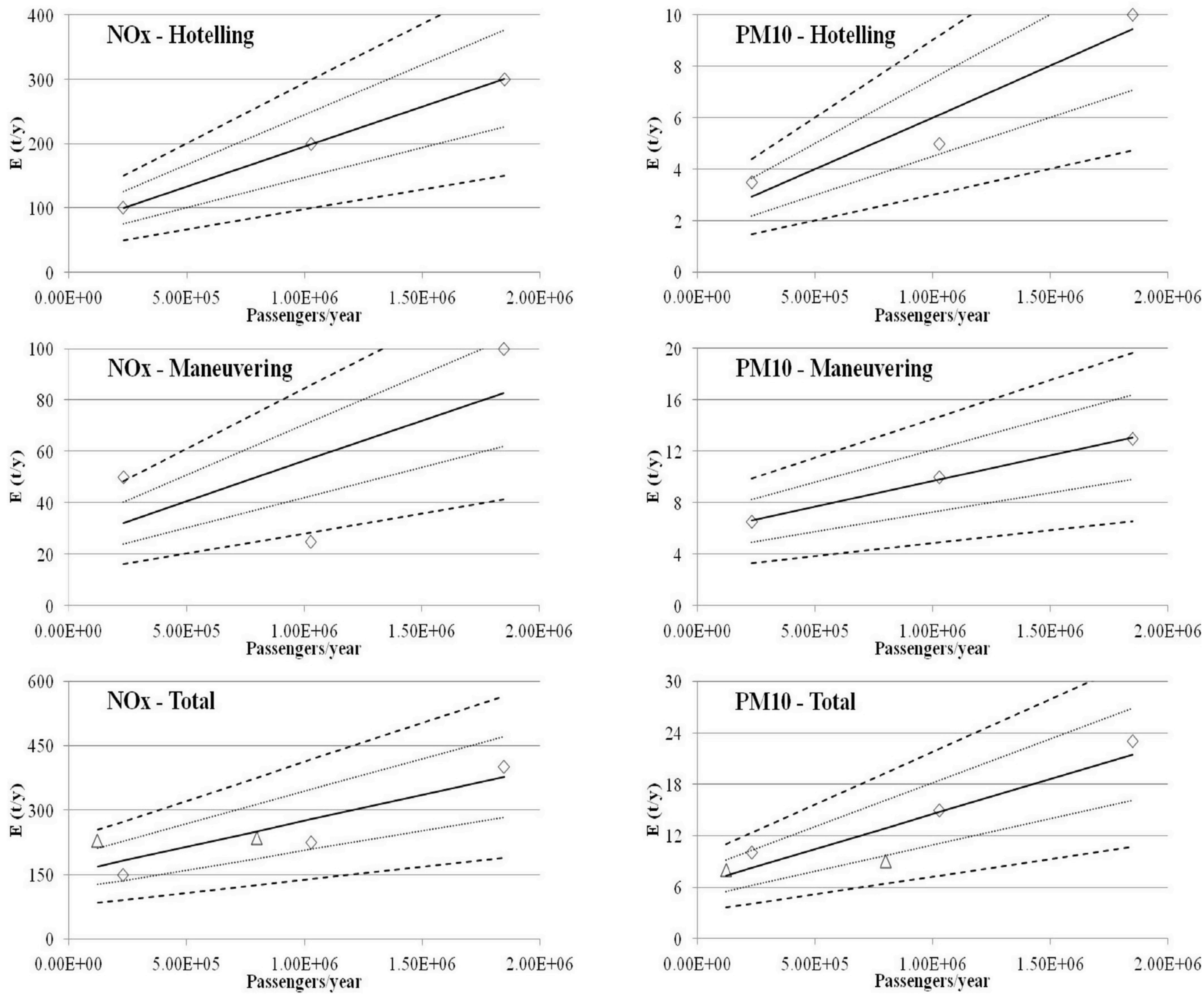

Fig. 10. Other passenger ships emissions against number of passengers: hotelling (up); total (bottom).

