

Spatiotemporal ship carbon emission exploitation and low-carbon shipping pathway evaluation¹☆

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HIGHLIGHTS

- Constructed a high-resolution carbon footprint for calling and non-calling vessels.
- Revealed inter-port emission disparities and liner-tramp spatial heterogeneity.
- Quantified abatement efficacy across differentiated low-carbon shipping pathways.

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ABSTRACT

Against the background of the global low-carbon transition in the transportation sector, greenhouse gas (GHG) emissions from the maritime industry pose a significant challenge to achieving the sector's decarbonization goals. Accurately quantifying and characterizing these emissions is a fundamental prerequisite for formulating effective emission reduction strategies. This study integrates multi-source maritime data and employs a power-based method and a combined spatial allocation model to construct a high-resolution spatiotemporal inventory of ship carbon footprints across complete operational cycles. Notably, the inventory accounts for non-calling vessels that anchor but ultimately depart without berthing. Furthermore, this study constructs multiple emission reduction scenarios from the dual dimensions of operational optimization and energy technology upgrades to comprehensively evaluate the decarbonization potential and emission reduction effectiveness of various strategies. The results indicate that significant disparities in emission profiles between the two studied ports stem from differences in arriving vessel types and operational modes. Emissions from non-calling vessels reached 46,843 tons, accounting for nearly 9% of total emissions in the study area, making their management an indispensable component of carbon governance within the port district. Scenario evaluations demonstrate that the Virtual Arrival policy effectively reduces anchorage emissions from tramp ships, but achieving systemic deep decarbonization fundamentally relies on comprehensive energy substitution. These findings provide a practical scientific basis for advancing green shipping.

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1. Introduction

In the process of global low-carbon transportation transformation, the shipping industry is facing increasingly severe decarbonization pressure [1]. Maritime transport accounts for approximately 80% of global international trade [2–4], serving as a fundamental mode of transportation supporting the global economy. It is also a weak link in carbon emission control within the transportation sector [5]. According to the Fourth Greenhouse Gas Study of the International Maritime Organization, greenhouse gas emissions in the shipping industry accounted for 2.89% of the total global anthropogenic greenhouse gas emissions in 2018. Compared to 2012, the total amount of greenhouse gas emissions in the shipping industry increased by 9.6%, and carbon dioxide emissions also increased by 9.3%. Pollution from shipping activities has become a major global concern. These emissions not only degrade air quality but may also exacerbate global warming and threaten human health [6–8]. In the face of this challenge, the IMO has taken a series of emission reduction measures [9–11]. The 83rd session of the Marine Environment Protection Committee (MEPC), held in London in April 2025, approved the draft amendments for the IMO Net-Zero Framework. This framework is aligned with the long-term emission reduction goals of the 2023 IMO GHG Strategy and aims to achieve net-zero greenhouse gas emissions from international shipping.

As a critical node connecting deep-sea shipping with inland logistics systems, ports serve as convergence points for water and land transport and act as core hubs within the global maritime network [12,13]. Existing studies have examined port operations from perspectives such as traffic safety, maritime perception, and intelligent navigation [14,15]. At the same time, ports are also areas where ship emissions are highly concentrated. Vessel activities within a port area encompass multiple stages, including navigation into and out of the port, waiting at anchorage, and operations at berths [16,17]. Each of these stages involves the operation of various systems, such as main engines, auxiliary machinery, and boilers. Overall, against the background of the green and low-carbon transition in shipping, the reduction of greenhouse gas emissions from ports and vessels has emerged as a core issue within the maritime sector [18,19]. Accurately quantifying emission characteristics within port areas and assessing the effectiveness of differentiated emission reduction strategies constitute the fundamental prerequisite for formulating scientific governance plans [20].

To address this need, this study focuses on the San Pedro Bay ports. Employing a bottom-up power-based approach and utilizing AIS data, it constructs a high-resolution inventory of ship carbon emissions that spans the entire operational cycle. In contrast to navigation where main engines dominate emissions, vessels in port areas shut down main engines or operate them at low loads during berthing and anchoring, with auxiliary engines and boilers becoming the primary emission sources. This study accordingly models each operational stage separately. Based on spatial allocation methods, emission results are mapped onto a gridded framework of the study area to reveal the spatial distribution characteristics of emissions. Four differentiated emission reduction scenarios are constructed from two dimensions: operational optimization and energy technology substitution, and the emission reduction potential of each strategy is quantitatively assessed. The remaining sections of this paper are organized as follows. Section 2 provides a review of relevant literature concerning methods for accounting for ship emissions, the application of port emission inventories, and the assessment of emission reduction strategies. Section 3 introduces the methodology adopted in this study. Section 4 presents the analysis results regarding the structural characteristics and spatial distribution of emissions, as well as the assessment results for the emission reduction scenarios. Finally, Sections 5 and 6 discuss the results and summarize the main conclusions and limitations, respectively.

2. Literature review

Automatic Identification System (AIS) data provide high-resolution information on vessel position, speed, and heading, and have been widely used to characterize vessel traffic dynamics in maritime environments [21–23]. Bottom-up emission calculation methods based on AIS data have been widely applied in studies on ship emissions [24–27], with relevant research spanning multiple spatial scales ranging from individual ports to national Exclusive Economic Zones. At the regional scale, Mou et al. [28] constructed a high-resolution ship carbon emission inventory for the U.S. Exclusive Economic Zone, revealing the dynamic variation patterns of ship carbon emissions at port, regional, and national scales. Sun et al. [29] extended this scope to inland waterway scenarios. At the port scale, He et al. [30] proposed a rapid emission estimation model based on regional stratified sampling, which significantly improved inventory compilation efficiency while maintaining a low error rate. However, few of the aforementioned studies explicitly quantified the emissions contributed by vessels that anchored within port waters but ultimately departed without berthing. Excluding these vessels from the accounting boundary may lead to a systematic underestimation of total emissions within port areas.

Regarding the analysis of emission structures, existing studies have examined emission characteristics from the perspectives of vessel type and operating conditions. Xiao et al. [31] systematically analyzed the characteristics of pollutant and carbon emissions across various vessel types and operational states. Chen et al. [32] further employed multiple energy efficiency indicators, including the Energy Efficiency Operational Indicator (EEOI) and Fleet Energy Efficiency Management Index (FEEMI), to evaluate the energy consumption and carbon emission characteristics of containerships, tankers, bulk carriers, and LNG carriers under different cargo loading and speed conditions. Through a comparative analysis of multiple ports, Styhre et al. [33] identified the berthing phase as the primary source of carbon emissions within port areas, noting that port-based emission reduction strategies must integrate vessel speed management with shore-to-ship power technologies. The aforementioned studies primarily focus on differences in total emissions across various vessel types, yet they lack a systematic analysis of the distinct behavioral patterns of each vessel type while in port and the subsequent impact of these patterns on the structure of emissions. Due to variations in functional roles and shipping route networks, different ports often exhibit significant disparities in both the composition of arriving vessels and their operational characteristics; these disparities constitute a major source of the heterogeneity observed in emissions across different ports. Consequently, identifying and comparing these differences in vessel composition and operational characteristics across various ports serves as a crucial prerequisite for understanding the disparities in emissions between them.

Emission reduction at ports is primarily achieved through operational optimization and technological substitution [34]. In terms of operational optimization, vessel speed reduction (VSR) is generally considered a highly cost-effective measure [35,36]. For instance, Elmi et al. [37] proposed a novel multi-objective optimization method that integrates Vessel Slowing Incentive Programs (VSRIPs), emission control regulations, and various recovery strategies to address the conflict between cost and environmental protection during recovery voyages. Yan et al. [38] developed an innovative neural network-based fuel consumption prediction model and optimized ship sailing speed profiles for bulk carriers, demonstrating that speed optimization can significantly improve ship energy efficiency and reduce emissions. In terms of technological alternatives, shore power and alternative fuels are currently widely studied topics. Daniel et al. [39] demonstrated through SWOT analysis and real-world ship case studies that shore power technology can eliminate berth emissions and significantly improve the carbon intensity index (CII). Balcombe et al. [40] comprehensively assessed decarbonization options for international shipping from technical, environmental and policy perspectives, emphasizing the need to

combine short-term transitional use of liquefied natural gas with long-term reliance on a diversified portfolio of technologies and strong policy incentives. Recent studies have also examined fleet deployment optimization, trajectory-based emission mapping, and intelligent traffic management for improving transport efficiency and reducing carbon emissions [41–45]. Together, these studies provide useful references for low-carbon transport management and port-related emission reduction, but research on differentiated carbon management of port clusters remains limited. Existing studies give limited attention to how variations in vessel composition across ports lead to distinct emission structures. Furthermore, previous studies have primarily focused on the navigation and berthing phases, often underestimating emissions generated by ships during extended stays at anchor. Therefore, it is necessary to reveal the different emission-driving mechanisms within port areas and design targeted decarbonization strategies accordingly to assess the effectiveness of emission reduction strategies.

3. Data and methodology

3.1. Research area

We selected the San Pedro Bay ports in Southern California as the study area. The ports include the Port of Los Angeles (POLA) and the Port of Long Beach (POLB), which together form the busiest container hub and international trade gateway in North America. The research area is a sector-shaped area extending 40 nautical miles outward from the Point Fermin Lighthouse, with its latitudinal extent ranging from 33.015°N to 34.025°N and its longitudinal bounds spanning from 119.125°W to 117.6°W. This area covers the core regulatory zone of the port authority's VSR program, including the complete operational cycle of vessels entering and leaving the port. Fig. 1 illustrates the spatial distribution of the study area and the division of port functional zones. The left side of Fig. 1 shows the overall extent of the study area with a radius of 40 nautical miles centered on Point Fermin Lighthouse, while the right side shows the core functional zones of the port, marking the access channels, precautionary zones, and north and south anchorages.

3.2. Data processing

We collected ship trajectory data for the study area in 2024 from the publicly available AIS dataset (<https://marinecadastre.gov/ais/>), containing approximately 100 million records. Due to factors such as signal transmission interference, equipment failure, or signal congestion, AIS data typically contains noisy signals such as position drift, speed anomalies, and duplicate timestamps. To ensure the physical validity of

the ship's trajectory, we set a speed threshold to handle speed anomalies, filtering out outliers where the speed exceeds the ship's maximum design speed. To correct for position errors, we calculated the theoretical speed based on the geometric relationship between adjacent trajectory points. If a significant deviation was observed between the calculated speed and the AIS-reported speed, the corresponding data point was classified as an anomaly and subsequently removed. Furthermore, we screened vessels based on their vessel type codes, retaining only the AIS data of six types of ocean-going vessels: containerships, tankers, cruise ships, bulk carriers, general cargo ships, and auto carriers. Finally, based on the vessels' final docking destinations, the data were divided into three subsets: POLA, POLB, and non-calling. Among them, non-calling specifically refers to vessels that entered the study area and remained at the anchorage for an extended period, but ultimately departed without entering the port area for cargo operations.

