Journal of Environmental Management 310 (2022) 114787

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

COVID-19 impact on maritime traffic and corresponding pollutant emissions. The case of the Port of Barcelona

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ARTICLE INFO

Keywords:
Air pollution
Vessel emissions
Maritime traffic
COVID-19 pandemic
Ports

ABSTRACT

The impact of the SARS-CoV pandemic has gone well beyond health concerns, reaching the maritime industry. The study on the environmental impact of shipping industry during COVID-19 pandemic can provide useful insights to propose new management policies regarding shipping operations, both in-port and on the route. We present a case study centred in the Port of Barcelona covering a 30 nautical miles range in the period March to July 2020, during which different levels of restrictions and stringent lockdown measures were enforced. In this paper, we assess the impact of COVID-19 on maritime traffic and its related emissions in port cities using real-time Automatic Identification System (AIS) data. Interestingly, results show that the decline in maritime traffic is not correlated with a decrease in maritime emissions due to changes in vessel operation. During lockdown (March to June 2020), we observed a 27.9% reduction in the number of port calls compared to the pre-lockdown scenario, whereas pollutant emissions show a moderate decrease (1.8% for CO_2), no significant reduction (SO_2 and PM) or a slight increase (1.3% for NO_x). This can be directly assigned to changes in vessel operation mode, i.e. vessels switched from *Underway* to At *Anchor* or *Moored* status, during which auxiliary engines are used at higher loads.

1. Introduction

The novel Coronavirus disease was first reported symptomatically somewhere between December 1 and December 8, 2019 in the land-locked Chinese city of Wuhan, Hubei. Human-to-human transmission was first confirmed by World Health Organization (WHO) authorities on January 20, 2020 (WHO, World Health Organization, 2020). The rapid spread of the disease across the world led to the global pandemic declaration on March 11, 2020, with subsequent disruptions in world industry, trade and economy. Thus, many countries placed actions to reduce COVID-19 transmission lowering social interaction, that in turn, resulted in a decrease in wheeled, rail, air and maritime traffic during the pandemic (Tobías et al., 2020).

Although the impact on worldwide maritime transport was initially not very significant, vessel activity slowed down its pace considerably as uncertainties kept growing (UNCTAD, 2020). For example, the 40% demand fall in the car manufacturing industry resulted, in turn, in a reduction of car carrier operations. So far, commodity trade seems the only sector able to weather the crisis with minor impact on cargo vessels. Since July 31, 2020, the industry has been on a slow recovery path although, at that time, passenger traffic was still limited mostly to ferry crossings as cruise tourism was still banned in major destinations across the globe (Doumbia-Henry 2020). However, the stored knowledge of the maritime industry management during the pandemic in the first semester of 2020, can be of high importance to reduce its future impact on environment, see (Ytreberg et al., 2021), and improve the resilience of the economic system around it.

Zooming in on greater Barcelona, it is observed that it ranks among the top most polluted areas in Spain and the EU in terms of NOx (nitrogen oxides) and CO_2. The 2018 indicators of NOx emissions and

Abbreviations: IMO, International Maritime Organization; AIS, Automatic Identifiacion System; PM, Particulate Matter; WHO, World Health Organization; STEAM, Ship Traffic Emissions Assessment; EF, Emission Factors; FC, Fuel Consumption; LSHFO, Low Sulphur Heavy Fuel Oil; MGO, Marine Gas Oil; LNG, Liquified Natural Gas; SFC, Specific Fuel Consumption; EL, Engine Load; MCR, Maximum Continuous Rating.

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https://doi.org/10.1016/j.jenvman.2022.114787
Received 20 July 2021; Received in revised form 10 January 2022; Accepted 20 February 2022
Available online 23 February 2022
0301-4797/

particles in suspension with a diameter of less than 10 μm (PM_{10}) revealed that the Port of Barcelona's emissions (from accessing vehicles, civil works, vessels and machinery used in port operations) represent between 15% and 20% of the total emissions of the metropolitan region of Barcelona (Ruiz-Guerra et al., 2019). In relation to environmental impact, the Port of Barcelona has estimated that cruise vessel emissions contribute to about 1.2% of the city's air pollution, 0.23% of NOx levels and 0.23% of PM_{10} levels (González-Aregall and Bergqvist, 2019).

The confinement measures adopted in Barcelona during the early COVID-19 outbreak led to a fall in the overall emissions of major air pollutants. An early study (Tobías et al., 2020) conducted during the first two lockdown weeks in Barcelona found that urban air pollution decreased, with substantial differences among pollutants. As stated by Baldasano (2020), during March 2020 the average hourly reduction in NO_2 emissions in the metropolitan areas of Barcelona and Madrid was 50% and 62%, respectively, in agreement with the lower levels observed by Tobías et al. (2020). Authors attribute the uneven decrease between the two cities to differences in the local weather conditions and dispersive capacity of the two cities. Moreover, the authors remark that Barcelona is a coastal city, whose port must be considered in its emissions pattern.

In this paper, we assess the impact that the SARS-CoV-2 pandemic had in maritime traffic from March–July 2020 by considering maritime traffic distribution and corresponding pollutant emissions. The initial hypothesis is to confirm that pollutant emissions due to maritime activity follow the same trend as the evolution of the shipping industry during the first semester of the COVID-19 pandemic. In order to confirm the hypothesis, we use acquired Automatic Identification System (AIS) data to account for the evolution and behaviour of the vessels in the area of the Port of Barcelona. AIS data is also used to estimate pollutant emissions depending on the ship type and navigational status.

2. Methods

Maritime traffic and port call evolution is assessed through AIS devices that all vessels over 300 gross tonnage are forced by law to carry. AIS maritime traffic data and real technical data from the Sea-Web database (IHS Markit, 2020) are used to estimate emissions for all vessels according to the STEAM algorithm (Jalkanen et al., 2012). This research analyses the study case of the Port of Barcelona (Spain) over a 5-month timespan, from March to July 2020.

2.1. AIS analysis of port call and maritime traffic evolution

The AIS is a ship-based VHF tracking system broadcasting and receiving automatically both technical and voyage particulars about the surrounding vessels within VHF range (IMO, 2015). Data used in the present research were acquired by an AIS receiver installed at the Barcelona School of Nautical Studies (FNB, UPC-Barcelona Tech). The height of the antenna is 17 m above sea level and the average height of the antenna on a container vessel is around 85–90 m. Thus, the AIS system is able to provide stable reception in a range of about 30 nautical miles (nm), with the maximum range being 120 nautical miles, weather permitting.