Emissions at hotelling in the port of Naples (Murena et al., 2018), symbol X in Fig. 8 up, are above the +50% CI both for NOx and PM10. In this case EMEP methodology was integrated with real data of engine power determining a higher power applied at hotelling.

Correlations of manoeuvring emissions against time is good for NOx but relatively low for PM10 (17% of values within ±25% CI). Data of emissions of PM10 during manoeuvring for the port of Marseille (rhombus in Fig. 8 middle) is much higher compared to the other ports (33 t/y in correspondence of 1500 h/y). This is a consequence of the assumption (CAIMANs, 2015) of the use of BFO during manoeuvring with a emission factor for PM10 equal to 0.8 [g/kWh] more than double the average emission factor used for other ports.

The correlations between total emissions (Fig. 8 bottom) with total time spent in port (hotelling + manoeuvring) are quite high with 40% of data for NOx and 27% for PM10 within ±25% CI and 73% of data (both for NOx and PM10) within the ±50% CI.

Finally, cruise ships' emissions are correlated with calls number per year (Fig. 9). In this case correlations in manoeuvring phase are not reported because the spread is very high.

Focusing on correlations between emissions at hotelling with number of calls (Fig. 9 up), it results that 79% of points for NOx and 32% for PM10 are in the ±25% CI.

The correlations get better when total emissions are considered. In fact, 89% of NOx data and 47% of PM10 are within ±25% CI, and 95% of data for NOx and 68% for PM10 are within the ±50% CI. Data of Barcelona (NOx and PM10) and of Marseille (PM10) fall outside the +50% CI (respectively square and rhombus in Fig. 9 bottom) for the reasons above reported.

Cruise ships - Discussion of results. The summary of all regression equations for cruise ships is reported in Table 1 with: R^2, number of points for regression and degree of reliability. We have assumed: i) "high" reliability of the correlation equation if $R^2 \geq 0.6$ and n° points ≥ 10; ii) "medium" when $R^2 \geq 0.4$ and n° points $5 \leq n < 10$; iii) "low" in all other cases. Table 1 shows how correlations of cruise ship emissions with traffic data are generally quite good and characterized by "high" or "medium" reliability. This is not surprising because "cruise ships" is a quite homogeneous and well-studied ships category with many data available. However, in the case of PM10 it must be observed the presence of a "outlier" when a different methodology based on fuel consumption (De Melo Rodriguez et al., 2017) is adopted. It would be necessary to have more data to realize whether results are really different from those coming from the application of load factor methodologies. The same effect is not observed for NOx emissions.

