



# Estimation of shipping emissions based on real-time data with different methods: A case study of an oceangoing container ship

Araks Ekmekçioğlu<sup>1</sup> · Kaan Ünlügençoğlu<sup>1</sup> · Uğur Buğra Çelebi<sup>1</sup>

Received: 23 April 2020 / Accepted: 19 June 2021 / Published online: 27 June 2021  
© The Author(s), under exclusive licence to Springer Nature B.V. 2021

## Abstract

The environmental consequences of ship-based greenhouse emissions have been increasingly significant as a result of the rise in the share of maritime transportation in international trade. Transnational organizations such as the European Union and the International Maritime Organization monitor these emissions and have come to limit some gas emissions such as SO<sub>x</sub>, NO<sub>x</sub>, PM, and CO<sub>2</sub>. These limiting measures are all needed and welcome. However, we need more accurate data to inform and implement even more concrete policies. This study contributes to such efforts by providing calculations of the emissions of NO<sub>x</sub>, NMVOC, PM, SO<sub>x</sub>, CO, and CO<sub>2</sub> from an oceangoing container ship during its 37-day voyage in 2019. The use of a real case scenario differentiates this study from others. We employed two conventionally used methods to make the estimations. One is the fuel-based approach (top-down) and the other is the activity-based approach (bottom-up). While there is some discrepancy of results produced by the two methods, there is also consistency in terms of percentages regarding which gas is emitted most and when. The results indicate that by taking appropriate measures such as reducing fuel consumption, and using low-sulfur fuel, as well as optimizing port traffic, the environmental damage of maritime transportation could be reduced.

**Keywords** Global warming · Port emissions · Green shipping · Container ship emissions

---

✉ Araks Ekmekçioğlu  
araks@yildiz.edu.tr

Kaan Ünlügençoğlu  
kunlu@yildiz.edu.tr

Uğur Buğra Çelebi  
ucelebi@yildiz.edu.tr

<sup>1</sup> Department Of Marine Engineering Operations At, Yildiz Technical University, Besiktas/Istanbul, Turkey

## 1 Introduction

Maritime transportation has seen a significant surge in the last century, currently amounting to the biggest share of international trade. Its environmental consequences are significant. Exhaust emissions, oil and fuel vapors, asbestos and lead compounds, metal and plastic particles, solid, liquid, and gas wastes damage human health and the natural environment. In its fourth greenhouse gas (GHG) study (IMO: Fourth IMO GHG Study 2020), International Maritime Organization (IMO) presented an updated inventory of maritime-related greenhouse gas emissions for the period 2012–2018 and developed emission projections for the period 2018–2050. According to this report, CO<sub>2</sub> emissions increased 8.4% from 2012 to 2018. Moreover, the share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018. IMO and the European Union (EU) had already undertaken measures to combat this challenge, for example, the creation of Special Emission Areas (SEA) which imposes restrictions on the most harmful gas' emissions such as nitrogen oxide (NO<sub>x</sub>), sulfur oxides (SO<sub>x</sub>), particulate matter (PM), volatile organic compounds (VOC), and carbon dioxide (CO<sub>2</sub>). More measures and more effective implementation are always needed.

This study contributes to our understanding of ship-based emissions by studying emissions from one vessel on its 37-day voyage in 2019. We calculated the emissions of the most harmful six gases, namely NO<sub>x</sub>, non-methane volatile organic compounds (NMVOC), PM, SO<sub>x</sub>, carbon monoxide (CO), and CO<sub>2</sub>. These are the gases that especially impact air quality in territorial waters, inland seas, canals, straits, bays, and port regions. They also lead to acid rains. Unlike most studies which use data from a large number of ships, this research uses just one ship during one voyage which adds to the preciseness of calculations which is not possible to achieve when using a big data set. The study uses two different methods (one fuel-based, the other activity-based) to measure the emissions. We came to the conclusion that relying on data from just one ship might lead to more accurate estimations than relying on a huge data set given how much uncertainties and aggregations go to the latter. We also concluded that methods that used fuel consumption data (bottom-up) rather than the ship activity data (top-down) likely yield more accurate results.

The paper is structured as follows: First is a review of current literature on the ship-based emission estimation methods; next, we provide detailed information on the released gases that we measure and their effects; third section is devoted to the vessel and voyage information, as well as calculations of estimates with two methods; in the fourth, we discuss the results of the calculations. Our conclusion highlights the future possible practical uses of this study and its scholarly contribution.

## 2 Literature review

Studies which estimate gas emissions from the ships use methods based on the information they have access to. We can broadly categorize them according to the data they use: the studies that use fuel consumption data (top-down) and those that rely on data from ship activities (bottom-up). In recent times, bottom-up methods have gained more prominence.

The authors of this study recently published an article using different bottom-up methods, Ekmekçioğlu et al. (2021). The authors of this study followed Turkey's four major ports for one year and calculated ship emissions. They proposed emission

estimation analysis methodology based on gross tonnage (GT) for container ships. Previously, Ekmekçioğlu et al. (2019) studied exhaust gas emissions from ships sailing to Turkey's Mersin and Izmir ports during the period of a year. As a result of the calculations using actual ship data and the real duration of the stay at a given port (bottom-up method), they compared the emissions released in the two ports. In another study using a similar method, Ekmekçioğlu et al. (2020) calculated ship emissions arriving at Turkey's Kocaeli and Ambarlı ports for a year by using ENTEC company's method. They determined the effect of ship emissions by the U.S. Environmental Protection Agency (EPA) Regulatory Model (AERMOD) and compared their results with the results of the air quality measurement station. In their work, these authors have been inspired by the important studies of (Ünlügençoğlu et al., 2019; Feng et al., 2018; Rødseth et al., 2018; H. Song et al., 2017; Kilic & Tzannatos, 2014).

In scenarios where the scientists do not have access to ship's engine power and load information, they instead use the top-down methods, which estimate emissions by using the fuel consumption data and the fuel type (Kanberoğlu & Kökkülünk, 2021; Kılıç et al., 2020; Fameli & Assimakopoulos, 2015; Endresen et al., 2007; Corbett et al., 1999). For example, Kuzu et al. (2020) estimated emissions of ships arriving at the port of Bandırma, Turkey, and built air quality modeling using AERMOD.

Studies using both methods provide additional contributions to the field by comparing existing methods and/or suggesting new ones. A good example of this is the innovative study of Trozzi (2013). They worked on different complex levels of predictability methodologies of emissions from ships. In their manual, they explained the emission estimation complexity in three different ways (Tier). Their methodology was based on fuel consumption as in the top-down method. In cases where fuel consumption was unknown, they calculated emissions based on installed power. Finally, in cases where installed power and fuel consumption were unknown, they calculated emissions by estimating gross tonnage. The functions were calculated from the Lloyd's register database using information from different ship types for 100,000 ships. Bilgili and Çelebi (2018) used three years of operational data of nine bulk carriers to calculate the emissions released from these ships employing different existing methods (Fameli et al., 2020).

A significant portion of the studies in this field is regional. They measure emissions in a certain port, strait, city, etc., and therefore estimate emissions based on a large number of ships. However, there are also studies in which a single ship or only a limited number of ships are examined in depth in the ship-based emission inventory, see for example (Sui et al., 2020; Ammar, 2019; Merien-Paul et al., 2018; Jahangiri et al., 2018; Bilgili & Çelebi, 2018). Similar to the study presented here, Moreno-Gutiérrez et al. (2019) studied only one ship (though ours is a container vessel while theirs is a passenger ship). They compared the results of existing calculation methods and proposed an altogether new activity-based method. They applied the existing and proposed methods to a roll-on/roll-off passenger-ship/ferry (*Ro-Pax*) as a case study.

