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Investigation of a port queuing system on CO_2 emissions from container shipping

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A R T I C L E I N F O

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A B S T R A C T

The maritime shipping industry is pursuing a diversity of strategies to meet its decarbonization goals, yet inefficiencies like traditional "first-come, first-served" port arrival systems, which encourages vessels to race to port to wait offshore, remain largely unaddressed despite their significant emissions impact. In 2021, the Ports of Los Angeles and Long Beach implemented a new queuing system for container ships that instead assigns predetermined positions when vessels depart their last port of call. Our research evaluates whether this system, implemented primarily to reduce port congestion during major disruptions, also reduces CO_2 emissions during transpacific voyages by enabling vessels to optimize speed. To examine this, we applied a bottom-up emissions model using vessel technical specifications and Automatic Identification System (AIS) data from 10,000 voyages by 1157 container ships across 6.5 years (2017–2023). We compared emissions before and after the new system was implemented at Los Angeles and Long Beach, observing 16–24 % reductions in emissions per voyage post-implementation, and compared emissions trends at three control ports along the West Coast of North America without similar systems. These comparison ports showed moderate emissions reductions, suggesting these decreases can be attributed to multiple combined factors (e.g. rising fuel prices, changing trade volumes, and new emissions regulations). We additionally found substantial variation in emissions efficiency among major ocean carriers, highlighting the influence of company-specific practices. Finally, we examine how additional queuing system modifications could even further reduce emissions.

1. Introduction

Maritime transport, the backbone of international trade, is responsible for moving over 80 % of global trade by volume (UNCTAD, 2023). Despite being one of the most efficient ways to transport goods (IMO, 2009), this sector contributes considerable pollution and greenhouse gas (GHG) emissions, thereby accelerating climate change (Eyring et al., 2010; Jutterström et al., 2021) and impacting human health (Corbett et al., 2007; Sun et al., 2024). Shipping contributed nearly 3 % of global GHG emissions and approximately 2 % of global carbon dioxide (CO_2) emissions in 2018 (IMO, 2021). As the volume of maritime trade continues to increase, experts project that without intervention, this sector's emissions could reach 90–130 % above 2008 levels by 2050 (IMO, 2021).

In response, the United Nations' International Maritime Organization (IMO), the specialized agency responsible for regulating maritime transport, has adopted a GHG abatement strategy that strives to reach net zero by or around 2050 and reduce the carbon intensity of shipping

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by at least 40 % by 2030, compared to 2008 (IMO, 2018a, 2023). Meeting these targets will require a comprehensive approach combining technological innovations and operational improvements. While technological measures (e.g. improvements in ship design and alternative fuels) have a high potential for emissions reductions (Aakko-Saksa et al., 2023; Balcombe et al., 2019; Bouman et al., 2017), they require significant up-front investments and time to develop and implement. In contrast, operational efficiency measures, such as speed and route optimization, can be implemented more rapidly and cost-effectively in the near term. These operational solutions primarily rely on software innovation, data sharing, and changes in stakeholder behavior, making them accessible options for immediate impact.

1.1. Port-based strategies for decarbonization

There is increasing recognition of the crucial role ports play in the supply chain and their potential to reduce GHG emissions (Alamoush et al., 2022a, 2022b; Poulsen et al., 2018; Styhre et al., 2017; Sun et al., 2025; Winnes et al., 2015). Vessel operations at sea account for the majority of maritime CO_2 emissions (75–90 % depending on ship type), however a substantial amount of emissions (10–25 %) also occur during port activities such as maneuvering, anchoring, or berthing near the port or terminal (IMO, 2021). This underscores the strategic importance of ports as intervention points in emission reduction efforts as they can, to some degree, shape both transit behaviors at sea as well as ship activities in ports. This includes such measures as alternative energy solutions and optimized port-vessel interfaces (Styhre et al., 2017).

These interventions implemented at or managed by ports are particularly significant when examining vessel waiting time. Building on this understanding, researchers and major shipping industry organizations have identified minimizing vessel waiting time at ports and anchorages as a strategic opportunity to improve operational inefficiencies and reduce emissions. Waiting time at ports can be attributed to several factors, including terminal closure during nights and weekends (Johnson and Styhre, 2015), limitations in berth availability, labor resources, and cargo handling equipment (Winnes et al., 2015), information fragmentation and insufficient coordination among stakeholders (Pahl and Voß, 2017), and divided responsibility among different governing bodies that make innovations difficult to implement, especially in ports managing logistics for a diversity of commodity trades (Heaver, 2021). Moreover, suboptimal berth allocation practices further compound these inefficiencies. Particularly problematic is the persistent reliance on traditional "first-come, first-served" berthing systems, which incentivizes a practice known as "Sail Fast, then Wait" where vessels rush to reach their destination port to secure a place in the berthing queue. If berth, fairway, and nautical services are not available, vessels have to wait at anchorage or loiter near ports at low speed for hours, days, or even weeks (GEF-UNDP-IMO GloMEEP Project and members of the GIA, 2020).

The environmental impact of this type of system is twofold: first, vessels traveling faster to secure earlier positions in berthing queues increases fuel consumption which in turn impacts GHG emissions (Alvarez et al., 2010) and increases environmental risks like ship strikes with wildlife (Silber et al., 2010) and underwater noise impacts on marine mammals (Findlay et al., 2023). Second, if vessels have to wait at port for available services, they continue to run their auxiliary engines and boilers while idling at anchorage, emitting CO_2 and other pollutants, like nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM), that are harmful to human health and could otherwise be reduced if wait time was minimized (Zhang et al., 2024).

Researchers have taken various approaches to solve the inefficiencies inherent with traditional first-come, first-served berthing systems. There has been extensive research over the last thirty years focused on how to best allocate berths, with many of the studies using stochastic programming to optimize berth scheduling (Rodrigues and Agra, 2022). Other research has tackled other parts of the port call process, reducing the uncertainty of predicting vessel arrival times through AIS data and machine learning models (Dobrkovic et al., 2016; Kolley et al., 2023). Underlying many of these technical solutions, is the need for digital platforms and tools to enhance ship-port collaboration and data sharing (Lind et al., 2021).

Among the various integrated approaches that have emerged from this research, "Just-In-Time" arrival represents one specific, potentially impactful, strategy within this broader port call optimization framework, focusing particularly on the coordination of vessel speed with berth availability. This approach enables ships to optimize speed during their voyage to arrive at the appropriate window of time for available facilities and services. The general logic of these Just-In-Time systems more closely matches the standard for similar industries, such as aviation, where airplanes adjust speed to the estimated time of landing to save on fuel, reduce emissions, and avoid congesting the airspace near airports (Andersson and Ivehammar, 2017; Sarkar, 2012).

Typically, in maritime shipping, as a vessel nears its destination it initiates the port call process by providing advance notice to the port authority (often 72–96 h prior to arrival) at which point coordination of facilities and services begins. The vessel's appointed agent, working as an intermediary between the vessel and shore-based entities, coordinates with terminal operators to secure docking space and establish a berthing time. This information is then communicated to the vessel master (ship captain) who must decide whether to proceed directly to berth or set anchorage if services aren't yet available. This approach to port involves complex real-time communication between Vessel Traffic Services, the vessel's bridge team, harbor pilots (who board the vessel to provide local navigation expertise), and tug crews (who assist with final positioning) (Poulsen and Sampson, 2020). The efficiency of this approach process is significantly influenced by both the port's governance structure and terminal ownership arrangements, particularly in container shipping where logistics integration through carrier-controlled terminals (vertical integration) can streamline coordination between vessels and berth facilities by reducing the number of independent stakeholders involved in decision-making (Paridaens and Notteboom, 2022).

