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Estimation of Ship Exhaust Gas Emission at Tanjung Priok Port Area Using AIS Data

Mohammad Danil Arifin[1*], Frans Josua Sanjaya Rumapea[2], Aldyn Clinton Partahi Oloan[3], Y. Arya Dewanto[4], Fanny Octaviani[5]
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Abstract**—** Maritime transportation is a major contributor to global trade but also generates significant atmospheric pollution from ship exhaust emissions. Tanjung Priok Port, Indonesia's largest seaport, experiences intensive vessel traffic that may adversely affect local air quality. This study estimates ship exhaust gas emissions in the Tanjung Priok Port area by integrating Automatic Identification System (AIS) data with the Trozzi emission estimation method. AIS data collected throughout 2024 were analyzed to determine vessel movements, ship types, gross tonnage, and operational modes (cruising, maneuvering, and hoteling). The busiest operational period was identified before estimating emissions of NO_x, CO, CO_2, VOC, SO_x, and PM. The results showed that November was the busiest month with 2,480 vessel movements, while 3 November 2024 recorded the highest daily traffic with 109 vessels. During the peak period, total emissions reached 641.81 kg/h of NO_x, 2,750.63 kg/h of CO, 719.67 kg/h of CO_2, 648.58 kg/h of VOC, 458.44 kg/h of SO_x, and 34.38 kg/h of PM. Container vessels were identified as the largest emission contributors, followed by tanker and cargo vessels. The study demonstrates that integrating AIS data with the Trozzi methodology provides a reliable activity-based emission inventory that can support sustainable port management, environmental monitoring, and maritime emission reduction policies in Indonesia.

Keywords—Automatic Identification System (AIS), AIS Data, Emission Estimation, Sustainable Port Management, Tanjung Priok Port.

[*]*Corrresponding Author : danilarifin.mohammad@gmail.com*

I. INTRODUCTION

Maritime transportation is the backbone of international trade, accounting for approximately 80% of global merchandise transportation by volume and more than 70% by value. The continuous growth of global shipping activities has significantly increased energy consumption and atmospheric pollutant emissions from marine diesel engines. Although maritime transport remains one of the most energy-efficient freight transport modes, it is also recognized as an important source of greenhouse gases (GHGs) and air pollutants, including carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), volatile organic compounds (VOC), and particulate matter (PM). These emissions contribute to climate change, acidification, photochemical smog formation, and adverse human health effects, particularly in densely populated coastal and port regions where shipping activities are highly concentrated [1]–[5].

Mohammad Danil Arifin, Department of Marine Engineering, Darma Persada University, Jakarta, 13450, Indonesia. E-mail: danilarifin.mohammad@gmail.com
Frans Josua Sanjaya Rumapea, Department of Marine Engineering, Darma Persada University, Jakarta, 13450, Indonesia. E-mail: fransrumapea02@gmail.com
Aldyn Clinton Partahi Oloan, Department of Marine Engineering, Darma Persada University, Jakarta, 13450, Indonesia. E-mail: clintonaldyn19@gmail.com
Y. Arya Dewanto, Department of Marine Engineering, Darma Persada University, Jakarta, 13450, Indonesia. E-mail: aryadewanto@yahoo.com
Fanny Octaviani, Department of Naval Architecture, Darma Persada University, Jakarta, 13450, Indonesia. E-mail: fanny_octaviani@yahoo.com

Recent studies have shown that shipping emissions have become one of the dominant contributors to air pollution in major international ports. Pollutants emitted from ship engines may deteriorate local air quality, increase respiratory and cardiovascular diseases, and accelerate environmental degradation. Consequently, reducing emissions from maritime transportation has become one of the primary objectives of the International Maritime Organization (IMO) through the implementation of increasingly stringent regulations on sulfur content in marine fuels, nitrogen oxide emission limits, and greenhouse gas reduction strategies. These regulations encourage researchers and policymakers to develop accurate ship emission inventories as a scientific basis for environmental management and sustainable port development [6-10].

A. Ship Emissions in Port Areas

Port areas represent emission hotspots because ships operate under different operational modes with varying engine loads and fuel consumption rates. Unlike vessels sailing in open seas, ships approaching or leaving ports continuously change their operating conditions through cruising, maneuvering, and hoteling activities. During cruising, the main propulsion engine operates at relatively high load factors, whereas maneuvering involves frequent engine adjustments due to reduced navigation speed and docking operations. Hoteling activities occur when ships are berthed alongside the quay while auxiliary engines continue supplying electrical power for onboard equipment, cargo handling systems, lighting, ventilation, and accommodation facilities. Although propulsion engines may be inactive during hoteling, auxiliary engines continue producing significant pollutant emissions over extended periods. Therefore, operational mode plays a crucial role in determining overall ship emissions within port environments [3], [8], [11-13].

Tanjung Priok Port, located in Jakarta, Indonesia, is the largest and busiest international seaport in the country and serves as the primary gateway for national and international maritime trade. Thousands of domestic and international vessels enter and leave the port every month, generating substantial atmospheric emissions from continuous shipping activities. The increasing vessel traffic intensity has raised concerns regarding the cumulative impacts of exhaust emissions on ambient air quality in surrounding urban areas. Despite the strategic importance of Tanjung Priok Port, comprehensive emission inventories based on actual vessel movements remain limited, highlighting the need for more accurate and activity-based emission assessments [14-16].

B. AIS-Based Ship Emission Estimation and Trozzi Method

Recent advances in Automatic Identification System (AIS) technology have significantly improved the capability to estimate ship emissions with high spatial and temporal resolution. AIS is an automatic vessel tracking system that continuously transmits dynamic and static information, including ship identity, geographical position, speed over ground (SOG), course over ground (COG), navigation status, heading, and voyage-related information through Very High Frequency (VHF) communication, as illustrated in **Figure 1**. Originally developed to improve navigational safety and collision avoidance, AIS has evolved into an essential data source for maritime traffic analysis, logistics optimization, environmental monitoring, and ship emission assessment [17]–[20].