3.3. Estimation of carbon emissions

We employed a power-based method to calculate the carbon emissions of ships in ports and their surrounding waters. The total carbon emissions (E_{total}) of a ship during an operational cycle comprise three primary emission sources [46]. The total emissions are calculated as the sum of the emissions from these three types of equipment across various operating modes (m), as expressed in Eq. (1):

$$E_{\text{total}} = \sum_m (E_{\text{ME},m} + E_{\text{AE},m} + E_{\text{AB},m}) \quad (1)$$

where m represents the five operating modes of the ship (cruising, slow cruising, maneuvering, anchoring, and berthing); $E_{\text{ME},m}$, $E_{\text{AE},m}$ and $E_{\text{AB},m}$ are the carbon emissions (g) from the main engine, auxiliary engine, and auxiliary boiler under mode m , (respectively)

The main engine provides propulsion power during navigation, and its energy consumption is highly dependent on the speed of the ship. The main engine calculates the instantaneous load based on the propeller law and determines its emissions according to Eq. (2). The auxiliary engine is mainly used to meet the ship's electrical power demands; its load does not depend directly on the speed but is determined by the operation mode of the ship. The emissions from the auxiliary engine are calculated using Eq. (3). The auxiliary boiler is mainly utilized to generate hot water and steam, fulfilling essential thermal energy requirements such as heavy fuel oil heating, cargo temperature maintenance, and crew accommodation needs. Its emissions are calculated as shown in Eq. (4):

$$E_{\text{ME},m} = P_{\text{ME}} \times (V_{\text{actual},m}/V_{\text{design}})^3 \times T_m \times \text{EF}_{\text{ME}} \times \text{LLA}_m \quad (2)$$

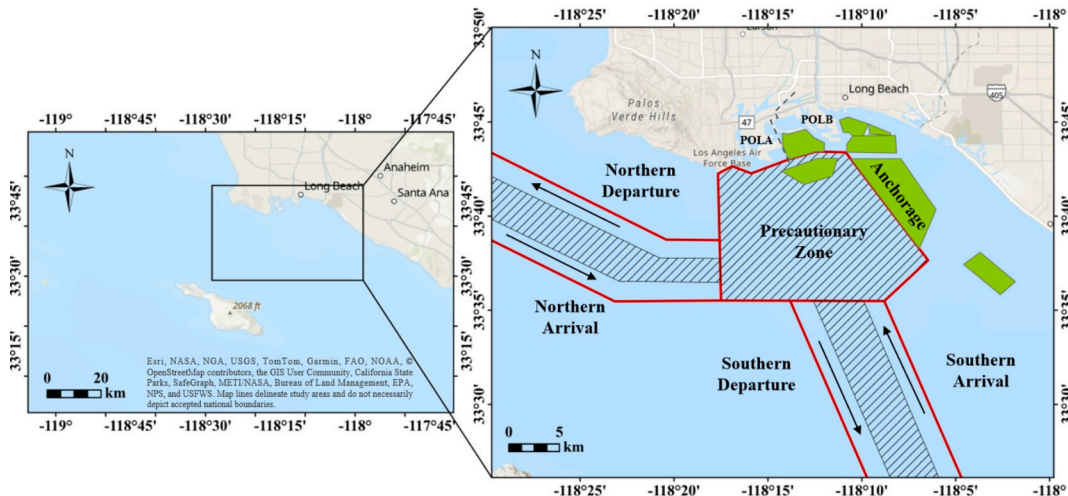


Fig. 1. Spatial distribution of the San Pedro Bay ports research area and port functional area.

$$E_{AE,m} = P_{AE,m} \times T_m \times EF_{AE} \times CF \quad (3)$$

$$E_{AB,m} = P_{AB,m} \times T_m \times EF_{AB} \quad (4)$$

where P_{ME} represents the maximum continuous rating of the main engine (kW); $V_{actual,m}$ represents the actual sailing speed of the ship under mode m (knots); V_{design} represents the maximum design speed of the ship (knots); T_m represents the operating time of the ship under mode m (h); EF_{ME} , EF_{AE} and EF_{AB} represent the carbon emission factors for the main engine, auxiliary engine, and auxiliary boiler, respectively (g/kWh); LLA_m represents the low load adjustment factor (dimensionless), which is utilized to correct for non-linearly increasing emissions when $(V_{actual,m}/V_{design})^3 < 20\%$; $P_{AE,m}$ and $P_{AB,m}$ represent the actual output loads of the auxiliary engine and auxiliary boiler under mode m , respectively (kW); and CF represents the control factor (dimensionless), used to account for the effect of emission reduction technologies such as shore power. If the ship is fully connected to shore power during berthing, $CF = 0$; otherwise, $CF = 1$.

3.3.1. Operational mode

The vessel operational mode determines the main engine load factor and the operating status of auxiliary engines and auxiliary boilers [47], and its accurate identification is a prerequisite for ship emission estimation based on AIS data. Compared with the conventional navigation stage, vessel activities in ports and adjacent waters are more complex, involving not only fairway navigation but also port-entry and departure maneuvering, anchorage waiting, and berthing. In this study, the classification rules for vessel operational modes follow established methods that identify vessel states based on actual speed over ground and spatial position [28]. Anchorage polygon features in the study area were further incorporated as spatial constraints. Accordingly, vessel operational modes were classified based on actual speed over ground, distance to shore, and the spatial relationship between vessels and anchorage areas, according to the following criteria. (1) A vessel is classified as berthing when its speed is less than or equal to 1 knot, its distance from the coastline is less than 500 m, and it is not within an anchorage; (2) A vessel is classified as anchoring if its distance from the coastline is greater than or equal to 500 m and its speed is less than or equal to 1 knot, or if its speed is greater than 1 knot and less than or equal to 3 knots while within an anchorage, or if its speed is less than or equal to 1 knot and its distance from the coastline is less than 500 m while within an anchorage; (3) A vessel is classified as maneuvering when its speed is greater than 3 knots and less than or equal to 5 knots, or when its speed is greater than 1 knot and less than or equal to 3 knots and it is not within an anchorage; (4) A vessel is classified as slow cruising when its speed is greater than 5 knots and less than or equal to 12 knots; and (5) A vessel is classified as cruising when its speed is greater than 12 knots.

In the berthing emission calculation, the use of shore power and equivalent emission control strategies was simulated to account for the influence of port emission reduction policies. The utilization data were obtained from the Ocean-Going Vessel Emission Inventory released by the California Air Resources Board (CARB). These data represent the proportion of berthing time during which CARB-approved emission control strategies (CAECS) were used, classified by regulated port and vessel type. In the ship-by-ship calculation, each individual berthing operation was used as the basic unit. The utilization rate was treated as a probability parameter, and random sampling was applied to determine whether shore power or an equivalent emission control strategy was used for each berthing operation. For berthing operations assigned to shore power or an equivalent control strategy, the connection and disconnection processes at the beginning and end of berthing were treated as transition periods. During these transition periods, auxiliary engine emissions were calculated under normal berthing conditions. During the stable power supply period outside the transition periods, the auxiliary engine power was set to zero. For berthing operations not

assigned to shore power or equivalent control strategies, the auxiliary engine operated under the normal berthing load throughout the berthing period. Auxiliary boiler emissions were retained because shore power mainly replaces onboard electricity generation by auxiliary engines.

3.3.2. Power system parameters and emission factors

(1) Determination of vessel power parameters.

We integrated data platforms such as the Lloyd's Register (LR) database, the China Classification Society (CCS) database, and the IMO database to obtain the core technical parameters of the vessels, including main engine power and design speed. Compared to the rated power of main engines, the rated power of auxiliary engines and boilers is challenging to obtain directly. Therefore, the power parameters for auxiliary engines and boilers utilized in this study were derived from the Vessel Boarding Program (VBP) implemented by the POLA and the POLB. The VBP collects actual operating parameters of arriving vessels through onboard surveys.

(2) Low load adjustment multipliers for emission factors.

When marine diesel propulsion engines operate under low load conditions, their combustion efficiency decreases significantly [48]. Under this condition, the absolute fuel consumption decreases, but the emission factor rises sharply. In order to accurately quantify the emissions of this operating mode, this study introduces the low load adjustment (LLA) coefficient of the main engine. Based on a methodology developed by the U.S. Environmental Protection Agency (EPA) and Starcrest, these dimensionless LLA coefficients are obtained by normalizing the theoretical emission factors in the low-load range with the emission factors at the 20% load point. When the main engine load factor is below 20%, the actual emission factors are obtained by multiplying the baseline emission factors by the corresponding LLA coefficients. Table 1 shows the LLA coefficients under different load conditions.

(3) Emission factors.

The emission factor refers to the carbon dioxide emissions generated by unit energy output (g/kWh). This study adopted the standards specified in the Port-Related and Cargo Transportation Mobile Source Emission Estimation Methodology published by the U.S. Environmental Protection Agency (EPA, 2020). The carbon dioxide emission factor is determined by equipment type: 593 g/kWh for the main engine, 696 g/kWh for the auxiliary engine, and 962 g/kWh for the auxiliary boiler.

3.4. Spatial allocation of carbon emissions

Traditional allocation methods mainly include the point density method and the activity-weighted method. The point density method directly attributes emissions from a trajectory point to the grid cell in which it is located, ignoring ship movement across multiple grids between two consecutive trajectory points. The activity-weighted method resolves cross-grid allocation by segmenting trajectory lines, but it is computationally redundant for stationary or slightly drifting anchored vessels. Taking the 1 km × 1 km grid as an example, 81.6% of the

Table 1
low load adjustment multipliers for emission factors.

load factor	adjustment factor	load factor	adjustment factor
1%	3.28	11%	1.21
2%	3.28	12%	1.17
3%	2.44	13%	1.14
4%	2.01	14%	1.11
5%	1.76	15%	1.08
6%	1.59	16%	1.06
7%	1.47	17%	1.04
8%	1.38	18%	1.03
9%	1.31	19%	1.01
10%	1.25	20%	1.00

approximately 2.835 million trajectory segments in this study were entirely located within a single grid cell. The two methods produced identical allocation results for these segments, indicating that line segmentation provided no additional spatial allocation benefit. The remaining 18.4% (520,685 segments) crossed multiple grid cells. If the point density method were applied to these cross-grid segments, approximately 16,387 tons of carbon emissions would be assigned to different grid cells compared with the activity-weighted allocation, accounting for 8.79% of dynamic navigation emissions. Cross-grid segments were distributed across 2.05 grid cells on average. The grid cell with the largest allocation share received 62% of emissions on average, and the remaining 38% was allocated to adjacent cells. Therefore, a combined spatial allocation method based on vessel movement states was adopted in this study.