The primary mechanism through which Just-In-Time arrival reduces emissions is by communicating and confirming berth availability sooner to minimize unproductive waiting time at ports or other maritime chokepoints, enabling vessels to adjust their speed throughout the voyage. Speed optimization has been widely studied in transportation research, with a comprehensive review by Bouman et al. (2017) analyzing 26 different studies on this topic and highlighting high emission reduction potential. In much of the literature, the relationship between vessel speed and fuel consumption is exponential–often simplified as a "cubic relationship" where consumption is proportional to the cube of speed, however, other research demonstrates this relationship is more complex in practice; fuel consumption depends not just on speed but significantly on payload, and is influenced by fuel prices, freight rates, cargo value, and loading condition (Psaraftis and Kontovas, 2014), as well as hull design, vessel type and size, and environmental conditions like currents and sea state (Adland et al., 2018).

Speed optimization also involves trade-offs, potentially requiring longer transit times or requiring additional vessels to maintain cargo throughput which could impact total emissions (Psaraftis and Kontovas, 2013). Despite these complexities, speed optimization is seen as one of the most effective operational measures for reducing emissions, especially in the short-term (Faber et al., 2017). Measures that eliminate unproductive waiting time at ports are particularly promising for emissions reduction since they enable speed optimization without disrupting scheduled cargo operations or requiring additional vessels. Initial studies suggest significant theoretical potential to reduce CO_2 emissions with Just-In-Time arrival at ports, with studies documenting fuel consumption savings ranging from 8 % to 19 % across various vessel types and implementation scenarios at ports (GEF-UNDP-IMO GloMEEP Project and members of the GIA, 2022; Grigoriadis et al., 2024; Jia et al., 2017; Kim and Eom, 2023), and could help reduce up to 1.8 million metric tonnes of CO_2 annually if implemented at maritime chokepoints like the Panama Canal (Fuentes and Adland, 2023).

1.2. Implementation challenges across shipping sectors

Despite the theoretical benefits of improved port call coordination and Just-In-Time arrival, implementation within the maritime shipping industry has been slow. Container shipping, the segment proportionally with the most CO_2 emissions (IMO, 2021), presents the most favorable environment for Just-In-Time adoption with fewer contractual barriers, predetermined schedules and routes, and standardized handling operations (GEF-UNDP-IMO GloMEEP Project and members of the GIA, 2020). It is more complex for tankers and dry bulk shipping which have irregular routes, more contractual obligations that require vessels proceed with "utmost dispatch" (as quickly as reasonably possible) to the destination port, split incentives between shipowners and charterers (Rehmatulla and Smith, 2015), irregular and short-notice port calls (Lind et al., 2021) and variable loading times across different commodities (Heaver and Atkins, 2024). While "Virtual Arrival" agreements attempt to address these issues by creating a contractual mechanism for vessels to reduce speed, they remain limited due to conflicting commercial priorities, lack of standardized frameworks for benefit-sharing, and industry traditions that view maximum speed as the default (Jia et al., 2017; Poulsen and Sampson, 2019).

Given these implementation challenges in the tanker and bulk shipping sectors, this study focuses on container shipping, where structural and operational conditions are more conducive to Just-In-Time arrival systems and where recent disruptions have catalyzed new approaches to vessel queuing. In recent years, several ports have begun piloting digital systems to coordinate vessel approaches and reduce time awaiting berth, particularly following the supply chain disruptions caused by the COVID-19 pandemic, which exposed critical vulnerabilities and caused major port congestion (Li et al., 2024). These disruptions, while challenging, presented a unique opportunity to reimagine longstanding inefficient practices, catalyzing digital innovation and new management approaches that might otherwise have taken years to implement under normal circumstances. Our study focuses on one such innovation: a new voluntary system for container shipping implemented at the Ports of Los Angeles and Long Beach in November 2021 called the "New Queuing System for Labor," hereafter referred to as the "queuing system."

1.3. The ports of Los Angeles and Long Beach queuing system

The Ports of Los Angeles and Long Beach, located directly adjacent to each other within the San Pedro Bay in Southern California, are the busiest port complex in the U.S. and ninth in the world according to 2022 container volume data, handling over 18 million twenty-foot equivalent unit (TEU) annually (11 % of the world's containerized trade) and approximately 40 % of U.S. imports from Asia (The Port of Los Angeles, 2021; UNCTAD, 2023). During the COVID-19 pandemic, these ports experienced unprecedented congestion with over 100 vessels anchored nearby for weeks awaiting berth (Fig. 1).

Prior to the crisis, the ports used a traditional first-come, first-served system for assigning berths and labor once ships were within 20 nautical miles of the ports. When pandemic-induced supply chain disruptions emerged, the system's inefficiencies became apparent as the vessel queue swelled from the typical 0–4 container vessels to >100. To address this crisis, a working group of maritime industry stakeholders rapidly designed and implemented the "New Queuing System for Labor" within a month of convening. The working group included representatives from the Pacific Maritime Association (association negotiating labor agreements), Pacific Merchant Shipping Association (trade association), and three separate Marine Exchanges (non-profits that promote safe and efficient maritime operations): Marine Exchange of Southern California (assemble the schedules and provide vessel traffic services for Southern California ports), and Marine Exchange of Alaska (track vessel movement and manage maritime safety information throughout Alaska's coastline).

The new voluntary queuing system fundamentally altered vessel queuing incentives by assigning each container vessel a position in line upon departure from its last port of call, rather than upon physical arrival. This position is determined using a "Calculated Time of Arrival" based on the vessel's departure time and a standardized transit speed (18 knots for standard vessels, 21 knots for expedited vessels). With queue positions secured in advance, vessels no longer need to travel rapidly to port, allowing captains to potentially optimize transit speeds for efficiency. The system also addresses local air quality concerns by requiring vessels that arrive early to wait outside a designated Safety and Air Quality Area 50–150 nautical miles offshore until 72 h before their scheduled berthing time, thereby reducing emissions near coastal communities (PacMMS, 2021).

To implement this, Marine Exchange of Southern California partnered with the Marine Exchange of Alaska to form Pacific Maritime Management Services (PacMMS), utilizing the 24/7 operations centers already established at the Marine Exchange of Alaska and developing a web-based registration system where ships log their departure information, which is then used to calculate arrival times at the ports ("About - PacMMS," 2015). The system communicates with vessels via satellite phone and email, technologies already widely available to ships, making it cost-effective and quick to implement during the crisis.

The New Queuing System for Labor represents a unique hybrid approach in the spectrum of port management systems. Rather than directly assigning specific berth times, it assigns a position in the queue based on when vessels depart their origin port. This creates a system that maintains elements of a first-come, first-served approach while changing the definition of first-come from physical arrival to a calculated virtual arrival time. Unlike a full Just-In-Time system, which would coordinate vessel arrivals precisely with berth availability and terminal readiness, this queuing system represents an intermediary step that does not directly synchronize vessel arrivals with specific berthing windows. Nevertheless, it offers a pragmatic model for ports seeking incremental improvements toward greater operational efficiency without requiring complete operational overhauls of terminal scheduling systems.

1.4. Research gap and study objectives

While preliminary analyses suggest that the queuing system at the Ports of Los Angeles and Long Beach appears to have been successful in reducing the number of vessels anchoring and loitering near these coastal communities (California Air Resources Board, 2022; Vukić and Lai, 2022), a critical research gap remains. No studies have yet examined whether this newly implemented system has enabled vessels to optimize speed throughout the entire transpacific voyage, potentially yielding significant CO_2 emissions reductions over distances up to 14,300 km (7721 nm).

Our research specifically addresses the question: Can a port queuing system implemented primarily to reduce port congestion during a time of major disruptions and crises also reduce CO_2 emissions during vessels' entire voyages by optimizing transit times between ports?

