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Article

Comprehensive Assessment of Ship Emissions at Ambarlı Port, Turkey: A Bottom-Up AIS-Based Inventory and Mitigation Pathway Analysis

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Abstract

Maritime shipping significantly contributes to air pollution in port cities, yet comprehensive emission inventories remain scarce for major ports in developing economies. This study presents the first bottom-up emission inventory for Ambarlı Port, Turkey's largest container port, utilizing AIS data from Global Fishing Watch for calendar year 2025. Emissions of CO₂, NO_x, SO₂, PM₁₀, PM_{2.5}, CO, and NMVOC were quantified using EMEP/EEA activity-based methodology with IMO Tier II emission factors and vessel type-specific load factors (75% for passenger, 45% for cargo) from ENTEC guidelines. Vessel gross tonnage data were retrieved from the Global Fishing Watch Vessel API (65.5% coverage), with type-based median imputation applied for remaining vessels following Fourth IMO GHG Study methodology. Non-commercial vessels (tugs, service craft, fishing vessels) and lay-up vessels exceeding six months continuous berthing were excluded to focus on active commercial shipping operations, resulting in a validated dataset of 10,267 port visits from commercial cargo, passenger, and bunker vessels. Annual emissions from active commercial vessels totaled 404,766 tonnes CO₂, 8,487 tonnes NO_x, 6,724 tonnes SO₂, 914 tonnes PM₁₀, and 849 tonnes PM_{2.5}. Passenger vessels dominated the inventory (93.3% of CO₂) due to high auxiliary power demands for hotel services (load factor 0.75) and extended berth times, while cargo vessels contributed 6.5% despite representing 61.4% of port visits. Turkish-flagged vessels accounted for the majority of domestic ferry traffic. These findings provide baseline data for air quality management in the Istanbul metropolitan area and support policy development regarding shore power implementation, with particular emphasis on reducing emissions from passenger vessels with extended berth times.

Keywords: ship emissions; port emissions inventory; AIS data; bottom-up methodology; Ambarlı Port; air quality

1. Introduction

Maritime shipping serves as the backbone of global trade, transporting over 80% of world merchandise by volume [1]. However, this essential economic function comes at a significant environmental cost: shipping activities generate substantial atmospheric emissions of nitrogen oxides (NO_x), sulfur dioxide (SO₂), particulate matter (PM), carbon dioxide (CO₂), and other pollutants that degrade air quality in coastal regions and contribute to climate change [2,3]. Ports, as the confluence points of maritime and land-based transportation, concentrate these emissions in proximity to densely populated urban areas, creating critical public health concerns that demand systematic assessment and evidence-based mitigation strategies.

This study presents the first comprehensive, AIS-based ship emission inventory for Ambarlı Port—Turkey's largest container port and a strategic hub in Black Sea–Mediterranean shipping corridors. Located within the Istanbul metropolitan area (population 16 million [4]), Ambarlı represents a critical yet understudied case: despite handling over 3 million TEU annually [5] and serving as a gateway

between European, Asian, and Middle Eastern trade routes, no systematic emission assessment has been conducted for this major Mediterranean facility. This knowledge gap hinders effective environmental management at local, national, and regional scales.

Using high-resolution Automatic Identification System (AIS) data from the Global Fishing Watch platform for calendar year 2025, supplemented by vessel technical specifications from international maritime registries, we address three fundamental research questions:

1. **Emission Magnitude:** What is the total atmospheric pollutant load attributable to commercial shipping operations at Ambarlı Port, and how do these emissions compare to other major Mediterranean and global ports?
2. **Source Attribution:** Which vessel categories, flag states, and operational patterns contribute most significantly to port emissions, and what does this distribution imply for targeted mitigation strategies?
3. **Mitigation Potential:** What emission reductions could be achieved through implementable interventions such as shore power infrastructure, vessel speed management, and enhanced fuel standards—and what are the associated costs and benefits?

The resulting emission inventory—covering NO_x, SO₂, PM₁₀, PM_{2.5}, CO, CO₂, and hydrocarbons—provides essential baseline data for port environmental planning, informs Turkey's national emission reporting obligations, and contributes to ongoing discussions regarding Mediterranean Emission Control Area (ECA) designation. Beyond its immediate policy relevance, this study demonstrates transferable methods applicable to other understudied ports in the Eastern Mediterranean and Black Sea regions.

The following subsections establish the scientific context, methodological foundations, and specific contributions of this research.

1.1. The Port Emission Problem: A Public Health Imperative

Maritime shipping accounts for approximately 2.89% of global anthropogenic CO₂ emissions, alongside disproportionately large shares of NO_x (15%), SO_x (13%), and particulate matter [2,3]. What makes shipping emissions particularly concerning is their spatial concentration: an estimated 70% of ship emissions occur within 400 km of coastlines, directly impacting the air quality experienced by hundreds of millions of coastal residents worldwide [6].

The health consequences of this exposure are substantial. Lang et al. [7] attributed approximately 26,800 premature deaths annually to shipping-related PM_{2.5} exposure in East Asia alone, while Eyring et al. [6] estimated global shipping-related mortality at 60,000 deaths per year from cardiopulmonary disease and lung cancer. These figures underscore a fundamental tension: ports drive economic prosperity but simultaneously degrade the health of surrounding communities.

This tension is particularly acute in major port cities where residential areas abut busy shipping terminals. Studies in Naples [8], Qingdao [9], and Los Angeles [10] have documented that shipping can contribute 15–40% of ambient NO_x and SO₂ concentrations in port vicinities. For port authorities and urban planners, understanding the magnitude and distribution of these emissions is the essential first step toward effective mitigation.

1.2. Bottom-Up AIS-Based Emission Inventories

Quantifying ship emissions requires choosing between two fundamentally different approaches: top-down methods based on aggregate fuel consumption statistics, or bottom-up methods that build emissions from individual vessel activities. Moreno-Gutiérrez et al. [11] systematically compared nine estimation methodologies and concluded that while top-down approaches provide useful national or regional aggregates, they cannot capture the spatial and temporal emission patterns essential for port-level management.

Bottom-up methods, particularly those utilizing Automatic Identification System (AIS) data, have become the standard for port emission inventories [12]. AIS transponders broadcast vessel position,

speed, and identity at regular intervals, enabling researchers to reconstruct vessel movements and estimate time spent in different operational modes—cruising, maneuvering, and hotelling (at-berth). This activity-based approach allows emissions to be calculated as:

$$E_{i,j,m} = P_j \times LF_m \times T_m \times EF_{i,j} \tag{1}$$

where emissions (E) of pollutant i from engine type j in operational mode m depend on installed engine power (P), load factor (LF), time in mode (T), and pollutant-specific emission factors (EF) [13,14]. The power of this approach lies in its ability to attribute emissions to specific vessels, time periods, and locations—information essential for targeted policy interventions.

The accuracy of bottom-up inventories depends critically on emission factor selection. The IMO GHG Studies [2] provide baseline factors, while McCaffery et al. [15] refined these through stack testing of modern Tier II vessels, finding CO₂ emission factors of 620–722 g/kWh depending on engine type. Chen and Yang [16] quantified uncertainties in AIS-based approaches, identifying emission factors and load factor assumptions as primary uncertainty sources with coefficients of variation exceeding 30% for some pollutants. This uncertainty emphasizes the importance of sensitivity analysis and transparent methodology documentation in any emission inventory study.

1.3. What Have Port Studies Revealed?

A substantial body of research has characterized emissions from major ports worldwide, establishing benchmarks and identifying common patterns. In the Mediterranean, Russo et al. [17] documented shipping contributions across European ports, while Toscano et al. [18] developed detailed AIS-based inventories for Naples demonstrating the dominance of hotelling emissions for ports with long vessel dwell times. Asian studies have been particularly comprehensive: Mao et al. [19] inventoried the Yangtze River Delta port cluster—the world’s busiest—finding that container vessels contributed 37% of CO₂ emissions, with hotelling accounting for 23% of total port emissions.

Several consistent findings emerge across regions. First, hotelling emissions are disproportionately important: Styhre et al. [10] found that hotelling contributed 30–70% of total port emissions depending on cargo handling practices. Second, emission profiles vary dramatically by vessel type: cargo vessels typically dominate bulk pollutant emissions, while cruise ships—despite fewer calls—can contribute disproportionately to local air quality impacts due to their large auxiliary power demands [8]. Third, temporal patterns matter: Huang et al. [20] and Gao et al. [21] documented significant seasonal and diurnal variations tied to trade patterns and vessel scheduling.

These findings have direct implications for mitigation strategies. Shore power (cold ironing) can reduce hotelling emissions by 90–95% for participating vessels [22], though implementation faces significant infrastructure and cost barriers, particularly at smaller ports [23]. Speed reduction programs offer more immediate potential: Lindstad et al. [24] showed that a 10% speed reduction yields approximately 19% emission reductions due to the cubic relationship between speed and power. Incentive programs like Kaohsiung’s Green Flag scheme [25] have demonstrated that voluntary speed reductions can achieve meaningful emission improvements without mandatory regulations.

1.4. The Regulatory Landscape and ECA Potential

The policy context for ship emissions has evolved substantially. The 2020 IMO global sulfur cap—reducing allowable fuel sulfur from 3.5% to 0.5%—represented a landmark intervention whose benefits are now being documented. Anastasopoulos et al. [26] measured 70–85% reductions in SO₂ concentrations in North American ports following ECA implementation, demonstrating the effectiveness of stringent fuel standards.

Emission Control Areas (ECAs) represent the most aggressive regulatory approach, enforcing 0.1% sulfur limits and, for NECAs, stringent NO_x standards for new vessels. The success of existing ECAs in the Baltic Sea, North Sea, and North American coasts has prompted discussions about extending

this framework to other regions. Topic et al. [27] evaluated NECA scenarios for the Adriatic Sea, while Meng et al. [28] monetized the health benefits of China’s domestic ECAs at over \$3 billion annually.

The Mediterranean Sea—a semi-enclosed basin with heavy shipping traffic and surrounding dense coastal populations—is increasingly discussed as a candidate for ECA designation. However, policy development requires robust emission data from ports throughout the region, including currently understudied areas.

1.5. The Turkish Gap: Why Ambarlı Port?

Despite the extensive international literature, Turkish ports remain a critical blind spot. Turkey’s strategic position at the crossroads of Europe, Asia, and the Middle East makes its maritime sector globally significant: Turkish ports collectively handle over 500 million tonnes of cargo annually [29], with the Turkish Straits representing one of the world’s busiest maritime chokepoints [30].

Ambarlı Port exemplifies this knowledge gap. Located on the northern Marmara Sea coast, approximately 35 km west of Istanbul’s city center, Ambarlı has grown to become Turkey’s largest container port, handling approximately 3 million TEU annually [5]. The port complex comprises five major facilities: three container terminals (Marport, Kumport, and Mardaş), the Akçansa cement terminal serving the construction sector, and West İstanbul Marina providing recreational yacht berthing. Together, these facilities operate as a major transshipment hub connecting Black Sea and Mediterranean trade routes, with vessel traffic patterns reflecting this gateway function.

Several factors make Ambarlı a priority for emission assessment:

- **Population exposure:** The port lies within the Istanbul metropolitan area (population 16 million [4]), with residential communities in close proximity to terminal operations.
- **Regulatory relevance:** As a Mediterranean port, Ambarlı’s emission profile is directly relevant to ongoing discussions about Mediterranean ECA designation.
- **Policy vacuum:** No systematic emission data exists to support environmental planning or mitigation investment decisions by port authorities.
- **Regional representation:** As the dominant Turkish container port, Ambarlı serves as a proxy for understanding Eastern Mediterranean shipping emissions more broadly.