Most of the studies thus far conducted in the field of gas emissions, especially the bottom-up method, use AIS, that is, the automatic identification system, see for example (Chen et al., 2016; Jalkanen et al., 2012; Huang et al., 2020; Chen et al., 2017; Ng et al., 2013; Weng et al., 2020; Song, 2014; Goldsworthy et al., 2019; Simonsen et al., 2019). IMO requires AIS on large ships. AIS transmits a ship's position so that other ships are aware of its position. It also reports static data (ship name, type, length, etc.) and dynamic data (ship's speed, position, port of arrival/departure, etc.).

While AIS and other such sources are highly valuable to these studies and have their specific uses, they aggregate data, have many assumptions, and lead to significant

uncertainties. For example, while these calculations consider the load factor, they ignore important determinants such as the wind, waves, and general weather conditions. They calculate the load factor by dividing the ship speed by maximum speed (Weng et al., 2020; Chen et al., 2017). When scientists do not have access to the technical specifications of the vessel, they estimate the engine power either by using the ship's size (Ng et al., 2013; Chen et al., 2016) or by interpolation and regression approaches (Weng et al., 2020). Some studies take the main and auxiliary engine's fuel types as "assumptions" which then lead to uncertainties in the selection of the right emission factor.

As opposed to these studies, the case presented here uses *real data* which leaves nearly no room for uncertainties. This is because the calculations we make are based on *just one ship* (as opposed to using AIS reports which aggregate many ship's results) and its data entry regarding fuel consumption, main and auxiliary engine power, load factors, operating mode, and the different types of fuel that vessel uses in different ports (per port legal requirements) are exact numbers, not estimations. Most importantly, sea and weather conditions which significantly influence the load of engines and fuel consumption, as well as the load factor, are accurate numbers rather than estimates or aggregations. Therefore, we claim that our method contributes to the already established large inventory of gas emissions by enabling future comparisons. In addition to regional studies, studies like ours that use minimum uncertainties add to the inventory of gas emissions.

### 3 Released gases and their effects

This study calculated ship emissions of six gases:  $\text{NO}_x$ , NMVOC, PM,  $\text{SO}_x$ , CO, and  $\text{CO}_2$ .

Volatile organic compounds (VOCs), which are petroleum-derived emissions, react with  $\text{NO}_x$  in sunlight to form ozone. This compound is often referred to as NMVOC. NMVOCs diffuse into the atmosphere from multiple sources, including combustion activities, solvent use, and production processes. NMVOCs are directly dangerous to human health. Annex VI, 15. rule of the International Convention for the Prevention of Pollution of the Seas by Ships (MARPOL), one of the IMO codes, introduced regulations for the VOC emissions. These regulations are only valid for tanker-type ships. VOC are ship-based emissions from fuels that evaporate during filling of petroleum products into tankers, during fuel intake by a ship, and in the fuel tanks. These are dangerous in loading ports and mix into the atmosphere ("VOC—Regulation 15" n.d.).

$\text{NO}_x$  is the general name of nitrogen oxide (NO) and nitrogen dioxide ( $\text{NO}_2$ ) emissions released from diesel engines and other nitrogen–oxygen combinations.  $\text{NO}_x$  gases react in the atmosphere to form ozone (Pulkrabek & W.W. 2004; Kökkülünk, 2010). Nitrogen oxide, which is an odorless and colorless gas, is released during the combustion of all fossil fuels. It is produced in the combustion chamber of the diesel engine. The process consists of the reaction of oxygen and nitrogen during the combustion phase. The  $\text{NO}_x$  production is largely dependent on the temperature inside the cylinder. This gas has many negative effects on human health due to its characteristic and concentration in the atmosphere. Nitrogen oxides are poisonous for living things, causes eye and ear discomfort, and affect the nervous system (Hasançebi, 2002).  $\text{NO}_x$  restrictions are mentioned in Annex VI of MARPOL, which was adopted by IMO in 1973. Tier 1-2-3  $\text{NO}_x$  limits were determined according to engine revolution per minute (rpm) and construction year.

PM are solid or liquid particles suspended in the air that have a grain size in the 0.002–500  $\mu\text{m}$  range and have various densities. In diesel engines, both air–fuel ratio and

fuel type cause the formation of PM. When a large amount of fuel is sent to the combustion chamber to increase power, there will be some amount of soot in the exhaust gases since there is not enough O<sub>2</sub>. If there is not enough temperature, O<sub>2</sub>, and time in the combustion chamber, PM is discharged from the exhaust outlet. The greatest effect on health is from particles with a diameter of 2.5 μm or smaller. Fine particulate matter is PM with a diameter of 2.5 μm and less (denoted as PM<sub>2.5</sub>). Fine particulate exposure has been associated with many serious health effects, including early death. Children and the elderly are considered the most susceptible to PM effects, as well as those with asthma, cardiovascular, or lung disease. PM is also responsible for environmental influences such as corrosion, contamination, damage to vegetation, and reduced visibility (“Fine Particulate Matter” n.d.).

CO is an air pollutant resulting from incomplete combustion reaction in ship diesel engines. CO gas emission is lower in high-power diesel engines than in low-power diesel engines. The reason for this is that combustion temperature is high in high-power diesel engines. However, the CO emission amount increases on ships, especially during the maneuver operation mode, due to the reduced power of the ship’s main engine. (Saraçoğlu et al., 2013; Sinha et al., 2003). CO has a negative effect on the human respiratory system. CO attaches itself to blood cells and prevents oxygen intake.

CO<sub>2</sub> absorbs the solar energy reflected from the ground and causes the temperature of the atmosphere to increase in what is referred to as greenhouse gas effect. Fossil fuel use is the primary source of CO<sub>2</sub> emissions. It may also result from human activities involving agriculture and other land uses, such as forest reduction and land degradation. Approximately, 76% of all greenhouse gases in the atmosphere is CO<sub>2</sub>. Approximately, 21% of the total CO<sub>2</sub> emitted worldwide originates from the transportation sector (Muntean et al., 2018). The amount of CO<sub>2</sub> emissions largely depends on the fuel consumption in the ship’s main and auxiliary engines. In addition, the carbon–hydrogen ratio in the fuel is an important factor that determines the amount of CO<sub>2</sub> emissions (Haglund, 2008). As is well-known, CO<sub>2</sub> has an important effect on global warming.

Sulfur dioxide (SO<sub>2</sub>) is the most common pollutant emissions of land and marine vehicles. Many fuels used in diesel engines contain a small amount of sulfur. In ship diesel engines, this ratio is quite high compared to land vehicles. The sulfur content in the world has been limited to various levels. MARPOL ANNEX VI, rule 14, sets limits on SO<sub>x</sub> and PM emissions. IMO has set emission limits for Emission Control Areas (ECA) and the regions within and outside these areas to control SO<sub>x</sub> emissions from maritime transportation. The SO<sub>x</sub> limits for 2019 require that the sulfur content in the fuel used in diesel ship engines be less than 3.5% outside ECA and less than 0.1% inside ECA. In regions other than ECA, the SO<sub>x</sub> limit has been reduced to 0.5% as of 01.01.2020. A decrease in this fraction will force international traders to meet new machinery technologies and use different types of fuel (“Sulfur oxides (SO<sub>x</sub>) and Particulate Matter (PM) – IMO, Marpol Annex VI, Regulation 14” n.d.).