To evaluate this question, we analyze high-resolution maritime activity data compiled from Automatic Identification System (AIS) data for 1157 container vessels traveling from East Asia to major ports along the West Coast of North America between January 1, 2017 and August 31, 2023. We estimate CO_2 emissions using a bottom-up approach as outlined in Olmer et al. (2017) and the *Third IMO GHG Study 2014* to compare the average emissions before and after the queuing systems implementation. To determine whether observed differences are specifically attributable to the queuing system rather than broader industry trends or alternate factors, we conduct a comparative analysis examining CO_2 emissions patterns during the same period for similar vessel

Fig. 1. Record number of cargo ships anchored offshore of the Ports of Los Angeles and Long Beach in September 2021. Photo by Mario Tama/Getty Images.

classes at four ports that did not implement comparable systems: Manzanillo (Mexico), Vancouver (Canada), and Seattle and Tacoma (United States). To better understand whether differences between operators shaped any of these patterns, we also analyze and report the emission efficiencies observed for ten of the largest ocean carriers operating in the Pacific. These results shed light on the degree of uniformity of response to the queuing system at the company level and illuminate pathways for adapting such systems to maximize their efficacy in acknowledgment that fleets vary in their operational goals and constraints. Finally, we model potential modifications to the current queuing system as implemented in the Ports of Los Angeles and Long Beach to identify opportunities for further emissions reductions.

2. Methodology

2.1. Study area and data sources

This study focused specifically on the East Asia trade route to the West Coast of North America, using 145°east latitude as the outer boundary to isolate the transpacific crossing (Fig. 2). We analyzed vessel activity and estimated emissions from 581 of container vessels enrolled in the new queuing system that made eastbound transpacific voyages to the Ports of Los Angeles and Long Beach, comparing activity before (January 2017–December 2021) and after (January 2022–August 2023) queue implementation. As comparison controls, we analyzed any container vessels call at three major West Coast ports without similar queuing systems (Manzanillo, Vancouver, and Seattle and Tacoma), which included an additional 576 vessels.

Our analysis integrates three primary data sources: (1) AIS from the data provider Spire, (2) vessel characteristics and port call information obtained from S&P Global, and (3) queuing system enrollment details from Marine Exchange of Alaska. The AIS data used in this study was processed by Global Fishing Watch, an international nonprofit organization that uses AIS data from Spire combined with cloud computing and machine learning to create and publicly share knowledge about human activity at sea (Kroodsma et al., 2018). The dataset included over 125 million AIS records reported every five minutes from 1157 vessels over the 6.5-year study period.

2.2. Data processing

The ship characteristics data from S&P's IHS Markit included essential vessel parameters including information on ship type, cargo capacity, engine specifications, vessel design, service speed, and operator information (Appendix A Table A.1). For the 8 vessels missing main engine power data, we backfilled using the average values of similar ships. For the 879 vessels that were missing max design speed, we conservatively used average maximum design speed values of similar ships, which resulted in lower emissions estimates than if we had backfilled using service speed (Appendix A Table A.2 & Fig. A.3).

Each vessel was assigned a capacity bin according to its ship type and cargo carrying capacity using the same bin categories as outlined in the *Third IMO GHG Study 2014* (IMO, 2015) (see Appendix A Table A.4). Each ship was also classified into one of seven engine types using engine characteristics and engine tier was determined using the keel laid date (Olmer et al., 2017). The majority of vessels in this study were slow speed diesel engines and Tier I with keel laid date between 2000 and 2010 (see Appendix A Tables A.5 & A.6).

We created a comprehensive database linking vessel attributes to AIS position using each vessel's unique identification number issued by the IMO, the unique identification number of its AIS transponder called the Maritime Mobile Service Identity (MMSI), and vessel name. Port call information was assigned to AIS positions based on timestamps and MMSI and filtered to only include inbound voyages from Asia (Appendix A Table A.7). Because transpacific voyages typically take 13 days depending on the departure port, voyages with <7 days of AIS data between ports were considered incomplete (~1 % of total voyages) and were excluded.

2.3. Estimating emissions

In this analysis, we use a standardized bottom-up approach to estimate CO_2 emissions using the methodology outlined in the International Council on Clean Transportation (ICCT) reports (Comer et al., 2017; Olmer et al., 2017) as shown by Eq. (1) (and outlined in more detail in Appendix B Eq. B.1). Generally, there are two methodological approaches for estimating emissions in shipping: a top-down approach that uses highly aggregated information on ship activity like bunker fuel sales to estimate broad emission trends (Corbett et al., 1999; Corbett and Fischbeck, 1997; Endresen et al., 2007), and a bottom-up approach that uses detailed vessel activity data and ship characteristics to estimate fuel consumption and emissions (IMO, 2021; Miola and Ciuffo, 2011). Top-down approaches can provide macro level emissions trends, but do not consider differences in ship characteristics and tend to be less accurate and reliable, thus bottom-up approaches have become the dominant method to create emissions inventories (Cheng et al., 2024).

Specifically for this analysis, we used AIS data and vessel characteristics to calculate the CO_2 emissions for each ship position as follows:

$$\mathrm{E}_i = \sum\nolimits_{t=0}^{t=n}\left(\left(\mathrm{P}_{ME_i} \times \left(\frac{SOG_{i,t}}{V_{max_i}}\right)^3 \times EF_{ME_{j,k,l}}\right) + \left(PD_{Aux_{m,i}} \times EF_{Aux_{j,k,l}}\right) + \left(PD_{Boil_{m,i}} \times EF_{Boil_l}\right) \times 1\ hour\right) \tag{1}$$

where the CO_2 emissions (grams) for each ship position (E_i) is calculated by determining the operating phase of the vessel, engine power demand, and emission factors for each engine type (main, auxiliary, and boiler). These calculations are then aggregated over time and the study area to estimate total emissions.

The operating phase describes the operations of a vessel while in service (includes at-berth, anchorage, maneuvering, and cruising) and is classified using proximity to shore and/or port and speed over ground (see Appendix B Table B.2 for designation matrix). AIS positions were assigned: at-berth if within 1 mile of port and traveling at <1 knot; anchorage if traveling at speeds <3 knots; maneuvering if traveling between 3 and 5 knots within 5 miles of the coast or traveling above 1 knot within 1 mile of the port; and cruising if traveling above 3 knots and >5 miles from shore, or any speed >5 knots regardless of proximity to shore.

In certain operational phases, specific engines were assumed to be off, thus the power demand for that engine type was zero: boilers were assumed to be off during cruising, main engines were assumed to be off when vessels were at-berth or anchorage, and auxiliary engines were assumed to be off at-berth at the Ports of Los Angeles, Long Beach, and Vancouver where shore-side electrical power is offered to container ships (Appendix B Table B.3).

The auxiliary power demand ($PD_{Aux_{m,i}}$) and boiler power demand ($PD_{Boil_{m,i}}$) were determined using standardized assumptions from the *Third IMO GHG Study 2014* based on the operating phase, ship type and capacity bin (Appendix B Tables B.4 & B.5). The main engine power demand was calculated by multiplying installed power (P_{ME}) by the main engine load, which assumes engine load is proportional to the cube of the vessel speed (SOG/V_{max}) according to the propeller law (MAN Energy Solutions, 2018). In instances where recorded speed exceeded the maximum design speed (0.5 % of data points), we replaced these values with the average speed for that specific ship and operating mode. Data points with speeds exceeding 1.5 the max design speed (0.0001 % data points) were removed as erroneous (Olmer et al., 2017).

The power demand for each engine was then multiplied by emission factors (EF_{ME}, EF_{Aux}, and EF_{Boil}) based on the engine characteristics and fuel type, assuming vessels switched to low-sulfur fuel within U.S.

