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The impact of shipping CO_2 emissions from marine traffic in Western Singapore Straits during COVID-19

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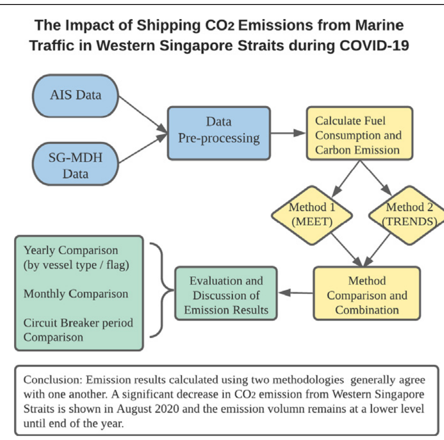
HIGHLIGHTS

- The MEET and TRENDS framework was used to estimate the CO_2 emission per vessel.
- Singapore flag vessel CO_2 emissions reduced by 10.68% from 2019 to 2020.
- Emission level dropped significantly in August 2020 and remained low until end of the year.
- Carbon emissions for ferries reduced considerably during the Circuit Breaker.
- This study contributes to the management of CO_2 emissions at the Singapore Port.

GRAPHICAL ABSTRACT



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ABSTRACT

The maritime industry plays a key role in reducing greenhouse gas (GHG) emissions, as an effort to combat the global issue of climate change. The International Maritime Organization (IMO) is targeting a 50% reduction in GHG emissions by 2050 compared to 2008. To measure Singapore's progress towards this target, we have conducted a comprehensive analysis of carbon dioxide (CO_2) emissions from the Western Singapore Straits based on the voyage data from Automatic Identification System (AIS) and static information from Singapore Maritime Data Hub (SG-MDH). Two methodologies, the MEET and TRENDS frameworks were applied to estimate the emission volume per vessel per hour. The data analysis results were next aggregated and visualised to answer key questions such as: How did the carbon emission level change from 2019 to 2020, in general, and for specific vessel types? What are the top vessel types and flags that had the highest carbon emissions? Did the traffic volume and emission level decrease during the Circuit Breaker period in 2020? The results of this study can be used to review Singapore's emission control measures and will be of value to the Maritime and Port Authority (MPA) of Singapore responsible for managing CO_2 emissions at the Singapore Port.

1. Introduction

1.1. Background

Climate change is an increasingly urgent global issue that crosses sectors and geographies. Among the different causes, greenhouse

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gases (GHG) emitted from human activities were reported as the most significant driver of observed climate change since the mid-20th century (IPCC, 2013), with carbon dioxide (CO_2) being the primary component and contributes to 76% of total GHG emissions globally in 2015 (*Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2015*, 2017).

As such, reducing carbon emission (and GHG in general) is at the forefront of many efforts to combat the potentially catastrophic rise in global temperatures. The shipping industry, which highly relies on the burning of fossil fuels for energy consumption, has a key role to play in this challenge.

According to the 4th International Maritime Organization (IMO) GHG study (https://docs.imo.org, 2020), maritime transport emitted around 1056 million tonnes of CO_2 in 2018 and is responsible for about 2.89% of global GHG emissions. Under a business-as-usual scenario, shipping emissions could double the current amount by 2050, undermining the goal of the Paris Agreement. As such, the IMO has implemented a series of strategies to tackle this problem and aimed to reach a 50% emission reduction by 2050 compared to 2008 (https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/IMO%20ACTION%20TO%20REDUCE%20GHG%20EMISSIONS%20FROM%20INTERNATIONAL%20SHIPPING.pdf, 2018).

Since 2013, new ships must comply with the IMO's requirements of Energy Efficiency Design Index (EEDI), which set increasingly strict carbon intensity standards. The IMO also implemented the Ship Energy Efficiency Management Plan (SEEMP) that same year, which provides a framework for operators to improve the energy efficiency of their vessels. The rest of the reduction is to be achieved by innovative measures, fuels and technologies.

Singapore, as one of the busiest ports in the world, is strictly following IMO's guidelines and actively researching on green technologies such as biofuels to build a sustainable marine environment. To measure the effectiveness of such efforts, we need to know how the emission level changes across months and years. Nevertheless, Singapore's carbon emission profile for the maritime sector is not publicly available from official sources. We were thus inspired to build a statistical model to estimate the emission volume based on other available marine traffic data.

1.2. Project objective

The project goal is to estimate the carbon footprint from Singapore's marine traffic using Automatic Identification System (AIS) data and other available resources. We want to find out how the emission level changes from 2019 to 2020, on a yearly and quarterly basis. We would also like to look at the breakdown by vessel types and flags, and to compare their performances.

Meanwhile, given the economic downturn brought by COVID-19 crisis, we are expecting a decrease in international trade and thus shipping activity in 2020. Combined with the effects of IMO's regulations, we would expect a carbon emission reduction in 2020, especially during the Circuit Breaker (CB) period. Through a targeted time-series analysis, we will find out whether there is a link between the lockdown and carbon emission from marine traffic.

2. Literature review

In general, there are two types of emission calculation methods adopted in recent studies, i.e., top-down and bottom-up methods. For the top-down approach, total emissions were calculated without considering the profile of each vessel and are later geographically located and assigned to the different vessels. For instance, Endresen et al. (Endresen et al., 2007) used the international marine fuel usage statistics reported by the Energy Information Administration (EIA) to estimate the CO_2 and SO_2 emissions across years. The limitation of this type of fuel-based approach is obvious: it could only generate a general emission trend but is not as accurate and reliable when assessing emissions of small targeted groups during designated study period.

The bottom-up approach, which calculates air pollutants emitted by a ship in a particular zone and then aggregates these estimates over the time and over the fleet for total emissions, provides more accurate results and more detailed emission profile, thus are preferable than the top-down approach in recent studies. Papers using this method mainly rely on the Automatic Identification System (AIS) as primary data source, which is also the data source for our study. In brief, AIS is a system that transmits a ship's position constantly so that other ships can spot vessels and avoid collision. Due to the great safety benefits offered by AIS, this technology is compulsory throughout the world in 2002 for all passenger ferries and vessels over 300 gross tonnes (Comar Systems, 2018).

Based on the same type of voyage data, different methodologies were adopted to calculate the emissions. Goldsworthy and Goldsworthy (Goldsworthy and Goldsworthy, 2015) have developed an AIS based model capable of providing a comprehensive analysis of ship engine exhaust emissions in a wide region which have many ports and have applied it to the Australian region. This model calculates ship emissions as the product of installed power of an engine type and the loading weight that was derived from the actual speed and maximum speed, the operating time and an emission amount. In the study of ship emissions from the port of Tianjin, China, Chen et al. (Chen et al., 2016) followed the same approach. Their results are relatively convincing and reliable because they have considered the difference in engine types and fuel types. However, such information is not included in AIS data and can be obtained from other commercial databases like Lloyd's database or Sea-web.

Other models that need the ships' engine properties as variables include the popular Ship Traffic Emission Assessment Model (STEAM) proposed by Jalkanen et al. (Jalkanen et al., 2009). It was further developed into 'STEAM3' by Johansson et al. (Johansson et al., 2017) which compensates for missing information on technical specifications, scarcity of satellite data in some regions and allows for modelling of emission control areas.