First, a grid network for the study area was constructed. For any two consecutive AIS trajectory points, P_{start} and P_{end} , if the corresponding trajectory segment crosses grid boundaries, the geometric intersections between the trajectory line segment and the grid lines are calculated, thereby segmenting the trajectory into several sub-segments. As shown in Fig. 2, assuming that trajectory segment a_1 is divided by a grid boundary into a_{1-1} and a_{1-2} , the emission E of each sub-segment is proportionally allocated based on the ratio of its length to the total length of the original trajectory segment:

$$E = E_{total} \times \frac{L_{sub}}{L_{total}} \quad (5)$$

where E_{total} represents the total emissions calculated within the given time step, L_{sub} represents the length of the sub-segment within a specific grid cell, and L_{total} represents the total straight-line distance between the two points.

Based on this approach, the emissions generated by the vessel during its movement are accurately allocated to all the grid cells it passes through, thereby ensuring spatial continuity. For vessels in berthing and anchoring states, since their displacement is minimal and their trajectory points are highly concentrated spatially, the point density method is adopted for allocation. The calculated carbon emission value E_t within the time step is directly extracted and entirely allocated to the grid cell $Grid(i, j)$ where the vessel's current trajectory point P_t falls. Finally, the total emissions within any given grid cell $Grid(i, j)$ are the sum of the emissions from all trajectory sub-segments under navigating states and the discrete point emissions under stationary states within that grid.

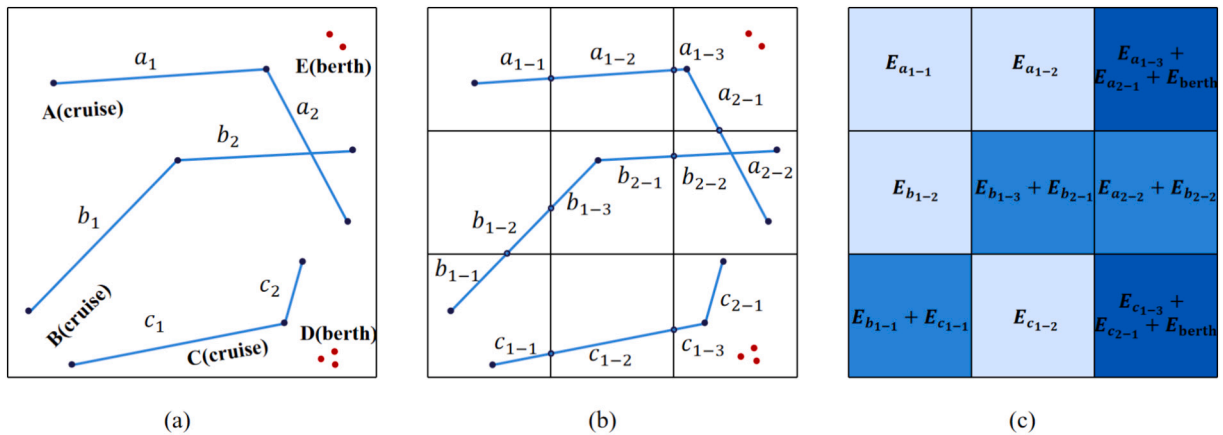


Fig. 2. Grid-based spatial allocation process of ship emissions: (a) Original trajectories and vessel states (b) Grid-based trajectory segmentation (c) Calculation of gridded emissions.

4. Results

4.1. Ship arrival statistics

Fig. 3 showed the distribution of arrivals for different types of ships at the Port of Los Angeles, the Port of Long Beach, and in the non-calling state within the study area in 2024. Regarding containerships, the annual numbers of arrivals at the Port of Los Angeles and Port of Long Beach were 971 and 857, respectively. Arrival patterns for tankers and bulk carriers differ. The Port of Long Beach recorded 491 tanker arrivals, approximately 3.4 times the number at the Port of Los Angeles. As shown in Fig. 3(b), the tankers arriving at the Port of Los Angeles consist exclusively of chemical tankers, Handymax, and Panamax vessels. In contrast, the Port of Long Beach accommodates the full spectrum of crude oil tanker classes, including Aframax and Suezmax vessels. These large crude tankers are equipped with high-power auxiliary boilers, used during cargo discharge to drive the cargo oil pumps and heat the crude oil. For bulk carriers, the Port of Long Beach recorded 200 arrivals, approximately 3.2 times the volume at the Port of Los Angeles, reflecting its additional role as a dry bulk hub. Furthermore, considerable non-calling vessel activity is present within the study area. This category of vessels consists primarily of tramp ships; specifically, 497 tankers and 281 bulk carriers entered the anchorage but departed without docking, engaged mainly in ship-to-ship transfers or waiting at anchor for charter assignments. Although vessels of this type do not berth at the terminals of the two ports, their auxiliary engines and boilers continue to operate while anchored; consequently, their emissions are concentrated within the port's ambient air environment, constituting a source of unaccounted emissions that is not included in conventional port emission inventories.

4.2. Structural characteristics of carbon emissions

4.2.1. Monthly variation characteristics of carbon emissions

To reveal the temporal variation in ship carbon emissions within the study area, monthly carbon emissions in 2024 were statistically analyzed. Fig. 4 showed the monthly carbon emission variations for the Port of Los Angeles, the Port of Long Beach, and non-calling vessels. Monthly emissions at the Port of Los Angeles were generally stable, ranging from 12,215 tons to 15,483 tons. The monthly variation was mainly related to changes in emissions from containerships and cruise ships. As the dominant emission source at the Port of Los Angeles, containerships maintained higher emission levels in the second half of the year and reached their annual maximum in August. Cruise ship emissions showed more evident monthly differences, with the monthly average from October to December being markedly higher than that from June to July. Overall, monthly total emissions at the Port of Los

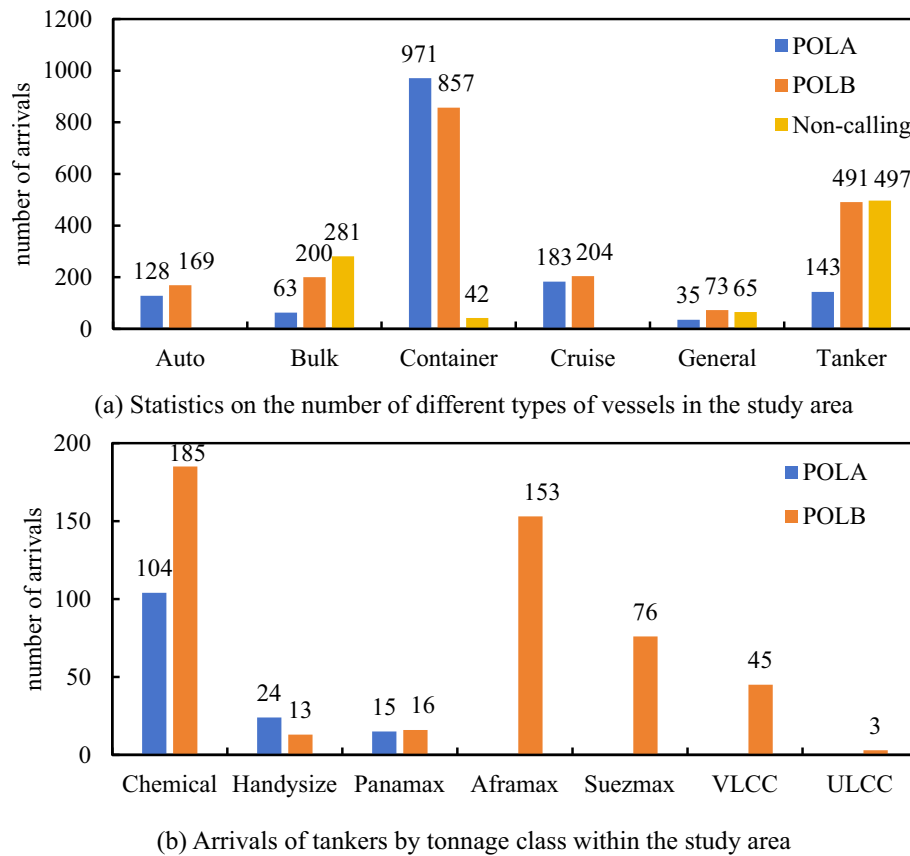


Fig. 3. Vessel arrival statistics in the San Pedro Bay study area.

Angeles did not fluctuate sharply, although variations among vessel types affected the intra-annual emission distribution. Monthly emissions at the Port of Long Beach were consistently higher than those at the Port of Los Angeles, ranging from 24,309 tons to 31,634 tons. Unlike the Port of Los Angeles, monthly variation at the Port of Long Beach was more closely associated with fluctuations in tanker emissions. Tanker emissions accounted for a large share in each month and remained high from May to July. The monthly total emissions reached the annual peak in July. For non-calling vessels, monthly emissions showed more pronounced variability, ranging from 2830 tons to 4881 tons. Non-calling vessels were mainly composed of tankers and bulk carriers, whose activities were less regular. Their emission variations reflected changes in anchorage waiting, temporary stays, and vessel scheduling activities within the study area. Compared with calling vessels, monthly emissions from non-calling vessels were less stable.