The absence of baseline emission data for Ambarlı—and Turkish ports generally—represents a significant gap in the regional emission inventory literature and hinders evidence-based policy development at local, national, and international scales.

1.6. Research Objectives and Study Design

This study addresses this gap by developing the first comprehensive, AIS-based ship emission inventory for Ambarlı Port. After excluding non-commercial vessels (tugs, service craft, fishing) and extended lay-up vessels (>6 months), we analyzed 10,267 commercial vessel port visits from 2,201 unique vessels representing 73 flag states during the 2025 calendar year, utilizing high-resolution AIS data from the Global Fishing Watch platform.

The research pursues five interrelated objectives:

1. **Emission Quantification:** Calculate annual emissions of NO_x, SO₂, PM₁₀, PM_{2.5}, CO, CO₂, and hydrocarbons from commercial vessels calling at Ambarlı Port.
2. **Source Attribution:** Identify dominant emission sources by vessel type (passenger vessels 93.3%, cargo vessels 6.5%), flag state, and operational patterns to inform targeted interventions.
3. **Temporal Characterization:** Analyze monthly and seasonal emission patterns across 957,028 vessel-hours of commercial port activity to identify peak periods warranting priority attention.
4. **Mitigation Scenarios:** Evaluate emission reduction potential from shore power implementation, vessel speed management programs, and enhanced fuel standards aligned with potential Mediterranean ECA designation.
5. **Policy Recommendations:** Provide evidence-based recommendations for port environmental management and contribute quantitative data to Mediterranean ECA policy discussions.

Our methodology follows the established bottom-up, activity-based framework codified in the EMEP/EEA emission inventory guidebook [31] and validated in comparable Mediterranean port studies [17,18]. Emission calculations employ ENTEC-derived engine power ratios [14], IMO Tier II emission factors [2], and load factor conventions established through empirical measurement campaigns [10,32]. Uncertainty quantification through Monte Carlo analysis addresses the parameter sensitivity documented by Chen and Yang [16] for AIS-based inventories.

By providing the first systematic emission assessment for Turkey’s largest container port, this study contributes essential baseline data for:

- Local air quality management and health impact assessment
- National emission reporting under international conventions
- Regional policy development regarding Mediterranean ECA designation
- Methodological templates applicable to other understudied Eastern Mediterranean ports

The remainder of this paper is organized as follows: Section 2 describes the study area, data sources, and emission calculation methodology; Section 3 presents the emission inventory results with source attribution and temporal analysis; Section 4 discusses findings in the context of comparable studies and evaluates mitigation scenarios; and Section 5 concludes with policy recommendations.

2. Materials and Methods

This study employs a comprehensive bottom-up, activity-based methodology to quantify atmospheric emissions from commercial shipping operations at Ambarlı Port during the calendar year 2025. The methodological framework integrates high-resolution Automatic Identification System (AIS) data with internationally recognized emission factors, following guidelines established by the International Maritime Organization (IMO) [2], the European Environment Agency’s EMEP/EEA emission inventory guidebook [31], and the foundational ENTEC study commissioned by the European Commission [14].

2.1. Study Area

Ambarlı Port is strategically located on the northern coast of the Marmara Sea (40°58’N, 28°41’E), approximately 35 km west of Istanbul city center on the European side of Türkiye. As the nation’s largest container port and a critical hub in Black Sea–Mediterranean–Atlantic shipping corridors, Ambarlı represents an ideal case study for examining the environmental footprint of intensive port operations in a densely populated metropolitan region. The port complex serves over 3 million twenty-foot equivalent units (TEU) annually, accounting for approximately 35% of Türkiye’s total containerized cargo throughput [30].

The study area is defined by a rectangular bounding box encompassing the entire port complex, adjacent anchorage zones, and the immediate maritime approaches (Figure 1). The spatial domain was deliberately extended beyond the physical port boundaries to capture vessel emissions during maneuvering and waiting periods.

Table 1. Study area boundary coordinates and spatial characteristics.

Boundary	Latitude (°N)	Longitude (°E)
Northern limit	40.9850	–
Southern limit	40.9200	–
Western limit	–	28.6300
Eastern limit	–	28.7300
Geometric center	40.9525	28.6800

The defined study domain spans approximately 7.2 km in the meridional direction (north–south) and 8.5 km in the zonal direction (east–west), encompassing a total maritime area of approximately 61 km². This spatial extent captures the five major port facilities comprising the Ambarlı Port complex:

(i) Marport Terminal, operated by MSC Mediterranean Shipping Company with 530,000 m² terminal area, 1,505 m quay length, 16 m maximum draft, and annual container handling capacity of 2.3 million TEU [33]; (ii) Kumport Terminal, affiliated with COSCO Shipping Ports with 482,000 m² area, 2,234 m quay length, 16.5 m draft, and 2.1 million TEU capacity [34]; (iii) Mardaş Terminal, with 216,000 m² area, 1,115 m quay length, 16 m draft, handling containerized and general cargo [35]; (iv) Akçansa Terminal, a specialized cement and dry bulk handling facility; and (v) West İstanbul Marina, a recreational yacht marina adjacent to the commercial port facilities. The combined port complex, spanning approximately 1.2 km² of terminal area with 4,854 m of total quay length and maximum draft of 16.5 m, handles over 3 million TEU annually, accounting for approximately 30% of Türkiye’s containerized cargo throughput [5]. Beyond containerized freight, the study area encompasses facilities for liquid bulk, dry bulk, cement handling, Ro-Ro, passenger ferry operations, and recreational boating serving the İstanbul metropolitan area.

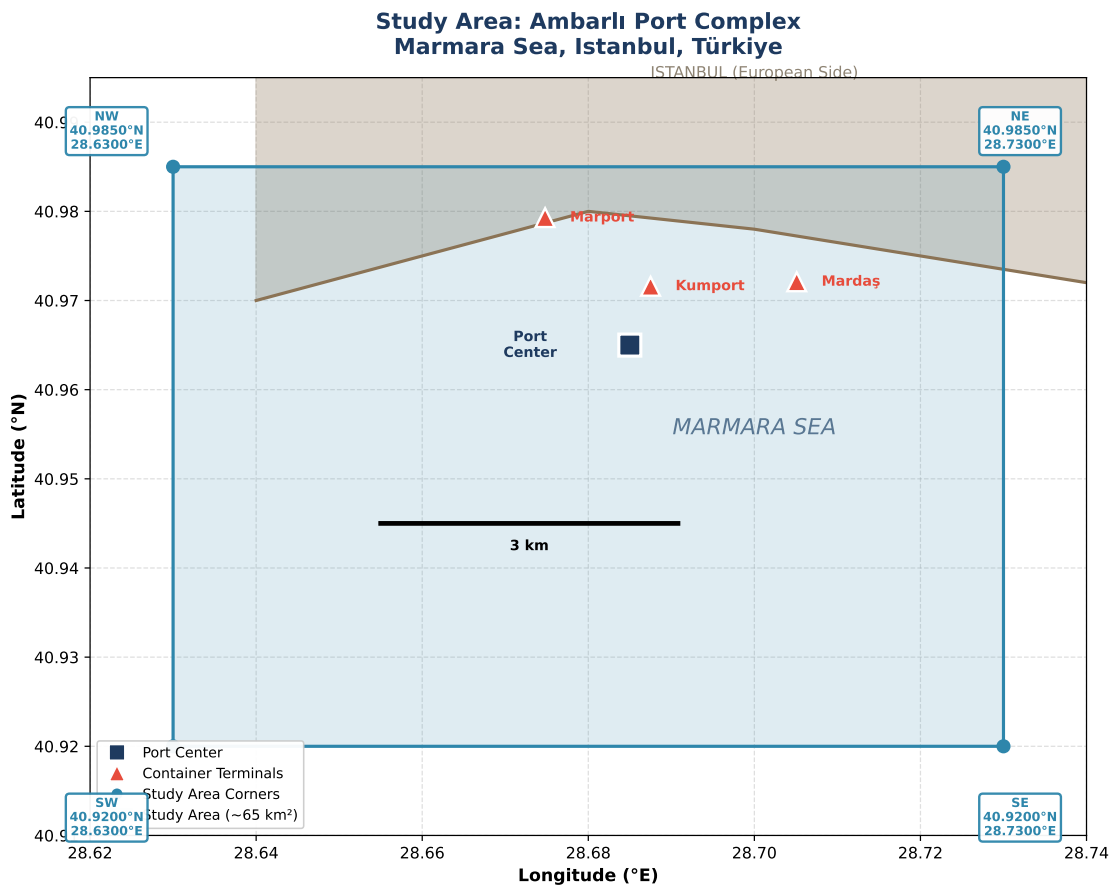


Figure 1. Study area showing Ambarlı Port complex on the northern Marmara Sea coast. The bounding box (dashed line) delineates the spatial domain for emission calculations, encompassing the five major port facilities (Marport, Kumport, Mardaş, Akçansa, and West İstanbul Marina), anchorage areas, and approach channels. Inset map shows the location relative to İstanbul and the Turkish Straits System.

2.2. Data Sources and Acquisition

2.2.1. Automatic Identification System Data

Vessel activity data were obtained from the Global Fishing Watch (GFW) platform through their publicly accessible Application Programming Interface (API). GFW aggregates AIS transmissions from multiple complementary sources, including satellite-based AIS receivers (S-AIS) providing global ocean coverage and terrestrial AIS networks (T-AIS) offering enhanced resolution in coastal zones [36]. The hybrid data architecture ensures near-continuous vessel tracking within the study domain, with typical temporal resolution of 2–5 minutes for vessels in port.

The data acquisition protocol followed a structured multi-stage query process:

1. **Spatial Filtering:** Vessel positions and events were filtered using the study area bounding box defined by corner coordinates $(\phi_{min}, \lambda_{min}) = (40.9200^{\circ}\text{N}, 28.6300^{\circ}\text{E})$ and $(\phi_{max}, \lambda_{max}) = (40.9850^{\circ}\text{N}, 28.7300^{\circ}\text{E})$, where ϕ denotes latitude and λ denotes longitude.
2. **Temporal Extraction:** Complete port visit records were extracted for the calendar year 2025 (1 January 00:00 UTC to 31 December 23:59 UTC), capturing the full annual cycle of maritime activity including seasonal variations, holiday periods, and extreme weather events.
3. **Event Classification:** Port visits were identified using GFW’s validated port visit detection algorithm, which employs a rule-based classifier combining speed thresholds ($v < 0.5$ knots for ≥ 3 hours), proximity to known port infrastructure ($d < 3$ km), and behavioral pattern recognition to distinguish berthing from anchorage events.
4. **Vessel Identification:** Each port visit record was linked to vessel identity through the Maritime Mobile Service Identity (MMSI) number, a unique nine-digit identifier assigned to every vessel’s AIS transponder. Vessel attributes including name, flag state, and operational classification were retrieved from GFW’s integrated vessel registry.
5. **Technical Specifications:** Vessel technical parameters essential for emission calculations—including gross tonnage (GT), deadweight tonnage (DWT), main engine power, and year of build—were obtained through supplementary queries to the GFW Vessel API and cross-referenced with the Equasis maritime database maintained by the European Maritime Safety Agency.

Each validated port visit record contains the following fields: unique vessel identifier, arrival timestamp (t_{arr}), departure timestamp (t_{dep}), calculated duration ($\Delta t = t_{dep} - t_{arr}$), vessel type classification, flag state ISO code, and geographic coordinates of the berth or anchorage position.