Fortunately, two other commonly quoted frameworks 'MEET' and 'TRENDS' are slightly simplified models that could be adopted given the limited data access in our study. MEET stands for the European project 'Methodologies for Estimating air pollutant Emissions from Transport' conducted in 1999 (Trozzi and Vaccaro, 1999) and is a method for calculating the emissions from seagoing vessels was described, among the methodologies for other transport modes. Leong et al. (Leong et al., 2015) applied the MEET framework in the study of CO_2 emission from marine traffic in Singapore Straits, which is a similar study area as ours. A linear relationship assumption for the consumption of full power fuel using Gross Tonnage (GT) and different coefficients for specific vessel types. The required vessel type and GT information could be obtained from Singapore Maritime Data Hub (SG-MDH) using free Application Programming Interface (API). Thus, we have decided to follow the same framework in our analysis.

TRENDS, refers to the project of 'TRansport and ENvironment Database System'. The authors of TRENDS set up a method for determining the emissions from the four most important transport modes (road transport, railways, shipping, aviation). In the maritime module, Georgakaki et al. (Georgakaki et al., 2005) developed some relationships between the fuel consumption and size of different vessels, like the framework suggested in MEET. However, instead of a linear function, they used a power curve to estimate the fuel consumption and claimed that it performs better than the MEET approach, especially for smaller vessels. As such, we will also try the TRENDS method and compare the results calculated from both MEET and TRENDS.

3. Methodology

3.1. Data description and pre-processing

The datasets used for this project included two parts: dynamic data from an open AIS data repository and supplementary static data from Singapore Maritime Data Hub.

The AIS data was downloaded from an open repository created by the Liánchéng project (AIS Logs, 2013). The data messages were received through an AIS receiver, and a GPS receiver positioned at School of Computing, NUS (103.7739°E, 1.294°N). The red circle in Fig. 1 below roughly delimits the covered zone, which is the western part of Singapore Straits.

To remove outliers, we further restricted our study area to the box bounded by [0.9854°N, 1.4942°N; 103.4232°E, 104.1297°E]. Fig. 2 below shows a spatial plot of all the position reports for March 2019 in the defined rectangular area.

The AIS data we downloaded for year 2019 and 2020 comes in JavaScript Object Notation (JSON) format and adds up to roughly 36 GB. The time interval between consecutive AIS reports for each vessel was typically 5 min. For each year of our study, there are around 100 million rows of records.

On the other hand, Singapore Maritime Data Hub (SG-MDH) is a one-stop data repository and centralised API gateway for maritime community data established by the Maritime and Port Authority (MPA) of Singapore (SG-MDH, n.d.). SG-MDH allows us to retrieve vessel particulars for any stated vessel name/IMO number/call sign. Thus, we will use this source for accessing static data which provides the important vessel type and gross tonnage information required in our fuel calculation.

Since the AIS data we obtained was vast in scale, plus the access to SG-MDH data was not so straightforward, as there were some important data cleaning and pre-processing steps, before computing the fuel consumption and carbon emissions.

As shown in the flow chart in Fig. 3 below, the position report extracted from the AIS data was first filtered by four conditions, and then grouped by MMSI, date, hour, and labelled with an aggregated average speed. The purpose of this step was to standardise the time interval of consecutive position reports to 1 h, to facilitate further calculations. Result of this step was represented by Table A in Fig. 3. Here, MMSI stands for Maritime Mobile Service Identity, which is a nine-digit vessel identification number but is not accepted as a variable when making API calls from SG-MDH website. Hence, we needed to generate a one-to-one reference table for MMSI and IMO numbers from type 5 AIS report. This table, as represented by Table B in Fig. 3, was then merged with Table A to produce Table C. Table C is the cleaned dynamic data that contained 5 columns: MMSI, IMO, date, hour and speed. Pandas in Python was not capable of handling such a huge dataset (36 GB) thus the above-mentioned data cleaning process used PySpark, and the API was written in Python to support Apache Spark.

In total, there are 19,244 unique IMO numbers found in Table C in Fig. 3 and, we had the vessel particulars for 18,780 of them (97.6%) from SG-MDH database by making API calls recursively. This set of static data was clean and we selected the following variables for Table D: 'imoNumber', 'mmsiNumber', 'vesselName', 'vesselType', 'flag', 'grossTonnage' and 'yearBuilt'.

3.2. Emission calculations

3.2.1. Method 1: MEET

We are following a slightly simplified version of the MEET framework (Trozzi and Vaccaro, 1999) from Leong's implementation (Leong

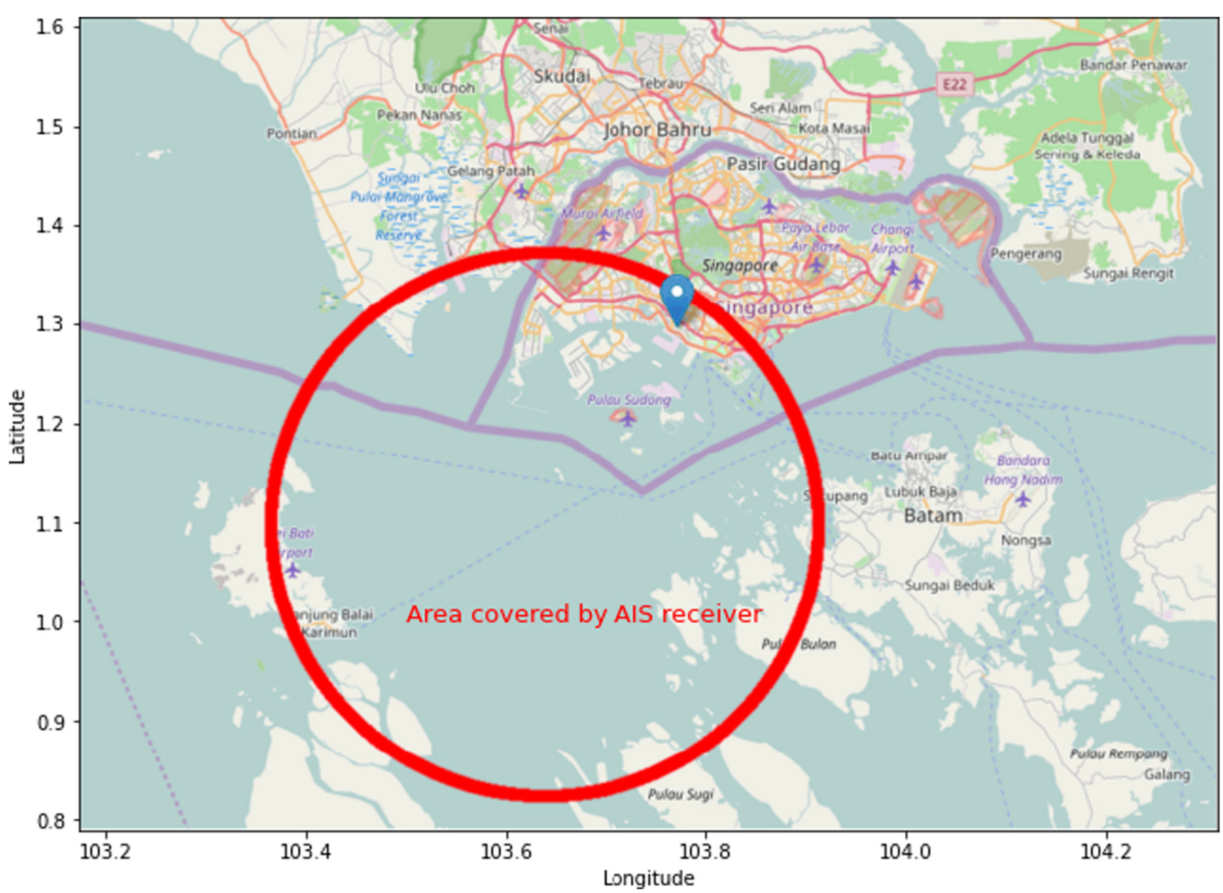


Fig. 1. Area covered by AIS receiver (Western Singapore Straits).