Compared with conventional top-down emission estimation methods based solely on fuel sales or national fuel consumption statistics, AIS-based bottom-up approaches provide considerably higher accuracy because emissions are calculated from actual vessel trajectories and operational characteristics. AIS data enable researchers to determine ship speed, operational mode, sailing duration, and vessel activity patterns continuously, thereby reducing uncertainties associated with aggregated statistical methods. Consequently, AIS-based emission inventories have become the preferred approach for evaluating shipping emissions in many international ports, including those in Europe, North America, and East Asia [2], [5], [18], [21]–[23].

Numerous studies have demonstrated the effectiveness of AIS-based methodologies for estimating emissions from commercial shipping activities. High-resolution ship emission inventories developed using AIS data have been successfully implemented in the Baltic Sea, the Pearl River Delta, Shanghai Port, Tianjin Port, and several Mediterranean ports. These studies reported that container ships, cargo vessels, and tankers generally contribute the largest proportions of total emissions because of their higher engine power, larger gross tonnage, and greater operational frequency. Furthermore, AIS-derived emission inventories have been widely used to support air quality modeling, exposure assessment, and maritime emission-reduction policy development [4], [7], [9], [22]–[25].

C. Trozzi Activity-Based Emission Model

Among the various approaches to estimating ship emissions, the activity-based methodology proposed by Trozzi and Vaccaro remains one of the most widely adopted techniques for port emission studies. Unlike conventional statistical approaches, the Trozzi model estimates emissions by considering actual ship operational modes, engine characteristics, fuel types, engine load factors, and pollutant-specific emission factors. Emissions are separately calculated for cruising, maneuvering, and hoteling operations before being aggregated into total emission inventories. This methodology more accurately represents real operational conditions because it incorporates variations in engine performance during different phases of vessel activity. Consequently, the Trozzi model has been extensively applied in numerous studies investigating ship emissions in international ports and coastal regions [3], [24], [26].

C. Research Gap, Novelty, and Objectives

Although AIS-based ship emission inventories have been extensively developed in Europe, China, South Korea, and North America, relatively few studies have

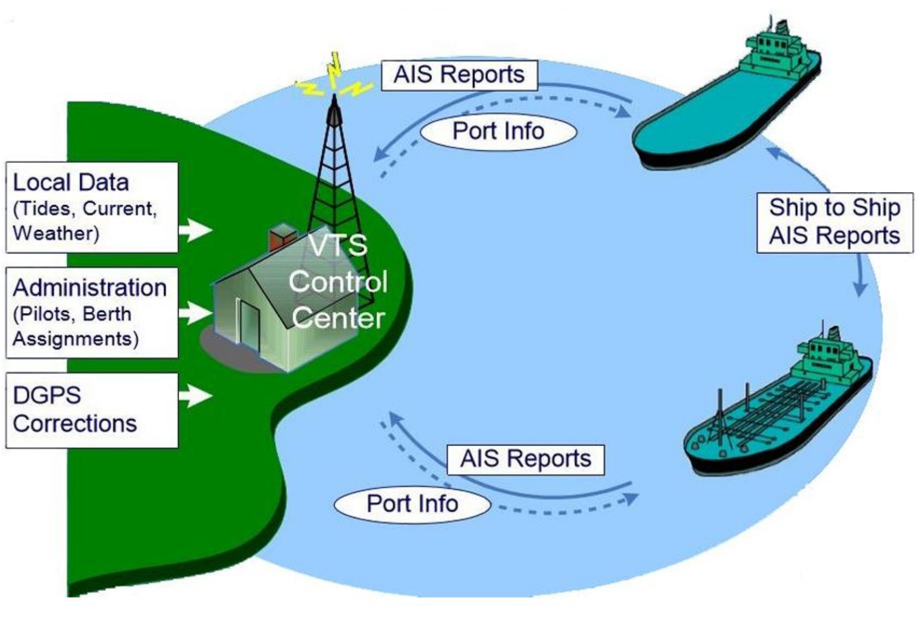


Figure 1. Vessel Traffic Service (VTS) integrates real-time information

investigated ship exhaust emissions in Indonesian waters using high-resolution AIS data. Previous maritime studies in Indonesia have primarily focused on navigation safety, vessel traffic density, port logistics, and greenhouse gas estimation without comprehensively evaluating the contributions of individual ship types, operational modes, and pollutant categories within major seaports. Moreover, no comprehensive AIS-based bottom-up emission inventory has specifically examined hourly vessel activity, peak traffic periods, and operational-mode-specific emissions in Tanjung Priok Port, Indonesia's busiest maritime gateway [14], [15], [27].

Therefore, this study develops an activity-based ship emission inventory using one year of AIS data collected from Tanjung Priok Port during 2024. Vessel movements are classified according to cruising, maneuvering, and hoteling operational modes, while pollutant emissions are estimated using the Trozzi methodology by considering ship type, gross tonnage, engine characteristics, fuel type, operational duration, and emission factors. Unlike previous Indonesian studies, this research identifies the busiest month, busiest day, and busiest operational hour before estimating emissions of NO_x, CO, CO_2, VOC, SO_x, and PM generated by different ship categories. The findings provide a high-resolution emission inventory capable of supporting evidence-based environmental management, sustainable port operation, and future maritime emission reduction strategies in Indonesia.