4.2.2. Emission characteristics of different ship types

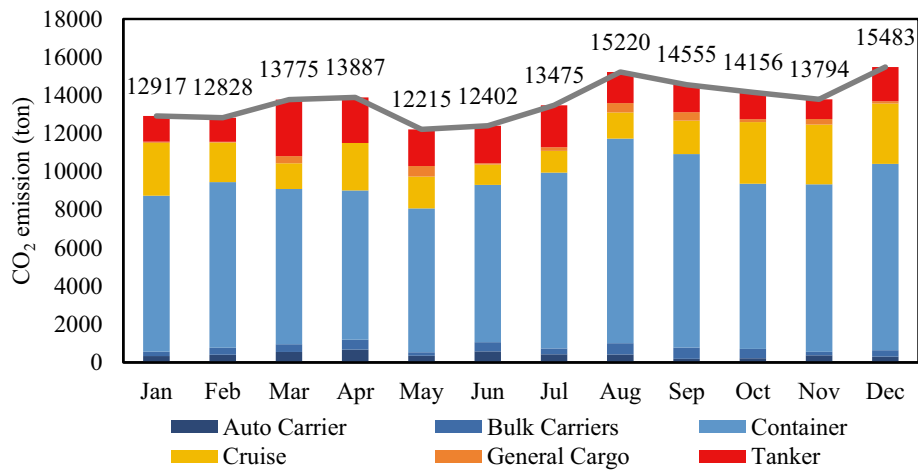
To further examine the emission contributions of different vessel types, Fig. 5 illustrated the composition of annual carbon emissions by vessel type at POLA, POLB, and for non-calling vessels, respectively. The total carbon emissions within the study area in 2024 amounted to approximately 537,763 tons, comprising 164,707 tons from the Port of Los Angeles, 326,213 tons from the Port of Long Beach, and 46,843 tons from vessels not calling at port. The two ports exhibit distinct emission profiles. As shown in Fig. 5(a), the Port of Los Angeles displays a typical emission pattern dominated by containerships, with emissions from this category totaling 105,885 tons, followed by cruise ships and tankers. Fig. 5(b) revealed the emissions structure of the Port of Long Beach, with tanker emissions reaching 163,038 tons, which is approximately equal to the total annual emissions of the Port of Los Angeles, making tankers the single largest emission source at the Port of Long Beach. This structural disparity is primarily attributable to differences in the

composition of the tanker fleets at the two ports. The emissions from tankers at the Port of Long Beach are 7.6 times those of the Port of Los Angeles, exceeding the ratio of 3.4 times the number of arrivals. This disproportionate emission intensity stems from large crude oil tankers that berth exclusively at the Port of Long Beach. During cargo unloading operations, these vessels operate high-power auxiliary boilers to drive cargo pumps and heat the crude oil; consequently, their emissions per voyage are significantly higher than those of the small to medium-sized chemical and product tankers calling at the Port of Los Angeles.

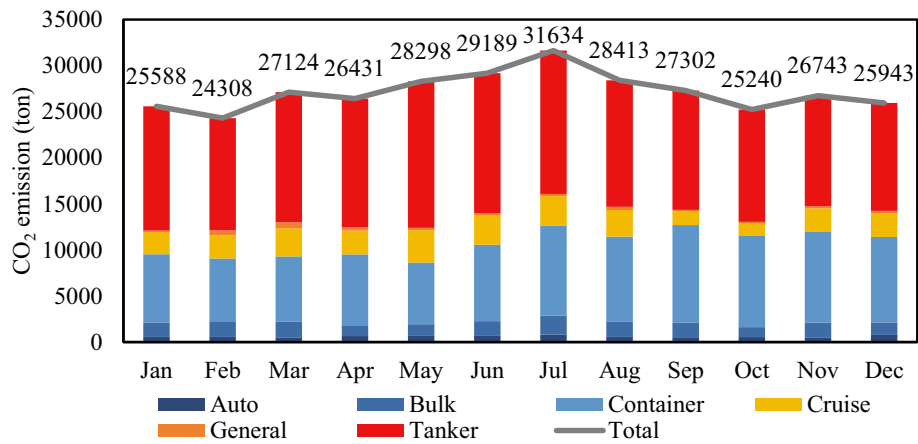
Emissions from vessels not calling at port similarly exhibit a highly concentrated distribution across specific vessel types. Fig. 5(c) illustrated the annual emissions from these vessels. Annual emissions from tankers reached 36,993 tons, accounting for 79.0% of total emissions from vessels not calling at port. This figure exceeds the total annual emissions from all tankers at the Port of Los Angeles. The anchorage activities of these vessels constitute a significant regional source of emissions and are therefore incorporated into the accounting boundary for the comprehensive assessment of the port cluster's total emissions.

4.2.3. Emission characteristics under different operating modes

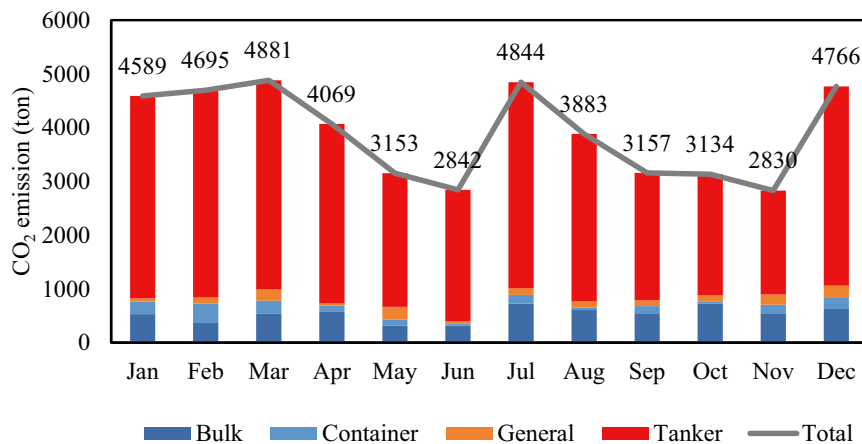
To further examine the contribution of different operational modes, Fig. 6 illustrated the composition of carbon emissions for each vessel type under different operating modes. In 2024, the shore power utilization rates for containerships and cruise ships at the Port of Los Angeles were 91% and 74%, respectively, while at the Port of Long Beach, they were 79% and 73%. In this study, the berthing emissions for the relevant vessel types represent the results simulated under the scenario of shore power connection. As shown in Fig. 6(a) and 6(b), berthing and slow cruising constitute the predominant emission modes for vessels calling at the two ports. At the Port of Los Angeles, emissions during berthing account for over 60% of the total for tankers, bulk carriers, and general cargo vessels. This is primarily attributable to the fact that these vessel



(a) Monthly carbon emissions of vessels calling at the POLA



(b) Monthly carbon emissions of vessels calling at the POLB



(c) Monthly carbon emissions of non-calling vessels

Fig. 4. Monthly variations in carbon emissions by vessel type in 2024. The stacked bars represent emissions from different vessel types, and the gray line represents total monthly emissions.

types have not yet widely adopted shore power connections and typically experience extended dwell times within the port. Although the shore power utilization rate for containerships has reached 91%, emissions during berthing still account for over 50% of the total. This is mainly due to emissions generated during the process of connecting to

and disconnecting from shore power, as well as emissions from boilers that are not covered by the shore power supply. For cruise ships, the primary emission mode is the sailing state. Berthing accounts for only 22%, a result of the high utilization rate of shore power. The emissions profile of the Port of Long Beach is fundamentally similar to that of the