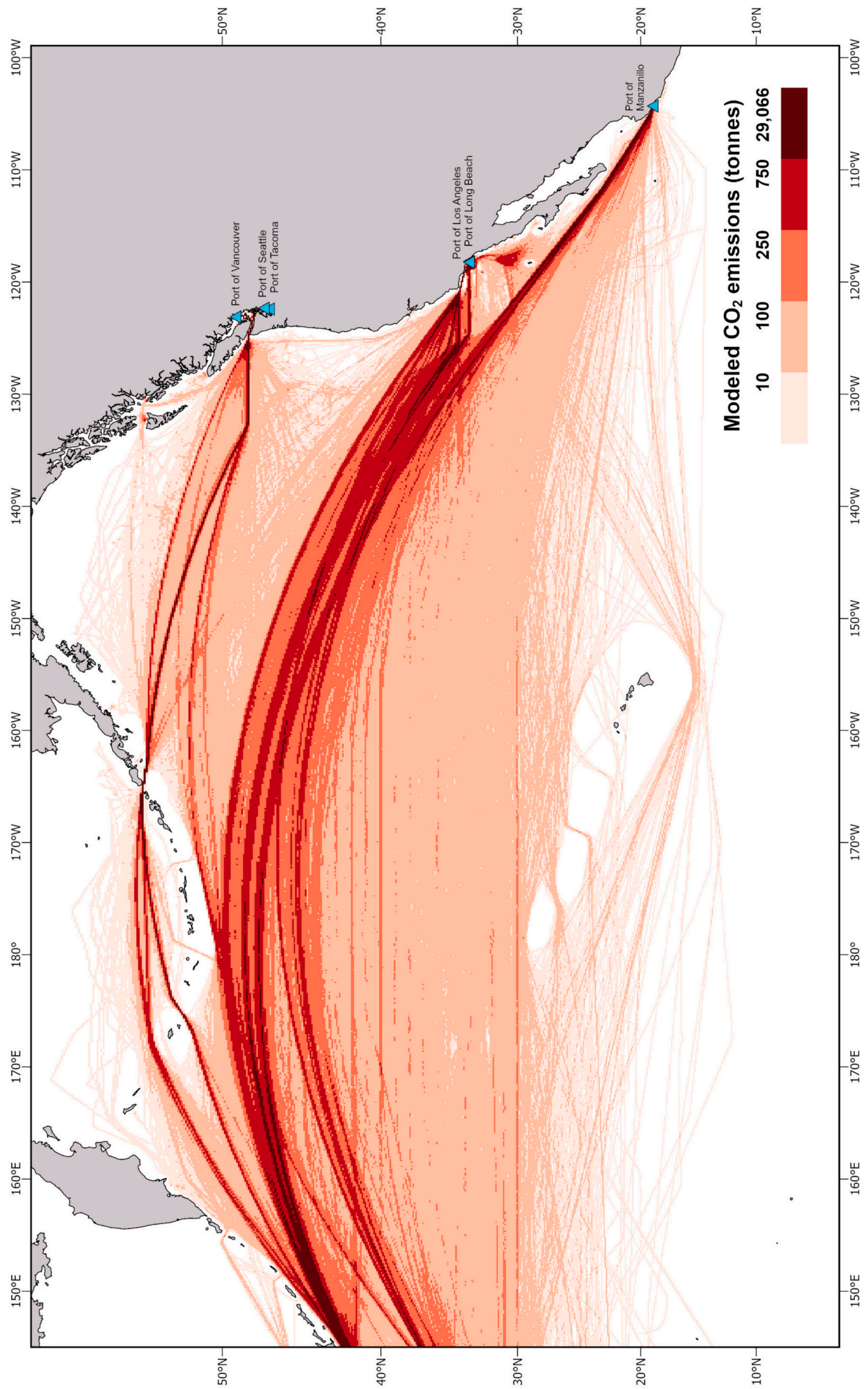

Fig. 2. Map of study area showing modeled CO_2 emissions of eastbound container ships from ports in East Asia to six major ports along the West Coast of North America from January 1, 2017, through August 31, 2023, at 0.1 × 0.1-degree resolution.

waters in compliance with Annex VI requirements (Appendix B Table B.6).

The CO_2 emissions for each ship position was then aggregated over time and the study area to estimate the total metric tonnes of CO_2, the average CO_2 emissions per nm traveled, and the average CO_2 emissions per voyage for each year at each port. We also calculated the distance-weighted average speed per voyage by calculating the speed and distance traveled for each time interval at each ship position (*i*):

$$\textit{Distance Weighted Average Speed} = \sum(\textit{Calculated Speed}_i \times \textit{Distance}_i) \Big/ \sum \textit{Distance}_i \tag{2}$$

where the *Calculated Speedi* was determined based on the distance and time from the previous point. To further isolate whether any changes in speed were occurring during the open-ocean portion of transpacific voyages, we calculated the average sail time per voyage from 145°east latitude to the U.S. EEZ using the minimum and maximum timestamps from the AIS data associated with each voyage.

2.4. Time series analysis

The estimated CO_2 emissions per nm traveled each month was averaged for enrolled container vessels calling at the Ports of Los Angeles and Long Beach. For comparison, we also estimated CO_2 emissions per nm traveled each month for all container vessels calling at each of our comparison ports (Ports of Manzanillo, Vancouver, and Seattle and Tacoma, i.e. ports not adopting a queuing system) to attempt to understand whether any observed differences at the Ports of Los Angeles and Long Beach can be attributed to the queuing system or other industry forcing mechanisms. To identify breakpoints, a point in the data set where a significant change occurs, we used the time series analysis breakpoints function in the *strucchange* package in R to find breakpoints in each of the port time series (Zeileis et al., 2002). This function takes advantage of dynamic programming in order to find the optimal number of structural breakpoints by minimizing residual sum of squares (RSS) of a linear model (Bai and Perron, 2003). The breakpoints identified represent points where there are statistically significant changes or structural shifts in the data, indicating external factors like policy changes, operational changes, or other factors may have meaningfully altered the ports' emission patterns. For any ports with a breakpoint within two months of the November 15, 2021 implementation of the queuing system, we then also conducted a generalized linear model comparing CO_2 emissions before and after this breakpoint, using before/after as our fixed effects and month as a random effect.

2.5. Emissions efficiency by operator

We examined the emissions efficiency by operator after the queuing system was put in place to better understand if and how variance between maritime shipping companies contributed to any of these patterns we observed. We compared emissions from transpacific voyages to the Ports of Los Angeles and Long Beach between January 1, 2022 and August 31, 2023 and summarized comparisons for the top 10 companies by distance traveled.

2.6. Hypothesized speed scenarios

Finally, to explore potential system modifications that could help maximize emissions reductions, we modeled seven hypothetical scenarios using one year of AIS data (July 2022–June 2023), estimating total CO_2 emissions if vessels had traveled at speeds ranging from 12 to 18 knots, with 18 knots representing the current Business-As-Usual scenario used to determine queue positions.

3. Results

In this study we analyzed a total of 1157 container vessels completing 10,043 eastbound transpacific voyages traveling over 47 million total nm between January 1, 2017 and August 31, 2023. In aggregate, we estimate that over 31 million tonnes of CO_2 were emitted during these voyages (Fig. 2). The majority of this traffic called at the Ports of Los Angeles and Long Beach (5589 port calls), followed by the Port of Manzanillo (2154 port calls), Ports of Seattle and Tacoma (1332 port calls), and the Port of Vancouver (960 port calls) (Fig. 3, Appendix C).

3.1. Trends in CO_2 emissions in Ports of Los Angeles and Long Beach

There was a significant observed reduction in estimated annual tonnes of CO_2 emissions per nm and per voyage at our focal Ports of Los Angeles and Long Beach after the queuing system was put in place (Table 1). In 2022, the first year after the queuing system was implemented, the average CO_2 emissions per nm dropped 22 % and 9.6 % in 2023 relative to the average pre-queuing system baseline period 2017–2021. We identified a single breakpoint in the emissions time series data for the Ports of Los Angeles and Long Beach occurring in October 2021; i.e. just prior to the implementation of the queuing system (Fig. 3). After this identified breakpoint, CO_2 emissions dropped precipitously and significantly from 0.74 +/− 0.03 t CO_2 per nm in the period prior to October 2021 to 0.60 +/− 0.07 t CO_2 per nm (DF 68.4, F = 169.8, $P < 0.0001$) in the subsequent period. In addition, we saw a 24 % reduction in average CO_2 per voyage in 2022 and 15.7 % reduction in average CO_2 per voyage in 2023 compared to the baseline (Table 1). The average sailing time for vessels traveling from 145°east latitude to the U.S. EEZ increased by 64 % in 2022 and 4.9 % in 2023 compared to the baseline average, indicating vessels were traveling at slower speeds after the implementation of the queuing system. This is also reflected in the distance-weighted average speed which dropped to 15.9 knots in 2022 and 17.6 knots in 2023 compared to the distance-weighted average speed of 18.6 knots during the baseline period.