P is number of passengers for year [#/year]; H is time spent in each

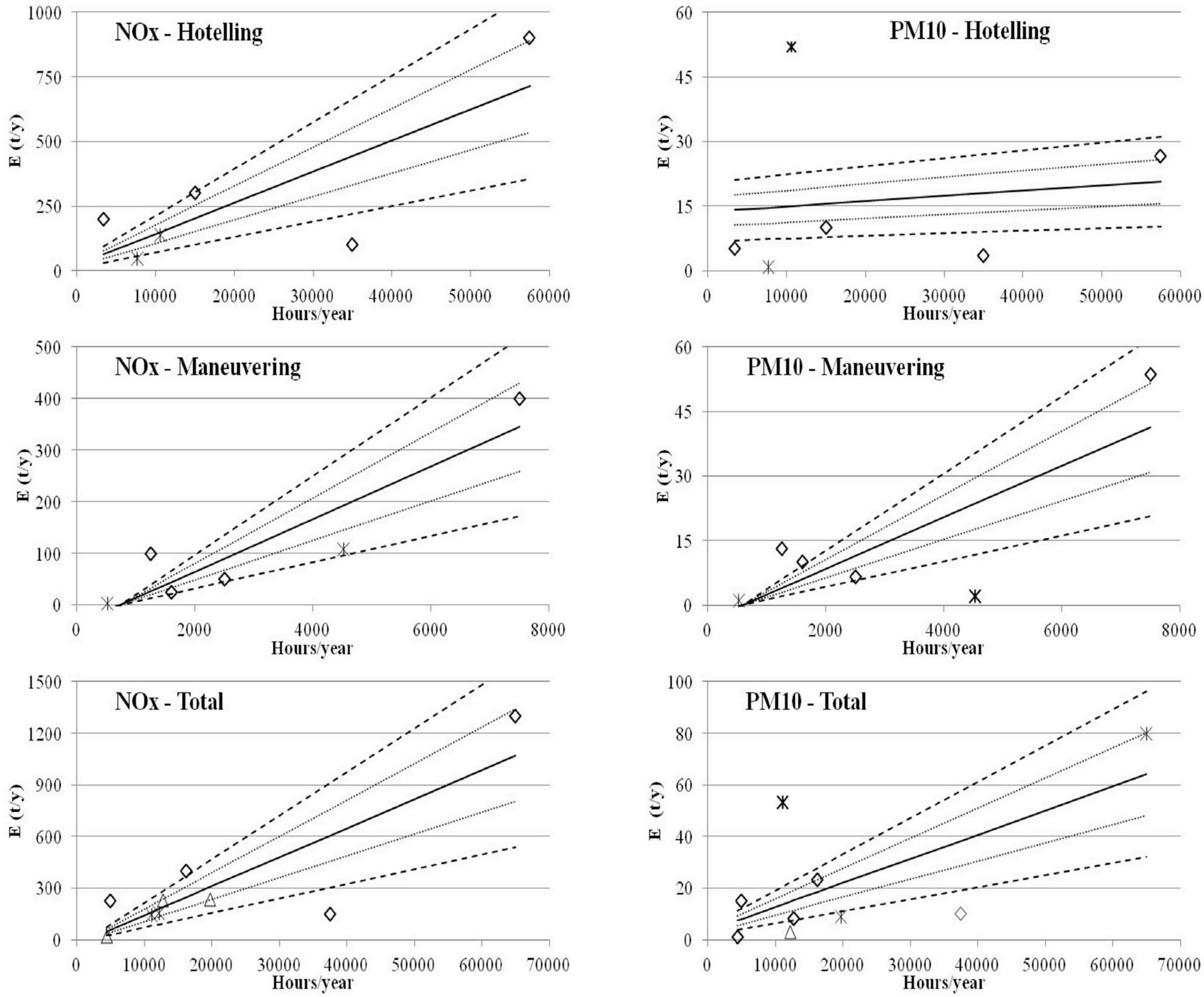

Fig. 11. Other passenger ship emissions against hours of activity: hotelling (up); manoeuvring (middle); total (bottom).

phase for year [hours/year] and C is number of calls per year [calls/year].

Passenger ships different from cruise are lumped in a single category named "other passenger ships". Data on emissions from this category of vessels are scarce.

Fig. 10 shows the regressions between emissions and the number of passengers per year. Data are available for each phase from a single reference (CAIMANs, 2015) and only for three ports (Barcelona, Genoa

Table 2
Summary of regression equations for other passenger ships.

