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Impacts of the COVID-19 epidemic on merchant ship activity and pollution emissions in Shanghai port waters

Kun Shi, Jinxian Weng *
College of Transport and Communications, Shanghai Maritime University, Shanghai 201306, China

HIGHLIGHTS
• To evaluate impacts of the COVID-19 epidemic on merchant ship pollutant emissions
• Strict COVID-19 quarantine measures cause more emissions from container ships.
• The unit ship emission cost is greatly reduced under the normal cruising status.
• Berthing and anchoring operations are associated with increased ship emissions.
• It is urgent to promote the use of shore power equipment during the epidemic period.

GRAPHICAL ABSTRACT

This study aims to evaluate impacts of the COVID-19 epidemic on merchant ship activities and corresponding atmospheric pollutant emissions in Shanghai port waters. Comparing AIS data from February 2019 and from February 2020, it is found that the merchant ship count and utilization frequency are reduced during the epidemic period. The epidemic could result in longer ship turnaround times because of more operation time for berthing and anchoring activities. Ship emission comparison results reveal that the cargo ship emissions are significantly reduced while container ships and tankers produce a slightly decreased emissions resulting by strict COVID-19 quarantine measures. In addition, the unit ship emission intensity is greatly reduced for ships which are under the normal cruising status while berthing and anchoring operations are associated with increased ship emissions. This implies that it is urgent to promote the use of shore power equipment for merchant ships during the epidemic period.

1. Introduction

The coronavirus disease 2019 (COVID-19) that broke out in January 2020 has brought great harm to the health and safety of people all over the world. This virus spreads quickly and will not disappear as the temperature rises (Byass, 2020). According to the disease report data, the COVID-19 epidemic may have further outbreak (Zhao et al., 2020). The intensification of human traffic activities will increase the risk of further spread of the COVID-19 epidemic (Lee et al., 2020). It was further reported that there are many cases of the COVID-19 on cruise ships (Morarty et al., 2020). Generally, the isolation method of Traffic Control Bundling can interrupt the transmission cycle to effectively block these highly infectious, thereby reducing the COVID-19 impact.
Chen et al. (2018) reported that air pollutants from ships will reduce the urban air quality. Fan et al. (2016) further investigated that the emissions from berths could reduce the urban air quality. Fan et al. (2016) characterized the maritime traffic and found that the air quality in South East Asian cities is greatly affected to environmental pollution in the coastal city (Liu et al., 2016a,b).

However, existing studies show that ship emissions can spread from emissions on land. In China, almost all important ports are located near the ocean to the land under the effect of the ocean breeze, which leads to emissions spreading to urban atmospheric pollution during the lockdown period. There are significant improvements in air quality in China (He et al., 2020). Despite the lockdown measures that can significantly improve air quality, the contributions in mitigating air pollution may vary at different cities (Wang et al., 2020).

For example, He et al. (2020) deemed that the significant reduction of air pollution is associated with the colder, richer and industrialized cities. Moreover, Otmami et al. (2020) found that the emissions of vehicle exhaust and industrial production have been significantly reduced in Salé City of Morocco, of which NO\textsubscript{2} emissions decreased by 96%. In the São Paulo state of Brazil, the concentration of \( O\textsubscript{3} \) increased by about 30% in cities affected by vehicle height due to the substantial reduction of NO and NO\textsubscript{2} (Nakada and Urban, 2020). The control of vehicle traffic is the main reason for the decrease in urban pollutant concentration (Collivignarelli et al., 2020). The ocean pollution was also reduced by the national lockdown period (Kanniah et al., 2020).

In order to control the spread of the epidemic, many ports take a number of measures to restrict the ship traffic activities. As an essential freight transportation mode that undertakes 90% of the total freight volume (Fan, 2014), the shipping industry has also been greatly affected in China. According to statistics, the export and import freight transportation volume have fallen by 17.2% and 4% year-on-year since the first two months of the COVID-19 epidemic (Shanghai International Shipping Center, 2020a), respectively. Some cruise terminals in Europe have gradually suspended their travel business and anti-epidemic measures are taken to ensure the port area’s sanitation and safety (EU, 2020). Compared with the previous period, the Venetian Lagoon saw a 69% drop in the number of ship activities, passenger flow decreased by 78% and fishing activity decreased by 84% (Depellegrin et al., 2020). Braga et al. (2020) pointed out that passenger ship activity is controlled by the government, which positively influences the water quality.

So far, many researchers focused on the changes in urban traffic and urban atmospheric pollution during the lockdown period. There are rarely literatures on the changes in ship traffic and air pollution emissions from ships. As a low-cost and high-volume transport mode, the maritime transportation plays an invaluable role in the global trade. However, existing studies show that ship emissions can spread from the ocean to the land under the effect of the ocean breeze, which leads to environmental pollution in the coastal city (Liu et al., 2016a,b).