The first step of AIS analysis of port call and maritime traffic evolution involved filtering out all received AIS messages to remove information that is not relevant for the present study. Only Class A messages were used in the present research since they contain information transmitted by merchant vessels. Messages classified as ID 1,2,3 (position reports) and 5 (static and voyage data) were used in the present analysis.

In order to obtain the number of port calls per ship, AIS position reports were filtered to determine whether vessels were located inside the port area. A circle centred in position longitude 002°05.5′E and latitude 41°21.2′N and with a radius $r = 4.4$ nm was considered, as it represented a circle tangent to both harbour entrances. To avoid false calls introduced by vessels already within the harbour limits at the beginning of the study, all the vessels in port at 00:00 UTC on March 1, 2020 were dropped from the dataset. Thus, we obtained data on specific vessels entering the port, dates and duration of stay in port.

Since the Sea-Web IHS Markit database contains IMO vessel-specific technical information, only merchant vessels were considered from the AIS dataset. The resulting dataset was split into 3 different subsets: (1) passenger vessel, (2) cargo vessel and (3) tanker vessel. AIS messages also contain information about vessel navigational status (namely AIS status): (a) *Underway* using engine, (b) *At Anchor*, (c) *Not Under Command* and (d) *Moored*. We analysed the evolution of port calls (vessel stops inside the port) and maritime traffic (vessel movements within a 30 nm range, inside and outside the port).

2.2. Emission model

2.2.1. Vessel operation mode

Ship emissions were computed independently for each vessel based on vessel operation mode and engine technical data from the IHS Markit database. Emissions were consequently estimated using emission models depending on vessel operation mode.

Power demand, and thereby ship emissions, vary with vessel dynamic behaviour and operation mode. Hence, emission models related to shipping within a spatial region typically consider separate emission modes for each vessel, i.e. (1) cruising, (2) manoeuvring and (3) hoteling. Moreover, we included a fourth mode, (4) anchored, to better discriminate the impact of anchored vessels.

Assigning the proper emission mode is crucial for an accurate pollutant emission estimation. For example, taking into account the fuel changeover approaching the port, from heavy fuel oil (HFO) to marine gas oil (MGO), (Langella et al., 2016). Even though AIS provides navigational status information, status is a fixed variable in the vessel. AIS status is switched by the ship crew manually, and therefore it is vulnerable to human error and delay. Hence, for every vessel, we selected one of the four emission modes based on vessel speed and location in the port area. Table 1-SM (in Supplementary Material) shows the emission mode used to estimate vessel emissions according to vessel speed and location (inside or outside port premises) and the corresponding navigational status provided by AIS status data.

2.2.2. Emission estimation

Emissions were estimated by the Ship Traffic Emission Assessment Model (STEAM, 2012) algorithm Jalkanen et al., 2009; Jalkanen et al., 2012; Johansson et al., 2017) due to its high accuracy, simplicity and compatibility with AIS data (Castells-Sanabra et al., 2020) compared to other methods (Coello et al., 2015; Goldsworthy and Goldsworthy, 2015; Sun et al., 2018).

Total emissions from each air pollutant, E_i, were calculated following the Tier I approach (Trozzi, 2013):

$$E_i = EF_i \cdot FC_i \tag{1}$$

where EF_i and FC_i are the Emission Factors and Total Fuel Consumption, respectively, for the pollutants $i = CO_2, SO_2, NO_X$, PM.

The Emission Factors (*EF*) were computed independently for each air pollutant (Jalkanen et al., 2009). Three different methods were used depending on the air pollutant nature, namely (1) fuel-related for CO_2 and SO_2, (2) engine-related for NO_X and (3) with special considerations for PM. For fuel-related emissions, *EF* s were obtained based on the engine instantaneous specific fuel consumption (*SFC* , Eq. (3)) and the chemistry of fuel burnt in each emission mode. Information on fuel type, i.e. low sulphur heavy fuel oil (LSHFO), marine gasoil (MGO) and liquefied natural gas (LNG), was readily available in the IHS Markit database for all the vessels involved. For engine-related emissions, EFs were obtained according to the maximum values recommended by the IMO (IMO, 2017). As these values are year and engine revolution dependent, the required information was gathered from the IHS Markit database for all the vessels. Only when such data were not readily available, medium-speed engine (500 rpm) was selected as the most representative value (Jalkanen et al., 2012; Sun et al., 2018). The method developed by (Jalkanen et al., 2012) was selected to compute PM.

Total fuel consumption for each pollutant, FC_i, was computed by Eq. (2) based on instantaneous power ($P_{1,2}$) and Specific Fuel Consumption (*SFC*), which, in turn, depends on engine and fuel type and emission mode (Goldsworthy and Goldsworthy, 2015; Jalkanen et al., 2009):

$$FC_i = \sum_p \left[\Delta t_{1,2} \cdot \sum_e \left(P_{1,2} \cdot SFC_{1,2}^{e,m,p} \right) \right] \tag{2}$$

with $\Delta t_{1,2}$ being the time difference between consecutive waypoints (hours), $SFC_{1,2}$ the instantaneous specific fuel consumption (g/kWh) and $P_{1,2}$ the instantaneous engine power between consecutive waypoints (kW). Sub-indexes *e*: Engine type, i.e. main engine or auxiliary engine; *m*: Fuel type, i.e. LSHFO, MGO or LNG; and *p*: Vessel emission mode, i.e. cruising, anchored, manoeuvring or hoteling. LSHFO, MGO or LNG were selected for cruising mode. While at anchor, maneuvering and hoteling modes, MGO and LNG were preferred over LSHFO.

The methodology to estimate *SFC* was based on the parabolic curve developed by (Jalkanen et al., 2012), in which the instantaneous specific fuel consumption, $SFC_{1,2}$, is computed through a base and a relative value, as in Eq. (3):

$$SFC_{1,2} = SFC_{base} \cdot SFC_{rel} \tag{3}$$

where SFC_{base} is the base specific fuel consumption (g/kWh) obtained from the IHS Markit database and SFC_{rel} is the relative specific fuel consumption (g/kWh) based on engine load and computed by Eq. (4) (Jalkanen et al., 2012) as obtained from assessment of specific fuel consumption curves by engine manufacturers:

$$SFC_{rel} = 0.455 \cdot EL_{1,2}^2 - 0.71 \cdot EL_{1,2} + 1.28 \tag{4}$$

where $EL_{1,2}$ is the instantaneous engine load factor (%) taken as

$$EL_{1,2} = EL_{max} \cdot \left(\frac{v_{1,2}}{v_{service}} \right)^3 \tag{5}$$

with $v_{1,2}$ being the vessel speed between two points in space and $v_{service}$ the vessel service speed defined in the ship design.