Phase	Traffic data	Pollutant	Correlation equations	R^2	Number of points	Reliability
Hotelling	Passengers	NOx	$71.9 + 1.24 \cdot 10^{-4}\,P$	1.0	3	Low
		PM10	$1.99 + 4.03 \cdot 10^{-6}\,P$	0.92	3	Low
	Hours	NOx	$22.0 + 1.20 \cdot 10^{-2}\,H$	0.63	6	Medium
		PM10	$13.7 + 1.22 \cdot 10^{-4}\,H$	0.63	6	Medium
Manoeuvring	Passengers	NOx	$26.0 + 3.12 \cdot 10^{-5}\,P$	0.44	3	Low
		PM10	$5.67 + 4.02 \cdot 10^{-6}\,P$	1.0	3	Low
	Hours	NOx	$-38.1 + 5.10 \cdot 10^{-2}\,H$	0.83	6	Medium
		PM10	$-3.48 + 5.98 \cdot 10^{-3}\,H$	0.62	6	Medium
Total	Passengers	NOx	$155 + 1.15 \cdot 10^{-4}\,P$	0.83	5	Medium
		PM10	$6.32 + 8.29 \cdot 10^{-6}\,P$	0.85	5	Medium
	Hours	NOx	$-26.8 + 1.69 \cdot 10^{-2}\,H$	0.73	9	Medium
		PM10	$3.35 + 9.34 \cdot 10^{-4} H$	0.59	9	Medium