Exhaust emissions from ships also bring about adverse impacts on the climate and human health (Eyring et al., 2005). Streets et al. (2000) found that the air quality in South East Asian cities is greatly affected by ship emissions, particularly in Sumatra, peninsular Malaysia, and Singapore. Song et al. (2010) pointed out that ship emissions in the waters near Busan Port increased the ozone concentration in coastal cities. Zhao et al. (2013) argued that ship emissions in port waters are similar to emissions on land. In China, almost all important ports are located near eastern cities where the air quality is seriously affected by the ship emissions. Ng et al. (2013) used AIS data to estimate the emission inventory in Hong Kong and Pearl River Delta for 2007 and concluded that the emissions from berths could reduce the urban air quality. Fan et al. (2016) further investigated that the air pollutants from ships will be affected by monsoon in the coastal cities near the East China Sea. Chen et al. (2018) reported that PM\textsubscript{2.5} generated by ships in the Bohai Sea area resulted in a large number of dry fog weather conditions in northern China.

Although the climate and health impacts of global shipping are well documented, it is still unknown whether shipping emissions continuously grow. Even worse, with the shock by the COVID-19 pandemic, it becomes more difficult for shipping emission abatement. Figuring out the response relationship between the epidemic and shipping emissions remains a challenge. Therefore, the objective of this study is to explore the effects of the COVID-19 epidemic on the merchant ship activities and their corresponding atmospheric pollutant emissions in Shanghai port waters.

2. Data and methods

2.1. Description of study areas

Shanghai Port waters are the most important shipping route in China. It is located on the front edge of the Yangtze River Delta, in the middle of China’s 18,000 km continental coastline and the mouth of the Yangtze River. It connects the coasts from north to south of China and the world ocean. Fig. 1 shows the layouts of Shanghai Port waters in China with the longitudines from 121.267° E to 121.533° E and the latitudes from 30.597° N to 31.833° N, according to the Shanghai Maritime Safety Administration. It is reported that there is a cargo throughput of 510.19 million tons and a container throughput of 43.50 million TEU in Shanghai Port in 2020 (SIPG, 2021). As the big city with a population of 25 million people, the air quality of Shanghai may be greatly affected by the ship activities in Shanghai port waters. For example, Fu et al. (2012) showed that a total of 12.0% \( SO\textsubscript{2} \) and 9.0% of \( NO\textsubscript{X} \) come from ships in Shanghai port waters.

In this study, the major focus is placed on three types of merchant ships in the water area, including cargo ships, container ships and tankers. This is because these merchant ships are the main shipping vessels in the shipping market, which can well reflect the impact of COVID-19 on the Shanghai Port waters.

2.2. AIS data

The Automatic Identification System (AIS) is a navigation aid system that can obtain the real-time ship trajectory information. Many researchers (e.g., Eriksen et al., 2006; Silveira et al., 2013) utilized historical AIS data to analyze ship traffic characteristics from the viewpoint of ship transportation safety and efficiency. For example, Silveira et al. (2013) characterized the maritime traffic volume along the coast of Portugal and evaluated the risk of ship collision on a basis of the archived AIS data. Wu et al. (2016) investigated waterway transportation characteristics in the southeast channel of Texas from a macro perspective and determined the hot spot area where ship collisions frequently occurred.

Based on the AIS data, we could extract the static and dynamic information including Maritime Mobile Service Identity (MMSI) number, the real-time ship latitude and longitude positions, speed over ground, the course over ground, ship type, ship length and etc. In this study, raw AIS data could be obtained from the AIS database provided by the Lloyd’s List Intelligence (https://www.seasearcher.com/). A total of 68,114,249 records were collected from 28,256 merchant ships sailing in Shanghai Port waters including 23,459 cargo ships, 1,494 container ships and 3303 tankers from February 2019 to February 2020.

Note that there are 12.36% AIS records with inaccurate speed information though the majority of collected records are accurate. It is inappropriate to abandon these records in view of the real-time data integrity. We employ data cleansing methods from Goldsworthy and Goldsworthy (2015) to update those AIS records with incorrect speed information in this study. Generally, the following three steps are implemented to update the inaccurate data.
Step 1: Calculate the mean speed for a given ship \( i \) from the time \( t \) to \( t + \Delta T \):

\[
v_i' = \sqrt{\left( (x_i' - x_i) \right)^2 + \left( (y_i' - y_i) \right)^2} / \Delta T \tag{1}
\]

where \( v_i' \) is the mean speed for a given ship \( i \) from the time \( t \) to \( t + \Delta T \).

Step 2: Check the reasonability of the mean speed by identifying whether it satisfies the following condition:

\[
v_i' - d_i \Delta T v_i' + a_i \Delta T \leq v_i \leq v_i' + d_i \Delta T v_i' + a_i \Delta T \tag{2}
\]

where \( d_i \) and \( a_i \) are the deceleration and acceleration rates for the ship \( i \), respectively.