II. METHOD

The estimation of ship exhaust gas emissions in this study was performed using the Trozzi method [14][15], which is widely employed in maritime emission inventory studies due to its ability to account for vessel operational modes and engine characteristics. The research methodology follows a structured workflow consisting of AIS data acquisition, vessel activity identification, operational mode identification, emission estimation, and result analysis. The complete research procedure is presented in **Figure 2**.

The total emission of a pollutant generated by the main engine was estimated using the methodology proposed by Trozzi and Vaccaro. According to the UNECE/EMEP approach, the total emission of pollutant i is calculated as the sum of emissions from different fuel types, ship categories, engine types, and operational modes, as expressed in Equation (1):

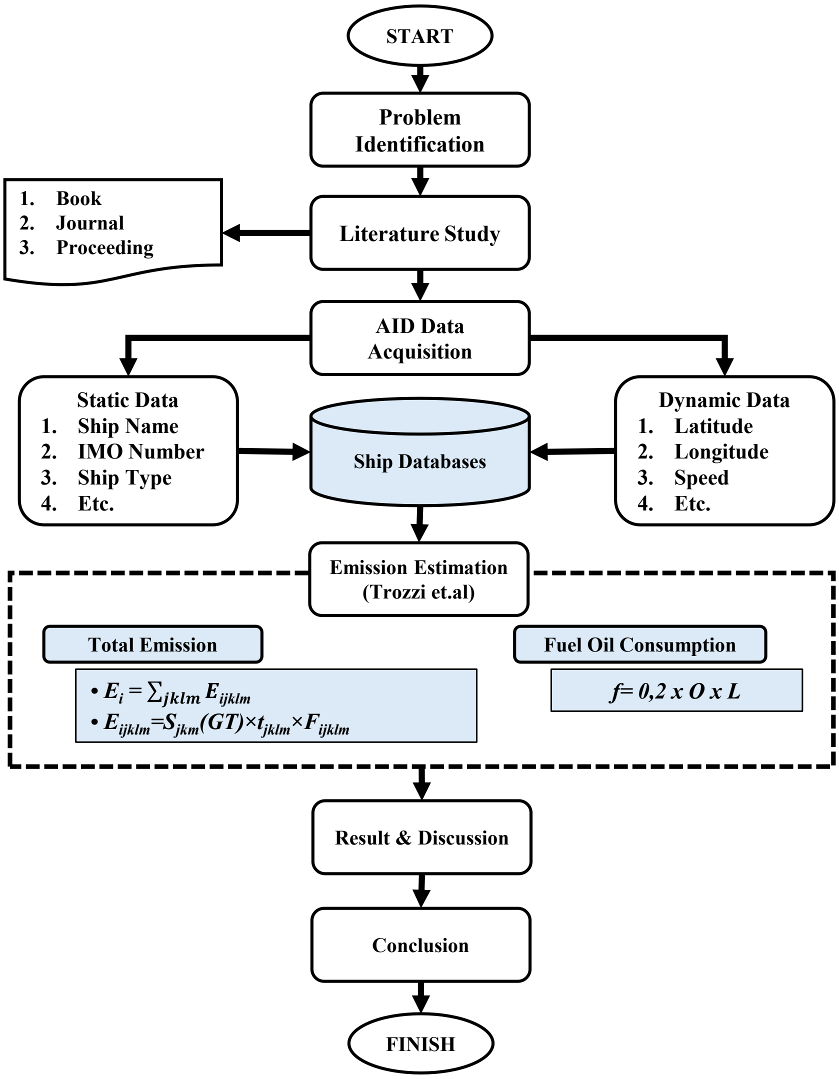


Figure 2. Flowchart

$$\boldsymbol{E_i = \sum_{jklm} E_{ijklm}} \quad \textbf{(1)}$$

where the emission contribution of pollutant *i* from fuel type *j*, ship category *k*, engine type *l*, and operational mode *m* is determined by:

$$\boldsymbol{E_{ijklm}=S_{jkm}(GT)\times t_{jklm}\times F_{ijklm}} \quad \textbf{(2)}$$

where E_i denotes the total emission of pollutant *i*; E_{ijklm} represents the emission of pollutant *i* associated with fuel type *j*, ship category *k*, engine type *l*, and operational mode *m*; F_{ijklm} is the average emission factor of pollutant *i* for fuel type *j*, ship category *k*, engine type *l*, and operational mode *m*; S_{jkm} (GT)denotes the daily fuel consumption of fuel type *j* by ship category *k* under operational mode *m*, expressed as a function of the vessel gross tonnage (GT); and t_{jklm} is the operating time corresponding to fuel type *j*, ship category *k*, engine type *l*, and operational mode *m*. The operational modes considered in this study include cruising, maneuvering, and hoteling, following the classification proposed in the Trozzi emission model.

In the methodology proposed by Trozzi et al. [15], the daily fuel consumption for each ship category is estimated using linear regression based on the vessel's Gross Tonnage (GT). The regression models establish empirical relationships between fuel consumption and GT for different ship types, providing the basis for estimating fuel consumption in the emission inventory. The regression equations adopted in this study are summarized in **Table 1**.

In addition to fuel consumption, ship exhaust gas emissions are estimated by considering several key parameters, including the main engine characteristics, the type of fuel consumed, and the vessel's operational mode. Each operational mode, namely cruising, maneuvering, and hoteling, has distinct engine load conditions and fuel consumption rates, resulting in different emission levels. The pollutant-specific emission factors, fuel consumption fractions, rated output (PS) fractions, classification of air pollutants, ship type, fuel type, ship engine type, and ship operational modes adopted in this study are based on the Trozzi methodology and are presented in **Tables 2** and **3**.