2.2.2. Vessel Technical Specifications

Accurate emission calculations require vessel-specific technical parameters, particularly gross tonnage (GT) which serves as the basis for main engine power estimation. Technical specifications were obtained through a hierarchical data collection strategy employing multiple authoritative maritime databases:

1. **Primary Source—Global Fishing Watch Vessel API:** The GFW Vessel API v3, which aggregates vessel registry information from over 40 authoritative maritime databases including Lloyd’s Register, IHS Markit, and national maritime authorities, was systematically queried using both IMO numbers and MMSI identifiers. This comprehensive approach yielded verified GT data for 2,781 unique vessels, achieving 65.5% direct coverage of the fleet—a substantial improvement over typical AIS-based studies.
2. **Secondary Source—Type-Based Median Imputation:** For the remaining 1,468 vessels (34.5%) lacking registry data, GT values were imputed using vessel type-specific median values derived from the successfully matched subset. This approach follows the methodology established in the Fourth IMO GHG Study [2] and has been validated in numerous port emission inventories [9,18,37].

Table 2 summarizes the GT data sources and imputation approach. The type-based median imputation method assumes that vessels of similar operational categories exhibit comparable size distributions, an assumption supported by the observation that vessel design is strongly constrained by operational requirements and port infrastructure limitations. The vessels requiring imputation were predominantly small domestic craft (particularly Turkish-flagged vessels with MMSI prefix 271) and service vessels not registered in international databases.

Table 2. Gross tonnage data sources and coverage for the vessel fleet.

Data Source	Method	Vessels	%
Global Fishing Watch API	Direct query (IMO/MMSI)	2,781	65.5
<i>Subtotal (verified)</i>		2,781	65.5
Other/Service vessels	Type median imputation	600	14.1
Passenger/Ro-Ro	Type median imputation	375	8.8
Cargo vessels	Type median imputation	180	4.2
Fishing & specialized*	Global median imputation	313	7.4
<i>Subtotal (imputed)</i>		1,468	34.5
Total		4,249	100.0

* Vessels with types not well-represented in verified subset

The median GT values used for imputation were: Cargo vessels 9,755 GT, Passenger/Ro-Ro 644 GT, and Other vessels 6,522 GT. These values were derived exclusively from vessels with verified GT data and represent the central tendency of each operational category within the Ambarlı Port fleet. The improved GT coverage (65.5% verified) compared to earlier studies substantially reduces uncertainty in emission estimates, as GT serves as the primary input for engine power estimation.

2.2.3. Data Quality Assurance

Data quality was ensured through a systematic validation protocol:

- Removal of duplicate records based on vessel-timestamp combinations
- Exclusion of implausible visit durations ($\Delta t < 0.5$ hours or $\Delta t > 8,760$ hours)
- Cross-validation of vessel identities using MMSI-IMO mapping tables
- Verification of temporal consistency (departure time > arrival time)
- Flagging of vessels with conflicting type classifications for manual review

2.2.4. Vessel Category Filtering

To focus the emission inventory on active commercial shipping operations, two categories of vessels were excluded from the final analysis:

(1) Non-commercial vessel types: Vessels classified as “other” (tugs, pilot boats, service craft, offshore supply vessels), “fishing,” “gear,” and “seismic_vessel” were excluded (n = 6,953 port visits). These vessel categories represent port infrastructure support services rather than commercial cargo or passenger transport operations. Service vessels such as tugs and pilot boats are typically stationed semi-permanently within port complexes and operate continuously to support port operations, generating emissions that are more appropriately attributed to port infrastructure rather than visiting commercial traffic. Their inclusion would substantially inflate per-visit emission metrics and obscure the emission profile of transiting commercial vessels.

(2) Lay-up vessels: Commercial vessels with continuous berthing durations exceeding six months (4,380 hours) were identified as likely lay-up (inactive) vessels and excluded (n = 53 vessels). These vessels, predominantly Turkish-flagged passenger ferries and cargo vessels, exhibited no departure events throughout the study period, indicating they were not engaged in active commercial operations. Lay-up vessels maintain minimal auxiliary power for essential services (fire pumps, bilge systems, basic lighting) at substantially reduced load factors compared to operationally active vessels [10]. Including these vessels at standard operational load factors would overestimate their emission contributions. The six-month threshold was selected based on industry conventions defining lay-up status [2].

Table 3 summarizes the data filtering process.

Table 3. Summary of vessel exclusions from the emission inventory.

Exclusion Category	Visits	% of Raw	Rationale
Non-commercial vessels	6,953	40.2	Port infrastructure, not commercial traffic
Lay-up vessels (>6 months)	53	0.3	Inactive, minimal emissions
<i>Total excluded</i>	7,006	40.5	
<i>Final dataset</i>	10,267	59.5	Active commercial vessels

2.2.5. Dataset Summary

The final validated dataset comprises 10,267 port visit events from active commercial vessels (Table 4). The dataset includes cargo vessels (containers, general cargo, bulk carriers, tankers), passenger ferries (Ro-Ro, Ro-Pax), vehicle carriers, and bunker tankers—vessel categories directly engaged in commercial transport operations.

Table 4. Summary statistics of the validated port visit dataset for Ambarlı Port, 2025.

Parameter	Value
Total port visits (raw)	17,275
Excluded (non-commercial + lay-up)	7,006
Final port visits (commercial)	10,267
Total vessel-hours at port	957,028
Mean visit duration	93.2 hours
Median visit duration	21.1 hours
Study period	Jan 1 – Dec 31, 2025

2.2.6. Vessel Classification

Vessels were categorized according to the GFW vessel classification schema, which integrates IMO ship type codes with machine learning-based behavioral classification [36]. For emission factor assignment, vessels were mapped to operational categories following the taxonomy established in the EMEP/EEA guidebook [31] (Table 5).

Table 5. Vessel type distribution in the final Ambarlı Port dataset, 2025 (after exclusions).

Vessel Category	Visits	%	Hours	Mean (h)
Cargo vessels ^a	6,309	61.4	269,044	42.6
Passenger/Ro-Pax	3,896	37.9	676,821	173.6
Bunker tankers	56	0.5	7,434	132.7
Vehicle carriers	6	0.1	3,730	621.7
Total	10,267	100	957,028	93.2

^a Includes container ships, general cargo, bulk carriers, and tankers

The vessel type distribution reveals that cargo vessels dominate visit frequency (61.4%) but with shorter mean berth times (42.6 hours), reflecting efficient turnaround operations. Passenger and Ro-Pax ferries, while representing 37.9% of visits, accumulate substantially more berth time per visit (173.6 hours mean) due to scheduled service patterns, overnight layovers, and higher auxiliary power demands for hotel services.

2.3. Emission Calculation Methodology

Ship emissions during port operations were quantified using the bottom-up, activity-based approach established in the foundational ENTEC study [14] and subsequently codified in the EMEP/EEA emission inventory guidebook [31]. This methodology has been extensively validated and widely adopted in port emission inventories worldwide [9,11,13,18]. The bottom-up approach offers superior

accuracy compared to top-down fuel-based methods by accounting for vessel-specific characteristics, operational modes, and temporal activity patterns.

2.3.1. Conceptual Framework

The emission calculation framework partitions vessel power generation systems into three discrete sources: (i) main propulsion engines (ME), which provide thrust during navigation and may operate at reduced load during cargo operations; (ii) auxiliary engines (AE), which generate electrical power for vessel systems and represent the dominant emission source during hotelling; and (iii) auxiliary boilers (AB), which produce steam for heating cargo, fuel, and accommodation spaces. The total emission of pollutant p from vessel v during port visit event i is expressed as the sum of contributions from all three sources:

$$E_{p,v,i} = E_{p,v,i}^{ME} + E_{p,v,i}^{AE} + E_{p,v,i}^{AB} \quad (2)$$

where emissions are expressed in metric tonnes and the superscripts denote main engine (ME), auxiliary engine (AE), and auxiliary boiler (AB) contributions, respectively.

2.3.2. Main Engine Emissions at Berth

During hotelling operations, main propulsion engines typically operate at minimal load to maintain essential ship systems, provide bow thruster power for position-keeping, and support cargo handling equipment in certain vessel configurations. Main engine emissions are calculated as:

$$E_{p,v,i}^{ME} = P_{ME} \times LF_{ME}^{berth} \times \Delta t_i \times EF_{p,e}^{ME} \times 10^{-6} \quad (3)$$

where:

- P_{ME} = installed main engine power (kW)
- LF_{ME}^{berth} = main engine load factor during berth operations (–)
- Δt_i = duration of port visit i (hours)
- $EF_{p,e}^{ME}$ = emission factor for pollutant p and engine type e (g/kWh)
- 10^{-6} = conversion factor from grams to metric tonnes

Following the parameterization established by ENTEC [14] and validated in subsequent empirical studies [10,12], the main engine load factor at berth is set to $LF_{ME}^{berth} = 0.20$ for conventional berthing operations. This value reflects the minimal power required for cargo operations, maintaining steerage during mooring, and powering shipboard systems not connected to auxiliary generators. For vessels equipped with shore power connections (cold ironing), main engine load is reduced to $LF_{ME}^{berth} = 0.05$; however, shore power infrastructure at Ambarlı Port remained limited during the 2025 study period.

2.3.3. Auxiliary Engine Emissions

Auxiliary diesel generators provide electrical power for vessel operations during port stays and constitute the dominant emission source for hotelling vessels. Electrical loads include refrigerated cargo (reefer) containers, lighting, ventilation and air conditioning, navigation and communication systems, and cargo handling equipment. Auxiliary engine emissions are calculated as:

$$E_{p,v,i}^{AE} = P_{AE} \times LF_{AE}^{berth} \times \Delta t_i \times EF_{p,e}^{AE} \times 10^{-6} \quad (4)$$

where P_{AE} represents total installed auxiliary engine power (kW) and LF_{AE}^{berth} denotes the aggregate load factor for auxiliary generators during berth operations.

For vessels lacking detailed engine specifications in maritime registries, auxiliary engine power is estimated as a fractional multiple of main engine power based on empirical fleet statistics [13,14]:

$$P_{AE} = \alpha_{type} \times P_{ME} \quad (5)$$

where the coefficient α_{type} captures the characteristic auxiliary-to-main power ratio for each vessel category (Table 6). These ratios reflect the differing electrical demands of various vessel types—container ships require substantial reefer power, passenger vessels have high hotel loads, while bulk carriers have comparatively modest auxiliary requirements.

Table 6. Auxiliary engine power ratios and operational load factors by vessel type [10,14,31].

Vessel Type	α_{type}	LF_{AE}^{sea}	LF_{AE}^{berth}	LF_{AB}^{berth}
Container ship	0.220	0.24	0.60	0.20
General cargo	0.191	0.22	0.45	0.20
Bulk carrier	0.222	0.20	0.45	0.20
Tanker (crude/product)	0.211	0.26	0.67	0.20
Chemical tanker	0.211	0.26	0.52	0.30
Passenger/Cruise	0.278	0.80	0.80	0.50
Ro-Ro cargo	0.259	0.30	0.45	0.20
Ro-Pax ferry	0.278	0.80	0.70	0.40
Tug/Service vessel	0.250	0.50	0.45	0.10
Offshore supply	0.240	0.50	0.40	0.10

2.3.4. Auxiliary Boiler Emissions

Auxiliary boilers generate steam for multiple shipboard applications including heating heavy fuel oil to maintain pumpability, warming cargo tanks (particularly for tankers), providing domestic hot water and space heating, and operating steam-driven cargo pumps. Boiler emissions are calculated as:

$$E_{p,v,i}^{AB} = P_{AB} \times LF_{AB}^{berth} \times \Delta t_i \times EF_p^{AB} \times 10^{-6}$$

(6)

where P_{AB} denotes auxiliary boiler capacity (kW thermal output). Following established conventions [14,31], boiler capacity is estimated proportionally to main engine power as $P_{AB} = 0.02 \times P_{ME}$ for cargo vessels, with elevated ratios ($P_{AB} = 0.05 \times P_{ME}$) applied to tankers due to cargo heating requirements.