Step 3: The incorrect speed related to ship \( i \) at time \( t \) will be replaced with the corresponding mean speed.

To date, there are many ways to estimate ship pollution emissions (Jalkanen et al., 2009). Based on high-frequency AIS data, the “bottom-up” method is considered to be a good alternative to estimate the atmospheric pollutant emissions from ship activities. This approach has been applied to construct ship emission inventories for multiple regions in previous studies. For example, Jalkanen et al. (2009) created a ship emission inventory for the Baltic Sea region in 2007. Weng et al. (2020) complied with the emission inventory of the Yangtze River estuary waters in 2014 and pointed out that ship emissions have intense temporal-spatial characteristics. It is affected by climate and local culture. For example, the Spring Festival could lead to a decrease in pollution from ships. Wan et al. (2020) pointed out that among China’s major port groups, the Yangtze River Delta region has the largest emissions, accounting for 47.85% of the total ship emissions in 2018. Shi et al. (2020) found that emissions significantly vary with different merchant ship types.

Mathematically, the “bottom-up” method for calculating the atmospheric pollutant emission from ships could be expressed by

\[
E_{ij,k} = P_j \times LF_{j} \times T_{k} \times EF_{ijk} \times 10^6 \tag{3}
\]

where \( E \) is the total atmospheric pollutant emissions of a single ship in the area (units: tons); \( P \) is the rated power of the ship’s engine (units: kw); \( LF \) is the load factor (units: %); \( T \) is the sailing time of the ship in the port area (units: h); \( EF \) is the emission factor for various substances (units: g/kWh); \( i \) is the pollution substance, including CO, CO\(_2\), HC, NO\(_x\), SO\(_2\), PM\(_{2.5}\), and PM\(_{10}\); \( l \) is the navigational status of ships; \( j \) is the type of ship engine, including main engine (ME), auxiliary engine (AE), and general cargo.

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**Table 1**

Sample vessels profiles.

| IMO       | MMSI           | Length | Breadth | Ship type      | TEU  | DWT   | Building year | Engine type       | Engine power (kw) | Speed (knot) |
|-----------|----------------|--------|---------|----------------|------|-------|---------------|-------------------|------------------|--------------|
| 9,237,486 | 209,366,000    | 220    | 32      | Container ship | 3091 | 41,748| 2004          | Diesel (slow)     | 25,578           | 22           |
| 9,507,714 | 209,444,000    | 148    | 23      | General cargo  | 1118 | 13,874| 2009          | Diesel (medium)   | 9730             | 20           |
| 9,260,245 | 210,516,000    | 222    | 30      | Container ship | 2700 | 37,867| 2007          | Diesel (slow)     | 20,580           | 21           |
| 9,295,244 | 211,431,000    | 335    | 43      | Container ship | 8750 | 103,800| 2005          | Diesel (slow)     | 69,591           | 25           |
| 9,215,177 | 219,974,000    | 217    | 32      | Container ship | 2833 | 35,097| 2001          | Diesel (slow)     | 31,920           | 22           |

FIG. 1. Shanghai Port water area.
boiler; $k$ is the fuel type of engine, including residual oil (RO), marine distillates oil (MDO), and marine gas oil (MGO) with a sulfur content of 2.70%, 1.00%, 0.50%. These fuels are widely used by ocean-going vessels (OGVs) and coastal vessels (CVs).

Note that there might exist boundary effects that the emissions at the boundary of the analysis water area would have a sudden change, which leads to the inaccurate emission estimation. This phenomenon may be caused by the uneven distribution of ship sailing time at the boundary of the analysis water area. Therefore, we will employ the method proposed by Liu et al. (2016a,b) with two nested domains to avoid the boundary effect of ship emission in Shanghai port waters.

### 2.4. Load factors and navigational status

The ship's engine load factor (LF) is an important parameter for the calculation of ship emissions. In general, the ship's engine LF could be determined by the maximum speed at rated power and the actual sailing speed. The engine LF can be calculated as follows:

$$LF = \left(\frac{AS}{MS}\right)^2$$  \hspace{1cm} (4)

where $AS$ represents the actual speed (units: knot); $MS$ represents the maximum design speed (units: knot). Note that different load factors indicate the combustion efficiency of ship engines that could further result in varying pollutant emissions.

According to Goldsworthy and Goldsworthy (2015), the ship navigational status can be divided into the following five types according to the actual sailing speed: (i) berthing, (ii) anchoring, (iii) maneuvering, (iv) slow-steaming and (v) normal cruising, as shown in Table 2.