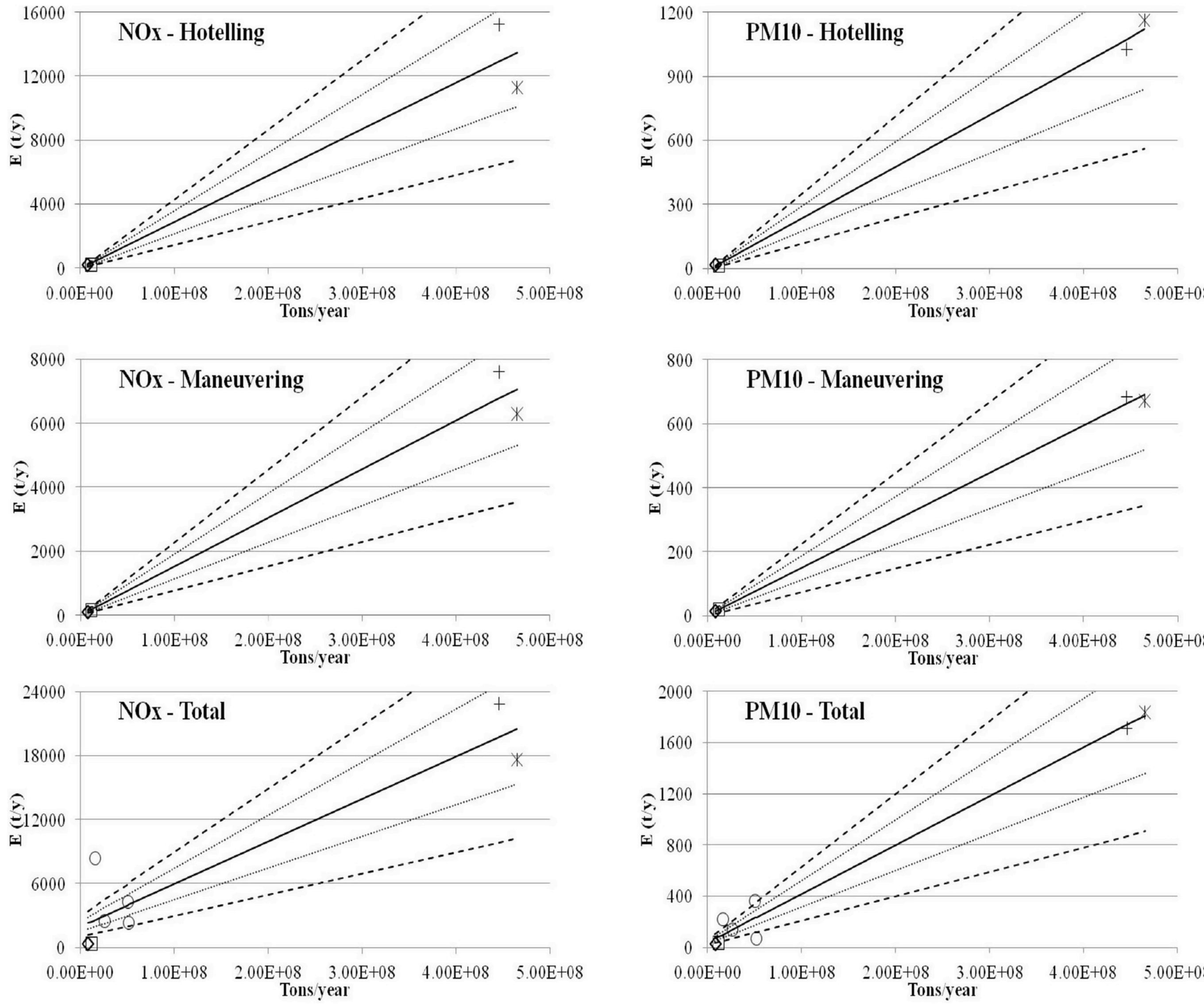

Fig. 12. Commercial ship emissions against tonnes of goods: hotelling (up); manoeuvring (middle); total (bottom).

and Venice) using EMEP/EEA methodology. Therefore, the correlations of emissions at hotelling are good both for NOx and PM10. On the contrary, emissions at manoeuvring show a high spread for NOx while a good correlation for PM10 (Fig. 10 Middle). This depends mainly on the differences among the ports regarding the length of the manoeuvring routes (longer for Venice) and the sulphur content in the fuel used during navigation in port, higher in Genoa and Barcelona (CAIMANs, 2015).

The correlations with total emissions include also the ports of Las Palmas and St. Petersburg (triangle in Fig. 10). Data of Hong Kong (Passengers = $2.60 \cdot 10^7$, E= 20 t/y for NOx and 1 t/y for PM10) (Tichavska et al., 2017) are not reported in Fig. 10 bottom because the emission is so low to seem unrealistic.

Correlations of "other passenger ship" emissions (t/year) for NOx (left) and PM10 (right) with the time spent in each phase (hours/year) (Fig. 11) include data from two different studies concerning 6 ports for hotelling and manoeuvring and from nine ports for the total.

In some cases, the spread is very high (mainly for PM10 at hotelling and also as total) determining a high uncertainty. A reason of the uncertainty is that generally it is not specified the kind of ships included in the "other passenger ships" category. As an example, Saxe and Larssen (2004), for the ports of Copenhagen and Elsinore, and Tichavska et al. (2017), for the ports of Las Palmas, St. Petersburg and Hong Kong, have considered only ferries. On the contrary in CAIMANs (2015) no information are available about the kind of vessels included in "other passenger ships".

"Other than cruise" passenger ships - Discussion of results. Table 2 shows the summary of all regression equations for "other than cruise" passenger ships. The main finding is that for this ship category the sample size is very limited. For this reason, the reliability of correlation equations is "low" or "medium". In some cases, only three data are reported. This is an insufficient sample size to make a correlation. For this reason, the reliability of the correlation is "low" even though $R^2 > 0.92$.

P is number of passengers for year [#/year]; H is time spent in each phase for year [hours/year].

The last category examined is commercial ships. Several kinds of vessels belong to this class: dry bulk cargo, liquid bulk cargo, solid bulk cargo, container, general cargo, carrier, cargo Ro-Ro, fridge cargo, other cargo. Due to the high number of different vessels of commercial ships and the absence, in many cases, of specific traffic data for each kind of vessel we have correlated emissions of the whole of commercial ships with data of traffic in terms of: tons of goods, hours at hotelling and number of calls.