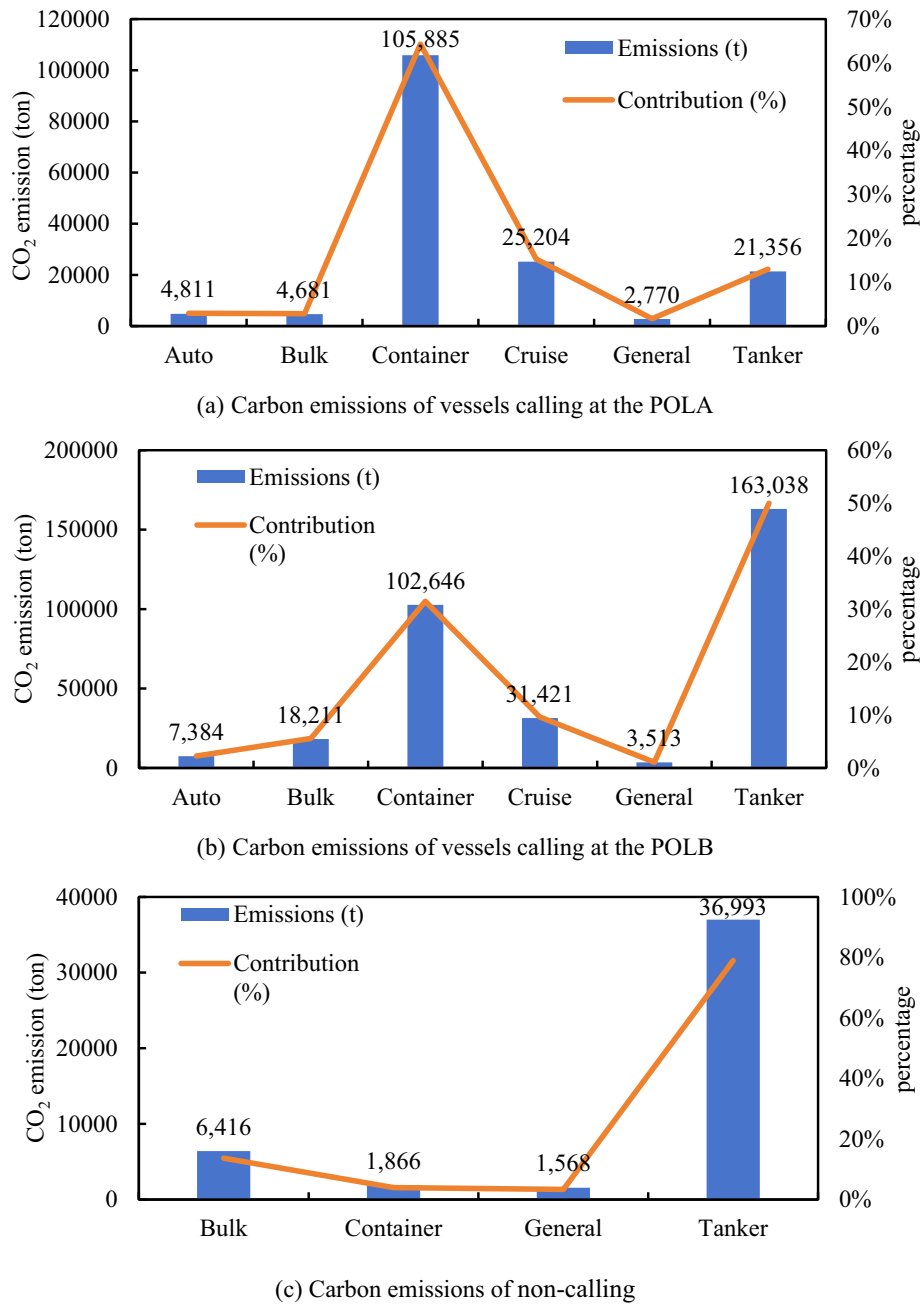


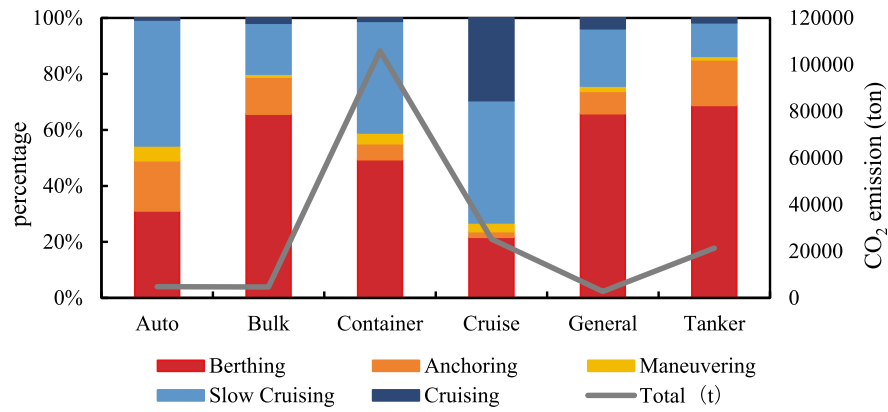
Fig. 5. Carbon emissions and contribution shares of different vessel types. The bar charts represent the absolute emissions, and the line charts represent the emission contribution rate of each vessel type.

Port of Los Angeles. However, the share of emissions attributable to anchored bulk carriers and tankers is higher at Long Beach. This is primarily due to the higher volume of arrivals for these vessel types at the port, resulting in longer waiting times at anchor. For non-calling vessels, emissions primarily originate from anchoring and navigating.

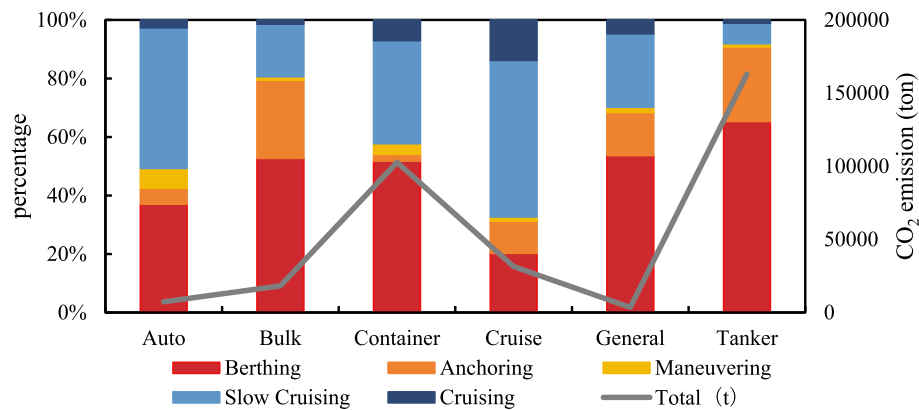
4.2.4. Emission characteristics of different power systems

To further identify the primary sources of emissions, this study analyzes the contribution of each emission source from the perspective of the power system. Fig. 7 illustrated the carbon emission contributions of three types of onboard power systems for each vessel type. As shown in Fig. 7(a) and 7(b), auxiliary engines and auxiliary boilers constitute the primary sources of emissions within the port area. This is consistent with the findings in Section 4.2.3, where berthing and slow cruising were identified as the primary operating modes. In both of these modes, the

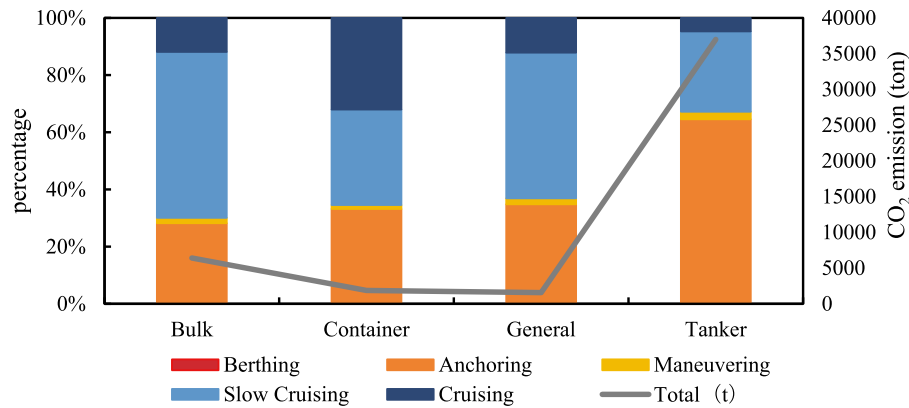
main engine typically operates under low load or remains shut down. At both ports, boiler emissions from tankers and container ships account for a higher proportion than those from other vessel types. During berthing, containerships utilize shore power to replace the load typically borne by auxiliary engines. However, boiler emissions remain unmitigated. For tankers, emissions stem from the continuous operation of high-power boilers during cargo discharge operations, which are required to heat the cargo and drive the cargo pumps. The emission profile of non-calling vessels differs from that of vessels calling at port. As shown in Fig. 7(c), main engines and auxiliary engines constitute the primary sources of emissions.



(a) Emission distribution of POLA



(b) Emission distribution of POLB



(c) Emission distribution of non-calling

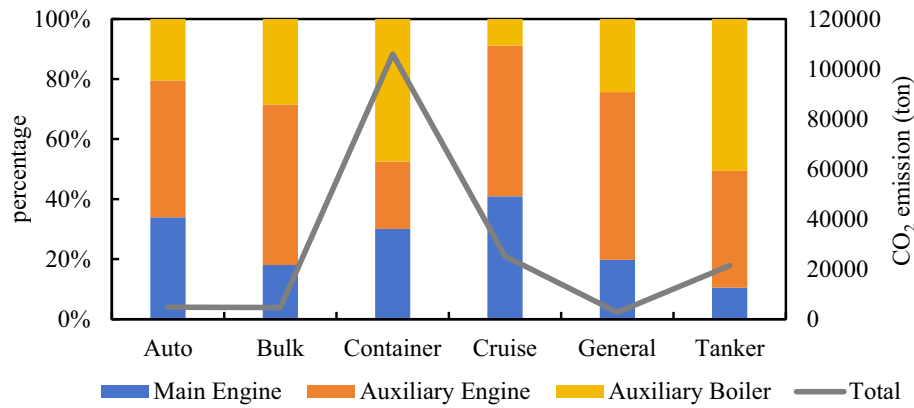
Fig. 6. The proportion of carbon emissions and total emissions of different types of ships at each operating mode. The percentage stacked bar charts illustrate the carbon emission contribution rates of different vessel types during five phases: Berthing, Anchoring, Maneuvering, Slow-Steaming, and Cruising. The gray line charts represent the total carbon emissions for each vessel type.

4.3. Spatial distribution of carbon emissions

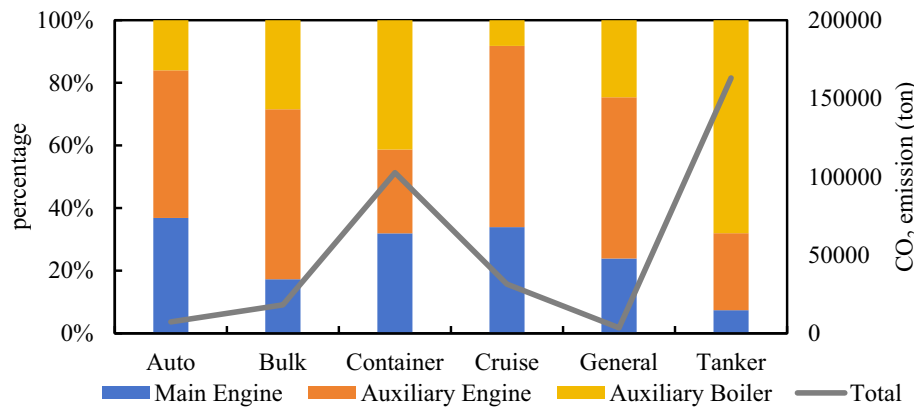
4.3.1. Overall spatial distribution

To reveal the overall spatial distribution characteristics of carbon emissions, the study area was divided into 1 km × 1 km grid cells, and the emissions of individual ships were mapped to the corresponding grids using a hybrid spatial allocation method. As shown in Fig. 8, the annual emissions in each grid cell are represented by a classified color scale, where cooler colors indicate lower emission levels and warmer colors indicate higher emission levels. Overall, ship carbon emissions exhibit a pronounced spatially heterogeneous distribution. The top 10%

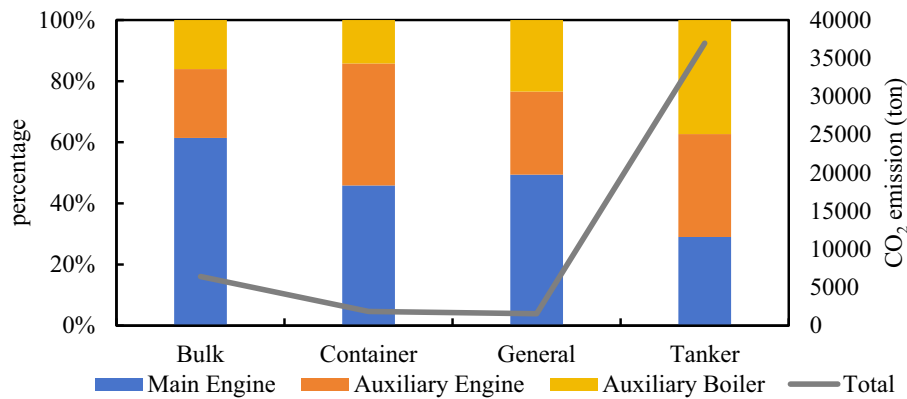
of grids with the highest emissions contributed 493,011.5 tons, accounting for 91.93% of the total gridded emissions, indicating a significant spatial concentration of port vessel carbon emissions. Within the berthing area, annual emissions per grid cell generally exceed 1000 tons, with extreme values surpassing 10,000 tons. This high level of emissions stems from the continuous operation of auxiliary engines and boilers after the main engines have been shut down during the berthing phase, particularly the high-power output of boilers during the unloading of large crude oil tankers. Along the main shipping channels leading into and out of the port, emissions form a north-south-oriented corridor, with annual emissions of approximately 1000 tons per grid cell. This zone



(a) Emission distribution of the POLA



(b) Emission distribution of the POLB



(c) Emission distribution of non-calling

Fig. 7. The proportion of carbon emissions and total emissions of power equipment of different types of ships. The percentage stacked bar chart showed the carbon emission contribution rate of the main engine, auxiliary engine and auxiliary boiler; The gray line chart showed the total carbon dioxide emissions of various ships.

corresponds to the vessel's deceleration transition area. As the vessel gradually shifts from a cruising state to a slow cruising and maneuvering state, the main engine operates under low-load conditions; when combined with the continuous power demand from auxiliary machinery, this results in a high emission density. The anchorage area situated outside the port also formed a significant cluster of emissions, with emission levels in some grid cells reaching as high as 10,000 tons. This is primarily due to the prolonged waiting periods of tramp vessels at anchorages, including a significant number of ships that never berthed. Taken together, the spatial pattern of carbon emissions in the port area is shaped by three distinct driving mechanisms.