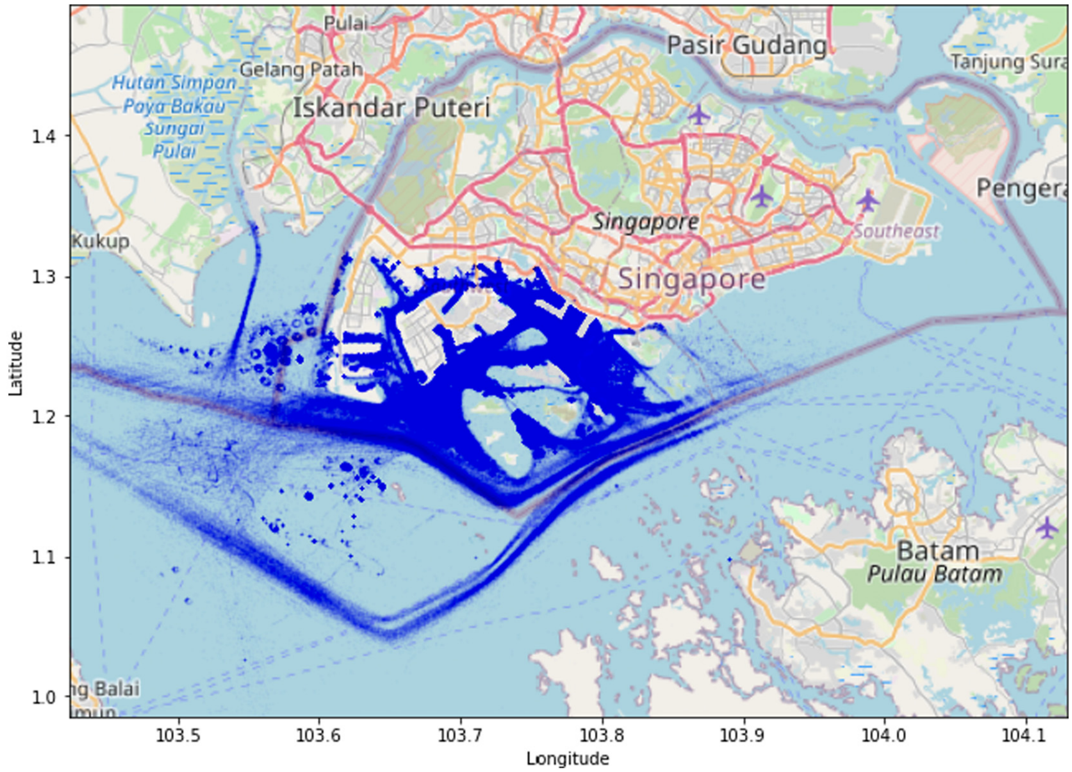


Fig. 2. Position plot for March 2019 AIS data.

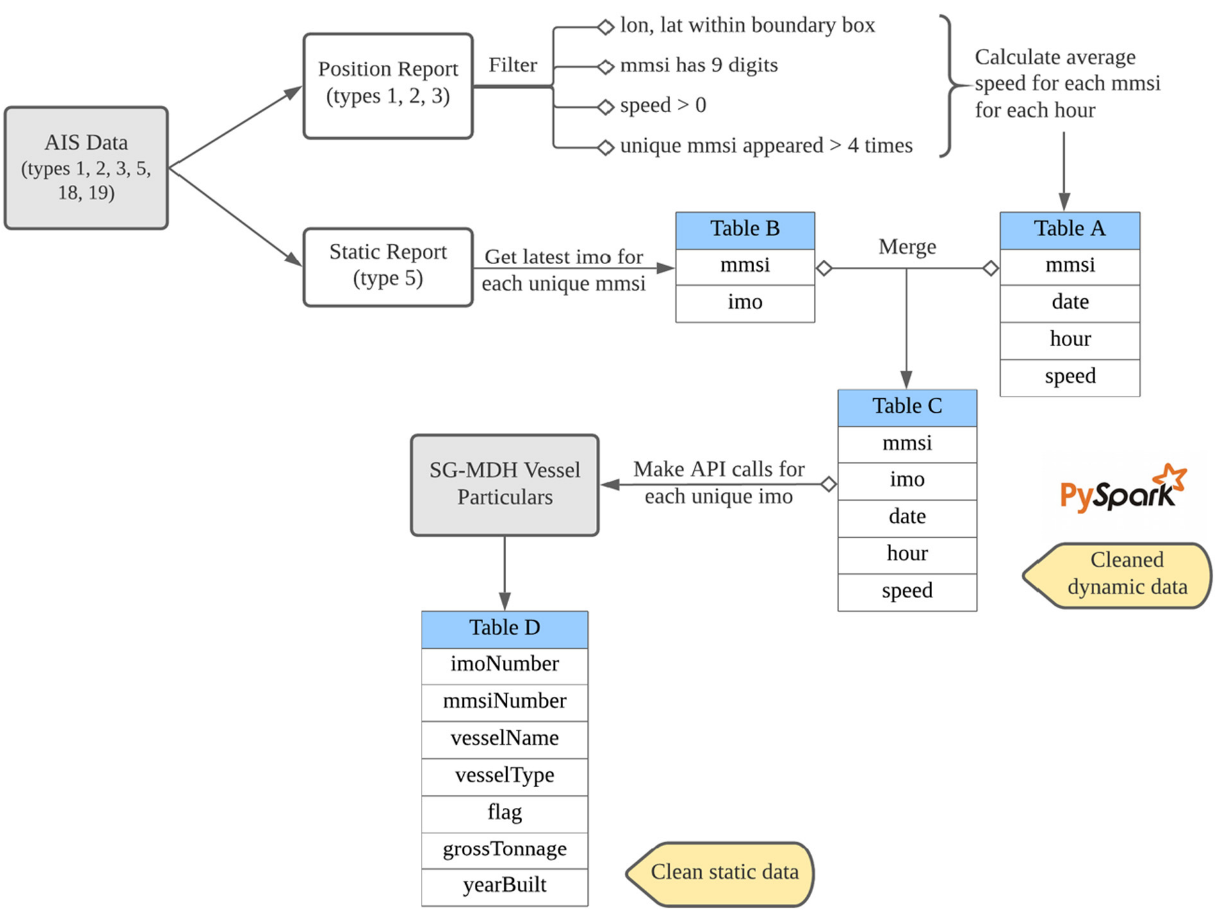


Fig. 3. Flow chart for data pre-processing steps.

Table 1
Consumption of full power fuel C_j vs gross tonnage GT.