Data of emissions in port are more limited with respect to cruise

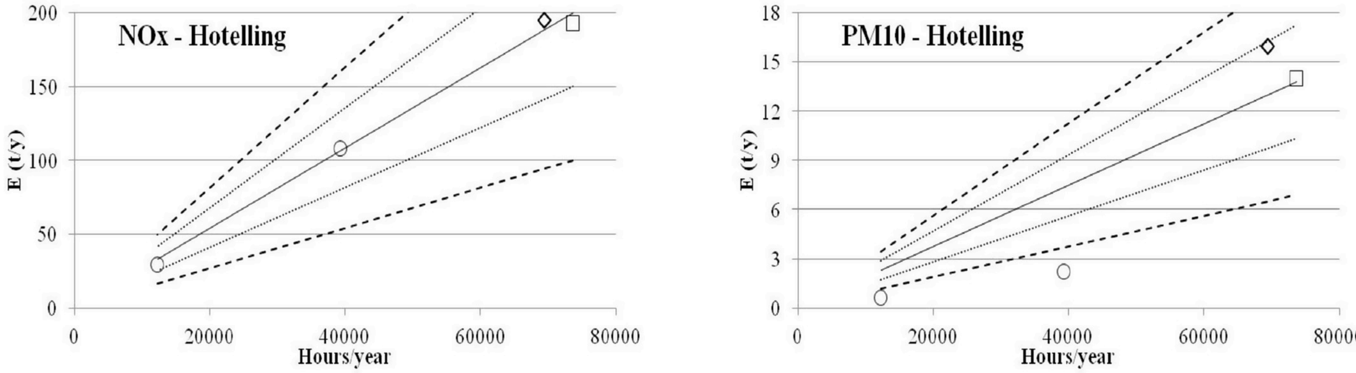

Fig. 13. Commercial ships hotelling emissions against hours.