Finally, $P_{1,2}$ in Eq. (2) is calculated by the Propeller Law (Goldsworthy and Goldsworthy, 2015), as shown in Eq. (6):

$$P = k \cdot v^3 \tag{6}$$

with *P* being the generic vessel power (kW), *k* the power to speed constant (kW·s/m), and *v* the vessel speed (m/s). The power to speed constant is a parameter that needs to be calibrated. To do so, the actual installed power is considered slightly higher than the actual required power. Then, the maximum engine load factor, EL_{max}, is the ratio between the service and the maximum installed power (Jalkanen et al., 2009):

$$EL_{max} = \frac{P_{service}}{P_{installed}} \tag{7}$$

where $P_{service}$ and $P_{\text{installed}} =$ are the service power related to the service speed (kW) and the maximum installed power (kW), respectively. EL_{max} is then related to the Maximum Continuous Rating (MCR) of the engine in %. By combining Eq. (6) and Eq. (7), constant *k* is easily obtained:

$$k = \frac{EL_{max} \cdot P_{installed}}{v_{service}^3} \tag{8}$$

Installed power and service speed are both known from the IHS Markit database. Among all the values in the literature (Coello et al., 2015; Goldsworthy and Goldsworthy, 2015; Jalkanen et al., 2009), we selected the prevailing value of maximum engine load $EL_{max} = 80\%$.

Using the results for constant *k* in Eq. (8), the instantaneous power was computed from Eq. (5) based on the vessel actual speed, $v_{1,2}$, provided by AIS messages. As AIS data contained information on vessel speed and position, engine power and engine load were merged into instantaneous power (Jalkanen et al., 2009). In (Goldsworthy and Goldsworthy, 2015), distance-over-time speeds are preferred to those provided by AIS messages. However, given the limited size of the location and based on literature research (Liu et al., 2019; Sun et al., 2018), AIS-provided speeds were considered this time. Therefore, using real-time data increased the reliability of the results compared to aggregated statistical data from port authorities. For hoteling and anchored emission modes, auxiliary engine power was preferred over main engine output. However, when auxiliary engines were not used, 20% and 10% load factors were considered for main engines, respectively (Guarasa et al., 2017; Jalkanen et al., 2009).

3. Results

This section presents the analysis and results of the evolution of maritime traffic (inside and outside port premises), fuel consumption and the derived emissions inventory of major air pollutants within the area of Barcelona for a 5-month period (March 1 to July 31, 2020). In this period, a total of 11, 860, 409 AIS messages were processed within the 30 nm range of the AIS receiver. Three different sub-periods were considered, as shown in Fig. 1-SM: Pre-lockdown (March 1–16), Lockdown (March 16-June 22), and Post-lockdown (June 22 - July 31). This should shed some light on the impact that political decisions taken during the pandemic might have had on the shipping industry and related emissions.

3.1. Analysis of port calls and maritime traffic

3.1.1. Port call evolution

Our methodology to identify port calls using AIS data showed high accuracy (97.1%) when compared to the number of port calls provided by the Port of Barcelona (Port de Barcelona, 2020). In particular, during the period March–July 2020, a total of 2734 ship calls were reported in the Port of Barcelona, of which 56.5% corresponded to cargo vessels, 15.0% to tanker vessels and 28.5% to passenger vessels. Total ship calls recorded in the period March–July 2020 dropped to 27.6% compared to the year average of those recorded in the same 5-month period during the previous years (detailed evolution shown in Fig. 2-SM). Fig. 1a illustrates this decrease in total calls and the number of port calls per ship type, with a prominent fall of 49.2% for passenger vessels, followed by cargo vessels (16.1%) and tanker vessels (1.2%). Fig. 1b plots the average daily port calls for the different ship types and periods (pre-lockdown, lockdown, post-lockdown) during the 5-month period compared to the year-average of the 2016–2019 period.

Results in Fig. 1b show a reduction of 27.9% in daily port calls during lockdown 2020, compared to the pre-lockdown scenario in 2020, attributed to a reduction of 60% in passenger ships. The post-lockdown period presents sign of recovery, with a lower decrease compared to pre-lockdown 12.4% drop. The observed variability in total port calls is not uniformly distributed among the ship types, but conditioned by the passenger ships type, that are directly affected by the imposed mobility restrictions at the time.

3.1.2. Maritime traffic evolution

Beyond aggregated maritime traffic, instantaneous AIS data enable a closer look at ship activity depending on ship type. During the 5-month period, 1160 different unique vessels were reported by AIS. Daily averaged activity during that period is presented in Fig. 2.

In Fig. 3-SM, the daily evolution of number of ships is shown. The total number of vessels (in black) shows a local minimum on March 16,

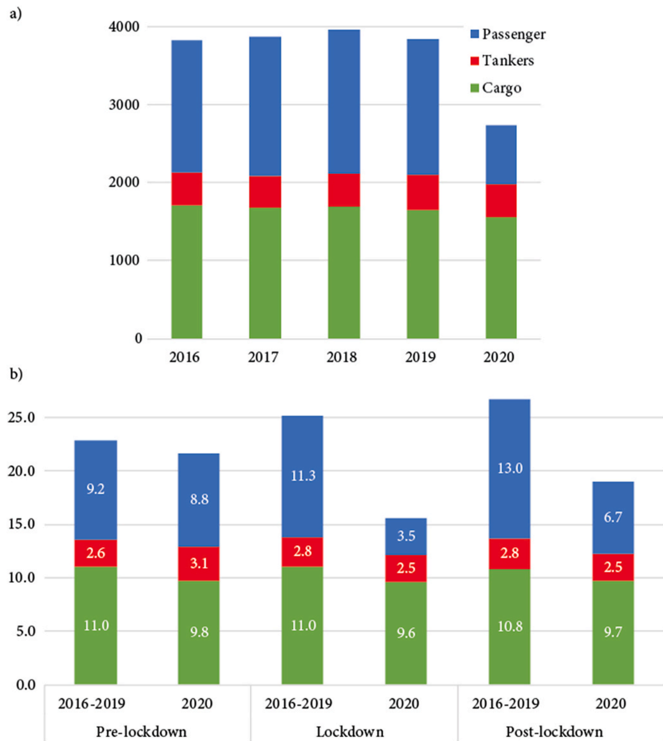

Fig. 1. Number of port calls by ship type. a) Total number of port calls for the March–July period (data from Barcelona Port Authority), and 2020. b) average of daily port calls for the sub-periods of analysis (Data from years 2016–2019 is provided by the Barcelona Port Authority and yearly averaged). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