Ship type	Consumption (tonne/h)
Bulk carrier (solid bulk)	$C_j = (20.186 + 0.00049 \times GT)/24$
Tanker (liquid bulk)	$C_j = (14.685 + 0.00079 \times GT)/24$
General cargo	$C_j = (9.8197 + 0.00143 \times GT)/24$
Container	$C_j = (8.0552 + 0.00235 \times GT)/24$
RoRo	$C_j = (12.834 + 0.00156 \times GT)/24$
Passenger	$C_j = (16.904 + 0.00198 \times GT)/24$
Ferry	$C_j = (39.483 + 0.00972 \times GT)/24$
Tugs	$C_j = (5.6511 + 0.01048 \times GT)/24$

et al., 2015). For each vessel, the hourly emission, E_{jk}, in kg/h, was calculated as shown in Eq. (1) below:

$$E_{jk} = C_j \times F_k \tag{1}$$

where, j is the ship type (Bulk carrier, Tanker, General cargo, Container, RoRo, Passenger, Ferry, Tugs); C_j is the hourly fuel consumption for ship type j at full power, in tonne/h; k is the operation mode (Cruising, Maneuvering, Hotelling); F_k is the average emission factors of CO_2 in kg/t fuel, depending on k.

In MEET, Trozzi (Trozzi and Vaccaro, 1999) used a database of 15,000 ships to construct a linear fit between daily fuel consumption $C_{j(daily)}$ and gross tonnage GT at full power for each vessel type. We assumed that the fuel type was marine diesel oil and after dividing $C_{j(daily)}$ by 24 h, we obtained the following linear equations between C_j and GT as shown in Table 1.

For the other half of Eq. (1), we assumed the emission factor, $F_k =$ 3173 kg/t of fuel used when the vessel was operating at cruising mode (Hulskotte and Denier van der Gon, 2010). When the vessel was operating under maneuvering or hotelling mode, we multiplied the emission factor by the 'fraction of maximum fuel used', 0.48 or 0.03 respectively. See Table 2 below.

The operating mode was classified based on the ship's maximum speed (Pitana et al., 2010) and the maximum speed was derived from the AIS dataset at 3 standard deviations from the mean speed for each vessel. Speeds above the maximum speed were identified as outliers and were removed.

Let us take an example of a tanker operating at 0.6 of its maximum speed during a certain hour, then it was defined to be operating in the maneuvering mode with the emission factor F_k calculated as $0.48 \times 3173 = 1523$ kg/t fuel. Given it has a gross tonnage of 20,000 GT, we calculated $C_j = (14.685 + 0.00079 \times 20{,}000) / 24 = 1.27$ t/h. See Table 5. Hence, the CO_2 emission for that hour for this tanker $= 1.27 \times 1523 = 1935$ kg ≈ 1.9 t.

We computed the total emissions per day by summing all the hourly emissions calculated for each vessel. Visualisation and discussion of the aggregated results are presented later.

3.2.2. Method 2: TRENDS

In TRENDS, Georgakaki (Georgakaki et al., 2005) proposed a more straightforward calculation model, based on the assumption that all ships under 2000GT have medium speed and those over 2000GT have slow speed engines. It was also assumed that the slow speed engines run on marine fuel oil (energy content 40.0–40.5 MJ/kg), while the medium speed engines run on marine gas oil (energy content 42.0–42.5 MJ/kg). The CO_2 emission per hour per vessel, E_j, in kg/h, is calculated as shown in Eq. (2) below:

$$E_j = C_j \times v \times E \tag{2}$$

where, j is the ship type (Bulk carrier, Tanker, General cargo, Container, RoRo/ferry, Passenger); C_j is the fuel consumption factor for ship type j per kilometre travelled, in kg/km; v is the speed per hour, in km/h; E is the emission factor of CO_2, taken to be 3.173 kg/kg fuel, consistent with Method 1.

The fuel consumption factors C_j was derived for the different ship categories using the in-house Technical University of Denmark (DTU) database. Instead of a linear relationship, Georgakaki constructed a power function between C_j and GT, as shown in Table 3 below.

Table 2
Operating mode and corresponding emission factor.

Operating mode	Speed classification	Fraction of maximum fuel used
Cruising	(0.8–1] of max speed	1.0
Maneuvering	(0.2–0.8] of max speed	0.48
Hotelling	(0–0.2] of max speed	0.03

Table 3
Relationship between fuel consumption and gross tonnage.

Vessel type	Fuel consumption (kg/km)
Bulk carrier	$C_j = 0.3059 \times GT^{0.5241}$
Tanker	$C_j = 0.2283 \times GT^{0.5589}$
General cargo	$C_j = 0.1637 \times GT^{0.6024}$
Container	$C_j = 0.0489 \times GT^{0.7381}$
RoRo/ferry	$C_j = 1.2324 \times GT^{0.3967}$
Passenger	$C_j = 0.173 \times GT^{0.6134}$

The speed 'v', was obtained from our cleaned dynamic dataset, but one needs to take note that the speed recorded in AIS data comes in the unit of knot, so we need to convert it to km/h based on 1 knot = 1.852 km/h.

Let us use the same example of a tanker with gross tonnage 20,000 GT, then $C_j = 0.2283 \times 20000^{0.5589} = 57.86$ kg/km, according to Table 3. Given it was operating at 6 knots = 11.1 km/h for that hour, then the CO_2 emission for that hour for this tanker $= 57.86 \times 11.1 \times 3.173 = 2038$ kg ≈ 2.0 t.

4. Results and discussion

4.1. Comparison of two methods

Table 4 summarises the total carbon emissions calculated by the proposed two methods for each vessel type for each year of 2019 and 2020.

We use a bar chart to visualize and compare the 2019 CO_2 emission by Method 1 and Method 2. See Appendix 1.

It is obvious that the calculated results, despite using two different methods, are extremely close to each other for container, passenger ships and tankers. The closeness of the two estimates from Method 1

Table 4
Carbon emissions for different vessel types by two methods.

Vessel type	CO_2 emission in 2019 (tonne)		CO_2 emission in 2020 (tonne)		Good match
	Method 1	Method 2	Method 1	Method 2	
Bulk carrier	147,963	241,783	170,351	280,810	
Container	937,819	926,101	960,540	928,537	✓
Ferry	136,654	50,945	33,247	12,105	
General cargo	27,222	39,374	26,976	38,997	✓
Passenger	24,082	25,020	17,967	17,276	✓
RoRo	8298	6182	8435	5991	✓
Tanker	817,567	896,986	862,670	955,154	✓
Tugs	131,641	NA	133,117	NA	NA

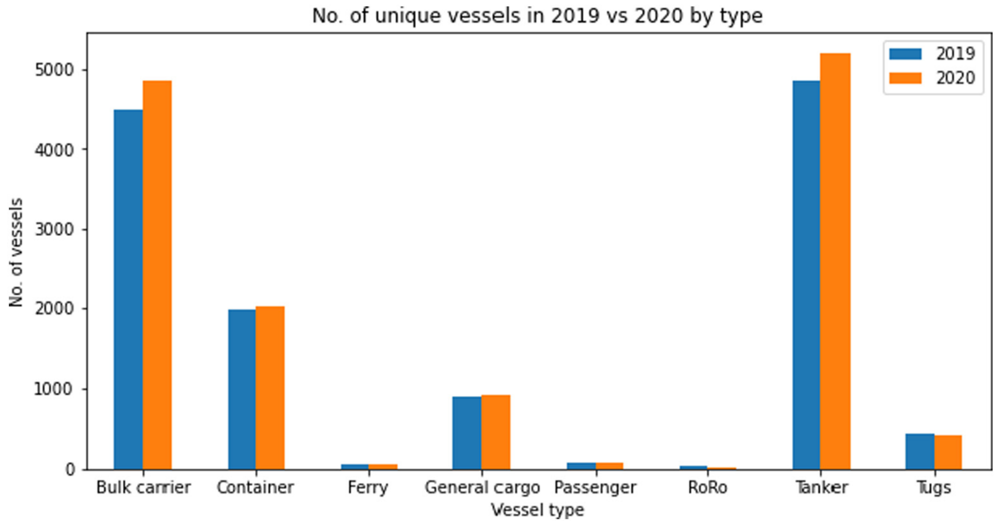


Fig. 4. Bar plot for no. of vessels by year by type.

and Method 2 validates and proves that our CO_2 emission estimation is reliable. The differences for other ship types also stay within an acceptable range. If we need to decide on one method to follow, Method 1 (MEET) would be slightly preferred than Method 2 (TRENDS) because it used a speed-based model which is more comprehensive than the distance-based model.