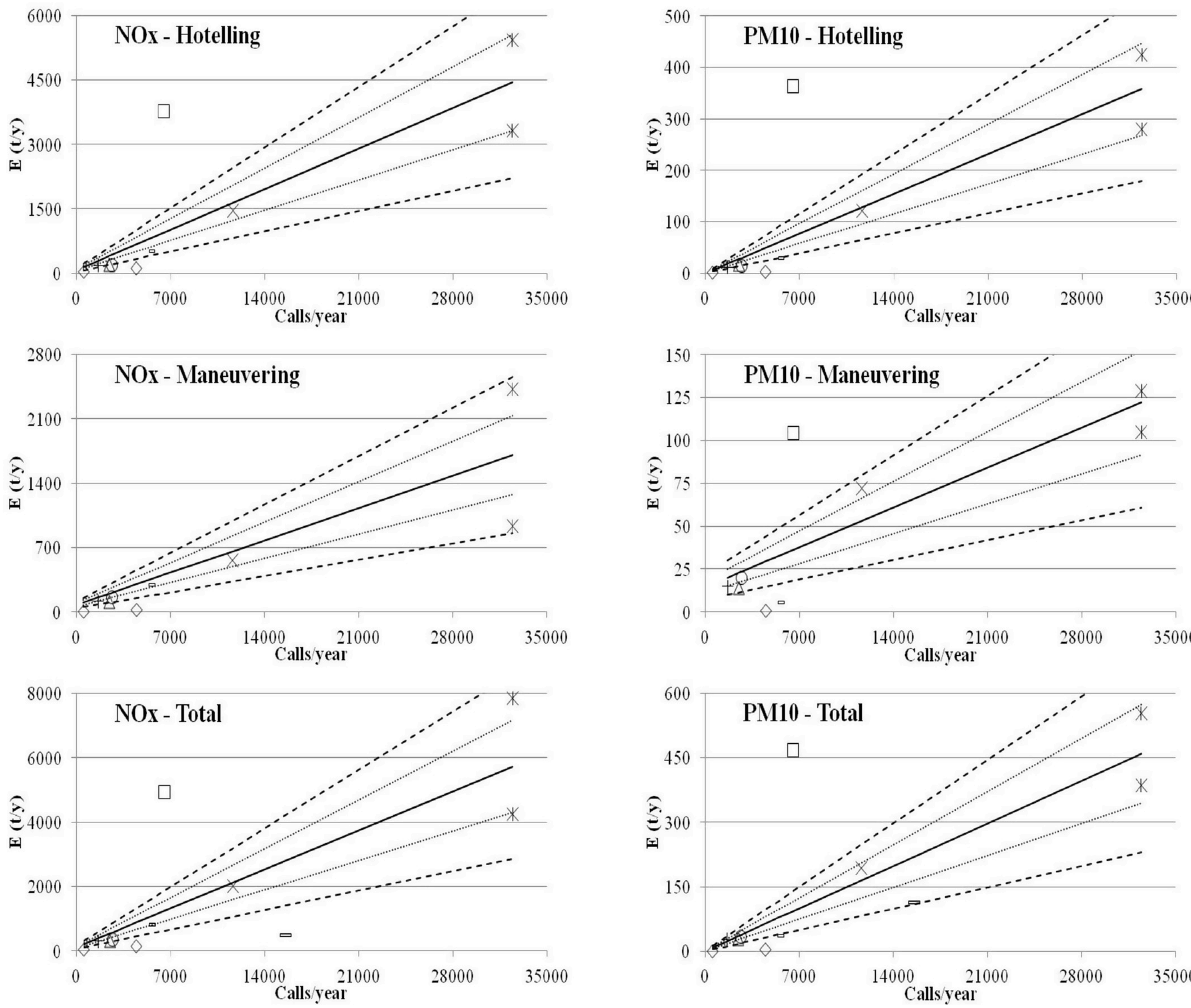

Fig. 14. Commercial ship emissions against calls: hotelling (up); manoeuvring (middle); total (bottom).

ships.

Fig. 12 shows the correlations between emissions and tons of goods per year, left for NOx and right for PM10. Data comes from 6 different studies concerning 9 ports: Barcelona, Genoa, Marseille, Venice, Thessaloniki and Izmir in the Mediterranean area (Saraçoğlu et al., 2013), Samsun in the Black sea (Alver et al., 2018), and Tanjin and Qingdao in the Chinese Sea (Chen et al, 2016, 2017). All these studies calculate the engine energy output corresponding at each activity phase

Table 3
Summary of regression equations for commercial ships.

Phase	Traffic data	Pollutant	Correlation equations	R^2	Number of points	Reliability
Hotelling	Tons	NOx	$2.91{\cdot}10^{-5}\,T - 49.3$	0.94	4	Low
		PM10	$2.43{\cdot}10^{-6}\,T - 10.2$	1.0	4	Low
	Hours	NOx	$2.71{\cdot}10^{-3}\,H$	0.96	4	Low
		PM10	$1.87{\cdot}10^{-4}\,H$	0.48	4	Low
	Calls	NOx	$1.35{\cdot}10^{-1}\,C + 73.0$	0.72	10	High
		PM10	$1.10{\cdot}10^{-2}\,C + 801$	0.67	10	High
Manoeuvring	Tons	NOx	$1.52{\cdot}10^{-5}\,T - 0.85$	0.97	4	Low
		PM10	$1.48{\cdot}10^{-6}\,T + 2.59$	0.99	4	Low
	Calls	NOx	$5.03{\cdot}10^{-2}\,C + 75.6$	0.65	10	High
		PM10	$3.31{\cdot}10^{-3}\,C + 14.6$	0.66	9	Medium
Total	Tons	NOx	$3.98{\cdot}10^{-5}\,T + 1.96{\cdot}10^{3}$	0.87	8	Medium
		PM10	$3.81{\cdot}10^{-6}\,T + 36.4$	0.98	8	Medium
	Calls	NOx	$1.73{\cdot}10^{-1}\,C + 112$	0.73	11	High
		PM10	$1.41{\cdot}10^{-2}\,C + 1.05$	0.85	11	High

starting from data of MCR (maximum continuous rated) engine power and LF (load factor), two of these studies (Chen et al., 2016) and (Chen et al., 2017) use data from AIS.