when lockdown entered into force, followed by a growth until the last week of March. After reaching a second minimum on April 1, this number grew again to achieve maximum values by April 7, followed by a slight reduction over time.

Table 1 lists the daily number of ships in the 30 nm range. Ship activity in the area over the three periods of analysis shows a drop of 8.4% during lockdown and a significant recovery of 5.3% during the post-lockdown. Maritime activity around the port area clearly increases during post-lockdown, which is in accordance with the recovery in the number of port calls inside port premises observed in Fig. 1.

AIS status data revealed the specific actions of the vessels. Fig. 3 shows that most of the vessels were *Underway* (55.6%) while the rest were *Moored* (34.9%) or *At Anchor* (9.2%). The number of vessels *Not Under Command* is merely residual (~0.3%), and is therefore, not considered in the research. As seen in Fig. 3, among all the periods, lockdown has the lowest value of vessels *Underway* per day, which results in the highest values of *Moored* vessels and vessels *At Anchor*. Pre- and Post-lockdown values are consistent and very similar, which confirms that the recovery started during post-lockdown.

Fig. 3b shows a high variability in AIS status for passenger vessels over lockdown, as opposed to cargo and tanker vessels. Also note that during lockdown the daily number of *Moored* passenger vessels is higher than that of passenger vessels *Underway* which indicates that passenger vessels remained in the berthing areas of the port.

Table 2-SM shows the variations in AIS status for the three analysis periods, using the pre-lockdown scenario as the baseline. Passenger vessels *Underway* drop to 46% during lockdown, whereas the number of *Moored* vessels is two times higher than during pre-lockdown. For cargo and tanker vessels, the decrease in the number of ships *Underway* per day is consistent with the trend observed for passenger ships, although less prominent. Contrarily, a huge increase in the number of ships at anchor in case of cargo and tanker vessels is observed during the lockdown period (31% and 54% for cargo and tanker ships, respectively). During the post-lockdown, a decrease of 17% in anchored tanker ships and 7% in anchored cargo ships, relative to the pre-lockdown, is observed.

Following the decreasing trend of vessels *Underway* in Fig. 3a, the lockdown period also saw a fall in average speed of all traffics (i.e. −4.4%), see Table 3-SM. In contrast, average speed for passenger vessels

Table 1
Average daily number of ships in the 30 nm range.

	Daily number of ships	Variations from pre-lockdown (%)			
		Cargo	Tanker	Passenger	Total
Pre-lockdown	19.8	–	–	–	–
Lockdown	18.1	−7.2%	4.9%	−27.3%	−8.4%
Post-lockdown	20.8	9.4%	3.6%	−3.2%	5.3%

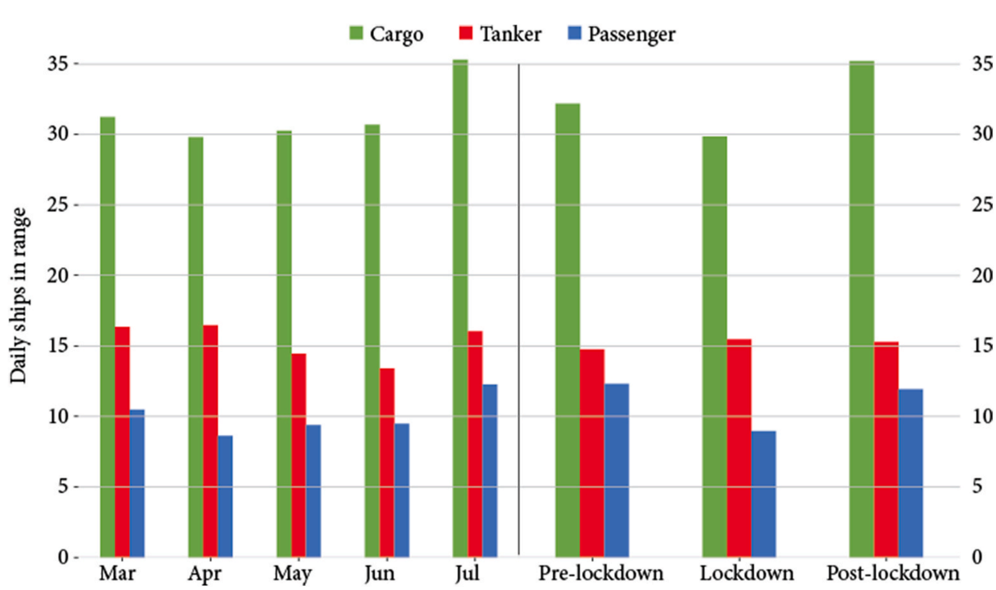

Fig. 2. Daily averaged number of ships in the 30 nm range for the March–July period (left) and according to analysis periods (right), detailed by ship type. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