However, we cannot guarantee that the results produced by Method 1 are closer to the true value since the true value is unknown. Hence, we reduced the bias by averaging the Method 1 and Method 2 values to estimate the CO_2 emission.

4.2. Yearly comparison

4.2.1. By vessel type

Before we look at the emission profile, let us first understand the vessel types that were most frequent in the Western Singapore Straits. As shown in Fig. 4 below, bulk carriers and tankers each contribute to about 35% and 38% of the total vessel numbers, in both years. Number of unique container ships also reaches around 2000 in our study area, while the rest vessel types are less dominant. Bulk carriers and tankers had increased from 2019 to 2020, while the counts for other vessel types did not have much difference.

The averaged emissions from the two methods for each vessel type for each year are summarised in Table 5 below.

The last column calculated the percentage change from 2019 to 2020 for each vessel type. We have also plotted the corresponding bar chart in Fig. 5 below. With reference to Table 5 and Fig. 5, the overall carbon emissions from bulk carrier, container, tanker and tugs increased from 2019 to 2020, while the emissions from ferry, general cargo, passenger and RoRo decreased. Bulk carriers had the highest emission growth at 15.70%, while ferry and passenger vessel show a significant drop at 75.82% and 28.35% respectively. This reduction matches our expectation because ferries and passenger ships are mainly used for non-essential travelling, which was not permitted during the COVID-19 period. Meanwhile, from the statistics we can understand that marine transport for essential resources and goods were as normal in 2020, and the overall carbon emissions for all vessel types increased by a small amount of 0.80% from 2019 to 2020.

Another interesting finding from Fig. 5, was that the carbon emission from the containers was the highest even although the number of container ships is only ranked the 3rd among all types of vessels. This could be due to the larger vessel size of the container ships, resulting in higher fuel consumption. The box plot of gross tonnage distribution by vessel type shown in Fig. 6 below, verifies our belief where container has the highest median GT among all types.

Table 5
CO_2 emission by year by type.

Vessel type	CO_2 emission 2019 (tonne)	CO_2 emission 2020 (tonne)	% Change
Bulk carrier	194,352	224,868	15.70%
Container	931,052	943,183	1.30%
Ferry	93,785	22,673	−75.82%
Gen. cargo	33,174	32,895	−0.84%
Passenger	24,549	17,590	−28.35%
RoRo	7235	7182	−0.73%
Tanker	852,294	904,688	6.15%
Tugs	131,641	133,117	1.12%
All	2,268,082	2,286,196	0.80%

4.2.2. By vessel flag

The flag state of a merchant vessel is the jurisdiction under whose laws the vessel is registered or licensed. With reference to Fig. 7 below, we can see that Panamanian, Marshallese, Liberian, Singaporean and Chinese (Hong Kong) are the most common flags for vessels in our study area, adding up to 65.6% of total numbers.

Fig. 8 below, shows the emission profile for top 10 flags in 2019 vs 2020.

Table 6 below, shows that Singaporean vessels have the highest contribution to carbon emissions in either year. However, the emission was reduced by 10.68% in 2020 as compared to 2019. Marshallese and Indonesian vessels also emit a smaller amount of CO_2 in 2020, yet the emission level for all other popular flags went higher from 2019 to 2020, with Bahamian giving a notable surge by 60.39%.

4.3. Monthly comparison

In Fig. 9 below, to better understand the periodical variation of carbon emissions along with time, we have divided the voyage data into months and plotted the total emissions for the 24 months from 2019 to 2020, stacked by vessel type.

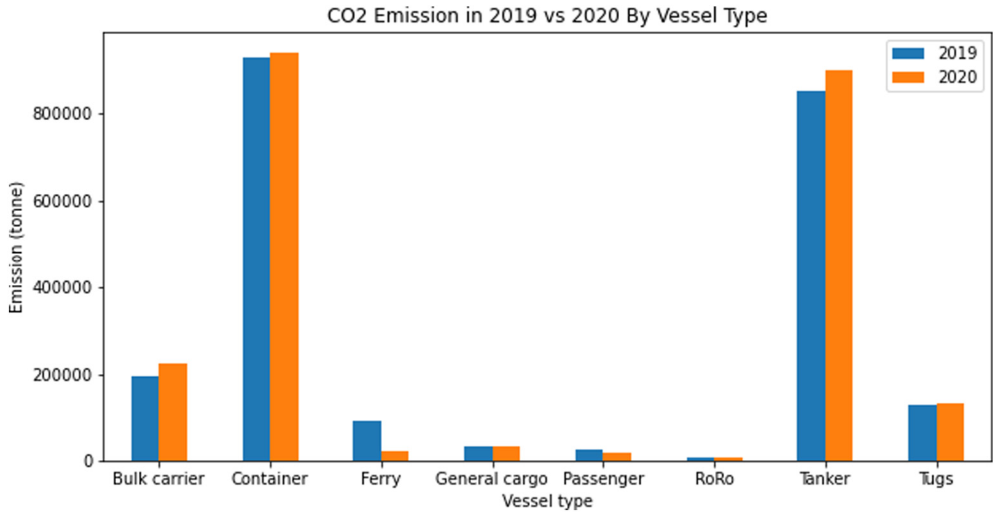


Fig. 5. Bar chart for CO_2 emission by year by type.

From Fig. 9, we can see that over the two years, monthly carbon emission from marine traffic generally fluctuates around 180,000 t and hits the peak in January 2020. There is a significant drop from July to August 2020 and remains at a lower level for the following months.

If we look at the breakdown by vessel types, we can see that the tankers and containers, coloured in pink and orange respectively, are the two major contributors to overall emissions across all months. We can also see that ferries and passenger ships, as coloured in green and purple in the middle part of the bars, diminish sharply since the second quarter of 2020. The reason has already been discussed in Section 4.2.1, and we will further delve in to study this special period in the next section.

4.4. Circuit breaker period comparison

The 2020 Singapore circuit breaker measures, abbreviated as CB, was a stay-at-home order and cordon sanitaire implemented as a preventive measure by the Government of Singapore in response to the COVID-19 pandemic in the country on 7 April 2020 (Wikipedia contributors, 2021). A complete timeline for the different stages of the CB is presented in Fig. 10 below. Prelude starts on 27 March, followed by Initial measures (7 April), Tightened measure (21 April), Relaxed measures (2 May) until the End of CB (1 June).

Following this timeline, we have taken a subset of AIS data from 1 March to 30 June for a comparative study of CO_2 emissions during different CB stages. The period from 1 to 26 March was defined as 'before CB' and the entire June was labelled, 'After CB'.