The main observation is the absence of data of ports with medium traffic of goods (from 1 to 3 $\cdot 10^8$ tons per year). The correlation with total emissions (Fig. 12 bottom) includes also data of the ports of Barcelona, Genoa, Marseille, Venice reported in APICE (2013).

Data of ports of Setubal, Leixoes and Sines in the Atlantic Ocean (Nunes et al., 2017a) are not reported in Fig. 12 because emissions are very higher than the others.

Data of emissions of commercial ships against time spent in each phase are very limited. Only data in function of time at hotelling are available from 4 ports: Copenhagen, Koge, Samsun and Izmir (Fig. 13). Emissions of PM10 in the ports of Koge and Copenhagen (Saxe and Larsen, 2004) are below the −50% CI (circles in Fig. 13). This is due to the emission factor 0.22 [g/kWh] used by Saxe and Larsen (2004) lower than that adopted by Saraçoğlu et al. (2013) and Alver et al. (2018) which is in the range 0.9–1.7 [g/kWh] in function of the different vessels type.

Fig. 14 shows the regression between emissions and number of calls for commercial ships. In this case data comes from 10 different studies concerning 10 ports. Data from Yangshan (Song, 2014) of the emissions in different phases are outside the +50% CI (square in Fig. 14), while those from Copenhagen (rhombus) are below the −50% CI. This finding is in contrast with Fig. 12 where emissions of NOx vs. hours at hotelling of Copenhagen's port are well correlated with those of other ports. The apparent discrepancy is due to the value of the ratio hours at hotelling per call in Copenhagen (8,8 h per call) lower with respect to other ports (22–36 h per call).

Commercial ships - Discussion of results. The summary of all regression equations for commercial ships is reported in Table 3. In this case the sample size is intermediate between cruise and "other than cruise" ships. The reliability of correlations is in the most of cases "high" or "medium". This seems a good result considering the large inhomogeneity of the category with the presence of many different types of vessel. Correlations with "tons of goods" refer to only small or big ports with the absence of data from ports of medium dimension. For this reason, we have assumed in all cases a "low" reliability.

T is tons of good for year [t/year]; H is time spent in each phase for year [hours/year]; C is number of calls per year [calls/year];

4. Conclusions

A review of yearly ship emissions of NOx and PM10 in ports is presented. Vessels are lumped into three categories: cruise, "other passenger ships than cruise" and commercial. Emissions are reported for the hotelling and manoeuvring phases and their sum. Then they are correlated for passenger ships with number of passengers, hours spent in each phase, number of calls; and for commercial ships with: tons of good, hours spent in each phase and number of calls for commercial ships. The correlations with traffic data show, as expected, a certain degree of uncertainty represented by data outside the ± 25% CI or ± 50% CI ranges. We have tried to interpreter the uncertainties analyzing the methodologies adopted to estimate emissions and the emission factors used. In some cases, this effort explains "outlier" values. Sometimes the uncertainties depend on anomalies in traffic data. A summary of regression equations is reported. Their reliability depends strongly on the amount and quality of data available. Cruise ships is a quite homogeneous category with a significant amount of data on emissions and traffic. Therefore, correlations of regression equations are more robust. Even though, we have evidenced a significant effect on the assessment of emissions if a fuel-consumption based instead of a load-factor based methodology is adopted. Data on "other than cruise" passenger ships are quite scarce. Therefore, the reliability of correlations reported is "low". Finally, reliability of correlation equations for commercial ships is intermediate between "cruise" and "other than cruise".

With the evidenced limitations, the set of equations reported can represent a very useful tool for port and public authorities for a preliminary assessment of NOx and PM10 emissions in port. At the same time, it can be used by researcher to compare their estimates of ship emissions with a large set of results reported in the literature.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeaoa.2019.100050.

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