3.2. Trends in CO_2 emissions in comparison ports without queuing systems

We observed an overall reduction in monthly average CO_2 emissions per nm at each of the three comparison ports of Manzanillo, Vancouver, and Seattle and Tacoma where a queuing system was not implemented (Fig. 3). However, determining the causes of these declines was complicated due to complex patterns in the data. We identified three breakpoints in the emissions time series data for the Port of Vancouver in February 2019, February 2020, and October 2021; a single breakpoint for the Port of Manzanillo in April 2022; and three break points in the time series for the Ports of Seattle and Tacoma in December 2017, January 2020, and June 2021. Aside from the aforementioned significant differences for the Ports of Los Angeles and Long Beach, the only other port with an October 2021 breakpoint was Vancouver. In this case CO_2 emissions declined from 0.54 t CO_2 per nm +/− 0.05 in the period prior to October 2021 to 0.45 t CO_2 per nm +/− 0.05 (DF 31.7, F = 33.0, <0.0001) in the period after.

3.3. Emissions variance by operator

We observed a substantial amount of variation in the CO_2 emissions efficiency among the top 10 container shipping companies, ranked by total distance traveled from ports in East Asia to the Ports of Los Angeles and Long Beach in the period after the queuing system was implemented, January 1, 2022 to August 31, 2023 (Fig. 4).

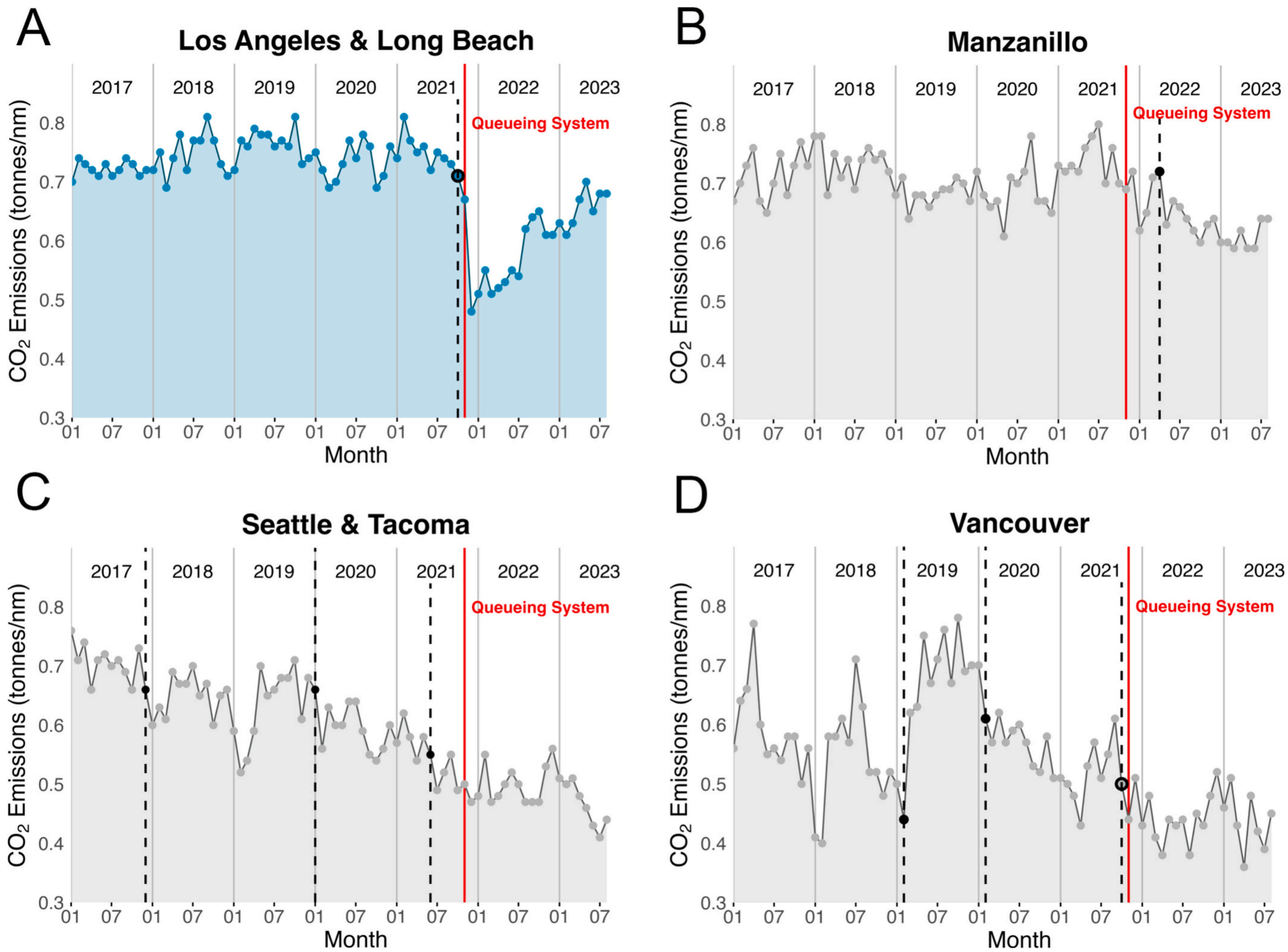

Fig. 3. Time series of total estimated CO_2 emitted per nm averaged monthly over the entirety of eastbound transpacific voyages for container vessels traveling from East Asia to the Ports of (A) Los Angeles and Long Beach, (B) Manzanillo, (C) Seattle and Tacoma, and (D) Vancouver. Breakpoints identified in times series analysis are shown in black; those that were statistically significant are represented by open black circles. The time at which the New Queuing System for Labor went into place at the Ports of Los Angeles and Long Beach (i.e. November 2021) is shown in red. A queuing system was not implemented in the Ports of Manzanillo, Seattle and Tacoma, and Vancouver. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
CO_2 emissions summary for 581 container ships enrolled in the queuing systems traveling eastbound from Asia to the Ports of Los Angeles and Long Beach.

Year	Vessels	Voyages	Average time to EEZ (hours)	Distance-weighted average speed (knots)	Distance (nm)	Total CO_2 (tonnes)	Tonnes CO_2 per voyage	Tonnes CO_2 per nm
2017	124	517	211	19.4	2,546,567	1,839,395	3558	0.72
2018	133	587	211	19.3	2,696,175	2,012,496	3428	0.75
2019	152	646	215	19.0	2,894,229	2,214,089	3427	0.77
2020	263	823	217	18.6	3,742,008	2,752,497	3344	0.74
2021	367	1054	242	17.8	5,198,894	3,720,971	3530	0.72
Average (2017–2021)	208	725	227	18.7	3,415,575	2,507,889	3457	0.73
2022	445	1256	373	15.9	5,850,743	3,312,940	2638	0.57
2023[a]	310	706	238	17.6	3,134,849	2,057,728	2915	0.66

[a] Note: 2023 data is not a complete calendar year–includes data from January 1–August 31, 2023.

3.4. *Estimating CO_2 emissions that could be achieved via changes to queuing system structure*

In our theoretical modeling experiments exploring the potential implications of reducing the average speed currently used to determine the Calculated Time of Arrival (i.e. 18 knots for the majority of ships) in this queuing system, we found that reducing the speed to 17 knots compared to the BAU 18 knots reduced the estimated total tonnes of CO_2 emissions by 9 % or 307,805 t. Reducing the speed to 16 knots would theoretically further reduce CO_2 emissions by 17.7 % or 594,532 t compared to BAU (Fig. 5). Similar emissions reductions appear to continue to be achieved with further reductions in speed.