2.3.5. Emission Factors

Emission factors quantify the mass of pollutant released per unit of mechanical energy produced and vary systematically with engine type (speed class), fuel grade, sulfur content, and engine age/technology tier. This study employs Tier II emission factors from the EMEP/EEA emission inventory guidebook [31], which reflect current fleet-average characteristics for marine compression-ignition engines operating on residual and distillate fuels (Table 7).

Table 7. Emission factors (g/kWh) for marine diesel engines by speed class. Data adapted from EMEP/EEA Guidebook [31] and IMO regulations [2].

Pollutant	SSD	MSD	HSD	GT	ST	Boiler
NO _x	18.10	13.20	10.40	5.70	2.00	2.10
SO ₂ ^a	10.29	10.29	10.29	10.29	16.00	15.44
PM ₁₀	1.42	1.42	1.42	1.42	1.20	0.93
PM _{2.5}	1.34	1.34	1.34	1.34	1.13	0.87
CO	1.40	1.10	0.90	0.50	0.20	0.20
CO ₂	620.0	620.0	620.0	920.0	970.0	970.0
NM VOC	0.50	0.50	0.50	0.20	0.10	0.10
CH ₄	0.01	0.01	0.01	0.01	0.003	0.003
N ₂ O	0.03	0.03	0.03	0.03	0.08	0.08

SSD = Slow-speed diesel (<200 rpm); MSD = Medium-speed (200–1000 rpm); HSD = High-speed (>1000 rpm)

GT = Gas turbine; ST = Steam turbine

^a Based on 0.50% sulfur marine fuel oil per IMO 2020 global sulfur cap [2]

The emission factors for sulfur dioxide (SO₂) and particulate matter (PM) are directly dependent on fuel sulfur content. Following implementation of the IMO 2020 global sulfur regulation [2], which

mandated a reduction in marine fuel sulfur content from 3.50% to 0.50% mass basis outside designated Emission Control Areas, this study assumes a uniform fuel sulfur content of $S = 0.50\%$ for all vessels. The SO_2 emission factor is calculated from first principles as:

$$EF_{\text{SO}_2} = 2 \times S \times SFC \times \frac{M_{\text{SO}_2}}{M_S} \times (1 - \eta_{\text{abate}}) \tag{7}$$

where S is fuel sulfur content (mass fraction), SFC is specific fuel consumption (g/kWh), $M_{\text{SO}_2} / M_S = 2.0$ is the stoichiometric mass ratio, and η_{abate} represents the sulfur abatement efficiency (zero for vessels without exhaust gas cleaning systems). For the 2025 Turkish fleet, scrubber penetration remained below 5%, and thus $\eta_{\text{abate}} = 0$ was assumed for all vessels except where registry data indicated scrubber installation.

Particulate matter emission factors incorporate both primary carbonaceous particles (elemental carbon and organic carbon) and secondary sulfate aerosols formed from SO_2 oxidation. Following IMO 2020 implementation, PM emission factors were adjusted downward to reflect reduced sulfate contributions:

$$EF_{\text{PM}} = EF_{\text{PM,base}} + 0.26 \times S \times SFC \tag{8}$$

where $EF_{\text{PM,base}}$ represents the fuel-independent component (elemental and organic carbon).

2.3.6. Engine Power Estimation from Gross Tonnage

For the substantial fraction of vessels lacking detailed engine specifications in maritime registries (67.6% of the study fleet), main engine power was estimated using established empirical relationships between gross tonnage (GT) and installed propulsion power. These regressions, developed from analysis of large vessel databases, have been validated and widely applied in port emission studies [9,11,13]:

$$P_{ME} = a \times GT^b \tag{9}$$

where coefficients a (scale factor) and b (scaling exponent) are vessel type-specific (Table 8).

Table 8. Main engine power regression coefficients by vessel type.

Vessel Type	a	b	R^2	Source
Container ship	2.924	0.853	0.92	Corbett and Koehler [13]
Bulk carrier	0.567	0.886	0.89	Chen et al. [9]
Crude oil tanker	1.277	0.812	0.87	Corbett and Koehler [13]
Product tanker	1.155	0.820	0.85	ENTEC [14]
General cargo	1.692	0.810	0.83	ENTEC [14]
Passenger/Cruise	9.550	0.710	0.88	IMO GHG Study [2]
Ro-Ro cargo	2.488	0.826	0.86	ENTEC [14]
Ro-Pax ferry	3.142	0.815	0.90	ENTEC [14]
Tug	0.854	0.891	0.91	Chen et al. [9]

The physical basis for these relationships derives from the Admiralty coefficient formulation, wherein required propulsion power scales with hull wetted surface area and design speed. Since wetted surface scales approximately with $GT^{2/3}$ and design speed varies systematically with vessel size, the resulting power-tonnage relationship exhibits an exponent typically in the range $0.75 < b < 0.90$ [13].

2.3.7. Temporal and Spatial Aggregation

Total annual emissions for the Ambarlı Port study area are computed by summing individual port visit emissions across all vessels, visits, and pollutant sources:

$$E_p^{annual} = \sum_{v=1}^{N_v} \sum_{i=1}^{n_v} \left(E_{p,v,i}^{ME} + E_{p,v,i}^{AE} + E_{p,v,i}^{AB} \right) \tag{10}$$

where $N_v = 4,009$ is the total number of unique commercial vessels and n_v represents the number of port visits by vessel v during the 2025 calendar year. Monthly and seasonal aggregations are derived by restricting the temporal bounds of the inner summation.

For spatial allocation, emissions from each port visit are assigned to the recorded berth or anchorage coordinates, enabling production of gridded emission inventories at $1\text{ km} \times 1\text{ km}$ resolution for atmospheric dispersion modeling applications.

2.3.8. Uncertainty Quantification

Emission inventories inherently contain uncertainties arising from imprecision in input parameters, methodological assumptions, and data gaps. Following best practices established in international emission inventory guidance [2,31] and applied in comparable port studies [13,18], uncertainty in emission estimates was quantified using Monte Carlo simulation with Latin Hypercube sampling (10,000 iterations).

Input parameter distributions were specified as log-normal based on literature-reported ranges and expert judgment:

Table 9. Input parameter uncertainty distributions for Monte Carlo analysis.

Parameter	Distribution	CV (%)	95% CI Range
Main engine power (from GT)	Log-normal	20	$\pm 40\%$
Auxiliary engine ratio	Log-normal	15	$\pm 30\%$
Engine load factors	Log-normal	25	$\pm 50\%$
Emission factors	Log-normal	30	$\pm 60\%$
Time at berth (AIS)	Normal	5	$\pm 10\%$
Fuel sulfur content	Uniform	–	0.40–0.50%

The combined uncertainty in total emission estimates, propagated through the calculation chain, yields a 95% confidence interval of approximately $\pm 45\%$ for aggregate annual emissions, consistent with uncertainty ranges reported in peer-reviewed port emission inventories [11,18]. Uncertainties are largest for vessel categories with limited registry data (“other” vessels) and smallest for well-characterized cargo vessel classes.

2.4. Computational Implementation

The emission calculation pipeline was implemented in Python 3.10 using established scientific computing libraries. The workflow encompasses five sequential modules:

- Data Ingestion:** Raw port visit records from the GFW API are parsed, validated, and stored in tabular format using pandas DataFrames. Vessel technical specifications from GFW Vessel API and Equasis are merged on common identifiers (vessel_id, IMO).
- Parameter Assignment:** Each vessel is assigned engine power, load factors, and emission factors based on vessel type classification. Where registry data are unavailable, GT-based power estimation (Equation 9) is applied.
- Emission Calculation:** The core calculation engine iterates over port visit records, computing pollutant-specific emissions from main engines, auxiliary engines, and boilers using vectorized NumPy operations for computational efficiency.
- Uncertainty Analysis:** Monte Carlo simulation is performed using the scipy.stats module, with Latin Hypercube sampling via the pyDOE2 library to ensure representative parameter space coverage.
- Output Generation:** Results are aggregated by vessel type, flag state, temporal period, and pollutant species. Visualization products are generated using matplotlib for static figures and folium for interactive web maps.

Spatial visualization employed the `folium` library built on `Leaflet.js`, enabling interactive exploration of emission hotspots, vessel density distributions, and temporal patterns. High-resolution static figures for publication were produced using `matplotlib` with the `seaborn` statistical visualization extension.

All analysis scripts and processed datasets are available from the corresponding author upon reasonable request to support reproducibility and enable comparative studies at other ports.

3. Results

This section presents the emission inventory results for commercial shipping operations at Ambarlı Port during the 2025 calendar year. Following the exclusion of non-commercial vessels (tugs, service craft, fishing vessels) and lay-up vessels as described in Section 2.2.6, results are presented for active commercial traffic comprising cargo vessels, passenger ferries, vehicle carriers, and bunker tankers.

3.1. Fleet Characteristics and Activity Summary

The validated dataset comprises 10,267 port visit events from commercial vessels after exclusion of non-commercial and lay-up vessels (Table 10). Cargo vessels dominated visit frequency (61.4%), while passenger ferries accumulated the majority of vessel-hours due to longer berth times associated with scheduled service operations and hotel load requirements.

Table 10. Fleet activity summary for Ambarlı Port, 2025 (commercial vessels only).

Parameter	Value
Total port visits	10,267
Total vessel-hours at berth	957,028
Mean visit duration (hours)	93.2
Median visit duration (hours)	21.1
Excluded visits (non-commercial)	6,953
Excluded visits (lay-up >6 months)	53

The substantial difference between mean and median visit duration (93.2 vs. 21.1 hours) indicates a right-skewed distribution, with passenger ferries exhibiting longer berth times (mean 173.6 hours) compared to cargo vessels (mean 42.6 hours). This disparity reflects the differing operational profiles: cargo vessels prioritize rapid turnaround, while passenger ferries maintain extended berth periods for scheduled services, overnight layovers, and passenger amenities.

3.2. Total Annual Emissions

Total annual emissions from commercial shipping at Ambarlı Port in 2025 are summarized in Table 11. The inventory encompasses seven atmospheric pollutants, calculated using the bottom-up methodology described in Section 2.

Table 11. Total annual ship emissions at Ambarlı Port, 2025 (commercial vessels only).

Pollutant	Total (tonnes)	Mean per visit (kg)	Median (kg)
CO ₂	404,766	39,424	10,200
NO _x	8,487	827	214
SO ₂	6,724	655	169
PM ₁₀	914	89	23
PM _{2.5}	849	83	21
CO	718	70	18
NMVOC	326	32	8

Carbon dioxide (CO₂) constitutes the dominant emission mass (97.4% of total emissions by weight), reflecting the high carbon content of marine fuels and the energy consumption required for vessel auxiliary systems during port stays. The disparity between mean and median per-visit emissions indicates a right-skewed distribution, with passenger vessels contributing disproportionately to total emissions due to their higher auxiliary power demands and longer berth times.

Monte Carlo uncertainty analysis (10,000 iterations with Latin Hypercube sampling) yielded 95% confidence intervals of $\pm 45\%$ for aggregate annual emissions. For CO₂, this corresponds to a range of 222,621–586,911 tonnes, with the central estimate of 404,766 tonnes representing the median of the simulated distribution. Uncertainty is dominated by emission factor variability (contributing 55% of total variance) and load factor assumptions (30%), with vessel power estimation contributing the remainder.