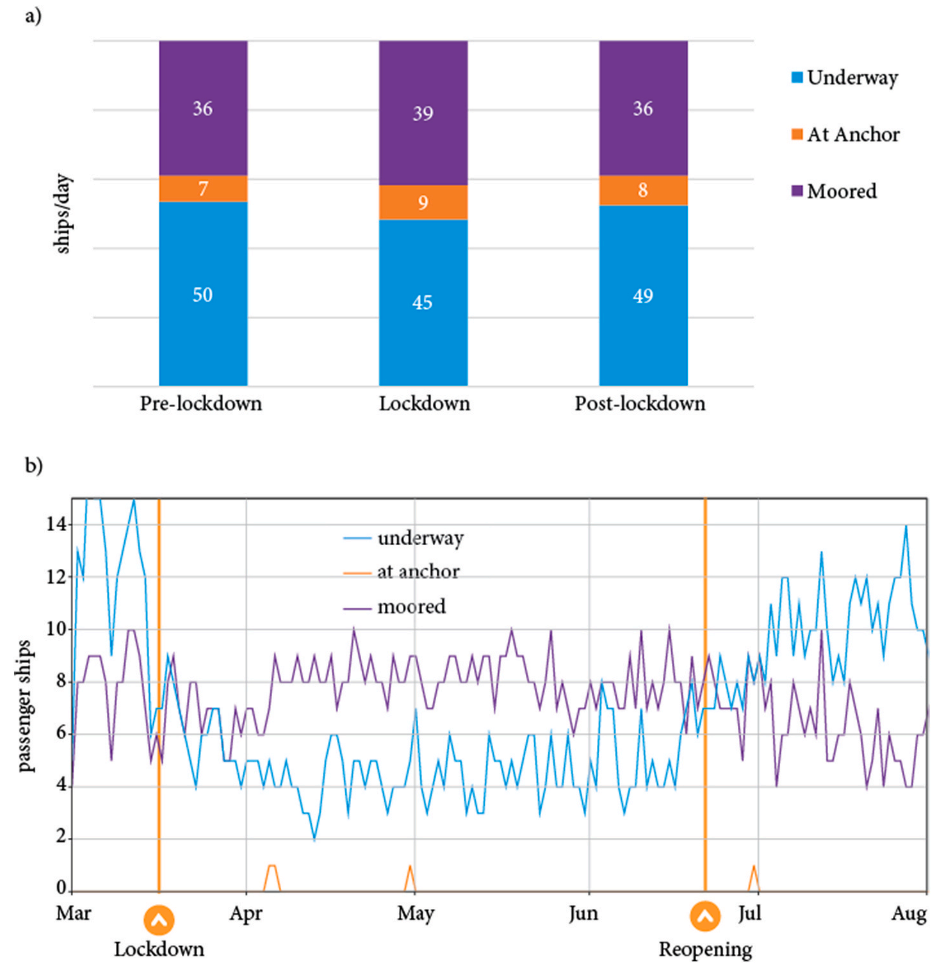

Fig. 3. a) Distribution of AIS status (ships/day) for all vessels in the 30 nm range per period, from March 1 to July 31, 2020; b) Daily evolution of passenger vessels at each AIS status. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

increased, mostly due to the drop in the number of cruise ships, which usually sail at speeds between 15 and 17 knots, whereas ferries (in operation despite lockdown restrictions) sail faster than 19 knots. Likewise, average speed was higher for tanker vessels too. This is due to the spot market operation, by which larger and slower vessels do not operate because of low fuel demand whereas smaller and faster tanker vessels can continue operating, leading to a rise in average speed (Millefiori et al., 2021). The most significant reduction is found for cargo vessels, with average speeds 2.5% lower during lockdown. The reliance on economies of scale allowed shipping lines to rationalize services and cost structure by deploying larger ships and idling smaller ones. (Notteboom et al., 2021). Overall, the daily evolution of average speed per ship-type, presented in Fig. 4-SM, indicates that the average daily speed dropped during the last two weeks of March and throughout April, slightly recovered by May and reached a higher, more common value by July.

Table 2a shows the daily-mean values averaged over the different sub periods. It indicates a significant decrease in unique passenger vessels (~-27.3%) during lockdown with a more significant decrease in calls (~-60.5%). This is mainly due to the fact that passenger vessels maintaining the activity were only regular ferry lines whereas cruise ships remained docked in the port area, and therefore they only account for a single call. This is confirmed by the increase in passenger vessel average speed also in Table 2b. Cargo vessel average speed is lower being less vessels in the area but the differences between pre-lockdown and lockdown sub-periods in port calls is insignificant. By contrast, tanker vessel speed increased slightly whereas the number of vessels grew up to 4.9% with a minor decrease of less than 1% in tanker vessel calls. Table 2b presents the variations of daily means in calls, vessels and speed averaged over lockdown with respect to daily means averaged over pre-lockdown days.

Table 2
a) Daily mean values averaged over the sub periods of analysis. In brackets, variations with respect to pre-lockdown stage. b) Variations in daily mean values averaged over lockdown with respect to daily mean values averaged over pre-lockdown values, for each shiptype.

a)	Calls (Calls/day)		Vessels (Vessels/day)		Speed (knots)	
Pre-lockdown	21.6		19.8		12.1	
Lockdown	15.6	(-27.9%)	18.1	(-8.4%)	17.7	(-4.4%)
Post/lockdown	18.9	(-13.9%)	20.8	(+5.1%)	12.8	(+5.8%)

b)	Lockdown		
	Calls	Vessels	Speed
Cargo	1.4%	−7.2%	−2.5%
Tanker	19.3%	4.9%	3.5%
Passenger	−60.5%	−27.3%	7.7%

3.2. *Fuel consumption and pollutant emissions*

Total fuel consumption depends on vessel type and the emission mode under which the engine operates. Total fuel consumption and emissions from March 2020 to July 2020 were computed using the methodology presented in section 2.2, and Table 4-SM shows total values for every pollutant calculated by the STEAM method.

Pre-lockdown daily consumptions show a higher average, with a total of 277 tons/day compared to lockdown, with a fuel consumption of 266 tons/day. Interestingly, the highest and lowest values are consecutive, on March 14 and March 16, when lockdown entered into force. Peaks concentrate mostly at the beginning of every month whereas lower consumptions were reported towards the end. A time evolution of fuel consumption during the same 5-month period is presented in Fig. 5-SM.

Even though only ~55% of the vessels were *Underway* (Fig. 3), these vessels contribute most to total fuel consumption and related emissions. As for emission modes, total fuel consumption for vessels cruising is dominant (73.6%), followed by hoteling (15%), anchored (7.4%) and manoeuvring (4%), see Fig. 4a. Regarding ship type, passenger vessels account for up to 46.2% of total fuel consumption, followed by cargo vessels (38.1%) and tanker vessels (15.7%), see Fig. 4b. Although passenger vessels were the second largest group in the number of port calls and third in the number of vessels in the 30 nm range, they dominate total fuel consumption.