4. Discussion

The implementation of a new queuing system at the Ports of Los

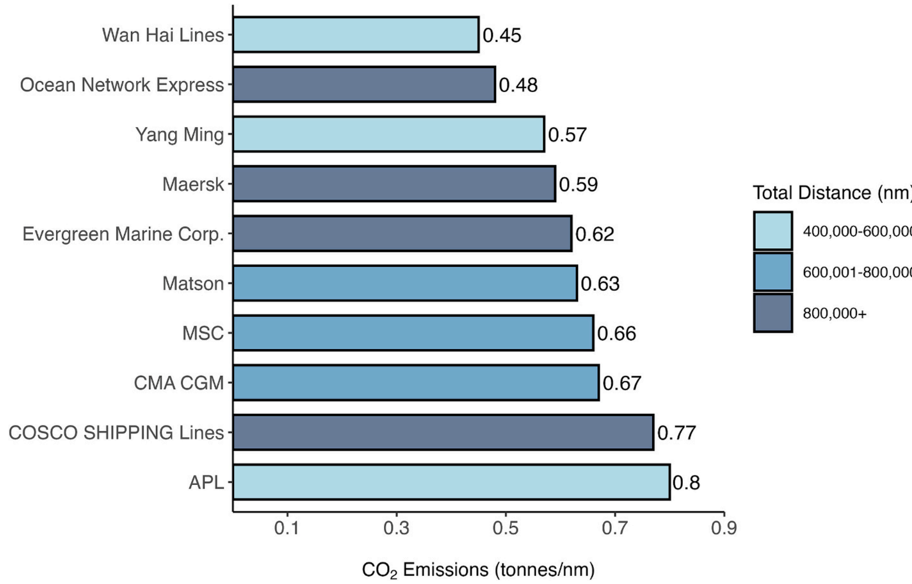

Fig. 4. Average CO_2 emissions per nm for the top 10 container shipping companies. Top operators were selected in respect to the total distance transited from East Asia to Ports of Los Angeles and Long Beach between January 1, 2022 and August 31, 2023. The observed variation in emissions efficiency between operators suggests the value of bespoke engagement with companies to optimize gains under the newly implemented queuing system.

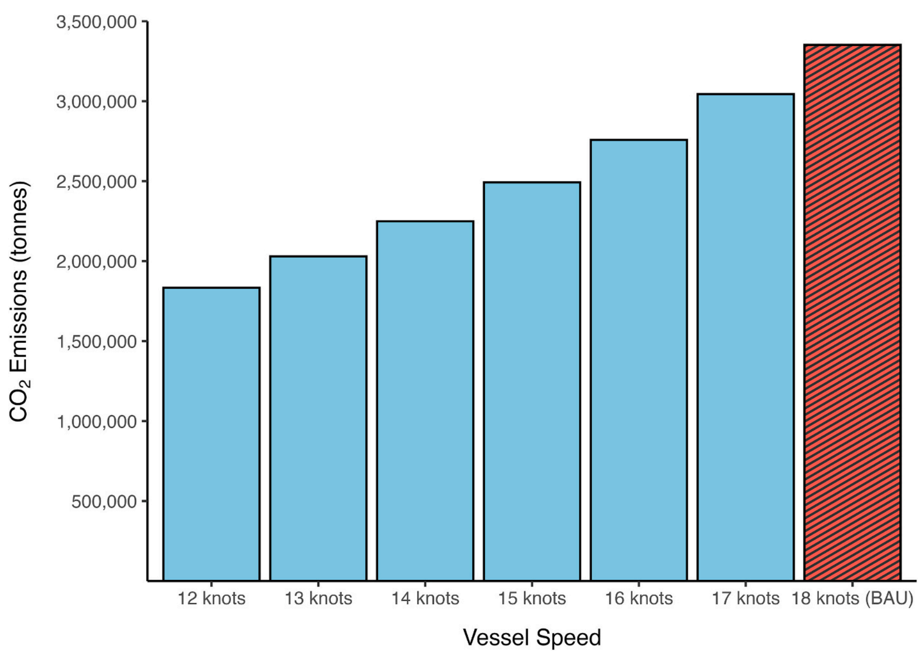

Fig. 5. Total CO_2 emissions projected across seven different hypothesized speed scenarios using AIS data from July 1, 2022, through June 30, 2023 for all inbound eastbound container vessels from Asia to the Ports of Los Angeles and Long Beach.

Angeles and Long Beach provided a unique opportunity to empirically examine the secondary benefits these efficiency reforms might have on reducing the CO_2 emissions of maritime shipping. During our study period, we observed an overall improvement in emissions efficiency after the queuing system was implemented. Container vessels traveled at slower speeds, with average CO_2 per nm decreasing, and average tonnes of CO_2 per voyage dropping by 24 % in 2022 and 16 % in 2023 (Table 1). These reductions align with other studies that found an average 14 % reduction in fuel consumption per voyage for fully optimized Just-In-Time operations for container ships (GEF-UNDP-IMO GloMEEP Project and members of the GIA, 2022) and an average 8 % reduction in fuel per voyage when optimizing speed in the last 24 h of the voyage at the Port of Rotterdam (IMO, 2020).

When looking at this data on a monthly basis using a time-series analysis (Fig. 3), we see a clear statistically significant breakpoint in October 2021 at the Ports of Los Angeles and Long Beach with a sharp reduction (i.e. 32 %) in CO_2 emissions per nm around the time the queuing system was implemented, between November and December 2021. The following six-month period, from January to July 2022, has relatively low emissions at the Ports of Los Angeles and Long Beach, which may have been impacted by the especially long COVID-associated wait times and backlogs that took six months to clear after the queuing system was established. During this time, vessels had to wait an additional 1–3 weeks after their given Calculated Time of Arrival, which may have influenced some vessels to slow down further.

When comparing emissions across ports, several important contextual factors must be considered. We acknowledge that it is difficult to compare directly across these different ports given that they host significantly different volumes of traffic (i.e. ports of Los Angeles and Long Beach together host approximately 2.6, 4.2, and 5.8 times more port calls considered in this analysis than the Ports of Manzanillo, Seattle and Tacoma, and Vancouver, respectively, see Appendix C). High-volume ports like Los Angeles and Long Beach operate closer to capacity constraints, creating greater competition for berth space and increasing congestion-related delays. In such high-pressure environments, vessels prior to the implementation of queuing systems would have had strong incentives to "sail fast, then wait" to secure position in the berthing queue, making the system's impact potentially more pronounced. Conversely, at lower-volume ports with less congestion, vessels have reduced incentives to rush to port since berth availability is more predictable, naturally leading to more efficient sailing speeds regardless of formal queue management systems. Additionally, the composition of port traffic matters and varies considerably between the ports examined herein. Vancouver, for instance, experiences significant congestion, but primarily with bulk cargo (not treated in these analyses) rather than container shipping (Heaver and Atkins, 2024; Heaver, 2021), creating a fundamentally different operational environment. Geographical factors further complicate these cross-port comparisons, as northern ports like Seattle, Tacoma, and Vancouver, are located at a higher latitude along a trade route that, while more direct, may experience more extreme oceanographic conditions that would require ships to travel at slower speeds to avoid inclement weather.

Despite these operational and geographic differences that make direct port-to-port comparisons challenging, examining emission patterns across all study ports can still provide valuable insights into the relative impact of the queuing system versus other industry-wide factors. Our results suggest that the emissions efficiency gains observed in the Ports of Los Angeles and Long Beach seem unlikely to be driven entirely by the queuing system. We did, for example, also observe reductions in CO_2 emissions during approximately the same time period in our outgroup comparison ports, Manzanillo, Vancouver, and Seattle and Tacoma; i.e. ports that did not have a queuing system. Average emissions in these three other ports were generally variable (Fig. 3). The Port of Vancouver emissions time series exhibited three breakpoints, including one breakpoint shared with the Ports of Los Angeles and Long Beach (October 2021). The emissions time series for the Ports of Seattle and Tacoma had three breakpoints occurring before the November/December 2021 start of the queuing system in the Ports of Long Beach and Los Angeles. The Ports of Seattle and Tacoma also exhibited a general declining trend in emissions over the entire study period, suggesting other factors are impacting industry behavior at these two ports. More research is required, but the starkness of the difference of mean emissions before and after the October 2021 breakpoint at the Ports of Los Angeles and Long Beach compared to Vancouver is suggestive that the queuing intervention is playing a contributing role to the emissions declines at the Ports of Los Angeles and Long Beach.