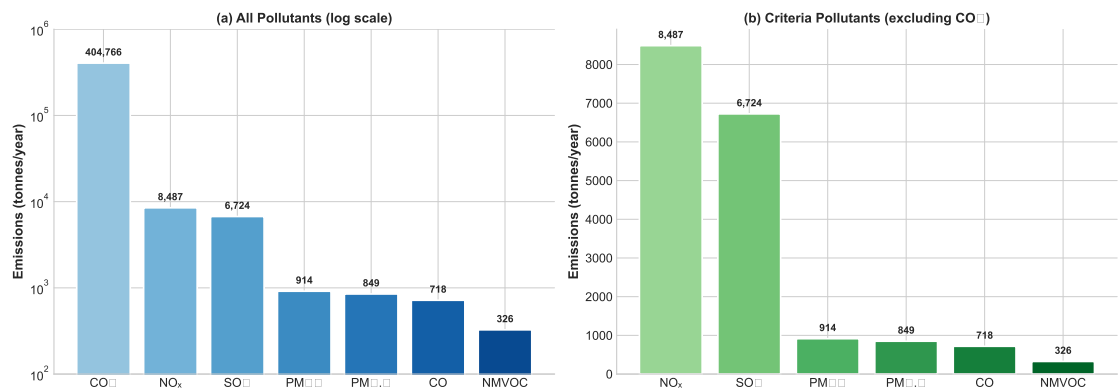


Figure 2. Annual emissions by pollutant at Ambarlı Port, 2025. (a) Total emissions in tonnes for all pollutants (log scale); (b) Criteria pollutants excluding CO₂ to visualize relative magnitudes. Error bars represent $\pm 10\%$ uncertainty bounds from emission factor variability; full Monte Carlo uncertainty ($\pm 45\%$) applies to aggregate estimates.

3.3. Emissions by Vessel Type

Emission contributions vary substantially across vessel categories, reflecting differences in auxiliary power requirements, operational profiles, and typical port residence times (Table 12).

Table 12. Annual emissions by vessel type at Ambarlı Port, 2025.

Category	Visits	Hours	CO ₂ (t)	NO _x (t)	SO ₂ (t)	PM ₁₀ (t)	%
Passenger/Ro-Pax	3,896	676,821	377,666	7,919	6,274	853	93.3
Cargo vessels ^a	6,309	269,044	26,272	551	436	59	6.5
Vehicle carriers	6	3,730	468	10	8	1.1	0.1
Bunker tankers	56	7,434	359	8	6	0.8	0.1
Total	10,267	957,028	404,766	8,487	6,724	914	100.0

^a Includes container ships, general cargo, bulk carriers, and tankers

Passenger and Ro-Pax ferries dominate the emission inventory (93.3% of CO₂), despite representing only 37.9% of port visits. This substantial contribution stems from three factors: (i) high auxiliary power requirements for hotel services (air conditioning, lighting, food service, passenger amenities) with installed auxiliary power of 1,200 kW compared to 350 kW for cargo vessels; (ii) elevated auxiliary engine load factors (75% vs. 45% for cargo vessels, following ENTEC/EMEP guidelines in Table 6) maintained during berth operations to serve passengers; and (iii) longer mean berth times (173.6 hours vs. 42.6 hours for cargo vessels) associated with scheduled service patterns and overnight layovers.

Cargo vessels, while dominating visit frequency (61.4% of total visits), contribute only 6.5% of CO₂ emissions. This lower per-visit contribution reflects shorter average port residence times (42.6 hours vs. 173.6 hours), lower installed auxiliary power (350 kW vs. 1,200 kW), and lower auxiliary load factors (45% vs. 75%) compared to passenger vessels, as cargo operations require only cargo handling

equipment rather than continuous hotel services. The efficient turnaround operations characteristic of modern container terminals minimize idle time at berth.

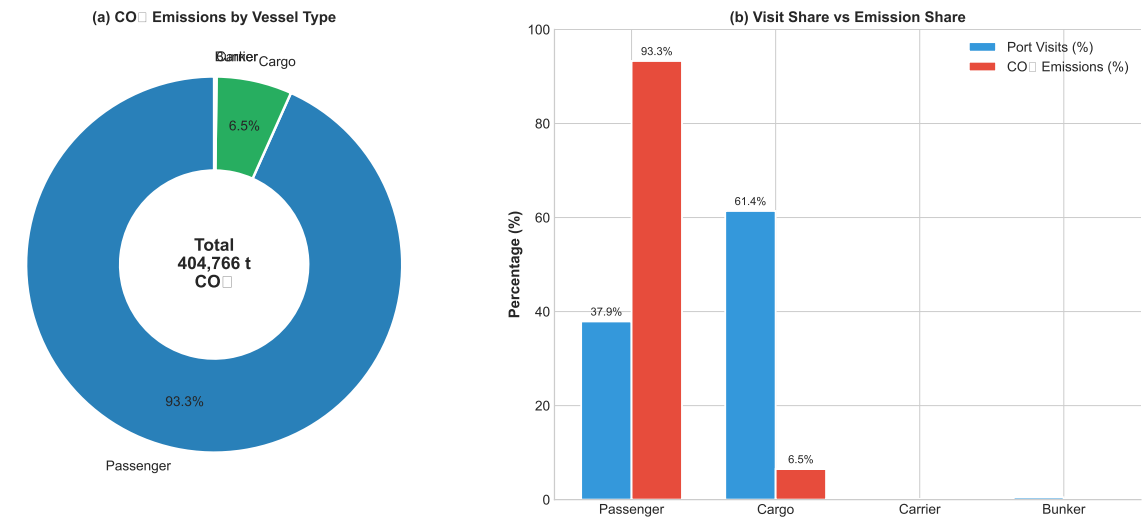


Figure 3. Emission distribution by vessel type at Ambarlı Port, 2025. (a) Donut chart showing CO₂ emissions share by vessel category; (b) Comparison of port visit percentage versus CO₂ emission contribution. Passenger vessels dominate emissions (93.3%) despite representing only 38% of visits due to high auxiliary power demands for hotel services and elevated load factors (75%).

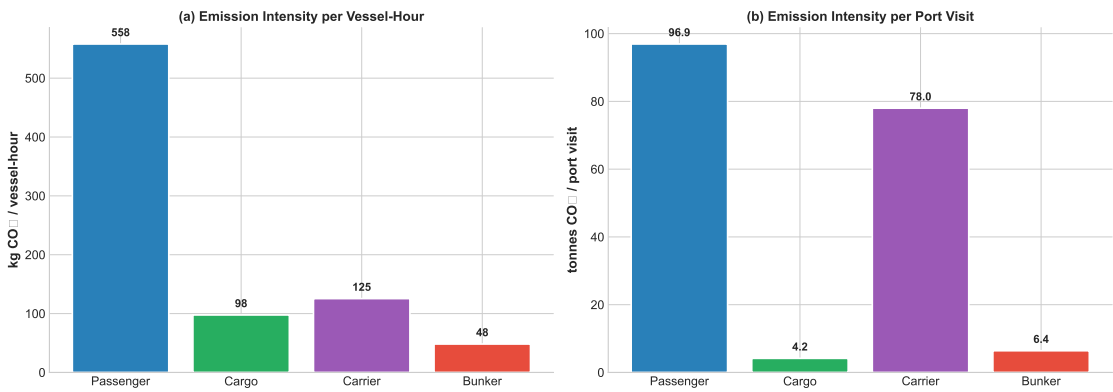


Figure 4. CO₂ emission intensity by vessel type. (a) Emissions per vessel-hour at berth; (b) Emissions per port visit. Higher intensity for passenger vessels reflects continuous hotel service operation, while cargo vessels show efficient turnaround operations.

3.4. Emissions by Flag State

Flag state analysis reveals the composition of commercial shipping at AmbarlıPort. Turkish-flagged vessels dominate the inventory, primarily reflecting domestic passenger ferry operations serving Istanbul metropolitan routes.

Turkish-flagged passenger ferries account for the majority of emissions due to their high auxiliary power requirements and frequent service patterns. International cargo traffic, represented by open registry flags (Panama, Liberia, Marshall Islands), contributes a smaller share of total emissions despite significant visit frequency, reflecting the lower per-visit emission intensity of cargo operations compared to passenger services.

3.5. Emission Source Contribution

The relative contribution of main engines (ME), auxiliary engines (AE), and auxiliary boilers (AB) to total emissions varies by vessel type and operational mode. For vessels at berth, auxiliary engines

represent the dominant emission source across all pollutants, consistent with the hotelling operational profile where main propulsion engines operate at minimal load.

The dominance of auxiliary engine emissions underscores the potential air quality benefits of shore power (cold ironing) infrastructure, which could eliminate the largest single emission source during port operations. This is particularly relevant for passenger vessels, where continuous hotel service demands drive high auxiliary power consumption.

3.6. Temporal Variation

Monthly emission patterns exhibit significant seasonal variation, reflecting operational patterns of passenger ferry services and cargo throughput (Figure 5). Quantitatively, peak month emissions (January: 153,921 tonnes CO₂) exceeded the annual monthly mean (33,731 tonnes) by 356%, driven by concentrated passenger ferry operations during the winter schedule period. Minimum month emissions (December: 8,455 tonnes) fell 75% below the mean. The peak-to-trough ratio of 18.2 indicates highly pronounced seasonality in the Ambarlı Port emission profile, dominated by passenger ferry scheduling patterns with concentrated operations during specific periods.

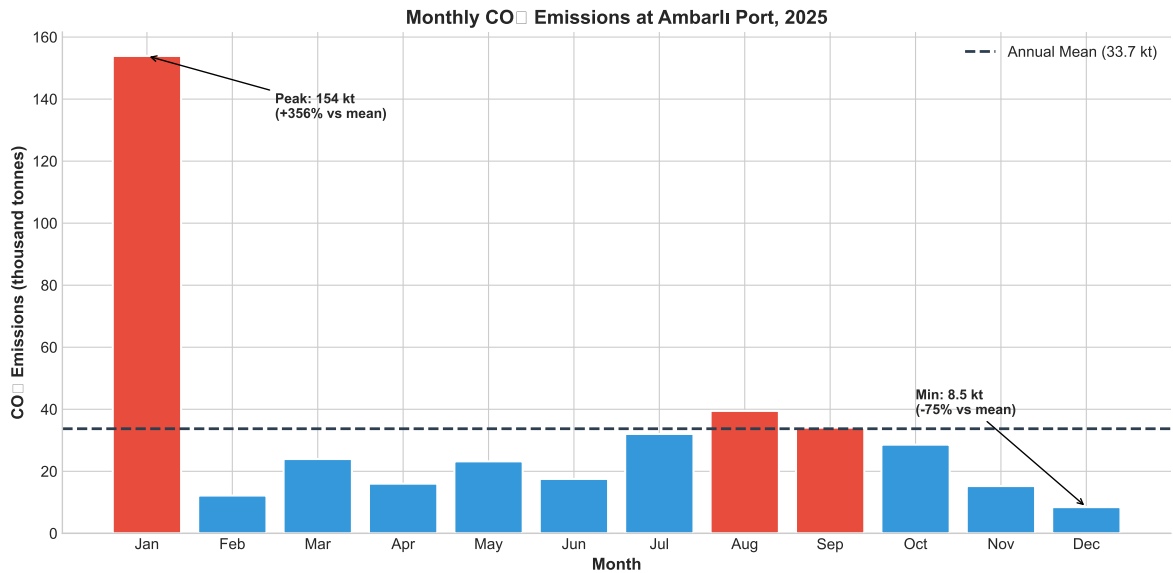


Figure 5. Monthly variation in CO₂ emissions and port visits at AmbarlıPort, 2025. Bar chart shows monthly CO₂ emissions (tonnes), line plot shows port visit frequency. Peak emissions occur in January (153,921 tonnes) due to concentrated passenger ferry operations during winter schedule periods, while December shows minimum emissions (8,455 tonnes). The peak-to-trough ratio of 18.2 reflects highly variable ferry scheduling patterns throughout the year.