Fig. 5a compares the daily evolution of fuel consumption, average speed, and number of ships in the 30 nm range. No correlation can be observed between these three variables, indicating that the fuel consumption cannot be directly related to either the number of unique vessels in the area or the mean speed of the entire fleet. Looking into detail of daily evolution in Fig. 7-SM, an interesting peak arises at the beginning of April, when home quarantine was enforced in the region: the mean speed drops down whereas the number of vessels and the fuel consumption increases. Moreover, in the same days of Fig. 7b-SM, the number of vessels underway slowly increase whereas vessels at anchor clearly decrease and moored vessels have an instantaneous decrease followed by an abrupt rise. This also confirmed in Fig. 5b, where both pre and post-lockdown show the number of ships underway clearly above the number of moored ships, whereas during the lockdown the number of underway and moored ships is similar.

CO_2, SO_2, NO_x and PM emissions were estimated using Eq. (1) and daily evolution of these pollutants is shown in Fig. 6-SM. Trends for pollutant emissions are similar to those for fuel consumption in terms of distribution per ship type. This can be observed in Table 3a, where fuel consumption and emissions generated by cargo vessels are ~40%, tanker vessels produce ~15% of emissions and consume the same percentage of fuel, and passenger vessels are responsible for ~45% of emissions. However, several differences are observed when looking at the variations for pollutants and fuel consumption over the sub-periods in Table 3b. Whereas fuel consumption and CO_2 emissions fall with a small increase in NOx during lockdown, the post-lockdown scenario turns out to show the best results in terms of fuel consumption and pollutant emissions.

CO_2 emission rates are mostly related to cruising (72%), 1.6 points below fuel consumption (see Fig. 4a), whereas hoteling accounts for 16.6%, 1.6 points higher than fuel consumption (Fig. 4a). This is due to the use of MGO during hoteling and LSHFO during cruising, with the former having a slightly higher quantity of carbon content.

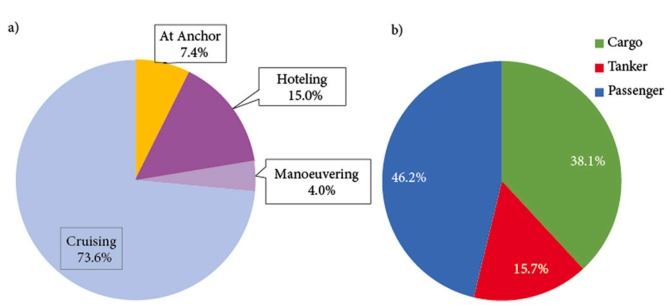

Fig. 4. Percentage of fuel consumption from March 1 to July 31, 2020 according to a) emission mode and b) ship type.

Changes in contribution to total SO_2 emissions per emission mode were small when compared to fuel consumption and results show the same distribution as in Table 3a. This is partly due to the fact that both LSHFO and MGO have by default similar sulphur contents. Distribution by ship type is quite similar to the other fuel-related emissions and fuel consumption. However, it is worth noting that there exists a slight fall in tanker and passenger vessel emissions related to the fact that some of these vessels are powered by LNG, with residual sulphur content leading to an overall reduced contribution of these types of vessel to total SO_2 emissions.

NOx emissions show a similar trend to that of fuel consumption, with some differences in the magnitude of peaks in Fig. 6-SM because NOx emissions are not fuel but engine related. This type of emissions is heavily dependent on engine characteristics and revolutions. This is the main reason why cruising-related emissions are higher than in previous cases, contributing 75.8% compared to 14.6% for hoteling, 6.1% for anchored, and 3.5% for manoeuvring mode. These differences are due to the engine configuration introduced in the model, as preference was given to auxiliary engines with higher revolutions and lower emission factors during hoteling compared to main engines operating at their fullest during cruising. The same applies to cargo and tanker vessels. These have greater contributions to NOx emissions than the more modern passenger vessels which, in compliance with Tier II requirements, typically operate with medium-speed engines with lower NOx emission factors than their counterpart.

In relation to PM emissions, variability between days was mostly noticed during the most restrictive days, Fig. 6-SM. Since PM emissions are both fuel and engine related, very similar mode trends to those of NOx emissions were found.

Fig. 6 compares the traffic values obtained from AIS data with fuel consumption as a function of ship type. It can be observed that the contribution of each ship type is dissimilar to the distribution of vessels in the 30 nm range during the 5-month period. Surprisingly, passenger vessels, which only represent an average of 17.2% of the traffic in the 30 nm range, have the highest fuel consumption and are responsible for the highest emissions, with a contribution of 46.2%. On the other hand, cargo vessels represent almost half of the total traffic (49.6%) and account for 38.1% of total emissions and fuel consumption. At the lower end, tanker vessels represent 33.2% of total traffic but account for ~15% of emissions and fuel consumption only.

Analysis of the navigational status of maritime traffic within the port hinterland and fuel consumption (and therefore, pollutant emission) contribution shows that ships *Underway* represent ~55% of traffic while producing up to 70% of emissions (see Fig. 7-SM). In contrast, *Moored* vessels represent ~34.9% of all vessels but have an emission contribution of less than 20%.

4. Discussion

Our results show that, during lockdown the number of vessels dropped by 8.4% compared to the pre-lockdown scenario, with a rise in tanker vessels of 4.9%, see Table 1. Moreover these vessels remained within the area for a longer time, which can be demonstrated by the fact that i) the number of vessels *At Anchor*, drifting for orders or *Moored* in the port of Barcelona increased, see Fig. 3 and Table 2-SM; ii) the overall speed of the vessels decreased because of rationalization of cargo vessels services, see Fig. 4-SM and Table 3-SM, and iii) the number of vessels returning to their homeport increased as global economy was being shut down. It is worth noticing that at the beginning of March fuel prices fell by 65%, reaching negative values by April 20, 2020, (OPEC, 2020). Reduced global fuel demand and impossibility to completely stop fuel extraction resulted in larger vessels turning into floating oil storage units drifting at sea waiting for oil buyers. Therefore, the reduction in speed is consistent with the global situation. However, in the present study results show that fuel consumption and emissions did not decrease with