While our findings suggest the queuing system may have contributed to emissions reductions, several concurrent industry-wide factors likely influenced observed trends across all ports. Following the COVID-19 pandemic, marine fuel prices rose dramatically, with very low sulfur fuel oil prices nearly doubling from January 2021 to June 2022 (Miller, 2023), creating economic incentives for slow steaming regardless of port systems. In the past, high oil prices and a downturn in the global economy has resulted in the slow steaming of container ships, as was the case between 2007 and 2012 (IMO, 2015). Simultaneously, there was an unprecedented surge in container freight rates, with the Shanghai Containerized Freight Index reaching five times pre-pandemic levels by January 2022, generating record profits for container carriers in 2022 (UNCTAD, 2023). This market spike affected ship operations, with many carriers initially prioritizing faster transit times to maximize voyages during the boom period, before shifting strategies toward fuel efficiency as rates normalized in early 2023. Additionally, global containerized trade volumes decreased by 3.7 % in 2022 and had low growth in 2023, while shipping capacity expanded, prompting slow steaming as a capacity management strategy (UNCTAD, 2023). Additionally, new emission regulations requiring Energy Efficiency Existing Ship Index (EEXI) calculations and Carbon Intensity Indicator (CII) ratings incentivized slower speeds to improve efficiency ratings. These market and regulatory shifts likely contributed to the emissions reductions observed across all study ports.

In general, ports have an important role to play and can implement programs and policies like this new queuing system that create a more supportive, predictable, and stable environment for more efficient, climate-smart shipping behaviors. Such programs, however, still depend upon proper and active participation by the companies involved. Following the queuing system's implementation, we observed significant variability in emissions efficiency among the ten largest container shipping companies (by total distance traveled) transiting from ports in East Asia to the Ports of Los Angeles and Long Beach (Fig. 4). There was an approximately 1.7-fold difference between the company with the lowest estimated amount of CO_2 emissions per nm and the company with the highest estimated emissions. This variation likely stems from several factors: differences in fleet composition (vessel size and age), varying operational priorities among companies (particularly regarding schedule reliability and on-time arrivals), and different climate strategies, with some companies, like Maersk, adopting more accelerated decarbonization goals of reaching net-zero by 2040 (Maersk, 2022). The size and age of vessels can fundamentally shape emissions performance, with newer ships benefiting from technological innovations like optimized hull designs and more efficient engines, while larger vessels typically require fewer voyages to transport the same cargo volume. Understanding how these factors influence emissions performance at the company level would require further research, but could be very valuable in helping to design a more optimized queuing system that maximizes emissions reductions across the diverse spectrum of container fleets.

This variation among shipping companies has important implications for the overall effectiveness of the queuing system. The substantial differences suggest that implementing the queuing system alone is not sufficient to ensure emissions reductions across all shipping companies. Companies with newer fleets or those already prioritizing fuel efficiency may have been better positioned to capitalize on the flexibility offered by the queuing system, while others with older vessels or different operational priorities might require additional incentives or regulatory pressure to achieve comparable reductions. These findings suggest that future refinements to port queuing systems might benefit from additional direct dialogue and consultation with specific companies to identify complementary policies or bespoke actions that can be adopted to address the unique challenges faced each by company and to potentially yield substantial additional emissions reductions beyond what the current system has achieved.

The observations in this study raise the important question of how this queuing system could be further modified in the future to generate more significant CO_2 emission reduction benefits, alongside the intended benefits associated with backlog prevention. Our simplified scenario testing suggests that, all other factors held the same, using slower predetermined average speeds for the Calculated Time of Arrival would be one way to further reduce CO_2 emissions (Fig. 5). For example, in the simplified scenarios projected CO_2 emissions decreased by almost 18 % (594,532 t of CO_2) if vessels traveled at 16 knots instead of 18 knots (reducing speed by 11 %). While such CO_2 reductions pertain solely to the container vessels included in this study, this general relationship between reduced ship speed and reduced CO_2 emissions for container vessels has been reported in other contexts. Other estimates, have for example, suggested emissions would decrease by 36 % with a 12 % reduction speed for a medium sized container vessel (Elkafas and Shouman, 2021), and 13–32 % emission reduction associated with 10–30 % speed reduction for container vessels (Faber et al., 2017). In the context of this queuing system, if 16 knots were used to determine the Calculated Time of Arrival, this would add approximately 36 h to the calculated voyage time of 13 days, 17 h for vessels traveling from Busan, South Korea to the Ports of Los Angeles and Long Beach. Such reductions in speed would be likely to generate other important benefits unrelated to emissions such as reduced marine mammal collision risk and reduced sound pollution (Findlay et al., 2023; McCauley, 2023; Vanderlaan and Taggart, 2007).

Such adjustments in speed may also not be feasible for all vessels due to mechanical constraints and business considerations, which partly explains why this queuing system remains voluntary and does not mandate slower speeds for Calculated Time of Arrival. For example, there are some mechanical risks of operating engines below design speed for specific vessels, which in some instances can increase fouling, corrosion in engines, and emissions of particulate matter, black carbon, and NOx due to inefficient combustion at low engine loads depending on the age and type of engine (IMO, 2018b). However, there are engine modification retrofitting options with upgrade kits that could alleviate some of these technical risks for some vessels (Zis et al., 2015). There are also some potential downsides of slowing down from a business perspective. While speed reductions have potential savings in fuel and emissions reductions, there are also potential increases in operating expenses associated with longer transit time that could have broader impacts on the entire supply chain and warrant further evaluation to understand the full impact. Whether these benefits outweigh the costs largely depend on market conditions (e.g. fuel prices, freight rates, customer time demands, fleet capacity), design speed of each vessel, type and volume of cargo, distance traveled, and weather conditions or other route disruptions (Vakili et al., 2023).

There are other challenges to scaling and enhancing this type of container queuing system due to different organization frameworks, governance structures, and stakeholders involved at ports around the world. Unlike the aviation sector, which operates through a highly centralized traffic management system with air traffic controllers having direct authority over aircraft movements, maritime shipping functions through a fundamentally decentralized approach where vessel masters retain primary decision-making authority for navigation while shore-based vessel traffic services typically provide only monitoring and advisory support (Praetorius et al., 2012). This decentralized maritime governance creates a complex operational landscape where vessels follow global IMO regulations, but ports and shoreside infrastructure operate under heterogeneous national frameworks that vary significantly between countries and sometimes even between ports within the same country (Lind et al., 2021). This results in a fragmented system where maritime authorities, port authorities, terminal operators, and service providers function with varying degrees of centralization, different technological capabilities, and often conflicting operational priorities, significantly complicating efforts to implement standardized approaches to emissions reduction. Additionally, the commercial relationships between carriers, terminal operators, and cargo owners often involve competing interests and misaligned incentives regarding vessel scheduling and berth allocation (Jia et al., 2017; Poulsen and Sampson, 2019; Rehmatulla and Smith, 2015). Furthermore, the absence of standardized data exchange protocols between stakeholders impedes the seamless information sharing required for effective Just-In-Time arrivals, with many communications still conducted through traditional methods such as email and phone rather than integrated digital platforms.