The vessel navigation status was used to determine the engine load factor (LF) and the corresponding emission factors associated with each operational mode. In the Trozzi methodology, ship operations are classified into three primary modes: cruising, maneuvering, and hoteling. The maneuvering mode includes vessel activities during port approach, anchoring, and departure from the port area, where engine loads vary significantly due to speed adjustments and navigation maneuvers.

TABLE 1.
SHIP EMISSION ESTIMATION EQUATIONS BASED ON THE TROZZI METHOD

Ship Types	Fuel Consumption (ton/day) as a Function of Gross Tonnage (GT)
Solid Bulk	$C_{jk} = 20{,}1860 + 0{,}00049 \times GT$
Liquid Bulk / Tanker	$C_{jk} = 14{,}6850 + 0{,}00079 \times GT$
General Cargo	$C_{jk} = 9{,}8197 + 0{,}00143 \times GT$
Container	$C_{jk} = 8{,}0552 + 0{,}00235 \times GT$
Ro-Ro Cargo	$C_{jk} = 12{,}8340 + 0{,}00156 \times GT$
Passenger	$C_{jk} = 16{,}9040 + 0{,}00198 \times GT$
High Speed Ferry	$C_{jk} = 39{,}4830 + 0{,}00972 \times GT$
Inland Cargo	$C_{jk} = 9{,}8197 + 0{,}00143 \times GT$
Sail Ship	$C_{jk} = 0{,}4268 + 0{,}00100 \times GT$
Tugs	$C_{jk} = 5{,}6511 + 0{,}01048 \times GT$
Fishing	$C_{jk} = 1{,}9387 + 0{,}00448 \times GT$
Other Ships	$C_{jk} = 9{,}7126 + 0{,}00091 \times GT$

The hoteling mode refers to the period when a vessel is berthed alongside the quay for cargo handling, loading and unloading operations, or other port-related activities, during which the main engine is typically shut down while auxiliary engines continue to operate. In contrast, the cruising mode represents normal sailing conditions in open waters, where the vessel travels at a relatively constant speed, and the main engine operates under stable load conditions. The classification of vessel operational modes is illustrated in **Figure 3**.

III. Results and Discussion

A. Analysis of Vessel Traffic Based on AIS Data

Automatic Identification System (AIS) data used in this study were obtained from Tanjung Priok Port, North Jakarta, Indonesia. The dataset covers vessel movements recorded continuously throughout the 2024 calendar year. AIS provides dynamic vessel information, including vessel identity, position, speed, heading, navigation status, and timestamp, enabling comprehensive monitoring of ship activities within the port area. These data were processed to classify vessel operations into three operational modes: cruising, maneuvering, and hoteling, which constitute the primary activity categories required by the Trozzi emission estimation method.

The purpose of the AIS analysis was to estimate the quantity of air pollutants generated by ship operations within the Tanjung Priok Port area. Since pollutant emissions depend strongly on vessel operational conditions, AIS-based activity analysis enables a more accurate representation of actual ship movements than conventional port statistics. The estimated emission

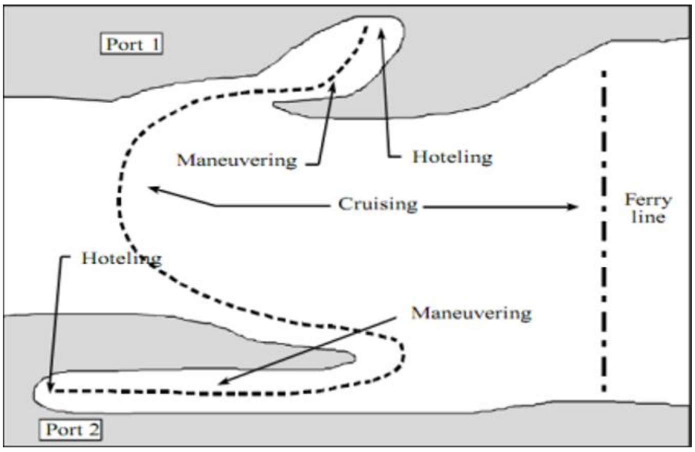


Figure 3. Ship Operation Modes

Table 2.
Ship Emission Factors (kg/ton)

Operational Mode	Engine / Fuel Type	NO_x	CO	CO_2	VOC	PM	SO_x
Cruising	SSD/BFO	87	7.4	3200	2.4	1.2	60
	MSD/BFO	57	7.4	3200	2.4	1.2	60
	HSD/MDO	70	9	3200	3	1.5	20
Maneuvering	SSD/BFO	78	28	3200	3.6	1.2	60
	MSD/BFO	51	28	3200	3.6	1.2	60
	HSD/MDO	63	34	3200	4.5	1.5	20
Hotelling	SSD/BFO	35	99	3200	23.1	1.2	60
	MSD/BFO	23	99	3200	23.1	1.2	60
	HSD/MDO	28	120	3200	28.9	1.5	20

SSD = Slow Speed Diesel Engine
MSD = Medium Speed Diesel Engine
HSD = High Speed Diesel Engine
PM = Particulate Matter
BFO = Bunker Fuel Oil
MDO = Marine Diesel Oil
VOC = Volatile Organic Compound

Table 3.
Maximum Rated Power Output Fraction (PS)

Ship category	2010 World fleet	Mediterranean Sea fleet (2006)
Liquid bulk ships	0.3	0.35
Dry bulk carriers	0.3	0.39
Container	0.25	0.27
General cargo	0.23	0.35
Ro Ro Cargo	0.24	0.39
Passenger	0.16	0.27
Fishing	0.39	0.47
Others	0.35	0.18
Tugs	0.1	–

inventory includes major atmospheric pollutants, namely carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), volatile organic compounds (VOC), and particulate matter (PM). The resulting inventory provides an overview of the contribution of port-related shipping activities to local air pollution and supports future environmental management strategies for sustainable port operations.