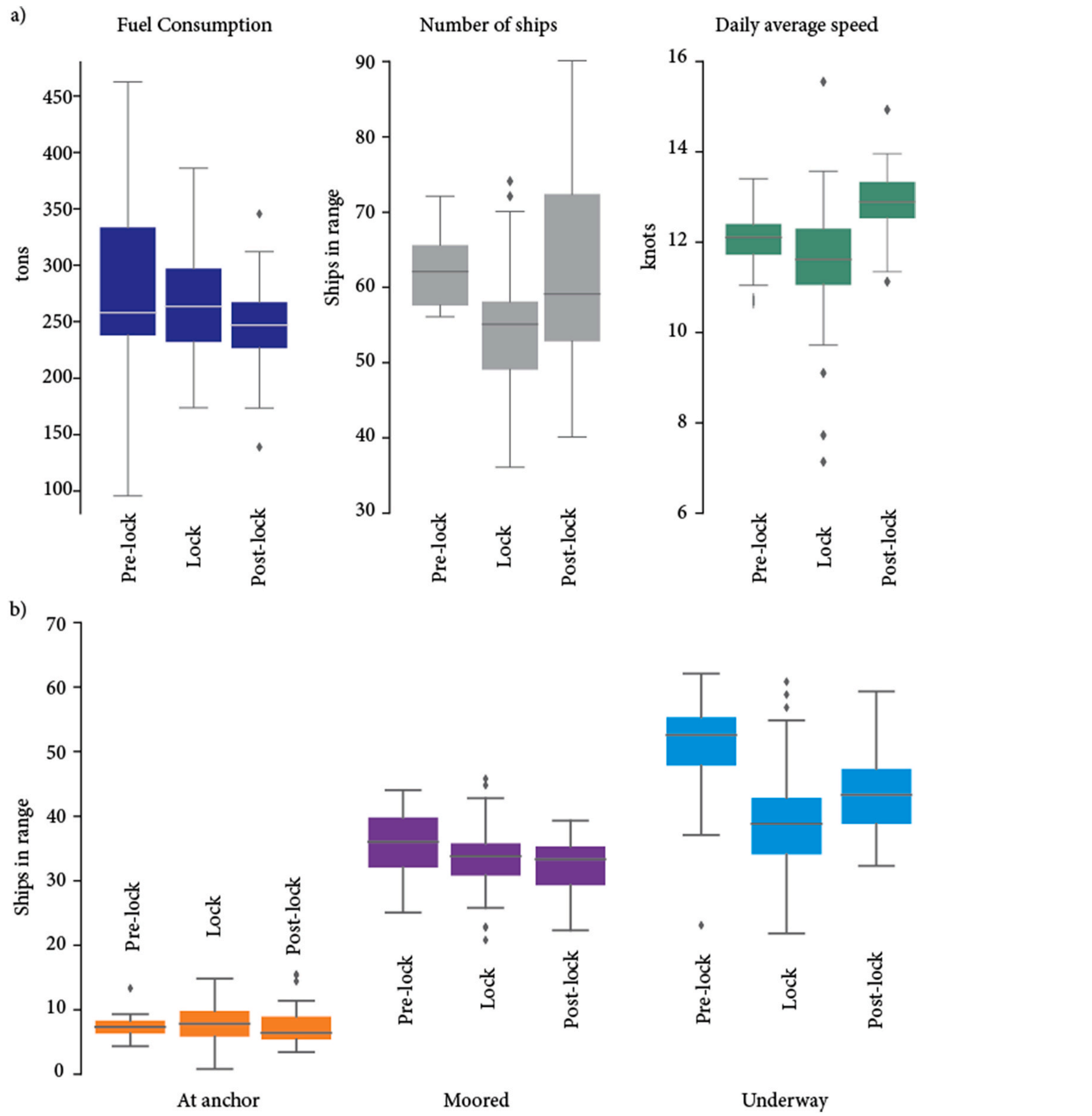

Fig. 5. Boxplots of the daily averaged evolution of a) fuel consumption (dark blue), number of unique ships in the 30 nm range (gray) and average speed (dark green) and b) AIS status during the different sub periods of analysis.

Table 3
Fuel consumption (FC) and emissions total average distribution per a) ship type from March to July 2020 and b) according to analysis periods.

a)	FC	CO_2	SO_2	NOx	PM
Cargo	38.1%	38.9%	41.1%	42.3%	39.0%
Tanker	15.7%	16.7%	15.3%	14.9%	15.2%
Passenger	46.2%	44.4%	43.6%	42.8%	45.8%
b)					
Pre-lockdown	–	–	–	–	–
Lockdown	−4.0%	−1.8%	0.0%	1.3%	0.0%
Post-lockdown	−9.4%	−8.0%	−7.4%	−4.0%	−3.8%

the same trend as the mean ship velocity and port calls. In fact, the number of port calls is significantly reduced during lockdown (−27.9%, Table 2a), summed to the reduction in the number of ships *underway* (−16%, Table 2-SM). At the same time, the mean velocity is slightly reduced (−4.4% Table 2a), also with a reduction of the total fuel consumption (−4%, Table 3b).

Differences between port calls and ships in the area (especially cargo and tanker vessels, Table 2b) are due to the maritime traffic parallel to the coast that does not call at the Port of Barcelona. However, in general, the increase in the number of vessels was partly related to a higher number of vessels with static or quasi-static positions, i.e. *Moored* and *At Anchor* during lockdown, see Fig. 3a. In fact, it is not that more vessels arrived but rather that vessels did not leave, increasing their time in port or in the anchorage area.

Although there is the preconceived idea of an apparent relationship between pollutant emissions, fuel consumption and number of vessels in the area, several other factors play an important role in the final pollutant emission values. Results indicate that maritime emissions did not decrease according to the observed decline in maritime traffic within the 30 nm range. The issue can be traced back to Fig. 5, as the average speed of vessels decreased by 9.1%, the number of vessels *Underway and Moored* dropped too, and the number of *At Anchor* vessels increased. During the lockdown the number of vessels decreased by 8.4% whereas emissions did not decrease as much (CO_2 showed a reduction of 1.8%) and some pollutants also increased (NO_x increased by 1.3%). Hence, the