### Table 2

| Navigational status | Standard of state division |
|---------------------|----------------------------|
| Berthing            | Less than 1 knots          |
| Anchoring           | 1 knot to 3 knots          |
| Maneuvering         | Greater than 3 knots and LF less than 20% |
| Slow-steaming       | LF between 20% and 65%     |
| Normal cruising      | LF above 65%               |

$^a$ LF is the ship's engine load factor.

In reality, when the ship is under the normal cruising or the slow-steaming status, the main engine and auxiliary engine are working while the boiler is closed. Note that the main engine, auxiliary engine and boiler will simultaneously work when the ship is under the maneuvering and anchoring status. However, when the ship undertakes the berthing activity, the main engine is closed while the auxiliary engine and boiler are still operating.

According to Eq. (3), the emission factor (EF) is the most critical parameter for the estimation of pollutant emissions. Note that this factor could be affected by various external factors including engine types (e.g., main engine, auxiliary engine, boiler), fuel types (e.g., residual oil, marine distillates oil, marine gas oil) and engine status (e.g., slow speed diesel, medium speed diesel). Table 3 tabulated adjustment factors for the engine types, fuel types and engine status that were suggested by Entec UK Limited (2002) and the Starcrest Consulting Group (2013). It should be pointed out that emission factors suggested in these two studies are applicable to the RO with a sulfur content of 2.7%. Since the sulfur emission control area (ECA) policy has been implemented in Shanghai port waters. Shi et al. (2020) pointed out that ships sailing in Shanghai port waters are forced to use fuel with sulfur content no more than 0.5%. Therefore, the fuel adjustment factor provided by Fu et al. (2012) should be also applied in order to take into account the effect of ECA policy, as shown in Table 4.

However, when main diesel-cycle engines (ME) are operated below 20% load requirements, emission factors tend to increase as the load decreases. This is because the diesel engines are less effective at low loads and combustion is not as complete as load decrease. Therefore, these emission factor should be adjusted as a function of engine load, the low load adjustment factor (LLAF) are applied when the ME load are less than 20%, as shown in Table 5 (Chen et al., 2017).

### 2.5. Comparative methods

The comparative methods are useful for the impact analysis of COVID-19 pandemic on the merchant ship traffic activity as well as the resulting emissions. By comparing aviation data during the outbreak period, Abu-Rayash and Dincer (2020) found that the global aviation
and tourism industry suffered unprecedented damage caused by this pandemic. With the comparative methods, Depellegrin et al. (2020) claimed that the number of vessel activities was reduced by 69% and fishing activities reduced by 84% during the lockdown period caused by the COVID-19 pandemic. Some researchers (e.g., Wang and Su, 2020; Sicard et al., 2020) also found that the outbreak of COVID-19 could mitigate the air pollution caused by the urban traffic using the comparative methods.

According to the time when the Chinese government took measures against the epidemic, we could define the essential time points with respect to the COVID-19 pandemic, shown in Fig. 3. Although some provinces gradually launched the first level of emergency response after the outbreak of epidemic, the official traffic control measures have been released by the Chinese government since the January 30th of 2020, e.g., the intercity transportation was suspended and the virus inspection was strengthened. In general, the epidemic precautionary measures at the Shanghai Port could be divided into the following categories: (i) take virus disinfection measures for ships upon arrival at the ports; (ii) carry out daily health checks of ship crews, including temperature-taking and checking for respiratory symptoms; and (iii) the embarkation and disembarkation are prohibited for the ship crew members without permissions. According to the recommendations issued by the World Health Organization (WHO) and IMO, specific pandemic measures taken by the Shanghai Port include (i) the examination of ship and cargo lists; (ii) strict disinfection measures should be implemented for containers to be exported or imported; (iii) to check and destroy the source of infection (e.g., cargo, container, transportation, and luggage); and (iv) to quarantine the crew and etc. Note that these control measures could cause major effects on ship activities. For example, the inspection procedures and strict declaration requirements directly lead to the increase of ship time in port, while the cargo disinfection examination may mitigate the port transportation efficiency as well as reduce the port competitiveness. Moreover, the reduction in market demand during the outbreak might result in lower volumes of international trade.

For simplicity, the ship traffic and ship emissions in February 2019 could be considered as the benchmark scenario (i.e., the before epidemic period). Hence, the effects of COVID-2019 pandemic on the ship traffic and ship emissions could be measured by the relative change rate of ship traffic volume and pollutant emissions, namely

$$\varphi = \frac{x_t}{x_i}$$

where $\varphi$ represents the change rate of ship traffic volume or ship emissions caused by the epidemic; $x$ represents the actual ship traffic volume

### Table 4

Correction factors of different fuel types.

| Fuel type | Sulfur content/\% | CO₂ | CO | HC | NOₓ | SO₂ | PM₂.₅ | PM₁₀ |
|-----------|------------------|-----|----|----|-----|------|-------|-------|
| RO        | 1.50             | 1.00| 1.00| 1.00| 1.00| 0.56 | 0.82  | 0.82  |
| MD        | 1.50             | 1.00| 1.00| 1.00| 0.90| 0.56 | 0.47  | 0.47  |
| MD        | 0.50             | 1.00| 1.00| 1.00| 1.00| 0.94 | 0.18  | 0.25  |
| MD        | 0.20             | 1.00| 1.00| 1.00| 1.00| 0.94 | 0.07  | 0.19  |
| MD        | 0.10             | 1.00| 1.00| 1.00| 1.00| 0.94 | 0.04  | 0.17  |

Note: RO is residual oil, MD is marine distillates.