Before performing the emission calculations, vessel traffic data were analyzed to identify temporal variations throughout the observation period. **Figure 4** presents the monthly distribution of vessel traffic recorded at Tanjung Priok Port during 2024.

As illustrated in **Figure 4**, vessel traffic varied throughout the year, with monthly ship movements ranging from 1,720 to 2,480 vessels. The lowest traffic volume was recorded in April, with 1,720 vessels, whereas the highest traffic volume occurred in November, reaching 2,480 vessels, followed by December with 2,463 vessels. This trend indicates a gradual increase in shipping activity during the final quarter of the year, reflecting higher maritime transportation demand and port operational intensity. Since ship exhaust emissions are directly influenced by the number of vessel movements and operational activities, November was identified as the representative month for detailed emission estimation because it represents the maximum shipping activity observed during the study period.

Following the identification of the busiest month, a more detailed analysis was conducted to determine the daily distribution of vessel traffic in November 2024. This analysis aims to identify the day with the highest concentration of vessel movements, thereby representing the period with the greatest potential for exhaust gas emissions. The daily vessel traffic recorded during November 2024 is presented in Figure 4.

Based on **Figure 5**, vessel traffic fluctuated considerably throughout the month, with daily vessel movements ranging from 61 to 109 vessels. The highest daily traffic occurred on 3 November 2024, during which 109 vessels were recorded operating within the Tanjung Priok Port area. Other days with relatively high vessel activity included 22 November and 30 November, each recording 103 vessel movements. The significant variation in daily traffic demonstrates that ship movements are influenced by operational schedules, cargo demand, and port logistics, which consequently affect pollutant emission levels.

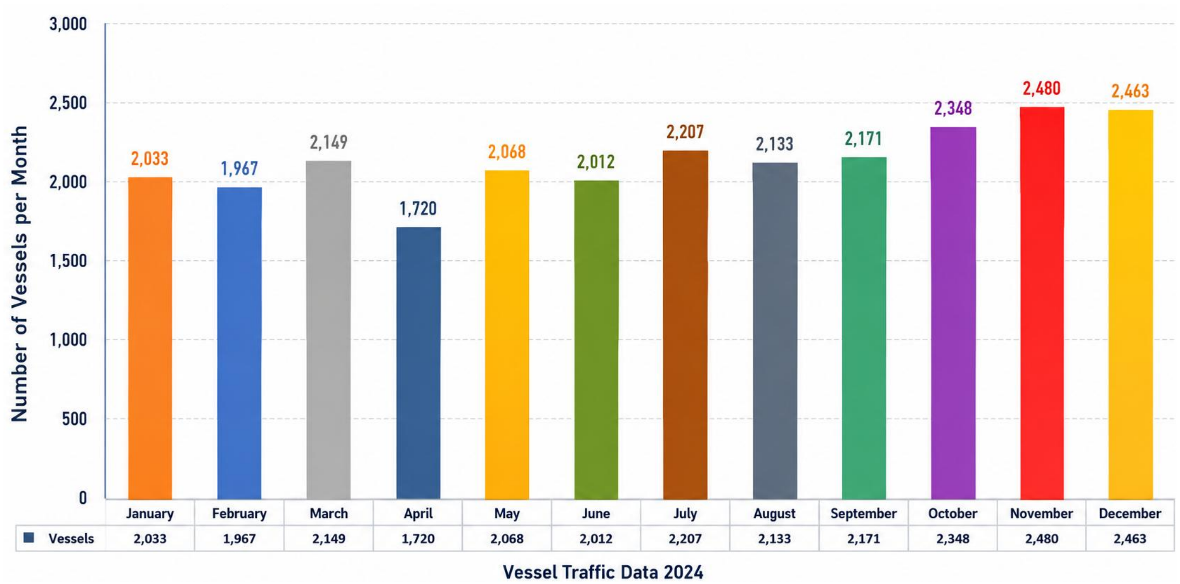


Figure 4. Monthly Vessel Traffic at Tanjung Priok Port in 2024

After identifying the peak traffic period, a detailed analysis was conducted to determine the composition of total of 110 vessels were identified operating within the study area during the selected observation period.