The complex, decentralized governance challenges described above were precisely what made the queuing system at the Ports of Los Angeles and Long Beach so noteworthy. Despite operating within this fragmented maritime landscape, these ports successfully implemented a system that, while primarily designed to address severe congestion, also yielded emissions reduction benefits. Its success relied heavily on the coordination capabilities of PacMMS and the Marine Exchange of Southern California, which provided the digital infrastructure and operational expertise necessary for effective vessel management. Equally crucial was the active participation of vessels and carriers, whose willingness to comply with the new protocols ultimately determined the system's effectiveness. The unprecedented supply chain disruptions during the pandemic created a unique window of opportunity for collaborative action, enabling diverse stakeholders to overcome traditional barriers to coordination that might have prevented implementation under normal circumstances. While similar systems could theoretically be implemented at other ports, their feasibility depends significantly on each port's governance alignment, institutional capacity, and digital maturity. Ports with more fragmented governance or those dominated by private interests may struggle to implement similar systems without clear mandates or incentives. The willingness of stakeholders to adopt such systems remains a critical factor that varies considerably across different port ecosystems. This case study contributes to the literature on port greening and stakeholder coordination by demonstrating how a pragmatic, incremental system that focuses only on queue position—rather than attempting to fully synchronize all aspects of port operations—can still achieve meaningful improvements.

Beyond governance and stakeholder considerations, terminal operations at ports are another critical factor affecting both the scaling and efficacy of the queuing system. Terminal operations vary widely from port to port and even within ports. One consideration not explored in this study was whether carriers with dedicated labor arrangements experienced different outcomes. Such arrangements could potentially create parallel operational structures for specific carriers that bypass the intended benefits of collaborative queue management. Additionally, this study did not examine how the queuing system impacted coordination capabilities across different terminal types—particularly the contrast between carrier-integrated terminals (owned/operated by shipping lines), which typically demonstrate greater efficiency in berth coordination due to their direct control over operations (Poulsen and Sampson, 2020), and independent terminals (operated by third parties serving multiple shipping lines). Future research could investigate any links, potentially revealing ways to scale and optimize this queuing system to other ports with different terminal configurations.

In addition to terminal operations, the port type is another important consideration. The ports analyzed in this study are primarily gateway ports that serve as entry points for cargo moving into their respective hinterlands, rather than transshipment ports where containers move between different vessels. This distinction is important when considering the generalizability of our findings. Gateway ports typically have more predictable vessel arrivals tied to landside logistics schedules, making them potentially more suitable candidates for queuing systems like the one implemented at Los Angeles and Long Beach. Transshipment ports, which primarily facilitate vessel-to-vessel transfers and serve as hubs in global shipping networks, face additional complexities in berth allocation. At these ports, berth assignments depend not only on berth availability but also on creating efficient connections between deep-sea and feeder vessels. Consequently, the benefits and implementation challenges of similar queuing systems would likely differ in transshipment-focused ports, where berth allocation is optimized for network connectivity rather than simply processing vessels in queue order. Further research would be needed to assess the potential CO_2 reduction benefits of modified queuing systems in primarily transshipment-oriented environments.

Alongside these scaling considerations, it is important to acknowledge several inherent limitations of the queuing system. First, the system does not fundamentally alter terminal operations or increase physical port capacity, meaning that during periods of extreme congestion, waiting times may still increase regardless of queue management approach. Second, the system's use of standardized transit speeds (18 and 21 knots) for queue position calculation may not optimally reflect the diverse vessel characteristics within the container fleet, which may be advantageous for certain carriers and vessel types over others. Third, weather disruptions and other unpredictable factors can significantly impact transit times, creating challenges for queue position calculations that assume relatively consistent conditions. These limitations highlight that while the queuing system represents a valuable incremental improvement, it is not a complete solution to the complex challenges of maritime emissions reduction and port congestion.

While there are challenges and limitations to scaling this queuing system, there are additional benefits beyond emissions reductions that might help incentivize other ports to adapt this type of system. One advantage is that it extends ports' visibility of incoming vessels from the typical 2–4 days to up to 16 days in advance. This information can help ports schedule, plan, and make operational decisions for shore-side logistics, in particular better planning for trucks and trains that move the cargo, which could be associated with further reductions in port emissions resulting from other actions underway (Sun et al., 2025). For example, the Ports of Los Angeles and Long Beach have integrated this information in their digital data-sharing platforms, Port Optimizer and Supply Chain Information Highway, which help improve port efficiency and increase throughput. Another benefit to this type of queuing system is that it can provide a more stable and predictable environment for all stakeholders during major disruptions related to labor shortages, global pandemics, natural disasters, and other unforeseen circumstances. Having a queuing system serves as a built-in resilience mechanism or "insurance" policy, helping ports maintain operations during these difficult times.

Our study has several important limitations worth noting. First, our emissions calculations relied on a bottom-up modeling approach using AIS data rather than direct fuel consumption measurements. While this approach provides valuable first insights into broad emissions trends, it involves assumptions and generalizations that introduce uncertainty (Chen and Yang, 2024). For example, our model was unable to account for vessel retrofits or upgrades, which could lead to overestimating emissions at the individual ship level. It also did not consider factors such as hull condition, wind currents, wave height, or draught, which can cause under or overestimations (Merien-Paul et al., 2018). Second, the complex nature of the shipping industry makes it challenging to discern mechanistic drivers of behavioral changes and isolate the specific effects of the queuing system from other contemporaneous factors like the COVID-19 pandemic, fuel price fluctuations, and changing trade patterns. Third, our relatively short post-implementation study period provides limited data on long-term effects.

Future research should address these and other limitations by extending the study period to assess whether more discernible CO_2 emissions reductions are achieved over longer time horizons as the queuing system remains in effect. Future studies could also improve on this modeling effort by incorporating in-situ emissions data collected directly on vessels and comparing against reported fuel consumption to provide more accurate emissions estimates (Fan et al., 2024). A more in-depth analysis of how variability in traffic volume at the comparison ports and other port types might have influenced our results would be valuable, as fluctuations in shipping patterns, seasonal demand changes, or regional economic factors could mask or amplify the emissions effects attributable to the queuing system itself. Additional valuable directions include examining how this compares to other Just-In-Time arrival systems being implemented or piloted at other ports, evaluating the economic implications of modifying the speeds used in the queuing system, and investigating the applicability of similar systems in transshipment-focused ports or different shipping sectors beyond container shipping.

5. Conclusion

This present work represents the first analysis of the impact of the queuing system implemented at the Ports of Los Angeles and Long Beach on CO_2 emissions from transpacific voyages. We observed a clear overall reduction in CO_2 emissions after the queuing system was implemented, although it was difficult to isolate the direct causality of the queuing system versus other shipping industry forcing mechanisms when comparing these changes in CO_2 emissions to other trends at comparison ports. We highlight some refinements in the way voyage speeds are used in these new queuing systems that may further improve the impact such systems may have on CO_2 emissions. We recognize and stress that successfully meeting the decarbonization goals of the shipping industry will require a portfolio of fundamental changes that include both technological and operational measures that require collaborative efforts from stakeholders across the entire supply chain, including ports. This type of queuing systems appear to present one relatively low-cost, easier to implement intervention that could be scaled to other major ports around the world, although such scaling would require consideration of different port governance and existing digital infrastructure. While far from a complete solution to shipping's emissions challenges, such systems can represent incremental steps forward in applicable contexts that contribute to a broader transition toward a more sustainable global maritime transportation system.

CRediT authorship contribution statement

Rachel Rhodes: Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Callie Leiphardt:** Writing – review & editing, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Hillary S. Young:** Writing – review & editing, Methodology, Formal analysis. **Jessica Morten:** Writing – review & editing, Methodology, Conceptualization. **Byron Hayes:** Writing – review & editing, Methodology, Conceptualization. **Jen Dillon:** Writing – review & editing, Methodology, Conceptualization. **Wendy Louttit:** Writing – review & editing, Methodology, Conceptualization. **Mark Powell:** Writing – review & editing, Validation, Methodology. **Douglas McCauley:** Writing – original draft, Methodology, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: co-authors (Byron Hayes, Jen Dillon, and Wendy Louttit) help administer the queueing system at the Ports of Los Angeles and Long Beach. 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118151.

Data availability

Ship characteristic data from S&P and AIS data from Spire is proprietary and unavailable. The supporting model code for calculating emissions will be made available on GitHub.

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