* Source from Fu et al. (2012).

### Table 5

Low load adjustment factor for main engines.

| Load | CO₂ | CO | HC | NOₓ | SO₂ | PM₂.₅ | PM₁₀ |
|------|-----|----|----|-----|------|-------|-------|
| 0.01 | 5.82| 19.32| 59.28| 11.47| 1.00 | 19.17 | 19.17 |
| 0.02 | 3.28| 9.68 | 21.18| 4.63 | 1.00 | 7.29  | 7.29  |
| 0.03 | 2.44| 6.46 | 11.68| 2.92 | 1.00 | 4.33  | 4.33  |
| 0.04 | 2.01| 4.86 | 7.71 | 2.21 | 1.00 | 3.09  | 3.09  |
| 0.05 | 1.76| 3.89 | 5.61 | 1.83 | 1.00 | 2.44  | 2.44  |
| 0.06 | 1.59| 3.25 | 4.35 | 1.60 | 1.00 | 2.04  | 2.04  |
| 0.07 | 1.47| 2.79 | 3.52 | 1.45 | 1.00 | 1.79  | 1.79  |
| 0.08 | 1.38| 2.45 | 2.95 | 1.35 | 1.00 | 1.61  | 1.61  |
| 0.09 | 1.31| 2.18 | 2.52 | 1.27 | 1.00 | 1.48  | 1.48  |
| 0.10 | 1.25| 1.96 | 2.18 | 1.22 | 1.00 | 1.38  | 1.38  |
| 0.11 | 1.21| 1.79 | 1.96 | 1.17 | 1.00 | 1.30  | 1.30  |
| 0.12 | 1.17| 1.64 | 1.76 | 1.14 | 1.00 | 1.24  | 1.24  |
| 0.13 | 1.14| 1.52 | 1.6  | 1.11 | 1.00 | 1.19  | 1.19  |
| 0.14 | 1.11| 1.41 | 1.47 | 1.08 | 1.00 | 1.15  | 1.15  |
| 0.15 | 1.08| 1.32 | 1.36 | 1.06 | 1.00 | 1.11  | 1.11  |
| 0.16 | 1.06| 1.24 | 1.26 | 1.05 | 1.00 | 1.08  | 1.08  |
| 0.17 | 1.04| 1.17 | 1.18 | 1.03 | 1.00 | 1.06  | 1.06  |
| 0.18 | 1.03| 1.11 | 1.11 | 1.02 | 1.00 | 1.04  | 1.04  |
| 0.19 | 1.01| 1.05 | 1.05 | 1.01 | 1.00 | 1.02  | 1.02  |
| 0.20 | 1.00| 1.00 | 1.00 | 1.00 | 1.00 | 1.00  | 1.00  |

* Source from Chen et al. (2017).
or ship pollution; i represents the benchmark year (i.e., 2019); j represents the comparison year (i.e., 2020).

3. Results analysis

The outbreak of COVID-19 pandemic has resulted in the global impacts. As mentioned above, existing studies mainly focused on the impact analysis of the epidemic on the urban traffic pollution while the effects on the ship traffic are rarely investigated. Therefore, this section will mainly discuss the impact of COVID-19 pandemic on the ship traffic activity as well as the atmospheric pollutant emissions estimated by using the collected AIS data in Shanghai port waters.

3.1. Effects of COVID-19 pandemic on the merchant ship activity in Shanghai port waters

3.1.1. Overall variation in the number of merchant ships

Fig. 4(a) presents the comparison results regarding the merchant ship count sailed in the Shanghai port water area at different periods (i.e., before and during the epidemic periods). As expected, it is found from Fig. 4(a) that there were 7770 different merchant ships sailed in the water area in the February of 2019, as compared with 4085 different merchant ships in February 2020. The reduction of merchant ship counts could probably be because the freight transportation demands were greatly reduced during the epidemic period. Moreover, the number of cargo ships has been reduced by 47.43%, while the container ship count decreased by only 2.18%. The reduction in the number of cargo ships may be due to the large-scale suspension measures taken by cargo shipping companies in order to mitigate the loss caused by the COVID-19 pandemic (Shanghai International Shipping Center, 2020a). It should be pointed out that merchant ships are far less utilized in this water area during the COVID-19 pandemic period (e.g., a reduction of 46.29% cargo ships), as shown in Fig. 4(b). The reduction of merchant ships and their smaller utilization frequency would cause a 24.20% reduction of cargo throughput, which is consistent with the finding that the China’s shipping market was severely damaged during the outbreak period (Shanghai International Shipping Center, 2020b). A possible reason might be that overseas customers cancel order due to the epidemic situation.