4.3.2. Spatial distribution of different vessel types

To further reveal the vessel-type-specific spatial distribution patterns and their underlying mechanisms, this study focuses on emissions generated after vessels enter the precautionary zone. Based on the overall spatial concentration identified in Fig. 8, the emissions of different vessel types were further mapped to 100 m × 100 m grid cells using the hybrid spatial allocation method. As shown in Fig. 9, all sub-figures use the same color classification scheme, with class intervals consistent with those in Fig. 8, allowing a direct comparison of the spatial emission patterns among vessel types. Containerships, cruise ships, and auto carriers operating under the liner shipping model exhibit

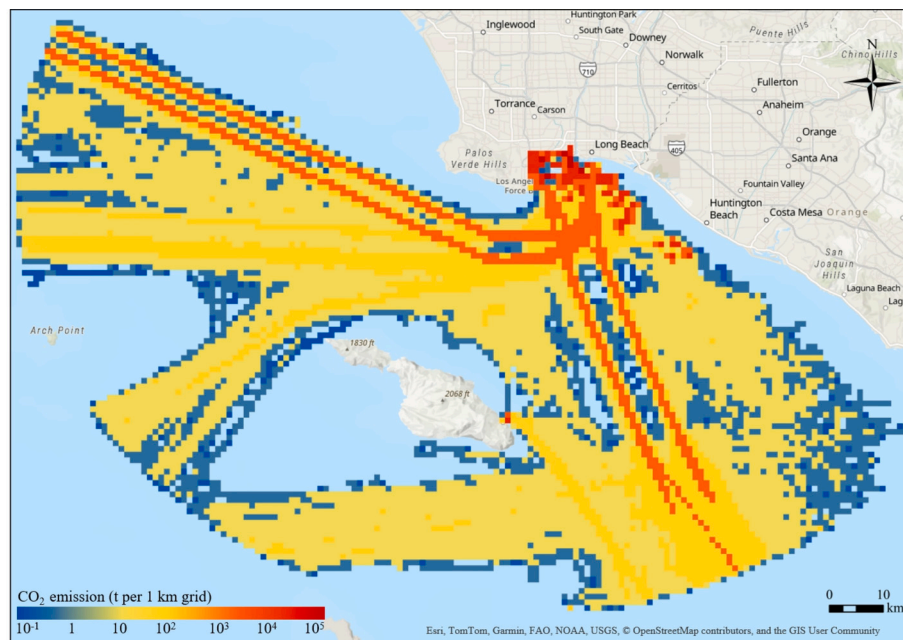


Fig. 8. Spatial distribution and localized features of carbon emissions in the Ports of Los Angeles and Long Beach and adjacent waters.

emission patterns characterized by a distinct linear corridor extending from the shipping lane to the berth. These vessels operate in strict adherence to their schedules. Upon arrival, they typically proceed directly into port to berth, with minimal waiting time at anchor. Consequently, their emissions form a continuous band-like distribution along the approach channels and are highly concentrated within their respective dedicated berthing areas. Emissions from tankers, bulk carriers, and general cargo vessels operating under the tramp shipping model form distinct clusters within anchorage areas. These vessels typically adhere to a queuing-based berth allocation system. Consequently, upon arrival, they often face prolonged waiting periods at anchorages while awaiting berth assignments or cargo arrangements. During the anchoring period, auxiliary engines and boilers remain in continuous operation, thereby creating multiple high-emission zones within the anchorage areas located both inside and outside the breakwater. Moreover, emissions from a substantial number of non-calling vessels are also aggregated within the anchorage zone. In summary, the spatial structure of carbon emissions within the port area essentially represents the combination of the emission characteristics of two shipping modes (liner and tramp).

4.4. Evaluation of differentiated carbon emission reduction scenarios

Based on the spatial heterogeneity of emissions and the driving mechanisms identified above, four categories of differentiated emission reduction measures were developed, incorporating current environmental regulations in California and recent advancements in international shipping technology. For operational optimization, a vessel speed reduction scenario was designed to evaluate the marginal benefits of stricter speed limits, and a Virtual Arrival scenario was constructed to quantify the emission reduction potential of shortened anchorage waiting times. For energy and technology substitution, a shore power expansion scenario was established to assess emission reductions at berth, and a clean energy substitution scenario was developed to evaluate the effects of fuel switching.

4.4.1. Mandatory vessel speed reduction

To simulate full compliance with the existing vessel speed reduction (VSR) program, this study established a mandatory compliance scenario by adjusting all trajectory points within the region that exceeded 12

knots to exactly 12 knots. As shown in Table 2, this reduced total carbon emissions by approximately 5700 tons (a reduction rate of 1.06%). The overall effect was limited, primarily because the majority of vessels were already operating at compliant speeds. Among the different vessel types, cruise ships at the Port of Los Angeles exhibited the most significant emission reduction effect due to their higher operational speeds. Conversely, tankers and bulk carriers, which typically operate at lower economic speeds, were minimally affected by the speed limits, with emission reductions of less than 0.2%.

4.4.2. Expansion of shore power application

To evaluate California's 2025 At-Berth Regulation, this study simulated the expanded use of shore power to auto carriers and tankers. As shown in Table 3, the combined emission reductions for both ports totaled 21,301 tons (5721 tons at the POLA and 15,580 tons at the POLB). Auto carriers demonstrated high emission reduction rates at both ports. This is attributed to the fact that their energy consumption during berthing is dominated by auxiliary engine electrical loads, allowing for a high degree of substitution through shore power. Although tankers at the POLB contributed the largest absolute emission reduction, their relative reduction rate was only 8.75%. This is primarily attributable to the specific composition of emissions at the Port of Long Beach. Shore power is capable of displacing only the electrical load of auxiliary machinery. It cannot offset the emissions generated by boilers providing steam for cargo oil pumps and heating systems. The 22.98% emission reduction rate observed for POLA tankers is linked to the relatively low reliance on boilers within their fleet. Based on a spatial analysis of ship emissions, the berth area constitutes one of the primary hotspots for emissions within the port district. The expansion of shore power capabilities can effectively reduce berthing emissions from vessel types whose emissions are predominantly driven by electrical loads. However, its impact is limited for vessel types where thermal loads predominate.

4.4.3. Implementation of virtual arrival mechanism

To address the high emissions caused by prolonged anchorage waiting of tramp vessels, this study constructed a virtual arrival scenario. In this scenario, 24 h was used as the upper threshold of anchorage duration to represent waiting events lasting more than one day. This threshold does not assume that all vessels can berth within 24 h. Instead, it was used as a baseline setting in the scenario analysis to

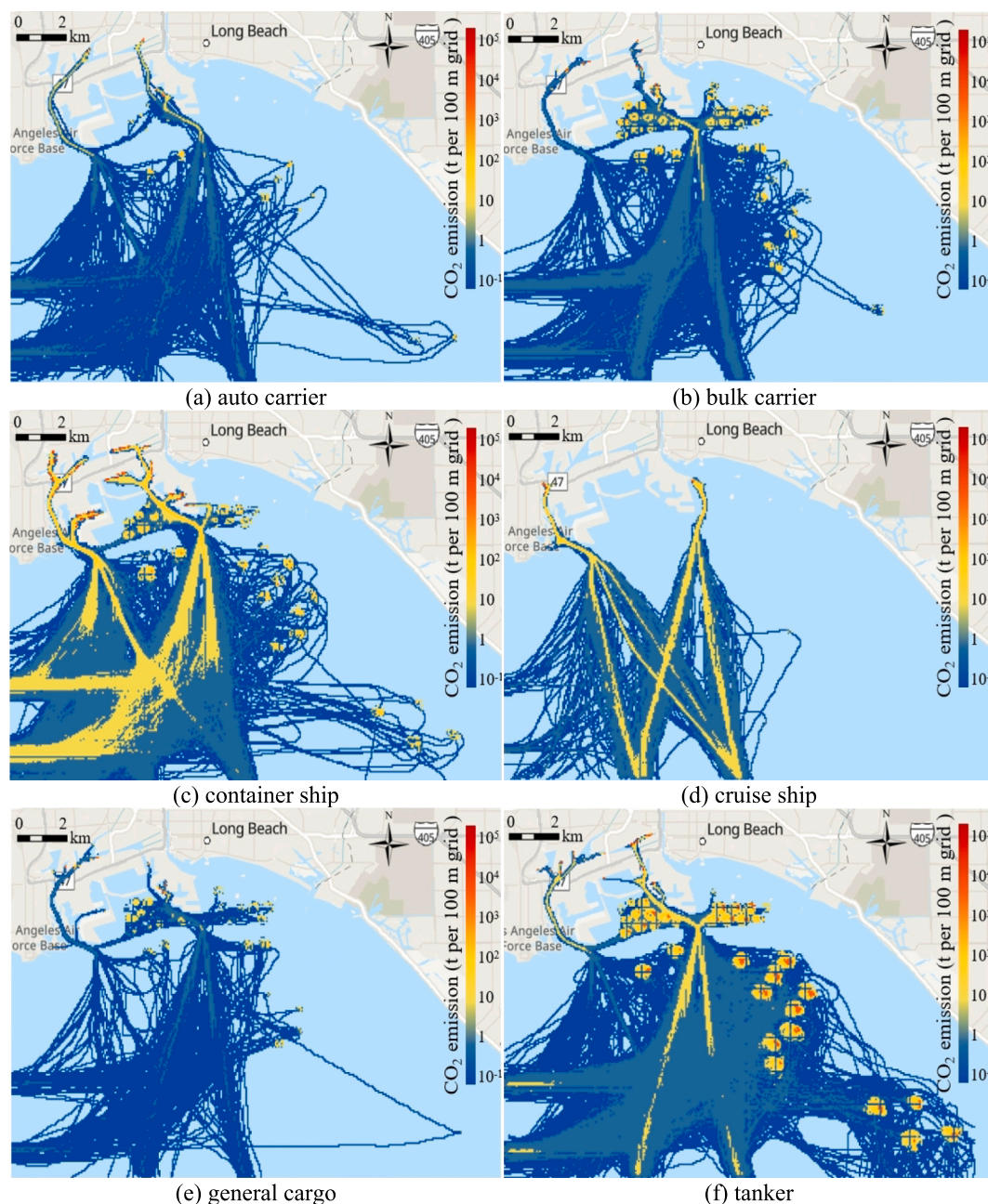


Fig. 9. Spatial distribution characteristics of carbon emissions from different vessel types. Basemap: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community.