## 4 Material and method

There are two main ship-based emission calculation methods for estimating emission values of air pollutants. Both were used in this study. First method, called “the bottom-up or activity-based approach,” extracts data from a ship’s main and auxiliary engine powers, engine revolution, and fuel type. This method uses the ship’s installed power and the time spent by ships in different operating conditions to determine emissions from ships. Emission amounts are

determined by multiplying the generated engine power by the time it remains at this power by the emission factor.

Second method, called “fuel-based or top-down approach,” uses ship fuel consumption values and relies on ship movements (maneuver-cruise-port-anchorage). This method uses the ship’s fuel consumption data to determine the total emissions, as well as emissions per unit of fuel. In the studies carried out using this method, the fuel consumed by the ship is determined from the marine fuel sales statistics. The amount of fuel consumed by the ship is multiplied by the emission factor. The emission volumes from the ship are thus determined.

While most similar studies rely on estimations for fuel and engine data, we used actual data from a real container ship.

#### 4.1 Vessel and voyage

Built in 2003, the oceangoing container ship from which this study’s data originates is 207.98 m long and 32.24 m wide. With 30,024 gross ton (GT), it has a low-speed main engine at 21,735 kW and 91 rpm and four auxiliary engines at 1260 kW and 720 rpm. Main and auxiliary engines can use either heavy fuel oil (HFO) or marine diesel oil (MDO) as fuel. Throughout the voyage, 380 centistokes (cSt) viscosity, 0.975 tons/m<sup>3</sup> density (density), 3.29% sulfur content bunker fuel oil (BFO) and 3.091 cSt viscosity, 0.8554 tons/m<sup>3</sup> density, and 0.089% sulfur content MDO were used.

We examined “noon reports” of the ship during a voyage in 2019. “Noon reports” are reports that ship operators send to their companies on a daily basis. These reports contain information such as the daily fuel and oil consumption, as well as data regarding the cruise, maneuver, and length of stay in the port.

As shown in Fig. 1, the container ship started its itinerary at the port of Tanger of Morocco (A point) located on the Strait of Gibraltar and continued with Algeciras Port of Spain (D point). Afterward, it passed through the Strait of Gibraltar to the Atlantic Ocean and docked at Congo’s Pointe Noire port (H point), Gabon’s Libreville port (L point), and Cameroon’s Douala port (P point). G, K, and O points in Fig. 1 are anchorage points of Pointe Noire, Libreville, and Douala, respectively. The ship returned to the port of Tanger and completed the voyage.

The ports, cruising-maneuvering-anchorage times, main and auxiliary engine loads, number of auxiliary engines used in the relevant mode and fuel consumptions of the container ship are shown in Table 1.

The ship used MDO as an auxiliary engine fuel during arrival/departure maneuvers and during port time in Spain’s Algeciras port as it is an EU country and needs to abide by IMO low-sulfur rules (“Cleaner Air in 2020” n.d.). In the other ports, auxiliary engines and main engine used HFO since they are not from EU member states or in the ECA/Sulfur Emission Control Areas (SECA) region.

#### 4.2 Calculations using the top-down (fuel-based) method

We made calculations by using the Tier 3 method in (Trozzi’s, 2013) study and formulas 1 and 2 (Trozzi, 2013).

$$E_{\text{Trip}} = E_{\text{Port}} + E_{\text{Cruising}} + E_{\text{Maneuvering}} + E_{\text{Anchorage}} \quad (1)$$



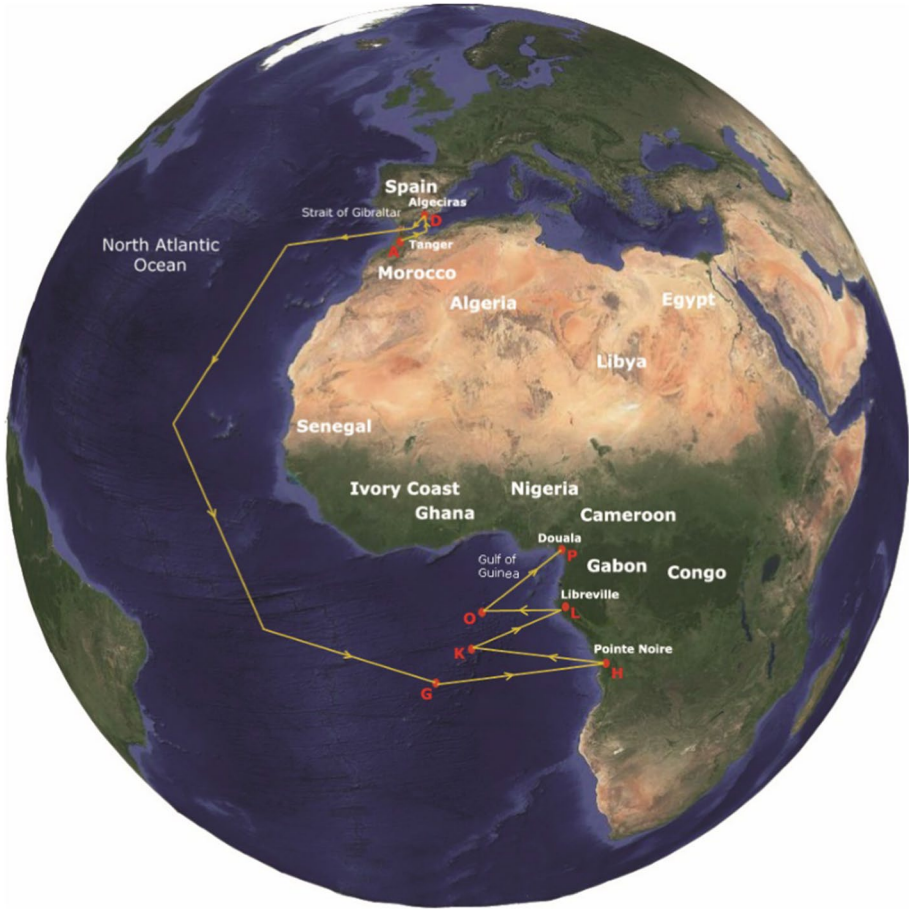


Fig. 1 Voyage and route of the ship (Google Earth, 2019)

$$E_{\text{Trip},i,j,m} = \sum_p (FC_{j,m,p} \times EF_{i,j,m,p}) \tag{2}$$

where  $E_{\text{Trip}}$  = Emission of complete trip (tonnes).  $FC$  = fuel consumption (tonnes).  $EF$  = emission factor (kg/tonne).  $i$  = pollutant.  $m$  = fuel type.  $j$  = engine type (slow-, medium-, high-speed diesel).  $P$  = operation mode of trip (port, cruising, maneuvering, anchorage).

Table 2 shows emission factors for different engine types, different fuel types, and different modes of operation. Note that, the source sites the fuel type as “BFO” which is similar to HFO in terms of its characteristics. While the container ship in question used HFO, the similarities between the two fuels make BFO parameters accurate substitutions for HFO.