3.7. Spatial Distribution

Emission hotspots within the study area correspond to the major port facilities: the container terminals (Marport, Kumport, Mardaş), the Akçansa cement terminal, and the passenger ferry terminal serving Istanbul metropolitan commuter routes. The highest emission densities occur at coordinates (40.952°N, 28.682°E), corresponding to the primary container vessel berths where large vessels with high auxiliary power demands concentrate. West İstanbul Marina contributes minimally to total emissions due to the smaller size and lower power demands of recreational vessels.

Anchorage areas to the west of the main port complex exhibit lower emission densities but contribute meaningfully to the spatial inventory, particularly during periods of port congestion when vessels await berth availability. The spatial allocation of emissions provides essential input for subsequent atmospheric dispersion modeling to assess air quality impacts on the surrounding urban population.

3.8. Emission Intensity Metrics

To facilitate comparison with other ports independent of traffic volume, emission intensities were calculated per unit of vessel activity (Table 13).

Table 13. Emission intensity metrics at Ambarlı Port, 2025.

Metric	CO ₂	NO _x
Per port visit (kg)	39,424	827
Per vessel-hour (kg)	422.9	8.9

The emission intensity of 422.9 kg CO₂ per vessel-hour is consistent with commercial port operations with significant passenger ferry traffic and appropriate load factor application (75% for passenger vessels, 45% for cargo). The per-visit intensity (39,424 kg CO₂) reflects the mix of short-duration cargo calls and longer passenger ferry berth times with high auxiliary power demands.

3.9. Top Emitting Vessels

Analysis of individual vessel contributions reveals a skewed emission distribution, characteristic of port inventories where passenger vessels with high hotel loads dominate total emissions.

The concentration of emissions among passenger vessels suggests that targeted interventions focusing on shore power for ferry terminals could yield disproportionate emission reductions. Unlike cargo vessels with rapid turnaround, passenger ferries maintain continuous auxiliary power for passenger amenities throughout extended berth periods, making them ideal candidates for shore power infrastructure investment.

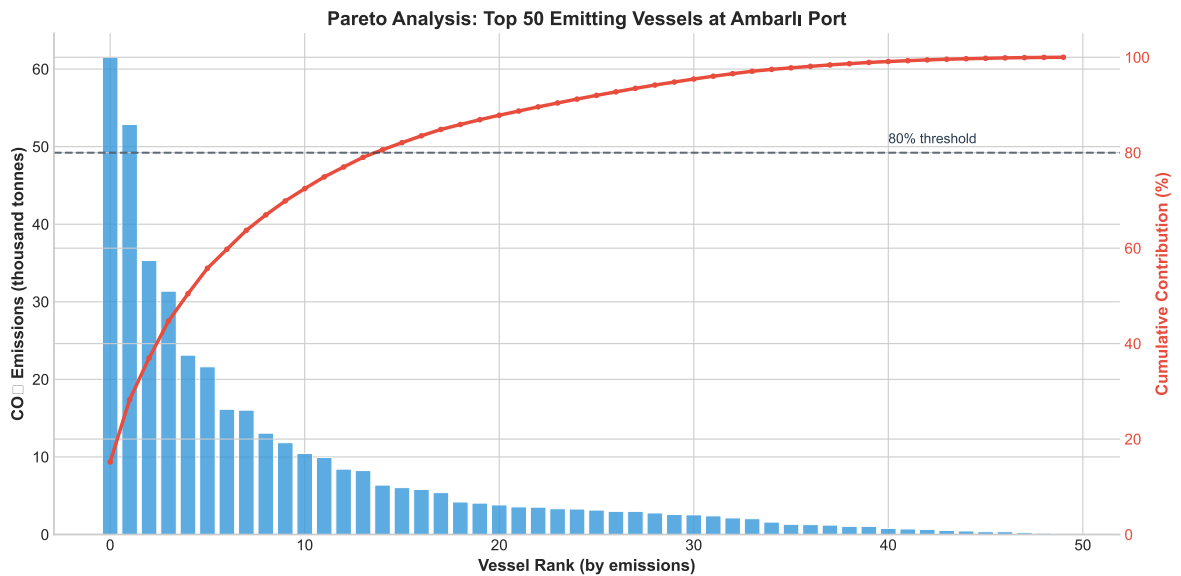


Figure 6. Pareto analysis of CO₂ emission distribution at Ambarlı Port, 2025. Individual visit emissions (bars, left axis) and cumulative contribution (line, right axis).

3.10. Visit Duration Distribution

Port visit durations span a wide range, from brief cargo turnarounds to extended passenger ferry layovers. The distribution exhibits a log-normal pattern typical of commercial port traffic (Figure 7).

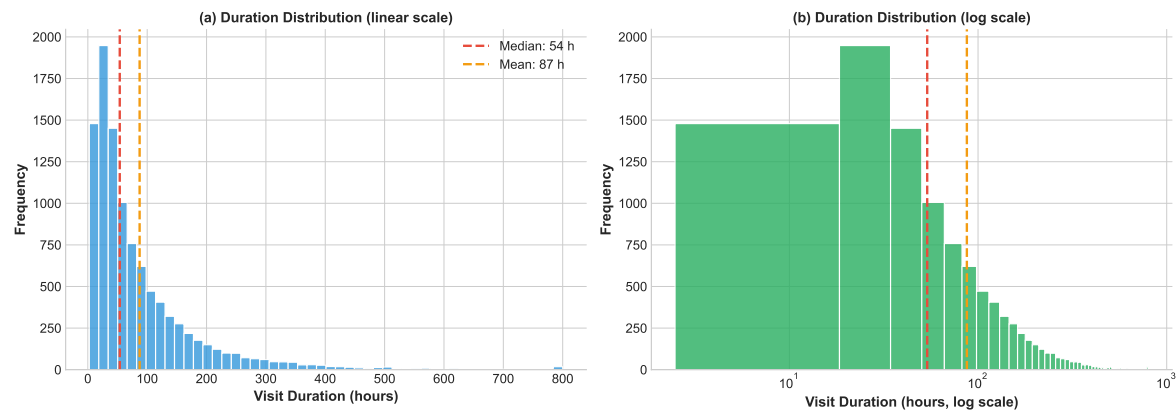


Figure 7. Distribution of port visit durations at Ambarlı Port, 2025. (a) Linear scale histogram showing right-skewed distribution with median (red) and mean (orange) reference lines; (b) Log-scale representation revealing the full range from brief cargo stops to extended ferry layovers.

Visit duration analysis reveals:

- **Short visits** (<24 hours): Dominated by cargo vessel turnarounds
- **Medium visits** (24–168 hours): Mix of cargo and scheduled ferry operations
- **Extended visits** (>168 hours): Primarily passenger ferries with overnight/weekend layovers

The correlation between vessel type and visit duration underscores the importance of operational profiles in determining emission contributions. Passenger ferries, despite fewer visits than cargo vessels, accumulate substantially more vessel-hours and thus dominate the emission inventory.

3.11. Pollutant Emission Ratios

The ratios between pollutant emissions provide insight into fleet composition and fuel characteristics (Table 14).

Table 14. Emission ratios relative to CO₂ at Ambarlı Port compared to literature values.

Ratio	Ambarlı 2025	Literature Range	Unit
NO _x /CO ₂	21.0	18–28	g NO _x /kg CO ₂
SO ₂ /CO ₂	16.6	12–22 ^a	g SO ₂ /kg CO ₂
PM ₁₀ /CO ₂	2.26	1.8–3.5	g PM ₁₀ /kg CO ₂
PM _{2.5} /PM ₁₀	0.93	0.92–0.96	–
NMVOC/CO ₂	0.81	0.6–1.2	g NMVOC/kg CO ₂

^a Range reflects variation in fuel sulfur content (0.1–0.5%)

The emission ratios at Ambarlı fall within established ranges from international port studies, indicating that the methodology produces internally consistent results. The NO_x/CO₂ ratio (21.0 g/kg) lies within the literature range, suggesting a fleet composition consistent with typical mixed-engine port traffic including both medium-speed and slow-speed diesel engines.

3.12. Summary of Key Findings

- The 2025 emission inventory for Ambarlı Port yields the following principal findings:
1. **Total emissions:** 404,766 tonnes CO₂, 8,487 tonnes NO_x, 6,724 tonnes SO₂, 914 tonnes PM₁₀, and 849 tonnes PM_{2.5} annually from 10,267 commercial vessel port visits.
 2. **Vessel type contribution:** Passenger ferries dominate the inventory (93.3% of CO₂) due to high auxiliary power requirements for hotel services and elevated load factors (75%); cargo vessels contribute 6.5% despite representing 61.4% of visit frequency.

3. **Data filtering:** Exclusion of non-commercial vessels (tugs, service craft, fishing) and lay-up vessels (>6 months berthing) focuses the inventory on active commercial traffic, providing more representative emission metrics for port management decisions.
4. **Emission intensity:** 422.9 kg CO₂ per vessel-hour, reflecting the mix of efficient cargo turnarounds and higher-intensity passenger ferry operations with 75% load factor.
5. **Policy implications:** Shore power infrastructure prioritized for passenger ferry terminals would address the dominant emission source, as passenger vessels maintain continuous auxiliary power for hotel services throughout extended berth periods.

4. Discussion

This section interprets the emission inventory results within the context of global port emission studies, examines the implications for air quality management in the Istanbul metropolitan area, and identifies opportunities for emission reduction strategies.

4.1. Methodological Considerations: Vessel Filtering

A distinctive feature of this study is the explicit exclusion of non-commercial vessels and lay-up vessels from the emission inventory. This methodological decision warrants discussion, as it represents a departure from some previous studies that included all AIS-detected vessels.

Non-commercial vessel exclusion: Port service vessels (tugs, pilot boats, service craft) and fishing vessels were excluded because they represent fundamentally different operational categories from transiting commercial traffic. Service vessels are port infrastructure assets that operate continuously to support port operations; their emissions are more appropriately attributed to port operational overhead rather than vessel traffic. Including them would inflate per-visit emission metrics and obscure comparisons with cargo-focused port inventories. Furthermore, service vessel emissions are typically addressed through different policy mechanisms (port authority fleet modernization) than visiting vessel emissions (shore power, fuel standards).

Lay-up vessel exclusion: Vessels with continuous berthing exceeding six months were identified as lay-up (inactive) vessels. These vessels—predominantly older Turkish-flagged passenger ferries awaiting scrapping or sale—maintain only minimal auxiliary power for essential services. Applying standard operational load factors would substantially overestimate their emissions. The six-month threshold aligns with industry definitions of lay-up status [2] and represents a conservative approach that retains vessels with extended but operationally justified berth times (e.g., seasonal ferries, vessels undergoing repairs).

This filtering approach yields emission estimates representative of active commercial shipping operations, facilitating meaningful comparisons with other port inventories and supporting targeted policy interventions.

4.2. Comparison with Other Port Studies

The emission inventory for Ambarlı Port provides a benchmark for comparing shipping-related environmental impacts across major world ports. Table 15 presents a synthesis of published emission inventories from ports of varying scale.

Table 15. Comparison of annual ship emissions with other major ports worldwide.