Table 2
carbon emission reductions under the vessel speed reduction scenario.

vessel type	POLA	POLB	Non-calling vessels
	reduction (ton) / rate (%)	reduction (ton) / rate (%)	reduction (ton) / rate (%)
Auto	10(0.21%)	61(0.83%)	0
Bulk	6(0.13%)	23(0.13%)	76(1.18%)
Container	209(0.20%)	2717(2.65%)	143(7.66%)
Cruise	1523(6.04%)	593(1.89%)	0
General	13(0.47%)	19(0.54%)	26(1.66%)
Tanker	33(0.15%)	128(0.08%)	120(0.32%)
Total	1794(1.09%)	3541(1.09%)	365(0.78%)

identify reducible waiting time that could be shortened through arrival-

Table 3
carbon emission reductions under the shore power expansion scenario.

vessel type	POLA	POLB
	reduction (ton) / rate (%)	reduction (ton) / rate (%)
Auto	814(16.92%)	1310(17.74%)
Tanker	4907(22.98%)	14,270(8.75%)
Total	5721(3.47%)	15,580(4.78%)

time coordination, delayed departure, or speed adjustment before arrival. The anchorage duration statistics show that the median and mean anchorage durations in the study area were 8.78 h and 29.95 h, respectively, indicating a right-skewed distribution in which a small number of long-duration anchorage events substantially increased the average value. Anchorage episodes exceeding 24 h accounted for only

26.73% of all episodes, but contributed 85.68% of the total anchorage duration. This indicates that prolonged anchorage waiting is an important source of anchorage-phase emissions and a key target for the emission reduction potential of the Virtual Arrival strategy.

As shown in Table 4, the virtual arrival scenario achieved a total emission reduction of 57,486 tons, corresponding to a reduction rate of 10.69%. Spatially, the reductions were mainly concentrated in the Port of Long Beach and non-calling vessels, with reductions of 35,826 tons and 15,999 tons, respectively. The reduction rate for non-calling vessels reached 34.16%, which was much higher than that for vessels calling at the ports. By vessel type, the reductions were mainly contributed by tramp vessels such as tankers and bulk carriers. Tankers at the Port of Long Beach achieved a reduction of 30,613 tons, while the reduction rate for non-calling tankers reached 41.27%. In contrast, containerships, auto carriers, and general cargo ships showed relatively limited reductions, and cruise ships showed no reduction under this scenario. These results indicate that the virtual arrival strategy is mainly applicable to tramp vessels with pronounced long-duration anchorage waiting and can effectively reduce anchorage-related emissions within and around the port area.

4.4.4. Transition to alternative marine fuels

To assess the emission reduction potential of alternative marine fuels, two fuel-switching scenarios were simulated based on the emission factors in Table 5. Scenario 1 involves a complete fuel conversion of the main engine, auxiliary engines, and auxiliary boiler to a dual-fuel operation mode with LNG as the primary fuel and MGO (3.5% by energy share) as the pilot fuel. Scenario 2 involves switching the fuel only for the main engine, with methanol as the primary fuel and 5% MGO as the pilot fuel. As shown in Table 6, with the comprehensive adoption of LNG substitution, the total emission reduction rates for POLB, POLA, and non-calling vessels reach 39.85%, 37.14%, and 35.16%, respectively. Notably, tankers at POLB achieve a reduction of 72,092 tons (44.22%), primarily because the LNG substitution covers the boiler systems operating during the at-berth period. In contrast, Table 7 demonstrates that when methanol substitution is implemented solely for main engines, the overall emission reduction rates for the two ports are merely 3.99% for POLB and 6.04% for POLA. This is because, in near-shore and in-port areas, vessels predominantly operate at low speeds or remain in a berthing state, resulting in low main engine loads, whereas the energy consumption of auxiliary engines and boilers accounts for a significant proportion. Therefore, deep decarbonization in port areas requires targeted emission reductions from auxiliary engines and boilers during berthing. Unlike shore power, LNG substitution covers all three power systems, including boilers. This explains why tankers at the POLB achieve the highest absolute reduction (72,092 tons) under this scenario. The emission source that shore power cannot reach is now directly addressed.

4.4.5. Comprehensive comparison and combined scenario analysis

To comprehensively compare the effectiveness of different emission reduction measures and further evaluate the emission reduction

Table 4
carbon emission reductions under the virtual arrival scenario.

vessel type	POLA	POLB	Non-calling
	reduction (ton) / rate (%)	reduction (ton) / rate (%)	reduction (ton) / rate (%)
Auto	477(9.91%)	223(3.01%)	0
Bulk	322(6.88%)	3683(20.22%)	441(6.87%)
Container	3123(2.95%)	978(0.95%)	55(2.94%)
Cruise	0	0	0
General	106(3.82%)	329(9.36%)	237(15.12%)
Tanker	1633(7.64%)	30,613(18.78%)	15,266(41.27%)
Total	5661(3.44%)	35,826(10.98%)	15,999(34.16%)

Table 5
carbon emission factors for different power systems under alternative fuel scenarios.

fuel type	ME emission factor (g/kWh)	AE emission factor (g/kWh)	AB emission factor (g/kWh)
LNG	461.3	464.9	474.2
Methanol	468.8	696	962

Table 6
carbon emission reductions under the LNG substitution scenario.

vessel type	POLA	POLB	Non-calling
	reduction (ton) / rate (%)	reduction (ton) / rate (%)	reduction (ton) / rate (%)
Auto	1592(33.09%)	2364(32.01%)	0
Bulk	1725(36.85%)	6749(37.06%)	1874(29.21%)
Container	40,547(38.29%)	37,846(36.87%)	573(30.70%)
Cruise	7618(30.22%)	9721(30.94%)	0
General	964(34.80%)	1221(34.75%)	501(31.94%)
Tanker	8727(40.87%)	72,092(44.22%)	13,523(36.56%)
Total	61,173(37.14%)	129,993(39.85%)	16,471(35.16%)

Table 7
carbon emission reductions under the methanol substitution scenario.

vessel type	POLA	POLB	Non-calling
	reduction (ton) / rate (%)	reduction (ton) / rate (%)	reduction (ton) / rate (%)
Auto	339(7.05%)	570(7.72%)	0
Bulk	176(3.76%)	656(3.60%)	828(12.90%)
Container	6685(6.31%)	6859(6.68%)	180(9.64%)
Cruise	2163(8.58%)	2232(7.10%)	0
General	115(4.15%)	177(5.04%)	162(10.33%)
Tanker	469(2.20%)	2516(1.54%)	2251(6.09%)
Total	9947(6.04%)	13,010(3.99%)	3421(7.30%)

potential of combined strategies, combined scenarios were developed based on the results of the individual scenario assessments. The results are presented in Table 8. S1-S5 represent the speed reduction, shore power expansion, virtual arrival, LNG substitution, and methanol substitution scenarios, respectively. C1 combines speed reduction and virtual arrival, representing an operational optimization scenario. C2 incorporates shore power expansion into C1 to evaluate the combined effect of operational optimization and shore power utilization during berthing. C3 further introduces LNG substitution, representing a deep decarbonization pathway integrating operational optimization, shore power expansion, and fuel substitution.

The results of the individual scenarios indicate substantial differences in emission reduction effectiveness among the measures. These

Table 8
Emission reductions under individual and combined scenarios.

Scenario	POLA	POLB	Non-calling	Total
S1	1794(1.09%)	3541(1.09%)	365(0.78%)	5700(1.06%)
S2	5721(3.47%)	15,580(4.78%)	0	21,301(3.96%)
S3	5661(3.44%)	35,826(10.98%)	15,999(34.16%)	57,486(10.69%)
S4	61,173(37.14%)	129,993(39.85%)	16,471(35.16%)	207,637(38.61%)
S5	9947(6.04%)	13,010(3.99%)	3421(7.30%)	26,378(4.91%)
C1	7455(4.53%)	39,367(12.07%)	16,364(34.93%)	63,186(11.75%)
C2	13,176(8.00%)	54,947(16.84%)	16,364(34.93%)	84,487(15.71%)
C3	69,826(42.39%)	163,884(50.24%)	25,901(55.29%)	259,611(48.28%)

differences are mainly determined by the operational stage affected, the applicable vessel categories, and the range of emission sources covered. The speed reduction scenario achieved the smallest reduction, with a total decrease of 5700 tons and a reduction rate of only 1.06%. This suggests that vessels in the study area already operate at relatively low speeds, leaving limited potential for further emission reductions through additional speed restrictions. The shore power expansion and methanol substitution scenarios reduced emissions by 21,301 tons and 26,378 tons, corresponding to reduction rates of 3.96% and 4.91%, respectively. Shore power expansion primarily affects auxiliary engine loads during berthing, whereas methanol substitution only changes the fuel used by main engines. As both measures target only part of the emission sources, their overall effects remain limited. In contrast, the virtual arrival scenario achieved a reduction of 57,486 tons, corresponding to a reduction rate of 10.69%. The reduction rate for non-calling vessels reached 34.16%, highlighting the considerable emission reduction potential of anchorage waiting-time management. The LNG substitution scenario produced the largest reduction, decreasing emissions by 207,637 tons and achieving a reduction rate of 38.61%. This result is attributable to its influence on major emission sources, including main engines, auxiliary engines, and boilers.