As shown in the traffic density plot in Fig. 11 above, the average number of vessels per day dropped from 780 before CB to 734 in prelude period. However, it bounces back during the initial measures period, and in general does not show a clear decreasing trend during the CB period. As such, the daily emission distribution box as seen in Fig. 12 below also fluctuates across the time periods, negating our assumption that carbon emission from marine traffic would decrease due to the CB measures.

Our analysis result has a slight deviation from the statistics published by the Ministry of Transport (MOT), where vessel traffic decreased during the CB period, as seen in Appendix 2.

However, this report from MOT measures the marine traffic based on cargo volume at the port only, which has a smaller scope than our

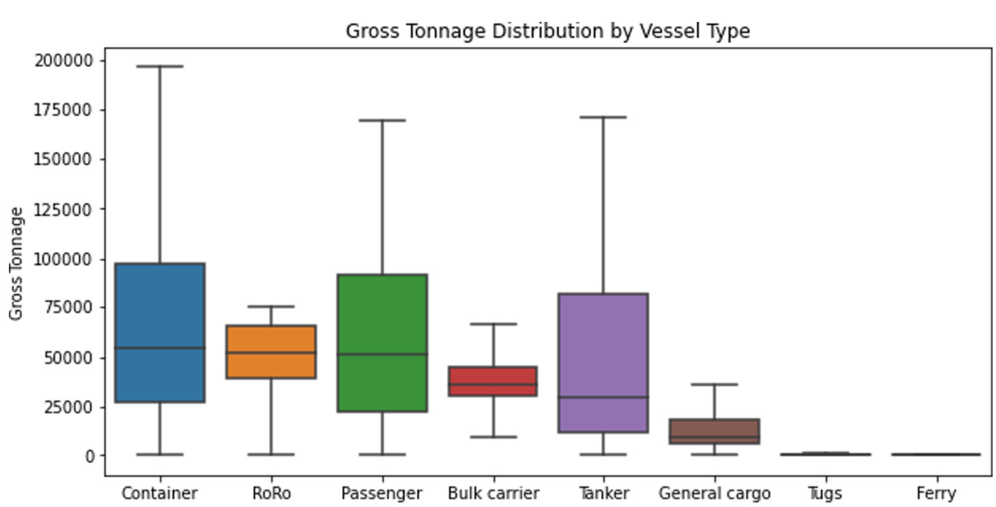


Fig. 6. Box plot for GT by vessel type.

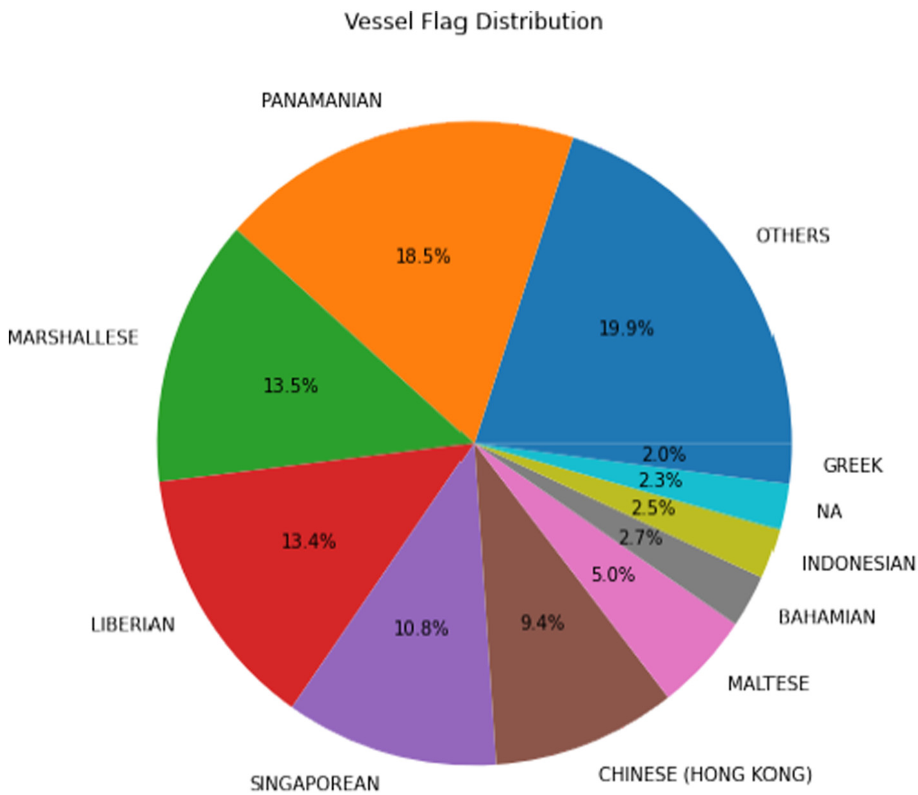


Fig. 7. Pie chart for flag distribution.

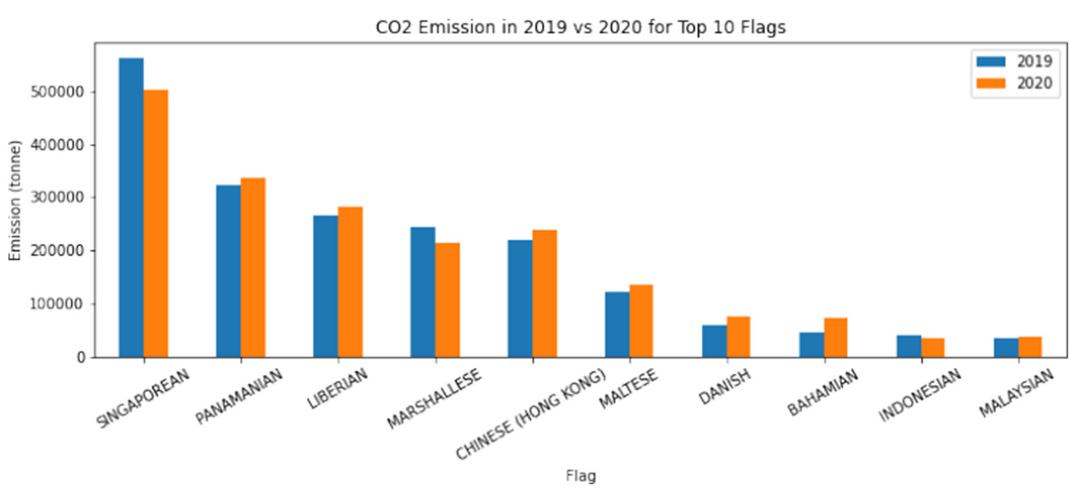


Fig. 8. Bar chart for CO_2 emission by year for top 10 flags.

Table 6
CO_2 emission for 2019 vs 2020 for top 10 flags.

Flag	CO_2 emission in 2019 (tonne)	CO_2 emission in 2020 (tonne)	Percentage change
Singaporean	563,306	503,166	−10.68%
Panamanian	323,783	337,003	4.08%
Liberian	265,305	283,082	6.70%
Marshallese	244,463	215,103	−12.01%
Chinese (Hong Kong)	219,383	239,029	8.96%
Maltese	120,716	134,258	11.22%
Danish	59,803	76,367	27.70%
Bahamian	45,662	73,236	60.39%
Indonesian	39,045	34,197	−12.42%
Malaysian	35,149	38,162	8.57%

study. Thus, it is not correct to think that the number of vessels and carbon emitted in our study area should have followed the same decreasing trend during the lockdown period. In fact, from this MOT report the effect of COVID-19 on Singapore's marine traffic is very minor as compared to other transport modes. Nevertheless, the impact on the usage of ferries is still very significant. As shown in Fig. 13 below, carbon emissions from ferries dropped to almost zero during the CB period and after the CB period.