Since the sample ship was built in 2003, the  $\text{NO}_x$  emission factor was taken from 2005.  $\text{NO}_x$ , NMVOC, and PM Tier 3 emission factors were taken from Trozzi’s study (Trozzi, 2013),  $\text{SO}_x$ , CO, and  $\text{CO}_2$  emission factors were taken from Cooper and Gustafsson’s study (Cooper et al., 2004).

**Table 1** Voyage data of the container ship

Point	Position	Operation mode	Duration(h)	AE no	AE load(%)	AE fuel type	AE fuel cons. (ton)	ME load(%)	ME fuel type	ME fuel cons. (ton)
A	Tanger port *	Port	17.2	2	0.4	HFO	3.8	0	HFO	0
A-B	Tanger dep. mnv	Maneuver	0.3	3	0.5	HFO	0.2	40	HFO	0.2
B-C	Algeiras cruising	Cruising	0.5	2	0.7	MDO	0.2	62	HFO	1.7
C-D	Algeiras arr. mnv	Maneuver	1	3	0.5	MDO	0.3	40	HFO	0.5
D	Algeiras port	Port	22.3	2	0.4	MDO	3.9	0	HFO	0
D-E	Algeiras dep. mnv	Maneuver	1.1	3	0.5	MDO	0.3	40	HFO	0.5
E-F	Pointe noire cruising	Cruising	251	2	0.7	HFO	95	68	HFO	537.6
F-G	Pointe noire anch. mnv	Maneuver	1	3	0.5	HFO	0.4	40	HFO	0.5
G	Pointe noire anchorage	Anchorage	23.2	2	0.4	HFO	5	0	HFO	0
G-H	Pointe noire arr. mnv	Maneuver	1.5	3	0.5	HFO	0.6	40	HFO	0.8
H	Pointe noire port	Port	28.3	2	0.4	HFO	6.2	0	HFO	0
H-I	Pointe noire dep. mnv	Maneuver	1	3	0.5	HFO	0.4	40	HFO	0.5
I-J	Libreville cruising	Cruising	29.2	2	0.7	HFO	11.1	68	HFO	62.6
J-K	Libreville anch. mnv	Maneuver	1.5	3	0.5	HFO	0.6	40	HFO	0.8
K	Libreville anchorage	Anchorage	71.3	2	0.4	HFO	15.5	0	HFO	0
K-L	Libreville arr. maneuver	Maneuver	1.2	3	0.5	HFO	0.5	40	HFO	0.6
L	Libreville port	Port	14.4	2	0.4	HFO	3.2	0	HFO	0
L-M	Libreville dep. mnv	Maneuver	2.2	3	0.5	HFO	0.9	40	HFO	1.2
M-N	Douala cruising	Cruising	16	2	0.7	HFO	6.1	53	HFO	17.8
N-O	Douala anch. mnv	Maneuver	1.5	3	0.5	HFO	0.6	40	HFO	0.8
O	Douala anchorage	Anchorage	85.5	2	0.4	HFO	18.4	0	HFO	0
O-P	Douala arr. mnv	Maneuver	2.4	3	0.5	HFO	1	40	HFO	1.3
P	Douala port	Port	47	2	0.4	HFO	10.2	0	HFO	0
P-R	Douala dep. mnv	Maneuver	2.6	3	0.5	HFO	1.2	40	HFO	1.7



**Table 1** (continued)

Point	Position	Operation mode	Duration(h)	AE no	AE load(%)	AE fuel type	AE fuel cons. (ton)	ME load(%)	ME fuel type	ME fuel cons. (ton)
R-S	Tanger cruising	Cruising	220.5	2	0.7	HFO	83.5	75	HFO	516
S-A	Tanger arr. mnv	Maneuver	2.3	3	0.5	HFO	1	40	HFO	1.3

\*Maneuver(Mnv.), Departure(Dep.), Arrival(Arr.), Anchorage(Anch.), Consumption(Cons.), hour(h)  
 Auxiliary Engine (AE), Main Engine (ME)

**Table 2** Emission factors for fuel-based approach (kg/tonne) (Trozzi, 2013)(Cooper et al., 2004)

Engine	Phase	Engine type	Fuel type	NO <sub>x</sub> EF 2005 (kg/tonne)	NMVOC EF (kg/tonne)	PM EF (kg/tonne)	SO <sub>x</sub> (kg/tonne)	CO (kg/tonne)	CO <sub>2</sub> (kg/tonne)
Main engine	Cruise	Slow-speed diesel	BFO	89.7	3.0	8.7	46	2.5	3179
			MDO	88.6	3.2	1.6	8	2.7	3179
	Maneuvering port anchorage	Slow-speed diesel	BFO	65.1	8.2	11.2	46	4.6	3179
			MDO	64.2	8.6	4.4	8	4.9	3179
Auxiliary engine	Cruise	Medium-speed diesel	BFO	62.5	1.7	3.5	46	3.9	3179
			MDO	62	1.8	1.4	8	4.1	3179

### 4.3 Calculations using the bottom-up (activity-based) method

We made calculations based on installed power and time spent in the different navigation phases by using the method in Trozzi's, 2013 study and formula III.

$$E_{Trip,i,j,m} = \sum_p \left[ T_p \sum_e (P_e \times LF_e \times EF_{e,i,j,m,p}) \right] \tag{3}$$

where  $E_{Trip}$  = Emission of complete trip.  $EF$  = Emission factor (g/kWh).  $LF$  = Engine load factor (%).  $P$  = Engine nominal power (kW).  $T$  = Time spent (hours).  $e$  = Engine category (main, auxiliary).  $i$  = Pollutant.  $j$  = Engine type (slow-, medium-, high-speed diesel).  $m$  = Fuel type (BFO, MDO).  $p$  = operation mode of trip (port, cruising, maneuvering, anchorage).

Table 3 shows emission factors in g/kWh for different engine types, different fuel types, and different modes of operation. Since the container ship was built in 2003, the  $NO_x$  emission factor was taken from 2005.  $NO_x$ , NMVOC, and PM Tier 3 emission factors were taken from Trozzi's study (Trozzi, 2013),  $SO_x$ , CO, and  $CO_2$  emission factors were taken from Cooper and Gustafsson's study (Cooper et al., 2004).

## 5 Results

During a voyage between 03.01.2019 and 04.06.2019, the ship spent 517 h in cruising, 180 h in anchorage, 129 h in port, and 19.5 h in maneuvering mode. The main engine spent 1146.2 tons of HFO, auxiliary engines spent 265.3 tons of HFO and 4.7 tons of MDO.

### 5.1 Results of the top-down method

We calculated the  $NO_x$ , NMVOC, PM,  $SO_x$ , CO, and  $CO_2$  emissions in the port, maneuver, cruising, and anchorage modes according to the fuel-based approach. Results are shown in Table 4.

For every pollutant, total absolute emissions are the highest in the cruising mode. The reason for this is that the cruising mode is the longest operating mode and the engines work at high power. For  $NO_x$ ,  $SO_x$ , CO, and  $CO_2$ , it is followed by anchorage, port, and maneuvering operation modes, respectively. For PM and NMVOC emissions, it is followed by maneuvering, anchorage, and port modes, respectively.

The total gas emissions amount to 4705 tons. The  $CO_2$  emission amount is 4501.8 tons. It is clear that  $CO_2$  emission forms the major part of the total emissions and therefore treated separately in this paper as follows.