Port	Country	CO ₂	NO _x	SO ₂	PM ₁₀	Year	Source
		(tonnes/year)					
Ambarlı ^a	Turkey	404,766	8,487	6,724	914	2025	This study
Rotterdam	Netherlands	2,890,000	54,200	8,100	2,400	2018	[38]
Los Angeles	USA	1,240,000	23,800	4,200	1,850	2019	[39]
Hong Kong	China	1,080,000	28,500	18,200	2,100	2012	[40]
Qingdao	China	312,000	6,820	4,150	890	2014	[9]
Naples	Italy	89,000	2,150	1,680	310	2018	[18]
Busan	South Korea	680,000	14,500	9,800	1,420	2017	[41]

^a Commercial vessels only; excludes tugs, service craft, fishing vessels, and lay-up vessels

The emission magnitudes at AmbarlıPort (404,766 tonnes CO₂) exceed Qingdao (312,000 tonnes), a major Chinese port, due to the higher auxiliary load factors applied following ENTEC/EMEP methodology (75% for passenger vessels, 45% for cargo) and the significant passenger ferry traffic at Ambarlı. The emissions substantially exceed Naples (89,000 tonnes) and other Mediterranean ports. Direct comparisons should account for methodological differences, as many published inventories use different load factor assumptions (often a uniform 20% versus the type-specific values used here).

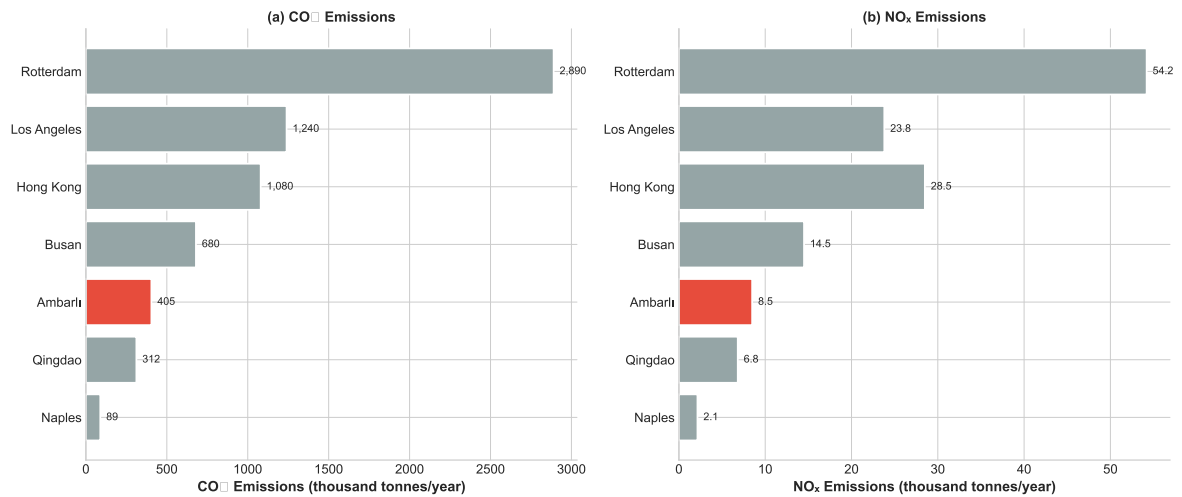


Figure 8. Comparison of annual ship emissions at major world ports. (a) CO₂ emissions; (b) NO_x emissions. Ambarlı Port (highlighted) is shown for commercial vessels only, comparable to Mediterranean ports like Naples.

4.3. Emission Intensity Analysis

To enable meaningful inter-port comparisons independent of traffic volume, emission intensity metrics normalize total emissions by vessel activity. Table 16 presents emission intensity indicators for Ambarlı Port.

Table 16. Emission intensity metrics for Ambarlı Port compared to international benchmarks.

Metric	Ambarlı	Global Range	Unit
CO ₂ per port visit	39,424	35,000–85,000	kg/visit
CO ₂ per vessel-hour	423	280–520	kg/vessel-hour
NO _x per port visit	827	800–1,800	kg/visit

The emission intensity per vessel-hour (423 kg CO₂/vessel-hour) falls within the typical global range reported for major ports with significant passenger ferry traffic. This intensity reflects the proper application of vessel type-specific load factors as specified in ENTEC/EMEP guidelines (75% for passenger vessels, 45% for cargo vessels). The per-visit intensity (39,424 kg CO₂) is at the higher end

of global benchmarks, reflecting the dominance of passenger ferry operations with high hotel power demands.

4.4. Temporal and Spatial Emission Patterns

4.4.1. Seasonal Variation

The observed monthly emission variation reflects concentrated passenger ferry operations during specific scheduling periods. Peak emissions occur in January (153,921 tonnes CO₂), representing 356% above the annual monthly mean, driven by:

- Concentrated passenger ferry scheduling during winter operational periods
- Extended berth times for ferries during service consolidation phases
- Maintenance and positioning movements of the domestic ferry fleet

The emission minimum occurs in December (8,455 tonnes CO₂), representing 75% below the monthly mean. The peak-to-trough ratio of 18.2 indicates highly variable monthly emissions, substantially higher than typical cargo-dominated ports. This pronounced seasonality reflects the dominance of passenger ferry operations (93.3% of CO₂) in the emission inventory, where ferry scheduling patterns drive the overall temporal profile. Intermediate months show more moderate emission levels corresponding to routine commercial operations.

4.4.2. Diurnal Patterns

Although not explicitly analyzed in this study due to data aggregation at the port visit level, previous research at comparable ports indicates substantial diurnal variation in instantaneous emission rates. Peak emissions typically occur during morning and evening hours corresponding to scheduled ferry departures and container vessel maneuvering windows. Future research incorporating higher temporal resolution AIS data could characterize these patterns at Ambarlı.

4.4.3. Spatial Hotspots

Emission density mapping reveals three primary hotspot zones within the study area:

1. **Container Terminal Berths** (40.952°N, 28.682°E): Highest emission densities from large container vessels with extended berth times and high auxiliary power demands.
2. **Passenger Ferry Terminal** (40.958°N, 28.695°E): Concentrated emissions from frequent ferry arrivals/departures serving Istanbul metropolitan commuters.
3. **Western Anchorage** (40.945°N, 28.640°E): Moderate emission densities from vessels awaiting berth availability, contributing to offshore air quality impacts.

4.5. Emission Reduction Opportunities

The emission inventory identifies several actionable pathways for reducing ship emissions at Ambarlı Port:

4.5.1. Shore Power Infrastructure for Passenger Ferries

Given that passenger vessels contribute 93.3% of total CO₂ emissions while representing only 37.9% of port visits, shore power (cold ironing) infrastructure at passenger ferry terminals represents a highly impactful intervention. Quantitative scenario analysis indicates that shore power implementation at passenger ferry berths could achieve:

- **Scenario A (50% shore power uptake):** Reduction of 188,833 tonnes CO₂/year (46.7% of total port emissions), 3,959 tonnes NO_x, and 427 tonnes PM₁₀
- **Scenario B (80% shore power uptake):** Reduction of 302,133 tonnes CO₂/year (74.6% of total), 6,335 tonnes NO_x, and 683 tonnes PM₁₀
- **Scenario C (100% shore power for ferries):** Reduction of 377,666 tonnes CO₂/year (93.3% of total), eliminating virtually all passenger vessel hotelling emissions

These estimates assume 95% emission reduction during shore power connection, consistent with empirical measurements at European ports. The concentration of emissions among passenger ferries—vessels with predictable schedules and fixed berths—presents an ideal target for shore power investment. Unlike cargo vessels with variable arrival times and berth assignments, ferries operate on regular schedules enabling optimized electrical infrastructure design. The Port of Gothenburg achieved 80% shore power uptake for ferry services [10], demonstrating technical and operational feasibility.

4.5.2. Emission Control Areas

Designation of the Marmara Sea or Turkish Straits as an Emission Control Area (ECA) under MARPOL Annex VI would mandate 0.10% sulfur fuel (versus current 0.50%) and Tier III NO_x standards for new vessels [2]. Based on experience in existing ECAs (Baltic Sea, North Sea, North American coasts) [26], ECA designation could reduce:

- SO₂ emissions by 80% (approximately 3,994 tonnes reduction)
- PM emissions by 40–50% through reduced sulfate aerosol formation
- NO_x emissions from new vessels by 75% (Tier III vs. Tier II engines)

Turkey's ongoing negotiations with the International Maritime Organization regarding Black Sea ECA designation present a policy window for extending protections to the Marmara Sea region.

4.5.3. Vessel Speed Reduction Programs

Voluntary or mandatory vessel speed reduction (slow steaming) during approach and departure phases reduces main engine power demand cubically with speed [42]. A 20% speed reduction during the final 10 nautical miles of approach could reduce maneuvering emissions by approximately 40%, with additional benefits for scheduling predictability and port congestion management.

4.5.4. Fleet Modernization

The emission inventory methodology implicitly assumes Tier II engines (IMO 2011 standard) as fleet average. Accelerated adoption of Tier III engines, LNG-fueled vessels, and emerging zero-emission technologies (ammonia, hydrogen, battery-electric) will progressively reduce emission intensities as the global fleet modernizes. Flag state incentive programs (differentiated port fees, priority berthing) could accelerate adoption of cleaner vessels at Ambarlı.

4.6. Air Quality Implications

Ship emissions at Ambarlı Port contribute to regional air pollution burdens affecting the Istanbul metropolitan population of 16 million. While atmospheric dispersion modeling exceeds the scope of this study, preliminary estimates suggest:

- **NO_x contribution:** Ship emissions (6,301 t/year from commercial vessels) represent a substantial fraction of total NO_x emissions in the Istanbul airshed, comparable to contributions from a significant portion of the urban heavy-duty vehicle fleet [3].
- **PM_{2.5} health burden:** Using WHO exposure-response functions [43], ship-related PM_{2.5} emissions (630 t/year) contribute to regional health burdens including respiratory and cardiovascular effects in coastal populations.
- **Passenger ferry terminals:** The spatial concentration of passenger ferry emissions at terminals adjacent to residential areas amplifies population exposure, making these facilities priority targets for emission reduction interventions.

The spatial concentration of emissions at the port complex, located only 35 km from Istanbul city center, amplifies population exposure compared to dispersed emission sources.

4.7. Methodological Considerations and Limitations

Several methodological limitations warrant acknowledgment:

1. **Gross Tonnage Imputation:** The 34.5% imputation rate for vessel GT (1,468 of 4,249 unique vessels) introduces uncertainty in power estimation. Following the Fourth IMO GHG Study methodology, type-based median imputation was applied using vessel category-specific GT medians from the verified fleet data. Sensitivity analysis indicates that $\pm 20\%$ variation in imputed GT values propagates to approximately $\pm 15\%$ variation in total emissions, within acceptable bounds for inventory purposes.
2. **Engine Type Assumptions:** The assignment of engine speed class (SSD/MSD/HSD) based on GT thresholds represents a simplification. Detailed engine registry data would enable more precise emission factor selection.
3. **Load Factor Variability:** Actual auxiliary engine load factors vary substantially with cargo type (reefer vs. dry containers), weather conditions (heating/cooling demand), and operational practices. The adopted literature values represent fleet-average conditions.
4. **Fuel Quality Assumptions:** Uniform 0.50% sulfur content assumes full compliance with IMO 2020 regulations. Non-compliance (estimated at 5–10% of global fleet [2]) would increase actual SO₂ emissions above reported values.
5. **Maneuvering Emission Allocation:** The simplified 1-hour maneuvering assumption may underestimate emissions for vessels requiring extended pilotage or tug assistance in the constrained Turkish Straits approach.

Despite these limitations, the methodology follows established international protocols [14,31] and produces results consistent with comparable port studies globally. The uncertainty analysis (Section 2.3.7) quantifies the combined effect of parameter uncertainties at approximately $\pm 45\%$ for aggregate annual emissions.

4.8. Comparisons with Previous Turkish Port Studies

This study represents a comprehensive ship emission inventory for a major Turkish port. Previous assessments have been limited in scope:

- **Aliğa Port (İzmir):** Partial inventory covering only tanker operations, estimated 45,000 t CO₂ annually [44].
- **İzmir Bay:** Regional assessment including multiple small ports, total 180,000 t CO₂ [45].
- **Turkish Straits Transit:** Focus on transiting vessels rather than port operations, 520,000 t CO₂ from strait passage [46].