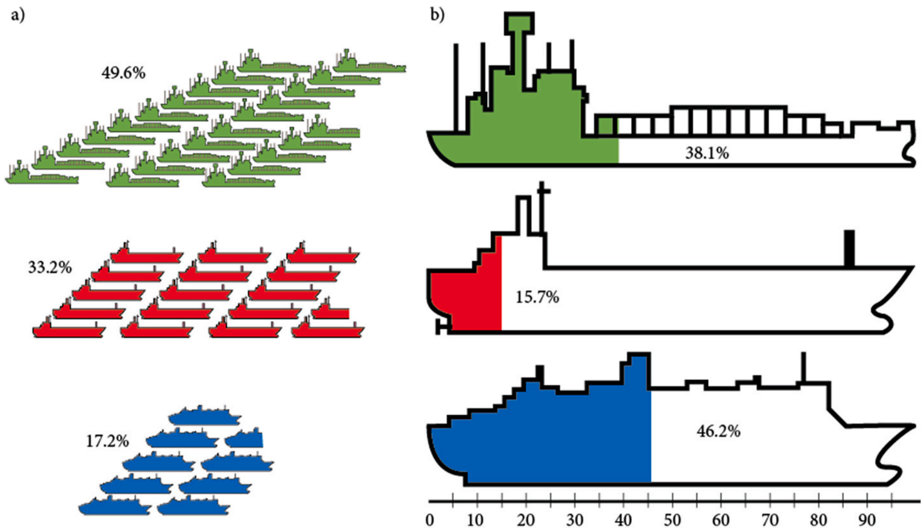

Fig. 6. Percentage with respect to the total data during the period of March to July 2020 of a) maritime traffic and b) fuel consumption per ship type (top: cargo, middle: tanker, bottom: passenger).

change in AIS status also had an impact on global values. The growth in NOx emissions during lockdown -i.e.1.3%- can be attributed to the higher number of tanker vessels in the area.

The average distribution of fuel consumption per ship type is of the order of that of emissions per ship type for all four pollutants, see Table 3a. This is, cargo vessels consume ~40% of the total fuel and produce the same amount of pollutants with very few differences between them. Likewise, tanker vessels consume ~15% of fuel and are the cause of the same trend of emissions. Finally, passenger vessels consume ~45% of fuel and produce the same percentage of pollutants.

The scenario presented in Fig. 6 is clearly related to the fact that passenger vessels operate at high load constantly and sail at very high speeds. Their shipboard services have a high-power demand, which explains their higher installed power. It is then clear that, despite the lower number of this type of vessels, they are a major pollutant in the area, and their contribution was related to the increase in average speed. There is a strong correlation between vessel operation mode and overall contribution to pollution, as plotted in Fig. 8-SM. This is in accordance with the fact that greener shipping can only be accomplished by reducing average vessel speeds and, of course, rethinking passenger vessel operations, as they were responsible for almost half of the emissions despite accounting for only 17.2% of the traffic in the area.

Post-lockdown fuel consumption and pollutant emission values are significantly lower (~8%) than pre-lockdown ones due to important decreases in cargo and tanker vessels *Underway*. Although passenger vessels are responsible for most of the emissions, the rise in the number of this type of vessels was not significant enough to return to pre-lockdown pollutant emission values due to the decrease in the number of cargo and tanker vessels *Underway*.

5. Conclusions

The COVID-19 pandemic had an impact on maritime traffic and related emissions owing to changes in maritime traffic. Pre- and post-lockdown maritime traffic values show a clear mismatch, as recovery from the initial economic downfall was not the same for all ship types.

Regarding maritime traffic in the 30 nm range, the pandemic brought a slight decrease of 8.4% in the total number of reported vessels in the area compared to pre-lockdown. However, this change did not match the decrease in the number of port calls in Barcelona (27.9%). The difference is due to the way vessels operated, i.e. average speeds reduced by 4.4% and increased number *At Anchor* and *Moored* vessels. It is not that more vessels were reported, but that the ones that were already in the 30 nm range stayed over for longer periods. Cargo and tanker vessels managed to weather the situation by adjusting capacity to real-time demand and showed early signs of recovery as of July 31, 2020. However, passenger vessels succumbed badly to travel restrictions due to the pandemic, and although ferry traffic was resumed when reopening was allowed, ongoing uncertainties related to a still spreading virus do not forecast a smooth second semester for the business.

Although fuel consumption decreased by 4%, NOx emissions rose because of the different operation modes. It is worth noting that the growth in fuel consumption and emissions during early lockdown was well below the rise in the number of vessels as a result of reduced speeds and an increased number of *At Anchor* and *Moored* vessels. Distribution of ship types in the 30 nm range does not correlate that of fuel consumption and emissions. In fact, passenger vessels were surprisingly responsible for more than 40% of fuel consumption and emissions, but represented only 17.2% of all vessels. The reason lies in higher installed outputs arising from higher power demands to sustain shipboard services and higher-than-average trading speeds. This raises the current ongoing discussion about sustainability of passenger business other than ferry crossings.

Results presented in the current analysis can yield interesting conclusions about shipping industry management. The hypothesis presented at the introduction based on a direct correlation between maritime traffic evolution and its subsequent pollutant emissions is refuted after looking into detail the navigational status of each ship and its particulars. The overall decrease of pollutants in the area of Barcelona has to be related directly to the reduction of road traffic activity since, as demonstrated in the present research, maritime industry did increase the pollutants at certain subperiods of the first semester of 2020. Moreover, passenger (ferry-type) vessels are the ship-type that accounts for the highest percentage of pollution and it is more necessary to bound their propulsion characteristics in order to reduce its impact on the global environment.

Credit author statement

Anna Mujal-Colilles: Conceptualization, Methodology, Software, Formal analysis, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Javier Nieto Guarasa**: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Jordi Fonollosa**: Resources, Methodology, Writing – original draft, Writing – review & editing. **Toni Llull**: Resources, Methodology, Writing – original draft, Writing – review &

editing. **Marcella Castells-Sanabra**: Supervison, Methodology, Validation, Project administration, Writing – original draft, Writing – review & editing, Funding acquisition.

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.

Acknowledgements

This work was partially funded by IAMU (FY2020/YAS202002) and by ACCIÓ (ACE014/20/000018); the Spanish MINECO program (DPI 2017-89827-R); the European Research Council (H2020-780262-SHARE4RARE); and Networking Biomedical Research Centre in the subject area of Bioengineering, Biomaterials, and Nanomedicine (CIBER-BBN), initiatives of Instituto de Investigación Carlos III (ISCIII). This work received support from the Departament d'Universitats, Recerca i Societat de la Informació de la Generalitat de Catalunya (expedient 2017 SGR 952). Jordi Fonollosa and Anna Mujal-Colilles acknowledge the support from the Serra Húnter program.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.114787.

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