When the sum of  $NO_x$ , NMVOC, PM,  $SO_x$ , and CO emissions is calculated, their percentage ratios are 58.8%, 1.9%, 5.4%, 32%, and 1.9%, respectively.  $NO_x$  and  $SO_x$  emissions are higher than other emissions in percentage because of higher sulfur content of the diesel fuel (MDO) used in ships (diesel engines of ships release higher  $NO_x$  than land diesel vehicle engines).

For human health, emissions during the waiting period at the port are even more important given the closeness to coastal human habitation. Therefore, we also

**Table 3** Emission factors for activity-based approach (g/kWh) (Trozzzi, 2013; Cooper et al., 2004)

Engine	Phase	Engine type	Fuel type	NO <sub>x</sub> EF 2005 (g/kWh)	NMVOC EF (g/kWh)	PM EF (g/ kWh)	SO <sub>x</sub> (g/kWh)	CO(g/kWh)	CO <sub>2</sub> (g/kWh)
Main engine	Cruise	Slow-speed diesel	BFO	17.5	0.6	1.7	9	0.5	620
			MDO	16.4	0.6	0.3	1.5	0.5	588
	Maneuvering port anchor- age	Slow-speed diesel	BFO	14	1.8	2.4	9.9	1	682
			MDO	13.1	1.8	0.9	1.6	1	647
Auxiliary engine	Cruise maneu- vering port anchorage	Medium-speed diesel	BFO	14.2	0.4	0.8	10.4	0.9	722
			MDO	13.5	0.4	0.3	1.7	0.9	690

**Table 4** Total emission amounts by ship operating modes for top-down method (ton)

Top-down	Duration (h)	NO <sub>x</sub>	NM VOC	PM	SO <sub>x</sub>	CO	CO <sub>2</sub>
Port	129.2	1.7	0.047	0.087	1.1	0.11	86.5
Maneuver	19.4	1.2	0.099	0.14	0.81	0.08	59
Cruising	517.1	114.1	3.7	10.6	61.2	3.7	4232.7
Anchorage	179.9	2.4	0.066	0.13	1.8	0.15	123.6
Total	845.6	119.4	3.9	11	64.9	4	4501.8

**Table 5** NO<sub>x</sub>, NM VOC, PM, SO<sub>x</sub>, CO, and CO<sub>2</sub> emission values (ton) released in ports (Top-down method)

Top-down	Duration (h)	NO <sub>x</sub>	NM VOC	PM	SO <sub>x</sub>	CO	CO <sub>2</sub>
Douala	47	0.64	0.017	0.036	0.47	0.040	32.37
Pointe noire	28.3	0.39	0.010	0.022	0.28	0.024	19.63
Algeciras	22.3	0.24	0.007	0.005	0.03	0.016	12.47
Tanger	17.2	0.23	0.006	0.013	0.17	0.015	11.94
Libreville	14.4	0.20	0.005	0.011	0.146	0.012	10.10

**Table 6** Total emission amounts by ship operating modes for bottom-up method (ton)

Bottom-up	Duration (h)	NO <sub>x</sub>	NM VOC	PM	SO <sub>x</sub>	CO	CO <sub>2</sub>
Port	129.2	1.83	0.052	0.093	1.16	0.12	93.3
Maneuver	19.4	2.9	0.3	0.43	2	0.2	141
Cruising	517.1	151.6	5.1	14.2	80.8	4.8	5571.7
Anchorage	179.9	2.6	0.07	0.15	1.9	0.16	130.9
Total	845.6	158.9	5.5	14.9	85.9	5.3	5936.9

calculated the same gas emissions, while the container ship was at the ports. Results are shown in Table 5 starting from the highest emissions going to the lowest.

In absolute numbers, emissions are highest at the Douala port, followed by Pointe Noire, Algeciras, Tanger, and Libreville. However, the order changes if we consider the time spent at the port. When we divide the amount of emissions by duration (thus reaching a unit of emission), we see that the ship emitted the lowest gas (for all gases) at the Algeciras port. This is because being an EU country, Spain has to use fuel with lower sulfur level. In accordance with IMO rules, the ship used MDO in Algeciras as fuel in auxiliary engines for a total of 2 h of berthing and leaving maneuver, 22 h of harbor waiting, and 0.5 h of cruising. A total of 4.7 tons of MDO was used. In the other ports, the main and the auxiliary engines used HFO since they are not from EU member states or in the ECA/SECA region.

## 5.2 Results of the bottom-up method

Emissions according to the activity-based approach while in the port, maneuver, cruising, and anchorage modes are shown in Table 6.

All gas emissions were the highest in the cruising mode, followed by maneuvering, anchorage, and port modes, respectively. The total gas emissions are 6207.4 tons. CO<sub>2</sub> emission forms the major part of the total emissions with 5936.9 tons.

When the sum of NO<sub>x</sub>, NMVOC, PM, SO<sub>x</sub>, and CO emissions is calculated, their percentage ratios are 58.8%, 2%, 5.5%, 31.8%, and 1.9%, respectively. NO<sub>x</sub> and SO<sub>x</sub> emissions are higher in percentage.

Results using the activity-based method for gas emissions during the waiting period are shown in Table 7.

Table 7 shows that the order of gases reached by the bottom-up method is the same. Douala is where the highest emission occurred but it is because of the length of the time spent in the port. When checked for time, it is Algeciras where unit emissions are the lowest. For all other ports, unit emissions are the same. This is because, as it is seen in Formula 3, in the activity-based method calculations main and auxiliary engine powers, engine load, and unit port durations are kept as constant. Emission factor is chosen depending on the type of fuel. Since the ship used a different kind of fuel in Algeciras (MDO), the estimated emissions in this port are different and lower from the other ports. The ship used HFO in all other ports; therefore, in this calculation, all other four ports showed the same exact amount of emissions.

## 5.3 Comparison of the results from the two methods

The acquired data allow to estimate the release of the different pollutant gases, as well as to perform comparisons between the predictions of the top-down and bottom-up models. Such a comparison could help understand the level of accuracy of the two models.

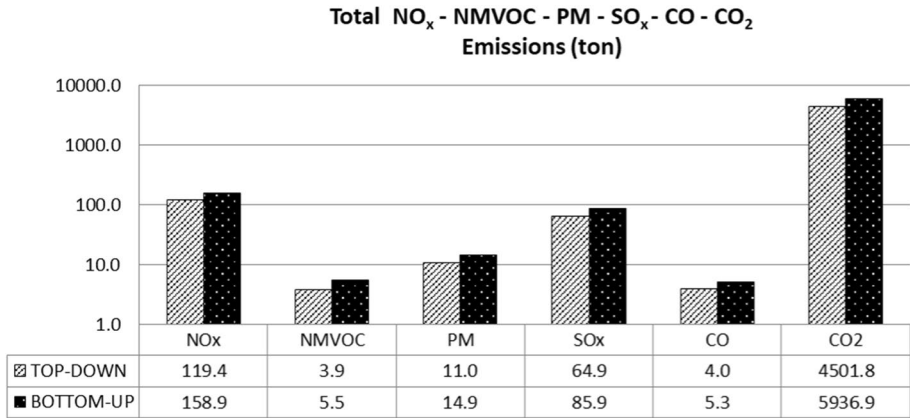
Fig. 2 shows a comparison of the sum of NO<sub>x</sub>, NMVOC, PM, SO<sub>x</sub>, CO, and CO<sub>2</sub> emissions calculated according to the top-down and bottom-up methods for this ship voyage.