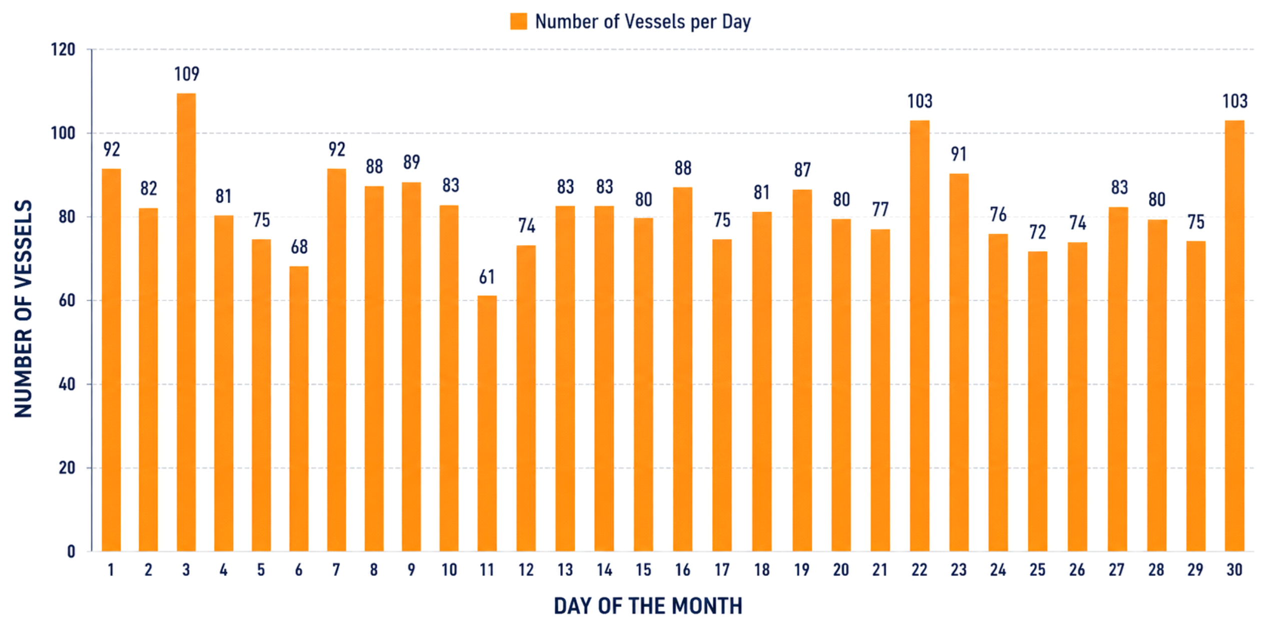


Figure 5. Daily Vessel Traffic in November 2024

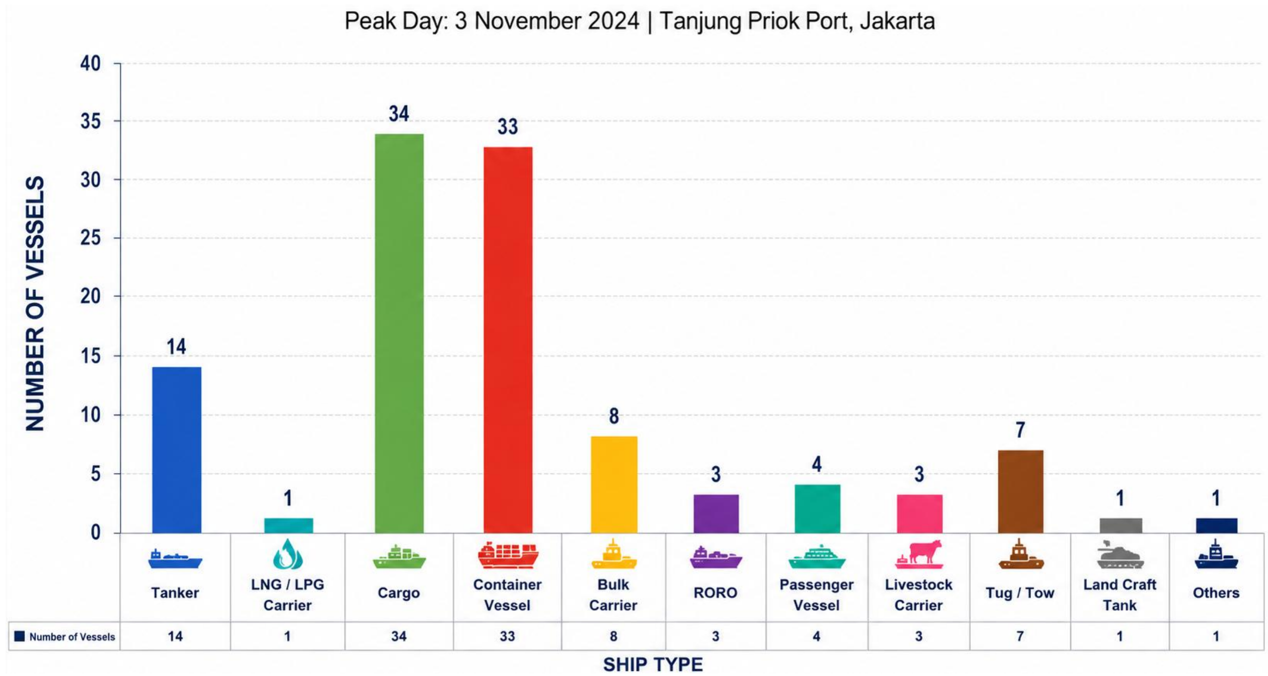


Figure 6. Number of Vessels by Ship Type

vessel types operating in the Tanjung Priok Port area on 3 November 2024, as detected by the Automatic Identification System (AIS). Identifying vessel types is an important step in the emission estimation process because different ship categories have distinct engine characteristics, fuel consumption rates, engine power, and emission factors. Consequently, the composition of vessel traffic significantly influences the magnitude of pollutant emissions generated within the port area.

Figure 6 presents the number of vessels classified by ship type on the busiest day, while **Figure 7** illustrates the percentage distribution of each vessel category. A

As shown in **Figure 7**, cargo ships constituted the largest vessel category, accounting for 34 vessels (31%), followed closely by container vessels with 33 vessels (30%). Tankers represented the third largest group with 14 vessels (13%), while bulk carriers accounted for 8 vessels (7%). Other vessel categories included tugboats (7 vessels, 6%), passenger vessels (4 vessels, 4%), Ro-Ro vessels (3 vessels, 3%), and livestock carriers (3 vessels, 3%). Meanwhile, LNG/LPG carriers, land craft tanks, and other vessel types were each represented by only one vessel (1%), indicating relatively limited operations during the observation period.

The percentage distribution shown in **Figure 7** demonstrates that cargo ships and container vessels together accounted for approximately 61% of the total vessel traffic. This finding indicates that commercial freight transportation dominates maritime activities within the Tanjung Priok Port area, reflecting the port's strategic role as Indonesia's principal international gateway for containerized and general cargo transportation. The dominance of these vessel categories is expected because Tanjung Priok handles most of the country's import and export activities, resulting in intensive cargo handling operations throughout the year.