The results of the combined scenarios indicate that the overall emission reduction effect increased progressively with the implementation of additional emission reduction measures. The operational optimization scenario achieved a reduction of 63,186 tons, corresponding to a reduction rate of 11.75%. This reduction was nearly equal to the sum of the reductions achieved by the speed reduction and virtual arrival scenarios, indicating that the two measures act on the navigation and anchorage phases, respectively, with little overlap in their emission reduction effects. For vessels not calling at port, the reduction rate reached 34.93%, which was close to that of the virtual arrival scenario, further suggesting that the reduction mainly resulted from shortened anchorage waiting times. With the further expansion of shore power based on operational optimization, the emission reduction increased to 84,487 tons, corresponding to a reduction rate of 15.71%. As shore power primarily affects the berthing phase, the additional reduction was generally consistent with that achieved under the shore power expansion scenario alone. Since vessels not calling at port cannot utilize shore power, their reduction rate remained unchanged from that of the operational optimization scenario. The deep decarbonization scenario achieved an emission reduction of 259,611 tons, corresponding to a reduction rate of 48.28%. This value was lower than the simple sum of the reductions achieved under the operational optimization plus shore power scenario and the LNG substitution scenario, indicating the presence of interaction effects among emission reduction measures. As LNG substitution had already substantially reduced emissions, the marginal reduction contributions of operational optimization and shore power expansion were correspondingly diminished in the combined scenario. The reduction rates for the Port of Los Angeles, the Port of Long Beach, and vessels not calling at port reached 42.39%, 50.24%, and 55.29%, respectively.

5. Discussion

Based on AIS data and a bottom-up power-based approach, this study constructed a 2024 carbon emissions inventory for ocean-going vessels within the San Pedro Bay ports. The annual carbon emissions estimated for the Port of Los Angeles and the Port of Long Beach were 164,707 tons and 326,213 tons, respectively. In the 2024 air emissions inventory reports released by the two ports, the carbon dioxide-equivalent emissions from ocean-going vessels were 162,042 tons and 316,130 tons, respectively. Using the official inventory data as a reference, the estimates in this study were approximately 1.64% and 3.19% higher, respectively. It should be noted that the official inventories report carbon dioxide-equivalent emissions, which include the combined effects of carbon dioxide, methane, and nitrous oxide, whereas this study only accounts for

carbon dioxide emissions. For conventional marine fuel combustion in shipping, carbon dioxide accounts for more than 98% of total greenhouse gas emissions on a carbon dioxide-equivalent basis. Therefore, the actual overestimation of this study relative to the carbon dioxide-only component of the official inventories may be slightly higher than the values reported above. Nevertheless, the deviations from the official carbon dioxide-equivalent inventory values remain within 5%, supporting the reliability of the power-based emission estimation model and vessel classification method used in this study.

At the level of spatial allocation, this study employs a hybrid spatial allocation method based on ship motion states, utilizing the activity-weighted method for navigating and maneuvering vessels and the point density method for anchoring and berthing vessels to attribute emissions. Compared to the traditional single-point density method, this approach effectively resolves the issue of spatial discontinuity in emissions when moving vessels traverse grid boundaries. Furthermore, in contrast to a uniform application of the activity-weighted method, this approach avoids redundant line-segment partitioning calculations when processing trajectory data from vessels in anchoring or berthing states. This significantly enhances computational efficiency in large-scale data processing while maintaining spatial accuracy. The results regarding the spatial distribution of carbon emissions reveal a high degree of spatial correspondence between high-emission zones and the core functional areas of the port, thereby further validating the spatial rationality of the proposed method. These validations provide a reliable empirical foundation for discussions concerning the differentiation of emission structures, underlying driving mechanisms, and the effectiveness of emission reduction strategies.

This study reveals the structural differences in carbon emissions between adjacent ports. Although the Ports of Los Angeles and Long Beach share waterways and anchorages, they differ in terms of total carbon emissions, dominant vessel types, and primary emission sources. The Port of Los Angeles exhibits a typical containership-dominated emissions pattern, with containerships accounting for 64% of the port's carbon emissions. The Port of Long Beach, by contrast, exhibits a tanker-dominated pattern, with emissions from tankers alone amounting to approximately the total annual emissions of the Port of Los Angeles. Existing comparative studies of multiple ports [33] typically focus on emission differences among geographically dispersed ports, analyzing each port as a relatively homogeneous emission unit. However, due to differences in functional positioning, the emission structures of adjacent ports exhibit distinct characteristics. This differentiation stems from varying functional positioning among ports, which results in distinct compositions of arriving vessel types. These compositional differences lead to variations in power system configurations and operational patterns, ultimately producing divergent emission structures. The policy implication of this finding is that a uniform emission reduction strategy is inappropriate for governing carbon emissions across all ports. For ports dominated by container vessels, emission reduction efforts should focus primarily on promoting the adoption of shore power. Conversely, for ports dominated by oil tankers, emission reduction strategies must specifically address the high-intensity emissions generated by boilers during cargo unloading operations. As this particular emission source cannot be mitigated through shore power technology, it necessitates reliance on fuel switching or process improvements.

In this study, the annual carbon emissions from non-calling vessels amount to 46,843 tons (with tankers accounting for 79%), exceeding the total annual emissions of all tankers at the Port of Los Angeles. Existing studies on port emissions [49] have not conducted a detailed analysis of this specific category of vessels. Measures targeting the berthing phase have no regulatory authority over emissions at anchorages; therefore, it is necessary to explore novel policy instruments such as anchorage time limits, virtual arrival mechanisms, or anchorage emission fees to mitigate this limitation. The four emission reduction scenarios examined in this study demonstrate significantly different levels of effectiveness. Vessel speed reduction yields extremely low marginal benefits within

the port area; this is because the vast majority of vessels already adhere to the 12-knot speed limit, and the primary source of emissions within the port area lies not in the main engines during the navigating phase, but rather in the auxiliary engines and boilers utilized during the berthing and anchoring phases. The effectiveness of expanding shore power availability exhibits a significant dependency on vessel type: while it achieves an emission reduction rate of 17% for auto carriers, this rate stands at only 8.75% for tankers at the Port of Long Beach. Shore power can only displace the electrical load of auxiliary engines; it cannot displace the thermal steam load of boilers, the latter being precisely the dominant source of emissions for large crude oil tankers during cargo unloading operations. Conversely, the virtual arrival mechanism demonstrates the potential to significantly reduce emissions from vessels operating under the tramp shipping model. The complete substitution of fuels with clean alternatives achieves the highest emission reduction rate, reflecting its ability to reduce emissions from main engines, auxiliary engines, and auxiliary boilers simultaneously. Overall, deep decarbonization in ports requires a combination of measures tailored to port-specific emission structures.

6. Conclusion

This study focused on ocean-going vessels in the San Pedro Bay port complex and its adjacent waters. A high-resolution carbon emission inventory covering the complete operational cycle was developed by integrating a power-based bottom-up method with a hybrid spatial allocation model. By distinguishing different operating stages and considering the activities of non-calling vessels, this study identified the differentiated formation mechanisms of port-area carbon emissions in berthing areas, fairways, and anchorages. Berthing emissions were mainly affected by the operation of auxiliary engines and auxiliary boilers. Fairway emissions were closely associated with main-engine operation under low-load conditions during low-speed navigation. Anchorage emissions mainly originated from the long waiting time of bulk carriers and tankers.

In terms of vessel-type contributions, the emission structures of the Port of Los Angeles and the Port of Long Beach differed markedly. The annual emissions of the Port of Long Beach were approximately twice those of the Port of Los Angeles, with tankers being the dominant emission source. In contrast, emissions at the Port of Los Angeles were concentrated in containerships. The relatively high proportion of large crude oil tankers among vessels calling at the Port of Long Beach partly explains this difference. These vessels require continuous auxiliary boiler operation during unloading to support cargo pump operation and cargo heating, thereby increasing emissions during the berthing stage. The emission differences between adjacent ports are therefore related not only to the composition of calling vessels, but also to the operational patterns and energy demands of different vessel types. In addition to vessels actually calling at port, non-calling vessels also represented an important component of port-area emissions. These vessels were mainly composed of tramp vessels such as tankers and bulk carriers. Although they did not enter terminals for cargo-handling operations, they still generated emissions during anchorage waiting and temporary stays, accounting for nearly 9% of total emissions in the study area. The spatial distribution differences among vessel types were closely related to their operating modes. Emissions from liner vessels were mainly distributed continuously along fairways and berths, whereas emissions from tramp vessels were concentrated in anchorage waiting areas. The scenario assessment indicates that deep decarbonization in port areas requires the coordinated implementation of operational optimization, shore power expansion, and clean fuel substitution, with control priorities determined according to the emission structures of different ports.

Although this study identifies the key characteristics of port-complex carbon emissions and evaluates the potential of different emission reduction strategies, certain limitations should be addressed in future research. The power parameters of auxiliary engines and auxiliary

boilers are mainly derived from fleet-level averages in the Vessel Boarding Program rather than real-time onboard measurements. They may not fully capture vessel-specific differences caused by vessel age, equipment condition, and actual operating conditions. This may introduce uncertainty into emission estimates during berthing and anchoring, and affect the accuracy of local emission hotspot identification. In addition, operational mode identification is mainly based on speed, distance from shore, and spatial relationships with anchorage areas. This approach is suitable for large-scale annual emission calculations, but it cannot fully describe detailed variations in port entry scheduling, berthing and unberthing operations, and cargo-handling processes. Port-area ship emission studies should not directly follow the calculation logic used for conventional navigation stages. Instead, stage-specific modeling is needed by considering port operation processes, vessel operating states, and equipment-level emission sources. Future research could further integrate port operation records, measured vessel equipment parameters, and real-time meteorological and oceanographic data to improve the accuracy of port-area ship carbon emission calculations and the applicability of low-carbon shipping pathway assessments.

CRediT authorship contribution statement

Xinqiang Chen: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yajie Zhang:** Writing – original draft, Data curation, Conceptualization. **Zhen Feng:** Methodology, Investigation, Formal analysis, Data curation. **Han Zhang:** Software, Methodology, Formal analysis, Data curation. **Salvatore Antonio Biancardo:** Software. **Wen-Long Shang:** Supervision, Software, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Xinqiang Chen reports financial support was provided by National Natural Science Foundation of China. Given his/her/their role as Associate Editor of Applied Energy, Wen-Long Shang had no involvement in the peer review of this article and had no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to another journal editor. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The AIS data used in this study are publicly available at <https://marinecadastre.gov/ais/>

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