Figure 2 shows that for all six gases, the calculations based on main and auxiliary engine powers are higher than the calculations based on fuel consumption data.

Regarding the differences in the estimates reached via the two different methods, it is apparent that the biggest discrepancy is in CO<sub>2</sub>, NO<sub>x</sub>, and SO<sub>x</sub> emissions, respectively. What is noteworthy here is that the discrepancy between the results in terms of percentages is quite similar: for NO<sub>x</sub> 24.8%, for NMVOC 29%, for PM 26%, for SO<sub>x</sub> 24.3%, for

**Table 7** NO<sub>x</sub>, NMVOC, PM, SO<sub>x</sub>, CO, and CO<sub>2</sub> emission values (ton) released in ports (Bottom-up method)

Bottom-up	Duration (h)	NO <sub>x</sub>	NMVOC	PM	SO <sub>x</sub>	CO	CO <sub>2</sub>
Douala	47	0.67	0.019	0.038	0.49	0.043	34.21
Pointe noire	28.3	0.41	0.011	0.023	0.30	0.026	20.6
Algeciras	22.3	0.30	0.009	0.007	0.038	0.020	15.48
Tanger	17.2	0.25	0.007	0.014	0.18	0.016	12.52
Libreville	14.4	0.21	0.006	0.012	0.15	0.013	10.48

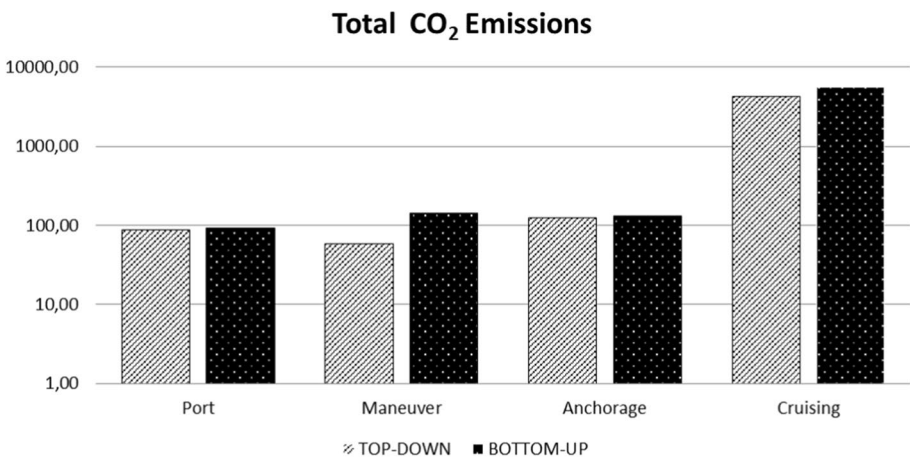


**Fig. 2** Comparison of the total NO<sub>x</sub>, NMVOC, PM, SO<sub>x</sub>, CO, and CO<sub>2</sub> emissions according to top-down and bottom-up methods

CO 24%, and for CO<sub>2</sub> 24%. This also indicates that the relative emissions between the gas types are very similar between the two predictive models.

According to both methods, CO<sub>2</sub> emission constitutes the major amount of the total emissions. During cruising, CO<sub>2</sub> emissions are significantly higher because the duration of cruising is significantly longer than port, maneuvering, and anchorage times. Just to give an idea, the ship’s longest cruise times during this voyage was between Algeciras and Pointe Noire Port which was 251 h (E–F points) and between Douala and Tanger Port (R–S points) with 220.5 h. During these cruises, the main engine consumed 470 tons of 24.

Figure 3 shows the CO<sub>2</sub> emissions calculated using the top-down and bottom-up methods in different operation modes. For the top-down method, CO<sub>2</sub> emissions were calculated as 86.5 tons for port mode, 59 tons for maneuver mode, 123.6 tons for anchorage mode, and 4232.6 tons for cruising mode. For the bottom-up method, CO<sub>2</sub> emissions were



**Fig. 3** Comparison of the total CO<sub>2</sub> emission according to top-down and bottom-up methods at port, maneuver, anchorage, and cruising modes



calculated as 93.3 tons for port mode, 141 tons for maneuver mode, 130 tons for anchorage mode, and 5571.7 tons for cruising mode.

Figure 3 shows that for CO<sub>2</sub> emissions, there is a remarkable difference for the maneuvering mode (58%) but not a real difference in the port (7%), anchorage (5.6%), and cruising (24%) modes. This is because the load of the ship's engines is not constant during maneuvering unlike it is during port and anchorage. Therefore, there is a significant difference between calculations using fuel consumption and load. In port and anchorage, the main engine does not work while auxiliary engine's work balanced.

Regarding the emissions in ports, Fig. 4 shows all gas emissions calculated with both methods in all five ports.

Figure 4 shows that percentages are quite similar for both methods. Even though the percentage distribution of all gas emissions in the total is almost the same in the port period, the overall emissions calculated according to the activity-based (bottom-up) approach are higher than the emission values calculated according to the fuel-based approach. It is 33% higher for NO<sub>x</sub> emission, 41% higher for NMVOC emission, 35% higher for PM emission, and 32% higher for SO<sub>x</sub>, CO, and CO<sub>2</sub> emissions.

#### 5.4 Discussion of the results from the two methods

The results of both methods show that the amount of gas released into the atmosphere from the ship's machinery directly depends on the amount and type of fuel consumed. The amount of fuel consumption in ships is affected by various factors such as the form of the ship, the surface roughness, the condition and the load of machinery on the ship, as well as the weather and sea conditions in the voyage.

We have enough data to be able to claim that bottom-up method calculations are closer to the truth. Various previous studies rightfully claimed that given the use of real-time data pertaining to the ships' activities, one can operate with the principle that bottom-up method yields better results (Chen et al., 2016); Ng et al., 2013; Jalkanen et al., 2012).

We need to take into account that human error has larger impact on estimates based on fuel consumption than other methods. In terms of fuel consumption data, the amount of fuel might not always be accurate because the flowmeter which provides these data might not be correct. Moreover, there is room for human mistake in tank measurements. The lead author of this study has worked in oceangoing ships for 10 years (3 of which as the chief engineer). Through experience, he knows that occasionally chief engineers might record the fuel consumption differently from the actual consumption in order to correct some other calculation and measurement mistakes or to make up for an abnormal fuel leak.