5. Conclusion

The emission results calculated based on the MEET and TRENDS methodologies generally agreed with each other and validated our

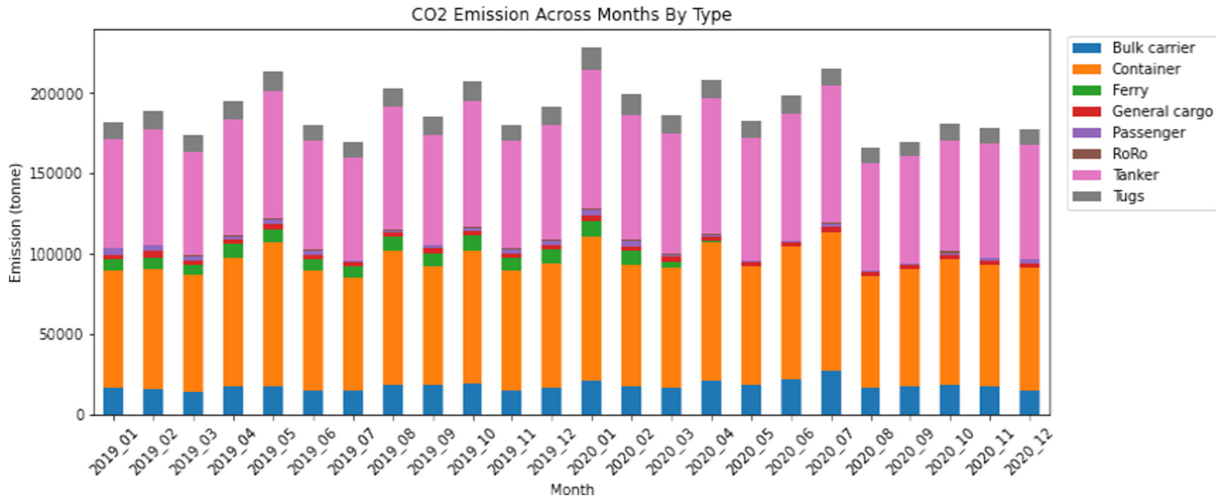


Fig. 9. Stacked bar plot for CO_2 emission by type across months.

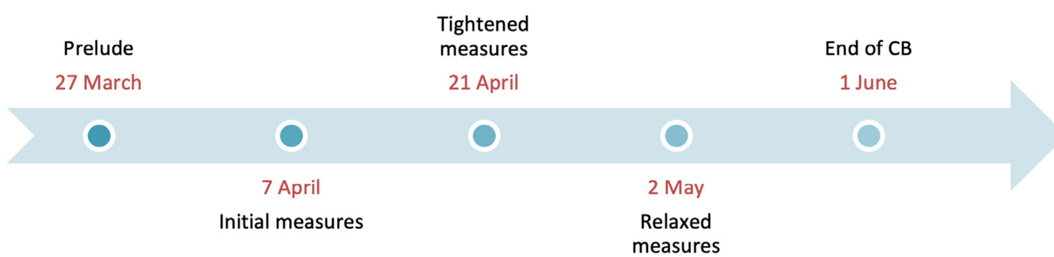


Fig. 10. Timeline for Singapore circuit breaker measures.

estimations. From 2019 to 2020, overall carbon emissions from marine traffic in the Western Singapore Straits increased by a small amount of 0.80%. Bulk carriers had the highest emission growth at 15.70%, while ferry and passenger vessel show a significant drop at 75.82% and 28.35% respectively. Carbon emissions from Singapore flag vessels were reduced by 10.68% from 2019 to 2020. Through a more detailed comparison across quarters and different Circuit Breaker periods, we get to understand that marine transports for essential resources and goods were generally conducted as normal despite the COVID-19 pandemic. However, after the Circuit Breaker period, we see a significant decrease in carbon emissions from June to August 2020, which remains at a lower level until end of the year.

The difference between our carbon emission values and the expected carbon emission could be due to the limitation that our model did not consider the different types of fuel used. Our calculation of fuel consumption was based on the simple assumption of marine diesel oil, but in fact, there could be more clean fuels used

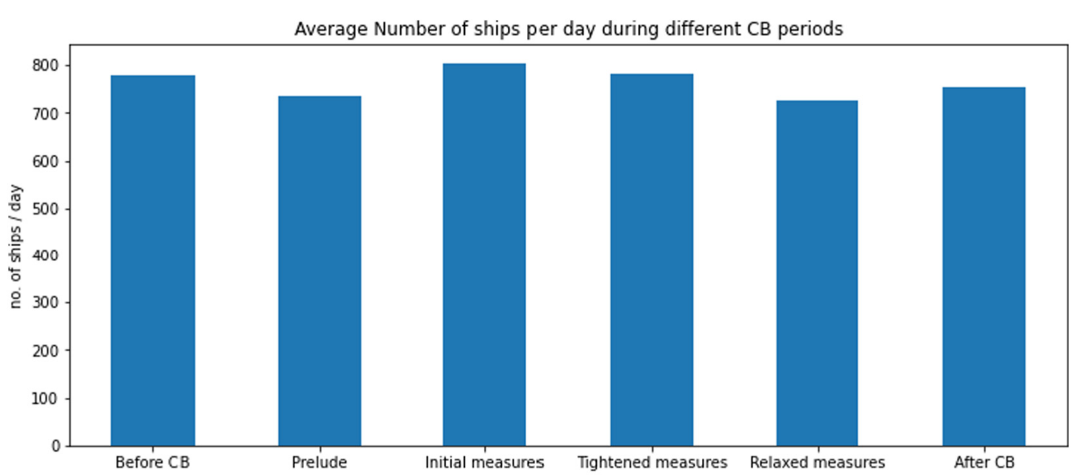


Fig. 11. Bar chart for avg. no. of ships per day during different Circuit Breaker (CB) periods.

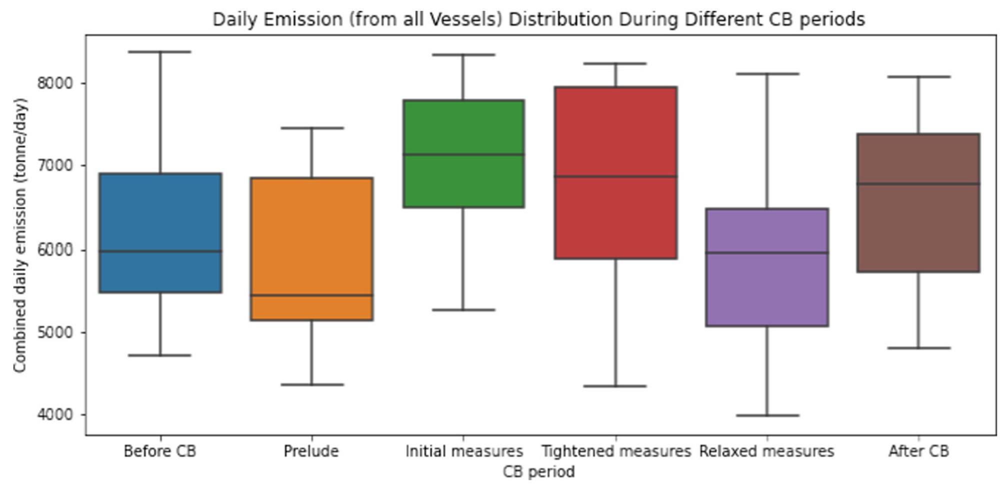


Fig. 12. Box plot of daily CO_2 emission distribution during different CB periods.

along with time. In the future, we can enhance our carbon estimation model by gaining access to more vessel particulars such as engine power and fuel types.