3.1.2. Variation in the utilization frequency of merchant ships with different sizes

Although the merchant ship count and the port throughput are both reduced during the epidemic period, the variation of ship utilization highly depends on ship sizes. For the simplicity analysis, this study will adopt the ship size classification criterion proposed from Drewery Maritime Research (2016) to divide each type of merchant ships into several groups, as shown in Table 6.

Fig. 5 shows the average utilization frequency of merchant ships with different sizes in 2019 and 2020. As shown in Fig. 5(a), it can be found that the average utilization frequency of cargo ships has generally increased, which may be due to the fact that the shutdown ratio of cargo ships is greater than the ratio of cargo reduction. A little number of cargo ships take on more freight tasks. Note that the utilization frequency of cargo ships in Category 5 and Category 6 increase by 133% and 140%, respectively. It might be explained by the fact that larger ship freight rates have dropped significantly. Fig. 5(b) shows that the utilization frequency of various types of container ships does not change significantly, except for the larger container ships.

Table 6
Classification of merchant ships with different ship sizes.

| Merchant ship type | Tonnage classification | Definition |
|--------------------|------------------------|------------|
| Cargo ship         | Category 6             | DWT > 120,000 |
|                    | Category 5             | 120,000 ≥ DWT > 85,000 |
|                    | Category 4             | 85,000 ≥ DWT > 65,000 |
|                    | Category 3             | 65,000 ≥ DWT > 40,000 |
|                    | Category 2             | 40,000 ≥ DWT > 10,000 |
|                    | Category 1             | 10,000 ≤ DWT |
| Container ship     | Large                  | TEU > 8000 |
|                    | Post-Panamax           | 8000 ≥ TEU > 5000 |
|                    | Panamax                | 5000 ≥ TEU > 3000 |
|                    | Sub-Panamax            | 3000 ≥ TEU > 2000 |
|                    | Handysize              | 2000 ≤ TEU > 1000 |
|                    | Feeder                 | 1000 ≤ TEU |
|                    | VLCC                   | DWT > 200,000 |
|                    | Suezmax                | 200,000 ≥ DWT > 120,000 |
|                    | Aframax                | 120,000 ≥ DWT > 80,000 |
|                    | Panamax                | 80,000 ≥ DWT > 55,000 |
|                    | Handy                  | 55,000 ≥ DWT > 10,000 |
|                    | Small                  | 10,000 ≤ DWT |

Note: classification standard of cargo ship is referred to bulk carrier.

Fig. 4. Changes in the merchant ship count and port throughput.
In general, the container throughput of Shanghai Port has been greatly reduced during the epidemic. Table 7 shows the density of various merchant ships in each water area. As expected, the density of cargo ships has been declined in the majority of port water areas (e.g., Baoshan, Chongming, Jinshan).

### 3.1.3. Variation of operation time for merchant ships under different navigation status

Fig. 6 shows the average operation time for each merchant ship type under different navigation status. The results show that the average ship turnaround time is generally longer during the epidemic period. This might be caused by the increased operation time for the berthing activity because of the strengthened measures to inspect and prevent COVID-19 virus at ships. The average ship berthing time during the epidemic period increases from 21.49 h to 32.79 h for cargo ships, from 27.81 h to 34.33 h for container ships and from 46.54 h to 60.63 h for tankers. Because of the reduced ship density and the increased ship number, the average ship sailing time during the epidemic period increases from 1.16 h to 4.64 h for cargo ships.

Fig. 7 shows the average berthing time for each merchant ships with different sizes in February 2019 and 2020. Fig. 7(a) shows that the berthing time of various sizes of cargo ships has increased significantly, especially for cargo ship in Category 6. As expected, it is found from Fig. 7 (b) that the berthing time from 45.28 h to 98.62 h for large container ships while feeder container ship does not change significantly. The results of Fig. 7(b) and (c) show that large ships with cargo ship and container ship have been most significantly affected. Note that the berthing time of Panamax tanker has increased by 252.15% (Fig. 7(c)), which may be due to the fact that the shipping market demand for Panamax tanker is down.