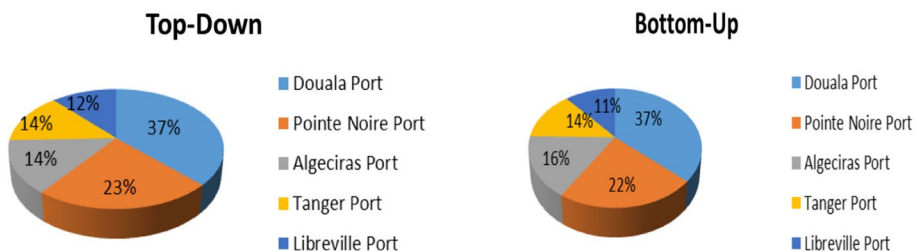


Fig. 4 Percentage distributions of total NO<sub>x</sub>, NMVOC, PM, SO<sub>x</sub>, CO, and CO<sub>2</sub> emissions in ports

Even though we accept that fuel-based calculations include some uncertainties, we used both methods to be able to show the differences in results. By comparing the fuel-based method results with the activity-based method results, we observe a difference of about 25%. Even though it might not make too much of a difference for a single ship, it is a significant difference if we apply it to a whole maritime fleet. In order for the gas emission inventories to be built on nearly accurate data, the scientists and policymakers need to decide which method is more true to reality and calculate the emissions accordingly. In order to decide as to which method works better for this purpose, we need to have more that use data from only a single ship or a few ships (Ammar, 2019; Moreno-Gutiérrez et al., 2019; Merien-Paul et al., 2018). Similar to (Chen et al., 2016; Jalkanen et al., 2012; Ng et al., 2013), this study too shows that bottom-up method is better than top-down methods in terms of accuracy. Moreover, it makes an emission estimation with more reliable inputs than methods using AIS data in the bottom-up method.

## 6 Conclusion and implications

In this study, we present actual data from a container ship, which, in addition to allowing the analysis presented in the study itself, can become basis for future studies of ship emissions. The calculations performed with the top-down and bottom-up method show clear discrepancies at the 20–30% level. These differences could be because of possible inaccuracies in the fuel consumption numbers which are typically manually entered into the ship logs by the crew. Alternatively, these differences may indicate that one of the models is inaccurate in its estimates. This calls for future studies involving direct measurements of the exhaust gases (such as by using a measurement device attached to the ship's funnel during voyage), which would allow for the validation of the said models or the development of more accurate models.

Regardless of the discrepancies, however, the data presented here show the level of environmental pollution just one container ship can cause. Yet it is possible to reduce their damage by minimizing ship-based emissions. It is a welcome development, therefore, that EU and IMO imposed major limitations on  $\text{NO}_x$ ,  $\text{CO}_2$ ,  $\text{SO}_x$ , and PM emissions. In considering especially human health in coastal areas, governments should expand ECA regulations and make sure that sanctions are applied globally and not just in the EU and a few other states. The concepts of 'Green Ship' and 'Green Harbour' need to be brought to the fore to raise environmental awareness.

It is important to note that new technologies can be used to reduce fuel consumption. Moreover, electric propulsion systems should be preferred for the propulsion system for new ships. For the existing ships, their main and auxiliary engines' exhaust systems should be equipped with exhaust gas scrubber systems (scrubber) and EGR (exhaust gas recirculation) which reduce emissions. Another way to reduce fuel consumption is to use "waste heat recovery systems" which increases energy efficiency, therefore, reducing emissions. These changes would inevitably push international trade ships to employ new machinery technologies and use different contents of fuel. The increase in the cost to the maritime industry might be a small cost to pay in considering the damage that the minimally regulated ship traffic causes to our ecosystem.

## References

- Ammar, N. R. (2019). An environmental and economic analysis of methanol fuel for a cellular container ship. *Transportation Research Part d: Transport and Environment*, *69*, 66–76. <https://doi.org/10.1016/j.trd.2019.02.001>
- Bilgili, L., & Çelebi, U. B. (2018). Developing a new green ship approach for flue gas emission estimation of bulk carriers. *Measurement: Journal of the International Measurement Confederation*, *120*, 121–127. <https://doi.org/10.1016/j.measurement.2018.02.002>
- Chen, D., Wang, X., Nelson, P., Li, Y., Zhao, N., Zhao, Y., et al. (2017). Ship emission inventory and its impact on the PM<sub>2.5</sub> air pollution in Qingdao Port. *North China. Atmospheric Environment*, *166*, 351–361. <https://doi.org/10.1016/j.atmosenv.2017.07.021>
- Chen, D., Zhao, Y., Nelson, P., Li, Y., Wang, X., Zhou, Y., et al. (2016). Estimating ship emissions based on AIS data for port of Tianjin, China. *Atmospheric Environment*, *145*, 10–18. <https://doi.org/10.1016/j.atmosenv.2016.08.086>
- Cleaner Air in 2020. (n.d.). 2020. [https://ec.europa.eu/commission/presscorner/detail/en/ip\\_19\\_6837](https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6837) Accessed 22 March 2020
- Cooper, D. A., Gustafsson, T., & Agency, S. E. P. (2004). Methodology for calculating emissions from ships: 2. Emission factors for 2004 reporting, (4), 1–11.
- Corbett, J. J., Fischbeck, P. S., & Pandis, S. N. (1999). Global nitrogen and sulfur inventories for ocean-going ships. *Journal of Geophysical Research Atmospheres*, *104*(D3), 3457–3470. <https://doi.org/10.1029/1998JD100040>
- Ekmekçioğlu, A., Kuzu, S. L., Ünlügençoğlu, K., & Çelebi, U. B. (2020). Assessment of shipping emission factors through monitoring and modelling studies. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2020.140742>
- Ekmekçioğlu, A., Ünlügençoğlu, K., & Çelebi, U. B. (2019). Ship Emission estimation for izmir and mersin international ports—Turkey. *Journal of Thermal Engineering*, *5*(10), 184–195.
- Ekmekçioğlu, A., Ünlügençoğlu, K., & Çelebi, U. B. (2021). Container ship emission estimation model for the concept of green port in Turkey. *Proceedings of the Institution of Mechanical Engineers, Part m: Journal of Engineering for the Maritime Environment*. <https://doi.org/10.1177/14750902211024453>
- Endresen, Ø., Sørgård, E., Behrens, H. L., Brett, P. O., & Isaksen, I. S. A. (2007). A historical reconstruction of ships' fuel consumption and emissions. *Journal of Geophysical Research Atmospheres*, *112*(12), 1–17. <https://doi.org/10.1029/2006JD007630>
- Fameli, K. M., & Assimakopoulos, V. D. (2015). Development of a road transport emission inventory for Greece and the greater Athens area: Effects of important parameters. *Science of the Total Environment*, *505*(2), 770–786. <https://doi.org/10.1016/j.scitotenv.2014.10.015>
- Fameli, K. M., Kotrikla, A. M., Psanis, C., Biskos, G., & Polydoropoulou, A. (2020). Estimation of the emissions by transport in two port cities of the northeastern Mediterranean. *Greece. Environmental Pollution*, *257*, 113598. <https://doi.org/10.1016/j.envpol.2019.113598>
- Feng, Y., Bie, P., Wang, Z., Wang, L., & Zhang, J. (2018). Bottom-up anthropogenic dichloromethane emission estimates from China for the period 2005–2016 and predictions of future emissions. *Atmospheric Environment*, *186*(May), 241–247. <https://doi.org/10.1016/j.atmosenv.2018.05.039>
- Fine Particulate Matter. (n.d.). <http://www.airqualityontario.com/science/pollutants/particulates.php>. Accessed 20 March 2020
- Goldsworthy, B., Enshaei, H., & Jayasinghe, S. (2019). Comparison of large-scale ship exhaust emissions across multiple resolutions: From annual to hourly data. *Atmospheric Environment*, *214*(July), 116829. <https://doi.org/10.1016/j.atmosenv.2019.116829>
- Google Earth. (2019). Retrieved from <https://earth.google.com/web/@14.8820005,1.72873091,-2749.27107234a,9256708.85844469d,35y,0h,0t,0r>. 13 March 2020
- Haglund, F. (2008). A review on the use of gas and steam turbine combined cycles as prime movers for large ships. Part III: Fuels and emissions. *Energy Conversion and Management*, *49*, 3476–3482.
- Hasançebi, A. (2002). *Measurement and evaluation of HC and CO emissions at istanbul atatürk airport pat field*. Istanbul University Institute of Science and Technology.
- Huang, L., Wen, Y., Zhang, Y., Zhou, C., Zhang, F., & Yang, T. (2020). Dynamic calculation of ship exhaust emissions based on real-time AIS data. *Transportation Research Part D: Transport and Environment*, *80*, 102277. <https://doi.org/10.1016/j.trd.2020.102277>
- IMO: Fourth IMO GHG Study 2020, IMO MEPC 75/7/15. (2020). <https://docs.imo.org/>
- Jahangiri, S., Nikolova, N., & Tenedkijev, K. (2018). An improved emission inventory method for estimating engine exhaust emissions from ships. *Sustainable Environment Research*, *28*(6), 374–381. <https://doi.org/10.1016/j.serj.2018.08.005>