B. Estimation of Ship Exhaust Gas Emissions

The estimation of ship exhaust gas emissions in this study was performed based on the methodology developed by Trozzi and Vaccaro (1998). This activity-based approach estimates pollutant emissions by considering the actual operational characteristics of vessels, thereby providing a more representative assessment of emissions generated during port operations. The methodology incorporates several important parameters that directly influence fuel consumption and emission rates, including ship type;

gross tonnage (GT); ship operational mode (cruising, maneuvering, and hoteling); and fuel type.

By applying Equations (1) and (2), as described in Section 3.6, the exhaust gas emissions produced by each vessel can be estimated. The calculation process combines vessel characteristics obtained from AIS data with fuel consumption regression models, engine operating conditions, and pollutant-specific emission factors. Consequently, emissions are calculated separately for each operational mode before being aggregated to obtain the total emissions generated within the study area.

Based on the emission calculations performed for both the main engine (ME) and the auxiliary engine (AE), the total emissions generated by vessels operating in the Tanjung Priok Port area were successfully estimated. The analysis was conducted using AIS data collected on 3 November 2024, representing the busiest day identified during the study period. Emission calculations were carried out continuously over the 24-hour observation period (00:00–24:00 WIB), allowing temporal variations in ship activity and exhaust gas emissions to be evaluated throughout the day.

The total estimated emissions amounted to 641.81 kg/h of NO_x, 2,750.63 kg/h of CO, 719.67 kg/h of CO_2, 648.58 kg/h of VOC, 458.44 kg/h of SO_x, and 34.38 kg/h of PM during the observation period. The total emission estimates are presented in **Figure 8**. As presented in **Figure 8**, container vessels were identified as the largest contributors to ship exhaust emissions among all vessel categories. The estimated emissions produced by container vessels reached 247.07 kg/h of NO_x, 1,058.86 kg/h of CO, 275.36 kg/h of CO_2, 247.99 kg/h of VOC, 176.48 kg/h of SO_x, and 13.24 kg/h of PM. These values account for approximately 38.5% of the total NO_x emissions, 38.5% of CO emissions, 38.3% of CO_2 emissions, 38.2% of VOC emissions, 38.5% of SO_x emissions, and 38.5% of PM emissions generated by all vessels operating during the study period.

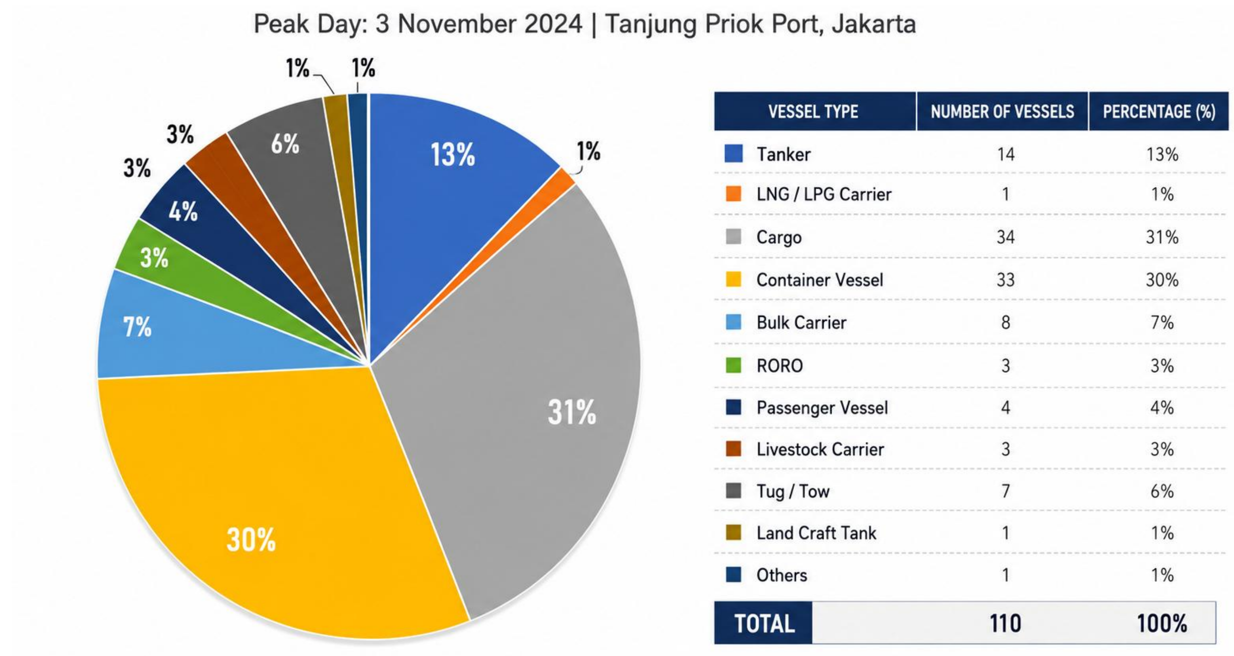
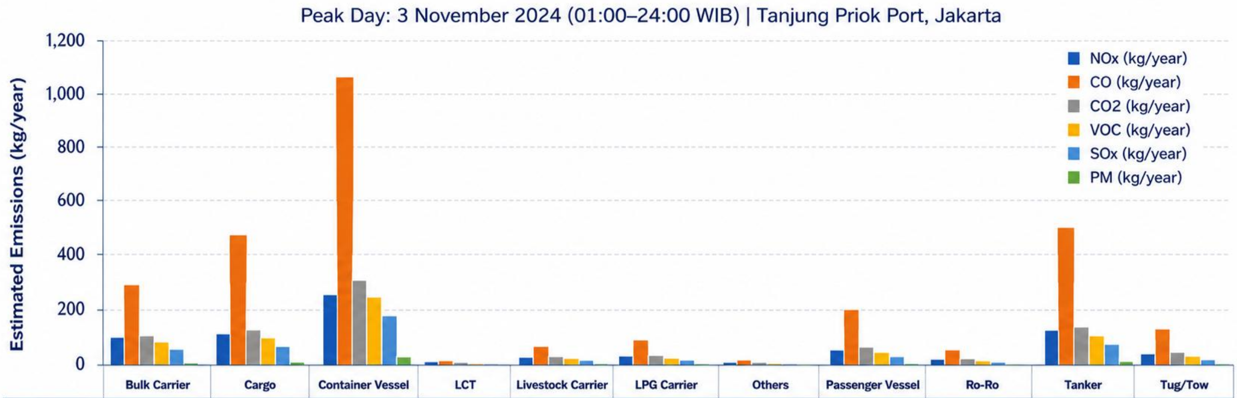