### 3.2. Effects of COVID-19 pandemic on the atmospheric pollutant emissions in Shanghai port waters

#### 3.2.1. Overall emissions from merchant ships

The estimated total merchant ship emissions from February 2019 to February 2020 is $6.3710 \times 10^8$ tons for CO$_2$, $6.475 \times 10^3$ tons for CO, $2.863 \times 10^2$ tons for HC, $6.932 \times 10^4$ tons for NO$_x$, $1.942 \times 10^2$ tons for NO$_y$, $2.701 \times 10^5$ tons for SO$_2$, $6.721 \times 10^3$ tons for PM$_{10}$, $7.281 \times 10^3$ tons for PM$_{2.5}$, and $1.94 \times 10^3$ tons for O$_3$. The emissions of CO$_2$ and NO$_x$ have increased significantly during the epidemic period, while the emissions of CO, HC, SO$_2$, PM$_{10}$, PM$_{2.5}$, and O$_3$ have decreased.
PM$_{2.5}$, 2.466 × 10$^4$ tons for PM$_{10}$, and 1.870 × 10$^4$ tons for SO$_2$, respectively. Fig. 8 shows the monthly variations of CO$_2$ emissions produced from merchant ships. It can be found that February and July are the two months associated with the least ship emissions, consistent with previous findings from Chen et al. (2016) and Fan et al. (2016).

3.2.2. Impact analysis of merchant ship emission inventory

Table 8 tabulates the merchant ship emission inventory for the before (i.e., February 2019) and during the epidemic periods (i.e., February 2020), respectively. Fig. 9 graphically describes the effects of COVID-19 pandemic on the merchant ship emission inventory. According to the figure, the negative values of the relative emission changes reveal that the overall ship emissions are generally lower during the epidemic period. More specifically, there would be an average reduction of 14.76% CO$_2$, 16.67% CO emissions, 10.53% HC, 13.30% NO$_x$ emissions, 16.31% PM$_{2.5}$, 16.17% PM$_{10}$, and 15.75% SO$_2$ emissions from three merchant ships during the epidemic period. According to the figure, the first four engine types of container ships show a much bigger reduction (by 38.32%) of atmospheric pollutant emissions than the other two merchant ship types. This main reason is that cargo ships are associated with the biggest decrease in the ship count, as shown in Fig. 4. The recession caused by the epidemic has directly reduced pollution from cargo ships.

Fig. 10 shows the distribution of atmospheric pollutant emission from different engine types. It can be seen from Fig. 10 that there is a very marginal change of emission share for cargo ships as well as tankers during the epidemic period. However, the COVID-19 pandemic caused a much bigger impact on the distribution of atmospheric pollutant emissions from three engine types of container ships. Specifically, for container ships, the proportion of emissions produced from their AE has increased by 11.15% while their MEs produced an 11.81% reduction of atmospheric pollutant emissions. In general, the proportion of emissions from the ME of ships has decreased, while emissions from AE and boilers have increased. As mentioned above, it would require more berthing operation time caused by strict quarantine measures with respect to the COVID-19 pandemic (Fig. 6), thus resulting in more CO$_2$ and SO$_2$ produced by boilers from merchant ships, as shown in Fig. 10. Chen et al. (2016) pointed out that the emissions of the ship come mainly from the MEs. Therefore, the COVID-19 epidemic could alter ship emission distributions by changing ship activities.

Table 8

| Year | Ship type       | CO$_2$ (t) | CO (t) | HC (t) | NO$_x$ (t) | PM$_{2.5}$ (t) | PM$_{10}$ (t) | SO$_2$ (t) |
|------|----------------|------------|--------|--------|------------|---------------|---------------|------------|
| 2019 | Cargo ship     | 160,758.86 | 189.29 | 82.23  | 2131.91    | 54.52         | 68.77         | 469.84     |
|      | Container ship | 132,060.87 | 216.29 | 88.44  | 2348.25    | 55.45         | 69.44         | 388.37     |
|      | Tanker         | 199,010.75 | 109.79 | 49.43  | 1149.50    | 43.51         | 56.37         | 590.64     |
|      | All merchant ships | 491,830.48 | 515.37 | 220.10 | 5629.66    | 153.48        | 194.58        | 1448.85    |
| 2020 | Cargo ship     | 99,153.49  | 126.68 | 65.67  | 1298.89    | 34.34         | 43.34         | 277.04     |
|      | Container ship | 129,276.71 | 204.80 | 83.75  | 2174.89    | 53.81         | 67.43         | 380.80     |
|      | Tanker         | 190,813.28 | 98.00  | 47.51  | 999.20     | 40.30         | 52.34         | 562.88     |
|      | All merchant ships | 419,243.48 | 429.48 | 196.93 | 4472.98    | 128.45        | 163.11        | 1220.72    |

Fig. 8. Monthly CO$_2$ emissions from merchant ships.

Fig. 9. Emission change rate for different merchant ship types.

Fig. 10. Atmospheric pollutant emissions share from various engine types.