- Jalkanen, J. P., Johansson, L., Kukkonen, J., Brink, A., Kalli, J., & Stipa, T. (2012). Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide. *Atmospheric Chemistry and Physics*, 12(5), 2641–2659. <https://doi.org/10.5194/acp-12-2641-2012>
- Kanberoglu, B., & Kökkülünk, G. (2021). Assessment of CO<sub>2</sub> emissions for a bulk carrier fleet. *Journal of Cleaner Production*. <https://doi.org/10.1016/j.jclepro.2020.124590>
- Kilic, A., & Tzannatos, E. (2014). Ship emissions and their externalities at the container terminal of Piraeus—Greece. *International Journal of Environmental Research*, 8(4), 1329–1340.
- Kılıç, A., YOLCU, M., Kılıç, F., & Bilgili, L. (2020). Assessment of Ship Emissions through Cold Ironing Method for Iskenderun Port of Turkey. *Environmental Research and Technology*. <https://doi.org/10.35208/ert.794595>
- Kökkülünk, G. (2010). *Investigation of the effects of exhaust gas recirculation (EGR) on performance and emissions in a water vapor injected diesel engine*. Institute of Science and Technology, Istanbul: YTU.
- Kuzu, S. L., Bilgili, L., & Kiliç, A. (2020). Estimation and dispersion analysis of shipping emissions in Bandirma Port, Turkey. *Environment, Development and Sustainability*, 23, 10288–10308. <https://doi.org/10.1007/s10668-020-01057-6>
- Merien-Paul, R. H., Enshaeh, H., & Jayasinghe, S. G. (2018). In-situ data vs. bottom-up approaches in estimations of marine fuel consumptions and emissions. *Transportation Research Part D: Transport and Environment*, 62, 619–632. <https://doi.org/10.1016/j.trd.2018.04.014>
- Moreno-Gutiérrez, J., Pájaro-Velázquez, E., Amado-Sánchez, Y., Rodríguez-Moreno, R., Calderay-Cayetano, F., & Durán-Grados, V. (2019). Comparative analysis between different methods for calculating on-board ship's emissions and energy consumption based on operational data. *Science of the Total Environment*, 650, 575–584. <https://doi.org/10.1016/j.scitotenv.2018.09.045>
- Muntean, E., M., G., D., S., E., C., M., S., E., O., et al. (2018). *Fossil CO<sub>2</sub> emissions of all world countries - 2018 Report*.
- Ng, S. K. W., Loh, C., Lin, C., Booth, V., Chan, J. W. M., Yip, A. C. K., et al. (2013). Policy change driven by an AIS-assisted marine emission inventory in Hong Kong and the Pearl River Delta. *Atmospheric Environment*, 76, 102–112. <https://doi.org/10.1016/j.atmosenv.2012.07.070>
- Pulkrabek, & W.W. (2004). *Engineering Fundamentals of the Internal Combustion Engine. Second Edition*, Pearson Prentice-Hall, New Jersey.
- Rødseth, K. L., Wangsnæs, P. B., & Schøyen, H. (2018). How do economies of density in container handling operations affect ships' time and emissions in port? Evidence from Norwegian container terminals. *Transportation Research Part d: Transport and Environment*, 59(February), 385–399. <https://doi.org/10.1016/j.trd.2017.12.015>
- Saraçoğlu, H., Deniz, C., & Kılıç, A. (2013). An Investigation on the Effects of Ship Sourced Emissions in Izmir Port, Turkey. *The Scientific World Journal*, 2013, 218324. <https://doi.org/10.1155/2013/218324>.
- Simonsen, M., Gössling, S., & Walnum, H. J. (2019). Cruise ship emissions in Norwegian waters: A geographical analysis. *Journal of Transport Geography*, 78, 87–97. <https://doi.org/10.1016/j.jtrangeo.2019.05.014>
- Sinha, P., Hobbs, P. V., Yokelson, R. J., Christian, T. J., Kirchstetter, T. W., & Bruintjes, R. (2003). *Emissions of Trace Gases and Particles from Two Ships in the Southern Atlantic Ocean*, 37(15), 2139–2148.
- Song, H., Ou, X., Yuan, J., Yu, M., & Wang, C. (2017). Energy consumption and greenhouse gas emissions of diesel/LNG heavy-duty vehicle fleets in China based on a bottom-up model analysis. *Energy*, 140, 966–978. <https://doi.org/10.1016/j.energy.2017.09.011>
- Song, S. (2014). Ship emissions inventory, social cost and eco-efficiency in Shanghai Yangshan port. *Atmospheric Environment*, 82, 288–297. <https://doi.org/10.1016/j.atmosenv.2013.10.006>
- Sui, C., de Vos, P., Stapersma, D., Visser, K., & Ding, Y. (2020). Fuel consumption and emissions of ocean-going cargo ship with hybrid propulsion and different fuels over voyage. *Journal of Marine Science and Engineering*, 8(8), 588. <https://doi.org/10.3390/JMSE8080588>
- Sulphur oxides (SO<sub>x</sub>) and Particulate Matter (PM) – IMO, Marpol Annex VI, Regulation 14. (n.d.). Retrieved from [http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-\(SOx\)---Regulation-14.aspx](http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)---Regulation-14.aspx). 10 February 2020
- Trozzi, C. (2013). EMEP/EEA air pollutant emission inventory guidebook - 2013: 1.A.3.d.i, 1.A.3.d.ii, 1.A.4.c.iii International navigation, national navigation, national fishing.
- Ünlügençoğlu, K., Kökkülünk, G., & Alarçin, F. (2019). Estimation of shipping emissions via novel developed data collecting and calculation software: A case study for the region of Ambarli Port. *International Journal of Global Warming*, 19, 1. <https://doi.org/10.1504/IJGW.2019.10022955>

Volatile organic compounds (VOC) – Regulation 15. (n.d.). [http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Volatile-organic-compounds-\(VOC\)—Regulation-15.aspx](http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Volatile-organic-compounds-(VOC)—Regulation-15.aspx). Accessed 28 March 2020

Weng, J., Shi, K., Gan, X., Li, G., & Huang, Z. (2020). Ship emission estimation with high spatial-temporal resolution in the Yangtze River estuary using AIS data. *Journal of Cleaner Production*, 248, 119297. <https://doi.org/10.1016/j.jclepro.2019.119297>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.