Figure 7. Percentage of Vessel Types

The dominance of container vessels is closely associated with their operational characteristics. Container ships generally possess larger gross tonnage (GT), higher installed engine power, and greater fuel consumption than most other vessel types. Furthermore, Tanjung Priok Port serves as Indonesia's principal container hub, resulting in a high frequency of container vessel arrivals and departures. Consequently, these vessels operate for longer durations during maneuvering and hoteling activities, leading to substantially higher fuel consumption and exhaust gas emissions compared with smaller vessel categories.



Pollutant (kg/year)	Bulk Carrier	Cargo	Container Vessel	LCT	Livestock Carrier	LPG Carrier	Others	Passenger Vessel	Ro-Ro	Tanker	Tug/Tow
NOx	65.07	108.16	247.07	1.51	7.24	12.52	1.61	44.98	8.71	115.90	29.03
CO	278.87	463.54	1,058.86	6.49	31.01	53.68	6.90	192.79	37.34	496.72	124.41
CO2	72.77	121.87	275.36	1.68	7.82	14.05	1.78	51.16	9.71	130.36	33.13
VOC	65.56	109.89	247.99	1.52	7.02	12.66	1.60	46.18	8.74	117.52	29.91
SOx	46.48	77.26	176.48	1.08	5.17	8.95	1.15	32.13	6.22	82.79	20.74
PM	3.49	5.79	13.24	0.08	0.39	0.67	0.09	2.41	0.47	6.21	1.56

Figure 8. Estimate Emission of NO_x, CO, CO_2, VOC, SO_x, and PM by Ship Type

The second-largest contributor was the tanker category, producing 115.90 kg/h of NO_x, 496.72 kg/h of CO, 130.36 kg/h of CO_2, 117.52 kg/h of VOC, 82.79 kg/h of SO_x, and 6.21 kg/h of PM. Tankers contributed significantly because they are generally equipped with high-powered propulsion systems and auxiliary engines to support cargo handling operations involving liquid bulk products. These operational requirements increase fuel consumption, particularly during maneuvering and hoteling within the port area.

The cargo vessel category ranked third in total emissions, generating 108.16 kg/h of NO_x, 463.54 kg/h of CO, 121.87 kg/h of CO_2, 109.89 kg/h of VOC, 77.26 kg/h of SO_x, and 5.79 kg/h of PM. Although cargo vessels represented the largest proportion of vessel traffic (31%), their total emissions remained slightly lower than those of container vessels because of differences in average gross tonnage, engine characteristics, and operational profiles. Other vessel categories, including bulk carriers, passenger vessels, tugboats, LPG carriers, Ro-Ro vessels, livestock carriers, landing craft tanks (LCTs), and miscellaneous vessels, contributed relatively smaller proportions to the total emissions due to their lower numbers, smaller engine capacities, or shorter operational durations within the study area.

Overall, the results demonstrate that container vessels, tankers, and cargo vessels constitute the dominant sources of ship exhaust emissions at Tanjung Priok Port, jointly accounting for most emissions estimated during the observation period. These findings indicate that emission reduction strategies implemented at the port should prioritize these vessel categories through measures such as cleaner marine fuels, shore power utilization during hoteling, optimization of vessel traffic management, and the adoption of more energy-efficient propulsion technologies. Such measures would provide the greatest potential for reducing both greenhouse gas emissions and local air pollutants in Indonesia's busiest seaport.

IV. CONCLUSION

This study successfully estimated ship exhaust gas emissions in the Tanjung Priok Port area by integrating Automatic Identification System (AIS) data with the Trozzi emission estimation methodology. The analysis of AIS data collected throughout 2024 enabled the identification of vessel movements, ship types, gross tonnage, and operational modes, providing a comprehensive activity-based emission inventory under actual operating conditions. The results identified November as the busiest month, with a total of 2,480 vessel movements, while 3 November 2024 recorded the highest daily traffic with 109 vessels. During the busiest operational period, estimated emissions reached 641.81 kg/h of NO_x, 2,750.63 kg/h of CO, 719.67 kg/h of CO_2, 648.58 kg/h of VOC, 458.44 kg/h of SO_x, and 34.38 kg/h of PM, indicating that intensive shipping activities represent an important source of atmospheric pollution in the port area. Among all vessel categories, container vessels were identified as the largest contributors to total emissions, followed by tankers and cargo vessels, mainly because of their higher traffic frequency, larger gross tonnage, and greater engine power. These findings demonstrate that integrating AIS data with the Trozzi methodology provides a reliable and practical approach for developing high-resolution ship emission inventories in Indonesian ports. The resulting inventory can support environmental monitoring, sustainable port management, and evidence-based maritime emission reduction policies by identifying the dominant emission sources and peak operational periods that should be prioritized for future mitigation strategies.

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