This project was challenging. It was very difficult to gain access to the vessel data. Further, the dataset, consisting of longitude and latitude data took a large amount of time to process. Further, most of the data was unclean. The framework described to compute the vessel carbon emissions and the algorithms developed to clean the data and calculate the carbon emissions will remain useful for future carbon emission research projects. This research project is valuable as useful insights on the carbon emissions of different vessel types before the COVID-19 period, during the COVID-19 period and after the COVID-19 period is provided. With the goal of reducing carbon emissions by 2050, our algorithms can help to manage and control carbon emissions at the Singapore Port. Our future research project is to develop our algorithm into an application that will contribute to making the Singapore Port a greener port.

CRediT authorship contribution statement

Carol Anne Hargreaves:

- Conception and design of the research paper
- Project administration and supervision
- Assisted in determining and reaching out to organizations for data collection
- Made suggestions for data analysis
- Revision and editing of the draft research paper
- Final approval of the version to be published

Ju Yuting:

- Assisted in determining and reaching out to organizations for data collection
- Determined the software to be used
- Data Extraction and Curation
- Formal Data Analysis and Interpretation
- Drafting of the research paper

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.

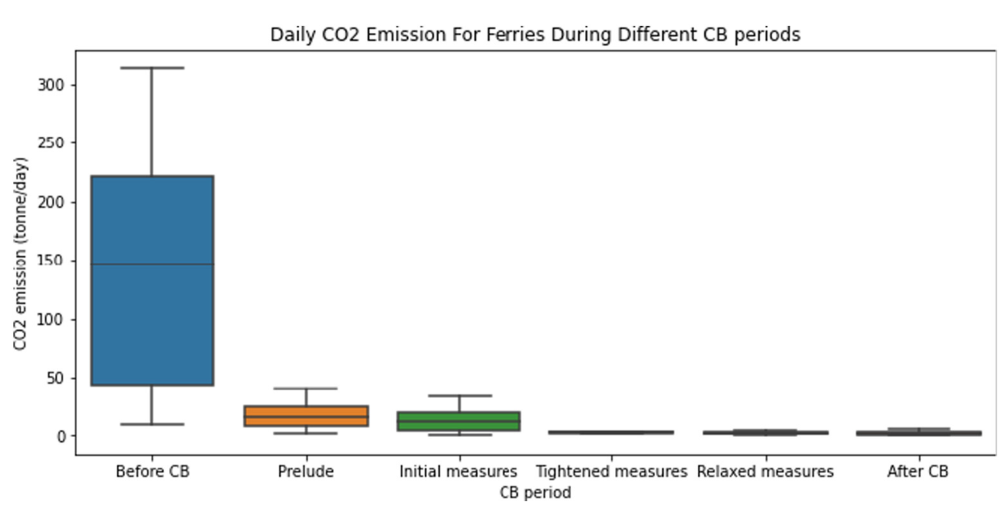
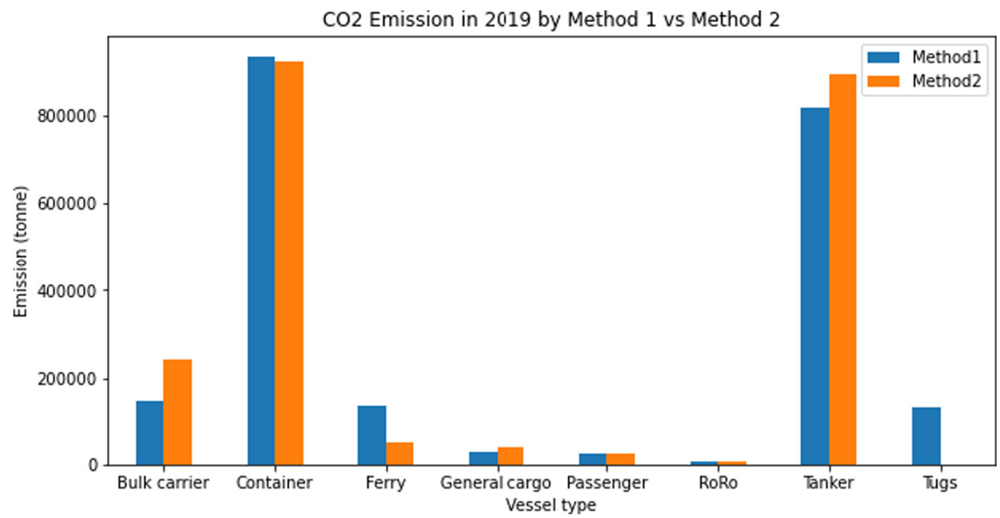
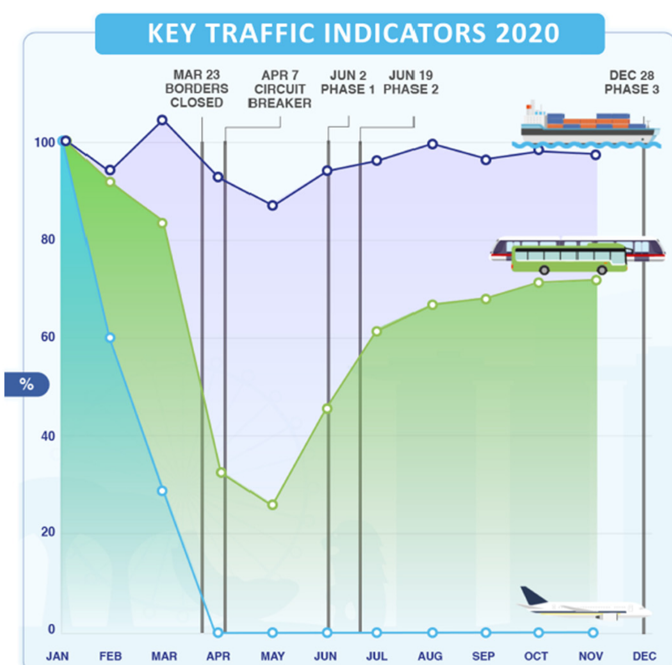


Fig. 13. Box plot of daily CO_2 emission for ferries during different CB periods.

Appendix 1. Bar chart for emission in 2019 by vessel types using Method 1 vs Method 2



Appendix 2. Key traffic indicators 2020 (from MOT Facebook page)



STATISTICS AT A GLANCE

MONTH	LAND: Public Transport Whole Day Ridership	AVIATION: Passenger Movement at Changi Airport	SEA: Cargo Volume
Jan 2020	100%	100%	100%
Feb 2020	92%	60%	94%
Mar 2020	83%	28%	105%
Apr 2020	32%	0.4%	93%
May 2020	25%	0.4%	87%
Jun 2020	45%	0.8%	94%
Jul 2020	61%	1.4%	96%
Aug 2020	67%	1.4%	99%
Sep 2020	68%	1.5%	96%
Oct 2020	71%	1.7%	98%
Nov 2020	72%	1.9%	97%

Jan 2020 (pre-COVID-19) for comparison at 100%

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