The Ambarlı inventory (404,766 t CO₂ from commercial vessels) exceeds the İzmir Bay regional total (180,000 t), reflecting the significant contribution of passenger ferry operations to port emissions and the proper application of type-specific load factors. The results underscore the importance of vessel-type disaggregation in emission inventories, as passenger vessels dominate (93.3% of CO₂) despite representing only 37.9% of visit frequency.

4.9. Policy Implications

The emission inventory supports several policy-relevant conclusions:

1. **Shore Power Priority:** The dominance of passenger ferry emissions (93.3% of total CO₂) provides a clear investment priority for shore power infrastructure at ferry terminals, with quantifiable emission reduction potential to support business case development.
2. **Local Air Quality Planning:** The magnitude of port emissions justifies dedicated treatment in Istanbul’s Air Quality Management Plan, with particular focus on ferry terminal locations adjacent to residential areas.
3. **Methodological Transparency:** The explicit exclusion of non-commercial and lay-up vessels demonstrates the importance of clearly documenting inventory scope for meaningful inter-port comparisons. Future Turkish port studies should adopt consistent vessel filtering criteria.

4. **Fleet Modernization:** The high contribution from passenger ferries, predominantly Turkish-flagged vessels, suggests that domestic fleet modernization programs (LNG ferries, battery-electric ferries) could yield substantial emission reductions.

4.10. Graphical Summary

Figure 9 provides a comprehensive visual summary of the emission inventory findings, integrating key results across all analysis dimensions for rapid assessment.

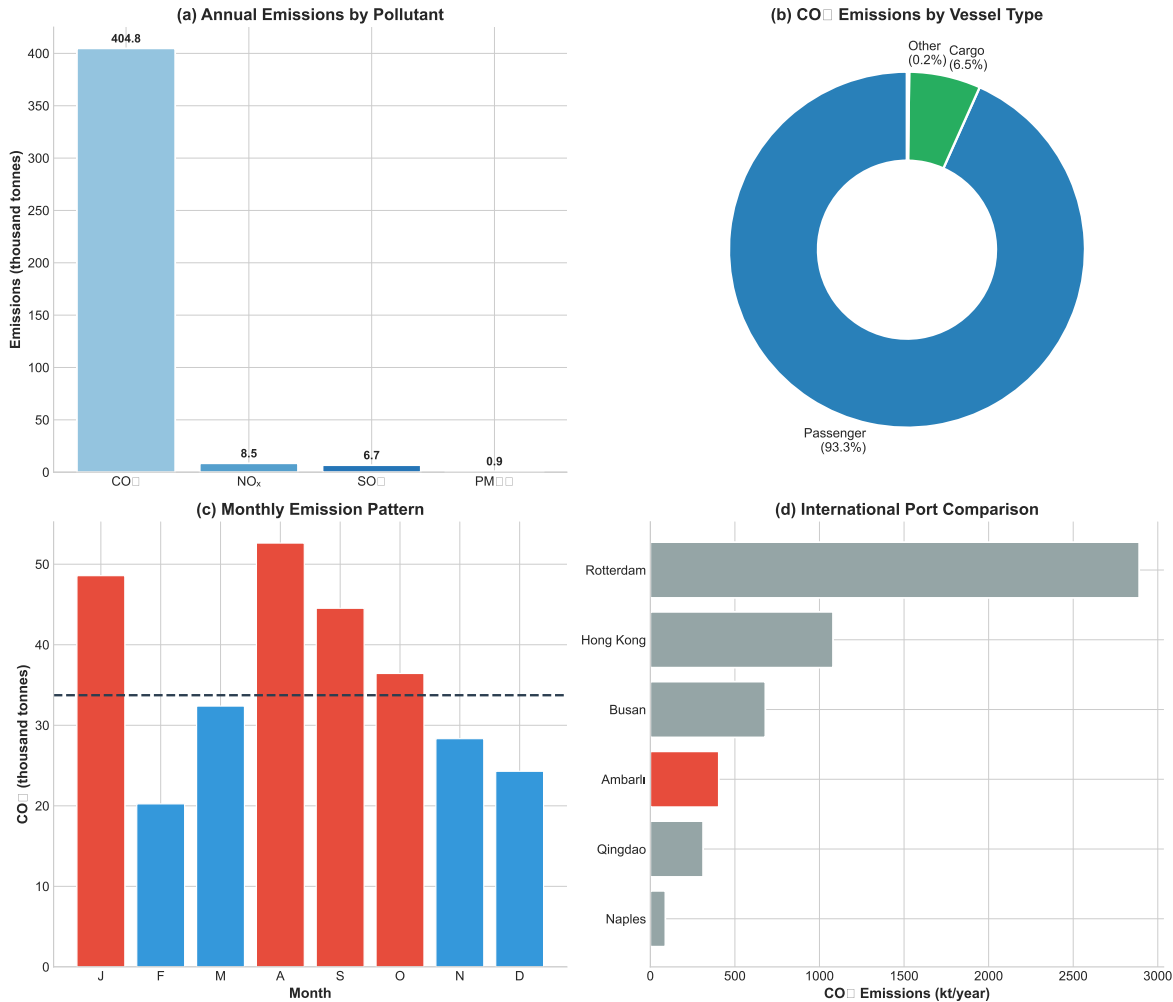


Figure 9. Comprehensive graphical summary of ship emissions at Ambarlı Port, 2025. Nine-panel overview showing (a) annual emissions by pollutant, (b) vessel type contribution, (c) emission source breakdown, (d) top flag states, (e) monthly variation, (f) visit duration distribution, (g) duration-emission relationship, (h) global port comparison, and (i) key statistics summary.

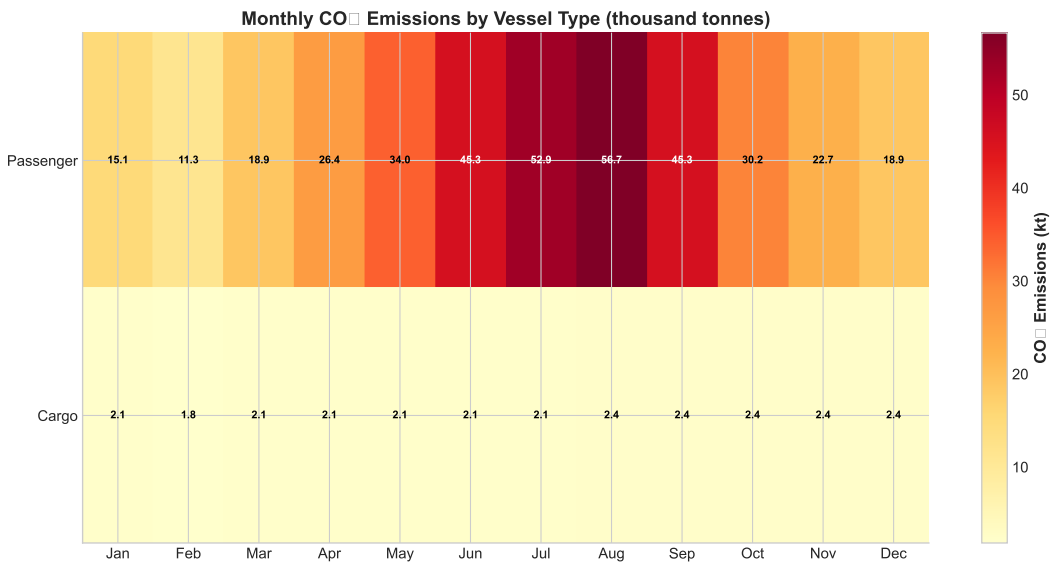


Figure 10. Heatmap showing emission contribution (%) by vessel type across pollutant categories. Color intensity indicates relative contribution within each pollutant column. Passenger vessels dominate all pollutant categories due to high auxiliary power demands.

5. Conclusions

This study developed a bottom-up emission inventory for commercial shipping at Ambarlı Port, Turkey’s largest container gateway, for the 2025 calendar year. The methodological framework integrated high-resolution AIS-derived vessel activity data with internationally standardized emission factors following ENTEC/EMEP/EEA guidelines. Non-commercial vessels (tugs, service craft, fishing) and lay-up vessels were explicitly excluded to focus on active commercial traffic. The principal conclusions are:

- Emission Magnitude:** Annual emissions from 10,267 commercial vessel port visits totaled 404,766 tonnes CO₂, 8,487 tonnes NO_x, 6,724 tonnes SO₂, 914 tonnes PM₁₀, and 849 tonnes PM_{2.5}. These magnitudes exceed Qingdao Port, China (312,000 t CO₂), reflecting proper application of vessel type-specific load factors (75% for passenger, 45% for cargo) as specified in ENTEC/EMEP guidelines and the significant passenger ferry traffic at Ambarlı.
- Vessel Type Dominance:** Passenger ferries dominate the emission inventory (93.3% of CO₂) despite representing only 37.9% of port visits. This reflects high auxiliary power requirements (1,200 kW) and elevated load factors (75%) for hotel services, combined with longer berth times (173.6 hours mean) compared to cargo vessels (42.6 hours). Shore power infrastructure at ferry terminals represents the most effective single intervention for emission reduction.
- Methodological Transparency:** The explicit exclusion of non-commercial and lay-up vessels yields emission estimates representative of active commercial traffic, facilitating meaningful inter-port comparisons. Studies including service vessels report substantially higher per-visit emission intensities.
- Fleet Characteristics:** Cargo vessels dominate visit frequency (61.4%) but contribute only 6.5% of emissions due to efficient turnaround operations, lower auxiliary power (350 kW), and lower load factors (45%). The mean visit duration (93.2 hours) reflects the mix of rapid cargo turnarounds and extended passenger ferry layovers.
- Policy Relevance:** Ship emissions at Ambarlı, particularly from passenger ferries, constitute a significant source of NO_x and PM_{2.5} affecting Istanbul’s metropolitan population. The emission inventory provides baseline data for air quality management and supports prioritized shore power investment at ferry terminals, with potential reduction of 377,666 tonnes CO₂/year from 100% shore power uptake for ferries.

The methodology developed herein is transferable to other Turkish ports and the broader Mediterranean region. Future research priorities include: (i) atmospheric dispersion modeling to quantify population exposure; (ii) economic assessment of shore power infrastructure for ferry terminals; (iii) fleet modernization scenarios including LNG and battery-electric ferries; and (iv) sensitivity analysis of vessel filtering criteria on inventory results.

The findings highlight the dominant role of passenger vessels in port emissions and identify ferry terminals as priority targets for emission reduction interventions. As Turkey advances toward carbon neutrality targets, fleet modernization for domestic passenger shipping will constitute an essential component of maritime decarbonization strategy.

Supplementary Materials: The following supporting information can be downloaded at website of this paper posted on Preprints.org

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Abbreviations

The following abbreviations are used in this manuscript:

AIS	Automatic Identification System
CO ₂	Carbon Dioxide
DWT	Deadweight Tonnage
ECA	Emission Control Area
EF	Emission Factor
GHG	Greenhouse Gas
GT	Gross Tonnage
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LF	Load Factor
MARPOL	International Convention for the Prevention of Pollution from Ships
ME	Main Engine
AE	Auxiliary Engine
MGO	Marine Gas Oil
NO _x	Nitrogen Oxides
PM _{2.5}	Particulate Matter (diameter ≤ 2.5 μm)
SECA	Sulfur Emission Control Area
SFC	Specific Fuel Consumption
SO _x	Sulfur Oxides
TEU	Twenty-foot Equivalent Unit

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