2.2.3. Merchant ship emission variations during the time of a day

Fig. 11 gives the comparison results of merchant ship emissions during the time of a day (i.e., Day versus Night). Consistent with the finding that the biggest reduction of total ship emissions is associated with cargo ships, Fig. 11 shows that there exists a much bigger reduction of atmospheric pollutant emissions from this merchant ship type during the daytime as well as nighttime periods. For instance, the atmospheric pollutant emissions from cargo ships are found to be lower by 32.11% during the daytime period and lower by 36.74% during the nighttime period. The more reduction in ship emissions during the nighttime period may be caused by the fact that the COVID-19 quarantine measures cause less ship activities at night.

2.2.4. Impact analysis of the epidemic situation on ship emission intensity

Theoretically, the amount of ship emissions may not only depend on the ship type but also be affected by the ship size. For the sake of comparison, we will introduce the ship emission intensity that takes into account the ship size to investigate the effects of COVID-19 pandemic on the emission of each ship type with various ship sizes. Hereafter, the emission intensity represents the amount of atmospheric pollutant emissions per nautical mile per deadweight ton at different navigational status (i.e., normal cruising, slow-steaming, and maneuvering).
The COVID-19 epidemic. This study made an attempt to investigate the variations in shipping activities and pollution emissions caused by container ships during the epidemic period. This implies that the emissions generated by the berthing and anchoring operations are much bigger during the epidemic period. From this viewpoint, it is of great significance to promote the use of shore power equipment for these merchant ships. Table 9 tabulates the emission intensity of different merchant ships which are under the normal cruising status. Comparing the emission intensities for merchant ships before and during the epidemic periods, it can be found that the ship emission intensities under the normal cruising status were significantly reduced during the epidemic period. More specifically, the unit emission intensity of CO₂ from one container ship has been reduced from 1319.00 g/nm/TEU to 209.45 g/nm/TEU which was caused by the COVID-19 pandemic. Note that the reduction of ship emission intensity could be explained by the fact that the average sailing speed increases as the ship density decreases in February 2020 (i.e., during the epidemic period). Previous studies found that fewer emissions are associated with the ship sailing at high speed. Note that the highest reduction rate of emission intensity is 84.17% for container ships, followed by tankers and cargo ships.

Table 10 further presents the average emission intensity considering the entire operation period from the time of a ship entering to the time of departing from the port water area. During the entire operation period, it will cover all ship activities including normal cruising, slow-steaming, maneuvering, anchoring and berthing. Interestingly, it can be found from Table 10 that the emission intensities of tankers and container ships would increase significantly after taking into account the part of emissions produced by ship berthing and anchoring operations. For example, the emission intensity during the entire ship operation period would increase by 77.92% for tankers and by 55.62% for container ships during the COVID-19 pandemic. This implies that emissions generated by the berthing and anchoring operations are much bigger during the epidemic period. From this viewpoint, it is of great significance to promote the use of shore power equipment for these merchant ships types (i.e., container ships) during the epidemic period.

4. Conclusions

The outbreak of the COVID-19 epidemic has led to great changes in the world economy and environment. Therefore, it is crucial to assess the variations in shipping activities and pollution emissions caused by the COVID-19 epidemic. This study made an attempt to investigate the effects of COVID-19 pandemic on the merchant ship activity and the resulting atmospheric pollutant emissions in Shanghai port waters. By comparing the AIS data in February 2019 and in February 2020, it can be found that the count and utilization frequency of merchant ships including cargo ships, container ships and tankers are reduced during the epidemic period. Furthermore, the reduced utilization frequency is found to vary with different ship sizes for each merchant ship type. In addition, it is found that the COVID-19 pandemic resulted in longer ship turnaround time that might be caused by more operation time required for completing the berthing and anchoring activities during the epidemic period.

With the traditional “bottom-up” approach, the merchant ship emission inventory has been estimated in this study. The ship emission inventory comparison results show that the overall ship emissions are generally lower during the epidemic period. For example, the COVID-19 pandemic caused a 13.3% reduction of NOₓ emissions. In addition, it is found that the biggest reduction of atmospheric pollutant emissions was associated with cargo ships. This finding could be explained by the fact that there was a bigger decrease in the cargo ship count in this port water area during the epidemic period.

In order further to investigate the effects of COVID-19 pandemic on the emission from different ship types with various ship sizes, the emission intensity representing the amount of atmospheric pollutant emissions per nautical mile per deadweight ton has also been calculated for the before and during the COVID-19 pandemic periods, respectively. Results show that the ship emission intensity under the normal cruising status was significantly reduced during the epidemic period. However, the quarantine measures for the COVID-19 pandemic resulted in an increment of the container ship emissions generated by their berthing and anchoring operations. This implies that there is a critical need to promote the use of shore power equipment for this merchant ship type during the epidemic period.

\textbf{Credit authorship contribution statement}

\textbf{Kun Shi}: Conceptualization, Methodology, Data curation, Writing-Original draft preparation. \textbf{Jinxian Weng}: Visualization, Investigation, Editing and Supervision.

\textbf{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.

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